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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 5, NDRC

VOLUME 1

GUIDED MISSILES AND TECHNIQUES

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 5
HUGH H. SPENCER, CHIEF

WASHINGTON, D.C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over 20 volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC; account must be taken of the monographs and available reports published elsewhere.

Division 5 was responsible for research and development work on guided missiles. As the war came to an end, work in this field rated a priority second only to that of the work on atomic fission, for its implications for any future war were seen to justify such evaluation. Thus, Division 5 both contributed to the winning of the war and laid a solid technical foundation for future research aimed at keeping the nation prepared against any emergency.

The Division, under the leadership first of Harold B. Richmond and later under Hugh H. Spencer, succeeded in developing a glide bomb that homed on its target by radar, and a visually guided high-angle bomb with radio remote control. These weapons were employed to destroy key communication links in Italy, France, and Burma, and Japanese shipping and naval units. The war's end prevented combat use of a heat-homing high-angle bomb, a television-guided medium-angle bomb, and a glide bomb promising very many times the accuracy of a conventional bomb.

The work of Division 5 is described in this Summary Technical Report. Preparation of the report was supervised by the Division Chief, and its publication has been authorized by him. To him and his colleagues, for helping to keep our armed forces in the forefront of the technical race which is modern warfare, we express our sincere appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

THIS SUMMARY TECHNICAL REPORT presents the guided-missile program carried out by the National Defense Research Committee [NDRC] during the war. The sponsor, Division 5, was created by the reorganization of NDRC some eighteen months after the start of NDRC's program of war research. Some of the work here reported, therefore, treats of projects completed by predecessor groups. Some represents activities which had been begun under the supervision of predecessors and were completed by Division 5.

The technical information presented here stems from the work of the Division's contractors. This principle is not unique with Division 5 but its reiteration is perhaps worth while. The function of the Division was one of critical administration rather than the exploration of new fields of scientific thought or the development of new techniques in applied science. It considered possible new fields of scientific study and assigned to contractors specific investigations within those fields. In addition, it directed the activities of contractors in the technologies necessary to bring to fruition the results of its contractors' scientific research.

Having established a group of working contracts, the Division then critically reviewed the work of the contractors and interpreted their results to the Services. It stimulated where additional efforts seemed indicated, and restrained where diversification of effort seemed profitless.

The material presented here, therefore, is a summary of the developments and discoveries of the Division's contractors. Credit for whatever is new herein is due contractors and not the Division, and where the text does not make this clear an oversight has occurred. The report is, however, something more than a mere distillate of contractors' reports. A large group of competent scientific and technological men and women was assembled by the Division's contractors, all working in the broad field of guided missiles. The views of these individuals were often divergent, occasionally contradictory. The book attempts to bring these divergencies into focus and to resolve them, to draw attention to contradictions and to assess the arguments supporting the hypotheses set forth.

The book is divided into four parts: a summary, followed by the body of the report in three parts.

The summary presents a résumé of the entire activities of the Division. It is intended to be sufficient to meet the needs of those generals and admirals having responsibilities in the guided-missile field but who are prevented by the pressure of other duties from undertaking its detailed study.

The Division directed the development of four systems of guided missiles. Two of these systems involved remote radio control; two were automatically target-seeking. Part I discusses these systems in detail. The whole experience of the Division proves conclusively that guided-missile development can be successfully prosecuted only by careful consideration of the integrated missile system—airframe, control surfaces, and means of guidance. This principle is fully supported by what has been reported of the experience of our enemies. Two of the missile systems developed by the Division reached combat. Another was ordered for combat, and combat teams were in training. A fourth was still incompletely developed as hostilities ceased. These four systems are broadly considered in Part I.

Part II discusses the components which the Division undertook to develop separately, as distinguished from the development of a system consisting of a missile and its controls. Only a few of the many proposed were prosecuted, the experience of the Division clearly teaching that such separation of effort can almost never lead to success. In addition to a description of the separate projects in control of missiles, Part II describes accessory techniques, such as the development of simulators and trainers, which the Division found to be of important assistance to its program.

Part III presents direct contributions from certain of the Division's contractors. Each of the groups having primary responsibility for a guided-missile system was invited to contribute a monograph chapter to this report. Dr. Hugh L. Dryden of the National Bureau of Standards, R. D. Wyckoff of the Gulf Research and Development Company, and Dr. W. B. Klemperer of the Douglas Aircraft Company accepted the invitation; the Massachusetts Institute of Technology declined.

Each of these authors is peculiarly qualified to write critically in the guided-missile field. Besides his work for the Division as director of the glide-bomb program, Dr. Dryden has served on the von Kármán

Committee of the Chief of Air Staff. This committee conducted a very broad investigation into the future possibilities of aerial combat. Mr. Wyckoff directed the development program of the Division's high-angle dirigible bomb, the only guided missile save the Japanese suicide devices to see combat use in significant quantity during the war. Dr. Klemperer directed the development of Project Roc at Douglas Aircraft Company. He brought to the project experience in both the airship and airplane fields. His knowledge gained from experience in the Roc project has been enriched by an extended tour of Germany since the cessation of hostilities there. As a member of the ALSOS Mission (under G-2, U. S. Army Intelligence) he was charged with the responsibility of evaluating the wartime development resources of Germany in the guided-missile field.

The facts presented in Parts I and II are the contractors'; the comments thereon are the authors'. In Part III the facts and their evaluation are the sole product of the contractors. No effort has been made to resolve differences which may appear between the points of view expressed in these chapters and those in the chapters of Parts I and II. Progress in science and in technology is made by the candid recognition of divergent views and by their resolution through frank discussion.

The book as a whole is repetitious. This is neither good nor inadvertent. It is the price paid for making each chapter self-sufficient. Thus the reader whose prime interest is in glide bombs need not read the chapter on Felix, although many problems are common to both projects and the findings in one program are apposite to the other.

Mathematics has been avoided but not shunned. The use of this language has been invoked when that form of speech (1) by its succinctness avoids verbiage; (2) by its exact limitation avoids the danger of generalization not justified by the experimental evidence; and (3) by its generality concisely states the scope of a conclusion. The editor has attempted to prepare the text so that the program will be clear even to those whose linguistics do not include mathematics; in general, therefore, neither the quantity of the mathematics nor its level is such as to repel the reader who has a basic technical background.

The book makes no attempt to recommend a broad program on guided missiles for the United States. Many other groups, both military and civilian, have undertaken that responsibility. What is attempted here is the presentation of such experience of the Division and the formulation of such principles arising from it as may profitably be brought to bear on the guided-missile program of this country as it develops.

In writing, the editor has been trapped into use of the phrase, "So far as the Division is aware . . . " This introduction to each statement is accurate but dishonest. As a result of considerable demobilization, the Division now consists of the editor and two technical aides with whom he is in continual touch. Serious effort has been made to obtain from former Division members their criticisms of the material as it has appeared. They have been most generous with their time and thought. The book should not, however, be taken as the outcome of deliberations by the men who formerly comprised the body of the Division. Where errors of omission, of emphasis, or of fact occur, the fault is the editor's.

A Summary Technical Report is hardly the medium for the expression of appreciation to colleagues. The editor can hardly close this foreword, however, without such a word of gratitude to all his former associates, who are enumerated in the list of OSRD appointees. Particularly is he indebted to Dr. E. W. Phelan and Dr. J. C. Boyce for their direct contributions to the text.

Hugh H. Spencer

Chief, Division 5

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Azon strikes on Taungup Road Bridge in Burma by Tenth Air Force, June 1945. Altitude, 12,000 feet.

SECRET

SUMMARY

The successful glide-bomb attack by the Germans on a British convoy in the Bay of Biscay on August 23, 1943, gave an impetus to American development of guided missiles which has intensified continuously ever since. This is not to say that American effort had not been concerned with weapons of this character before the German guided bombs made their appearance. On the contrary, the United States Services had been working for some years on guided bombs, both powered (drones) and unpowered (glide bombs). In addition, NDRC had had guided-missile projects under development for many months. The one successful combat test by the Germans of Hs 293 in August 1943, followed by their use of FX-1400 against the USS *Savannah* a few weeks later, however, did more to bring to the attention of senior executives at the planning level the possibilities in guided missiles than all the previous demonstrations and reports by research and development groups. This was perhaps as true in the Services as it was within NDRC. The V-1 buzz-bomb and the long-range V-2 rocket, while not guided in the sense that their trajectories could be altered after launching, stimulated a continuing interest. As World War II closed, there was probably no military development program, with the exception of atomic power, of higher priority than guided missiles.

NDRC had four systems of guided missiles in its development program. Two of these saw combat use, and a thiird was in production for combat with crews in train ng at the end of hostilities. These systems comprised radar-homing glide bombs, visually guided high-angle bombs with radio remote control, a heat-homing high-angle bomb, and a medium-angle bomb of high maneuverability guided by television. In addition, the program included the development of a few of the many components which were suggested to control or to assist in the control of bombs.

Glide Bombs

The glide bombs developed by Division 5, NDRC, were high-wing monoplanes which were characterized by two features. They had a high-wing loading so that they were self-supporting only at speeds considerably greater than those of conventional bombardment aircraft; they consequently had to be carried under the airplanes that attacked with them. Unlike the glide bombs of the Army Air Forces' program, they had no rudders or elevators. Controlled flight was obtained by trailing-edge wing flaps which altered the lift developed by the wings. These flaps were controlled through a linkage which permitted the flaps to be raised and lowered either exactly together or in opposition—one up, the other equally down. Simultaneous elevation or depression of the flaps provided control in range. Differential operation of the flaps provided control in azimuth. This design produced in the missile the characteristic of nearly constant angle between the fuselage and the line of flight for all inclinations of the glide path.

Thus a homing device mounted in the glide bomb could be bore-sighted so that its axis of scan was always approximately tangent to the flight path. All the work of the Division has indicated that this is the most important property of homing missiles. Unless the homing device scans along the line of flight, a computing device has to be inserted in the servo system to correct continuously for angular deviations between axis of scan and the flight path. The homing missiles of the Division's program were designed to look where they were going.

The radar-homing control equipment for the glide bombs came in two versions. The initial version, Pelican, was a Division project. The radar transmitter which illuminated the target was mounted on the carrying aircraft. The glide bomb carried the receiver. Some restriction was thus placed on the maneuvers which the aircraft could make after release, since it had to maintain a position and attitude which would permit continuous illumination of the target until impact. Actually, this restriction was not serious, as the transmitting equipment (ASG) had a considerable range and a substantial field. A very satisfactory maneuver was to drop the missile at a range of 12 to 15 miles, make a 180-degree turn, and withdraw. Such a maneuver kept the attacking aircraft beyond the range of antiaircraft defense while still providing strong radar illumination throughout the 4-minute flight of the missile.

In the second version, Bat, in which the Division acted as consultants to the Navy Bureau of Ordnance on the radar while continuing in a position of prime responsibility for the entire system, both the radar transmitter and receiver were mounted on the missile. This design removed all restrictions on the maneuverability of the aircraft after release, but the operation of the fourth-power law in the relationship between received signal and range to the target introduced a problem in automatic gain control that was solved only by restricting the launching range to a maximum of some 7 miles. The range restriction with Bat was deemed by the Navy to be of less severity than the maneuverability restriction with Pelican. Accordingly, Bat was pushed to completion and was successfully used against Japanese shipping and naval units during the last months of the war.

The project is continuing under naval direction, working toward the addition of lead prediction so that the missile need not fly a pursuit course against a moving target or a stationary target in the presence of wind.

A television-guided version, Robin, was successfully demonstrated early in 1943 but was not prosecuted because of its parallel development with the AAF glide bomb GB-4.

Azon and Razon

Two versions of controllable high-angle bombs were developed. Each was visually sighted and remotely controlled by radio. The objective was to develop a missile of considerably greater precision than the standard high-level bomb, but which could be carried in and released from the existing racks in the bomb-bays of standard aircraft. The main objective, therefore, precluded the use of any supporting aerodynamic surfaces much larger than the tail fin of a standard bomb. Aerodynamic control had to be obtained, therefore, from the bomb body itself.

Elimination of roll was important since in control of the bomb the identity of rudders and elevators—azimuth control and range control—had to be preserved. The problem was solved by ailerons. The ailerons were controlled by a free gyro (which preserved the bomb's orientation) and a rate gyro (which damped out roll oscillation). This problem is more acute in a bomb which is controlled in both senses, range and azimuth, than in one that is controlled in one sense only. With a conventional tail structure the simultaneous application of control in yaw and pitch produces roll torques which are more difficult to cope with than are the roll torques due to the unintentional asymmetries usually present in production bombs.

The Division, therefore, pressed the development of Azon, a visually guided bomb remotely controlled in azimuth only. Its successful demonstration to the military at Muroc California, occurred on September 10, 1943, a fortnight after the appearance of the first German guided missile. A rush production program was undertaken, and, in March 1944, a group of B-17 aircraft equipped with radio-control transmitters for Azon left for the Mediterranean Theater of Operations. The missile was effective there against transportation links of the enemy forces which were resisting the Fifth Army's advance in the Italian campaign. In particular, the Avisio Viaduct south of the Brenner Pass was closed by Azon. Other successful operations with Azon against the locks of the Iron Gate on the Danube led to the acceleration of Azon production.

Use of Azon in the European Theater was less successful, although successful missions were flown against key bridges on the Seine and Loire just prior to and during the Normandy operation. The principal reason for lack of success in this theater seems to have been organizational rather than technical. Specifically, the policy of evaluating the efficiency of a squadron on the basis of the tonnage of bombs dropped rather than on the number of targets destroyed militated seriously against the success of Azon in the ETO. However, in the Burma campaign, December 1944 to the end of hostilities, Azon was strikingly effective, thoroughly disrupting Japanese communications by repeatedly cutting bridges on the Taungup Road and the Bangkok-Chiengmai railway.

The accomplishment of remote control in both coordinate axes, range and azimuth, was more difficult. The normal cruciform tail-fin structure was abandoned in favor of an octagonal shroud, which is only slightly subject to roll torque due to simultaneous application of control in yaw and pitch. As a further assurance of roll stability, the area size of the ailerons and their speed of operation were increased.

A more important problem than roll stabilization, however, was that of parallax. It is impossible for an observer in the bombardment aircraft to estimate the range error of his bombs accurately since he looks along the plane of the bomb trajectory. The Germans solved this problem in FX-1400, their high-angle dirigible bomb, by a maneuver of the airplane which placed it well abaft the missile. This maneuver results in nearly stalling out the airplane, and was deemed by the Division unacceptable for combat.

Instead, the Division developed with the cooperation of the NDRC Fire-Control Division, the Crab attachment to the standard M14 bombsight. This very simple attachment superposed an image of Razon—the high-angle bomb controlled in range *and* azimuth only—onto the image of the terrain as seen through the bombsight at the point where the bomb would fall with no further control. This development permitted the bombardier to correct errors in aiming throughout the time of flight of the bomb.

The improvement in accuracy due to the use of Azon compared with standard bombing in some thirty times. That is to say for the *same high probability* of obtaining a hit on a target approximately 50 ft square, thirty times as many individually aimed standard bombs have to be dropped as are required with Azon. This figure of merit was developed by the NDRC Applied Mathematics Panel based on test data taken at the AAF Proving Ground and at the evaluation base of the Air Forces Board.

The improvement with Razon is some three hundred times. The gain due to range control—ten times—is less than the gain due to azimuth control since errors in estimation of time of flight, which contribute to the range error, cannot be corrected by the Crab sight. The addition of Jag (Just Another Gadget) eliminated about two-thirds of the range error caused by error in estimation of the time of flight, resulting in an overall improvement of some 700 times in accuracy over conventional bombing.

Units to take Razon into combat were in training when the war closed.

Felix

The visually guided high-angle bomb required a continuous bomb run from the release point until the instant of impact. To eliminate this requirement and to provide the possibility of precise night bombardment, the Division developed Felix, a heat-homing high-angle bomb.

The distinction between heat and other infrared radiations must be stressed even in this summary. For reasons that are fully developed in Chapter 3 and Appendix C, the Division concentrated on heat detectors in the region between 8.5 and 15.0 microns. The water-vapor absorption of infrared rays at other wavelengths make their use for missile control impracticable.

The statement is repeatedly made that the Germans had infrared detectors very much more sensitive than we had. So far as heat-homing missiles are concerned, this statement is insignificant without quantitative reference to the wavelength band. In the wavelength band where heat homing is practicable, the statement is not true.

The aerodynamic structure of Felix was substantially that of the Razon—a standard 1,000-lb GP bomb with an octagonal control tail. Stabilization in roll was accomplished by an identical gyro system as for Razon, controlling similar ailerons.

The missile was guided to the target by a heat-sensitive element which scanned the terrain toward which the bomb was falling and directed it toward the quadrant—up, down, right, or left—which radiated the greatest heat flux. Thus a thermal target such as a steel mill at night attracted Felix by virtue of the heat which it radiated. The missile structure developed considerable angle of attack in altering its trajectory. In order to make the axis of scan lie approximately tangent to the line of flight, the scanning head was mounted in gimbals and connected to the rudders and elevators. This is an approximation to the requirement that a homing missile look where it is going. A precise fulfillment of this requirement involves transient analysis of the response of the missile as an aerodynamic body. Techniques for such an analysis do not as yet exist.

The sensitivity of the heat-scanning head—10^{-7} watt per sq cm—was sufficient to make Felix an effective missile against many targets. Much further study of target heat radiation is required before the full effectiveness of Felix can be assessed and the advisability of developing more sensitive heat detectors determined. In any case, a study of the absorption of radiation in common atmospheres from the visible range out to 20.0 microns is seriously needed.

The missile was successfully tested against Channel Key, Florida, and units were in preparation for combat by the Twentieth Air Force as World War II closed.

Roc

Roc was a highly maneuverable medium-angle bomb developed by the Division as a homing bomb. Initial aims to utilize radar homing were frustrated when experiments by the Division's radar group discovered that satisfactory resolution at microwave frequencies could not be obtained at the glide angles which Roc could attain. The use of television was then planned.

As the war closed, development was incomplete. The project was transferred to the Army Air Forces when the research and developmental activities of the Division terminated.

Components and Techniques

In addition to the four missile systems just mentioned, the Division prosecuted development programs on various component devices and accessory techniques. Some of them are sufficiently noteworthy to merit review in this summary. In particular, a general conclusion which the experience of the Division emphatically taught should be pointed out. The independent development of components without regard to the *dynamic characteristics of all the components* which comprise a guided-missile system leads in general to failure. Overall responsibility for the complete system must be placed in a single coordinated group.

At present, the development of the guided-missile art does not permit the evaluation of the dynamic characteristics of the elements—for example, homing device, servomechanism, and airframe—which comprise a guided-missile system. Indeed no suitable vocabulary has been formulated for expressing them. Broad research studies involving such subjects as transient aerodynamic responses are seriously needed.

Television

The Division studied the application of television to guided missiles. Compact, lightweight television equipment utilizing carrier frequencies of 100, 300, 800, and 1,800 mc was developed. Amplitude modulation and frequency modulation were explored. In general, it can be said that no television-missile system was successful as World War II closed, although spectacular improvement in pickup sensitivity had been accomplished through the development of the image orthicon camera tube.

A problem, unsolved at the end of hostilities, was the interference between two television signals received at the controlling plane. Both of these signals originated at the television bomb: one was transmitted to the aircraft directly, the other was reflected to the aircraft from the surface of the ground. These two paths were continuously changing in length, the direct path lengthening as the bomb approached the ground and the ground-reflected path decreasing. Thus the two signals were received at apparently different frequencies, and their interference produced a moving pattern of bars across the received picture. The spacing, orientation, and motion of the bars in the pattern depended upon the relative velocity of the airplane and the bomb.

The only cure appears to be to use a television transmitting antenna so directional that no signal can reach the ground to be reflected upward to cause interference. In order to get directional antennas of a reasonable size and low aerodynamic drag it was necessary to go to higher frequencies. Work on a television transmitter for Roc operating at a carrier frequency of 1,800 mc was in progress as hostilities ceased.

Simulation

The problem of guiding a missile is one of complicated dynamics. The differential equations probably are at least of higher order than the second; the coefficients are, in general, nonlinear. Simulation is the only means readily at hand for coping with such problems.

The Division made a start in the development of the art of simulative solution of the motion of a guided missile. Much more work needs to be done. Especially required is a method of assessing a particular problem to determine whether the most economical attack lies through conventional mathematics with the necessary broad assumptions, through point-by-point analysis, through the use of some of the modern computing assemblies such as the Rockefeller differential analyzer, or through the design of a special simulative device.

PART I
GUIDED-MISSILE SYSTEMS

Chapter 1

GLIDE BOMBS

1.1 INTRODUCTION

Two broad purposes underlie the development of guided missiles: the improvement in accuracy and the extension of range so that the release point for the missile lies beyond the range of lethal antiaircraft defense. The Division attacked both problems simultaneously in the glide-bomb development (the Washington Project). Through the addition of wings to give increase in lift the range was extended. The development of a homing system—either manually through remote control and television or with a wholly automatic radar system—greatly increased the accuracy.

Even before the outset of the glide-bomb project in NDRC, remotely controlled aircraft had been flown as gunnery targets. A glide bomb was under development by the Army Air Forces and, in a preset unguided version, was ready for standardization as a combat weapon. In the Navy similar work was going forward on pilotless, engine-driven aircraft and gliders[a] remotely guided into a target.

In order to make the axis of received intelligence —i.e., television or radar—continuously tangent to the flight path, the missile was designed to fly with an angle of attack as nearly constant as possible. To achieve maximum range from the release point to the target the missile was made aerodynamically clean.

These principles were embodied in the three missiles shown in Figure 1: Robin—a missile of 12-ft wing span, carrying a 2,000-lb GP bomb and guided by television; Pelican—a missile of 8-ft wing span, carrying a 325-lb depth charge and self-guided by radar reflections from signals radiated by a transmitter located in the carrying aircraft; Bat—a missile of 10-ft wing span, carrying a 1,000-lb GP bomb and self-guided by radar reflections from signals radiated by a transmitter located in the missile itself. This combined transmitter-receiver equipment was developed for the Navy, the Division carrying the responsibilities only of a consultant.

Of these missiles one (Bat) reached combat. Robin reached a point of sufficient development to achieve the accuracy inherent in existing television. The relatively flat glide angle produces considerable foreshortening of the television picture, which makes it extremely difficult for the controlling bombardier to estimate and to correct the error in the range sense. Even with the improved quality of television now available, the desirability of pursuing the development of television-guided glide bombs is doubtful.

By the time Pelican was sufficiently developed for combat use, the submarine menace had been largely eliminated by other methods; a larger payload was required for other targets, and the limitation in maneuver placed on the airplane carrying the radar transmitter made the prosecution of the development of Bat in the 1,000-lb size more attractive to the using Service than the development of a 1,000-lb Pelican. The Bat method of control, however, poses problems not found in Pelican.

1.2 GENERAL

The general aspects of homing-bomb design are treated in some detail in Chapter 12. Barely more than a recitation of the problems which have to be solved will be attempted here.

1.2.1 Coordination of Missile and Control

The problem which has proved of greatest importance to this Division has not been one of pure science nor—in its most limited meaning—one of technology. It is what we have come to call *systems engineering* and has, perhaps, been most aptly expressed by Dryden in Chapter 12:

"The impression is prevalent that scientific advances in many fields have progressed to the point where the development of such a missile is purely a matter of engineering design on the part of specialist

[a] The distinction between *gliders* and *glide bombs* is a subtle one; of course, strictly speaking, the latter forms a specific group of the former. In this volume each term will carry a specific implication. *Gliders* are nonpowered winged missiles whose wing loading is low enough to make them self-supporting at the flying speed of ordinary aircraft; they can, in consequence, be towed. *Glide bombs* are nonpowered, winged missiles whose heavy wing loading requires a flying speed above that of conventional aircraft; they must, therefore, be carried.

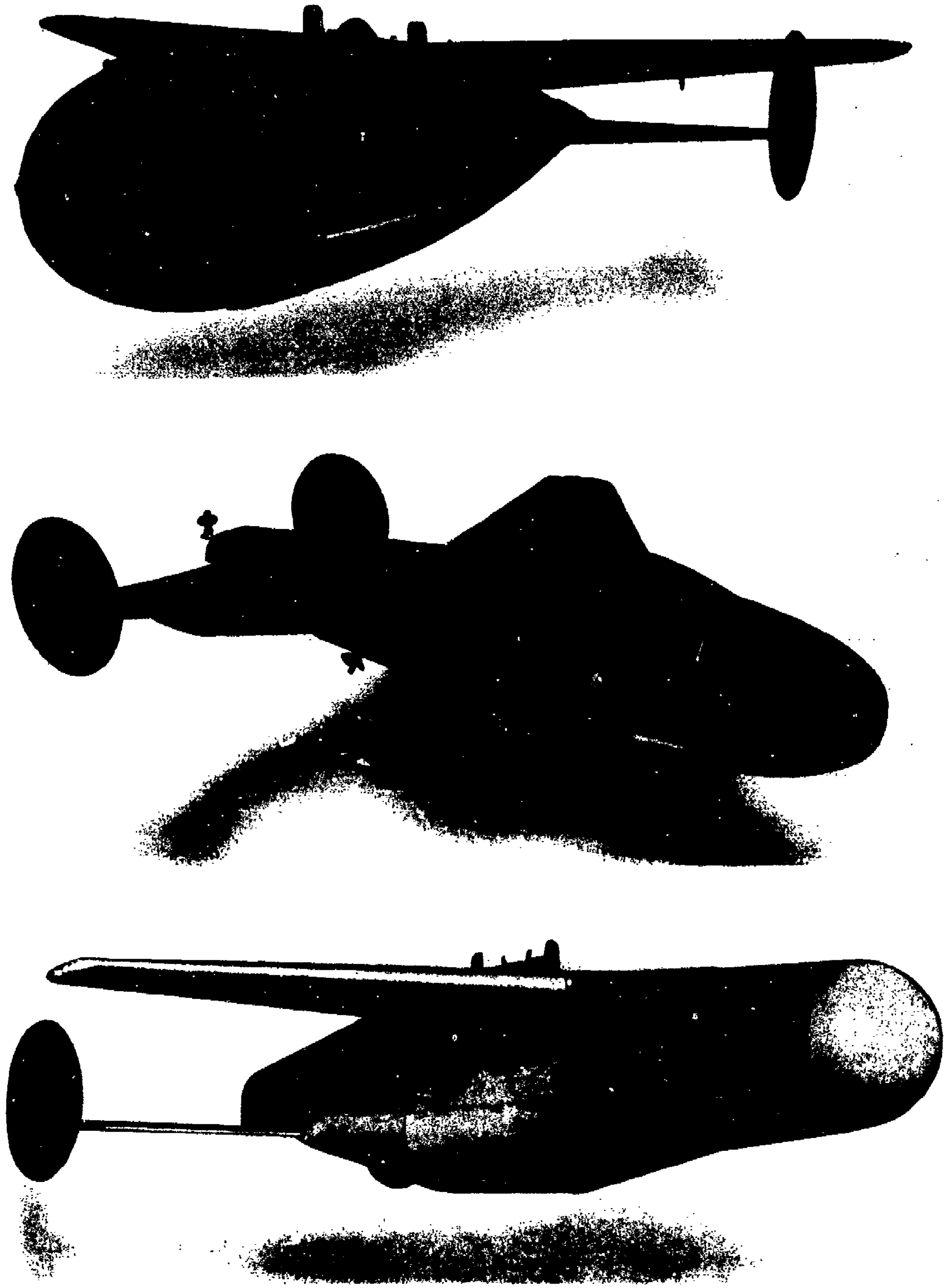


FIGURE 1. Washington Project television and radar glide bombs: Robin—television (top); Pelican—RHB radar (center); Bat—SRB radar (bottom).

groups with the usual coordination as to dimensional requirements, weights, and time of completion. Experience has taught otherwise. Optimistic time schedules based on such an assumption cannot be met. The development of successful homing aero-missiles requires the solution of certain research problems associated with the complete article, involving complex relationships between the performance characteristics of the component parts. *There is required a type of overall technical coordination beyond that required in the design of aircraft as ordinarily practiced.*" (Italics ours. *Ed.*)

Where this principle has been observed in the projects of this Division, a measure of success has been achieved (see Chapter 2 particularly); where it has been disregarded, failure has always resulted. It is noteworthy also that the Japanese, in the development of an infrared-homing glide bomb, fell into precisely this trap; in spite of having competent scientific personnel on each segment of the problem, they failed through absence of strong coordination between the investigating groups.

1.2.2 Target Discrimination and Tracking

Target discrimination in television depends upon the ability of the television equipment to furnish the bombardier with a clear picture of the target area. This in turn depends upon the sensitivity, resolution, and contrast capability of the pickup tube and the reliability of the radio link. These problems are discussed fully in Chapters 5 and 6.

With automatic radar homing the judgment of a human operator is not available for discriminating between the multiplicity of echoes which are usually returned from the target area. For certain special cases, e.g., an isolated aircraft in a cloudless sky, no ambiguity exists. In other instances, as with ships at sea, discrimination can be obtained by limiting the illuminated area to include only the target to be attacked. In pulsed radar there is also the possibility of utilizing the time of travel from transmitter to target to receiver as a means of discrimination. In this method it is necessary to have an automatic range-tracking element in the circuit so that the homing device will continue to respond to echoes from a single target as its attack is pushed home.

Range tracking is essential in any event to resolve the target from the signal from the ground or sea directly beneath the missile. This signal is always present, since the antenna system cannot be made completely directive. Indeed no radar-homing method appears to be currently available if the missile-to-target distance is less than the altitude of the missile, as it might be in some antiaircraft versions.

Tracking both in azimuth and in range is accomplished in the missiles of the Washington Project by so controlling the *missile* that it heads continuously for the target, i.e., on a pursuit course. A method which keeps the radar dish continuously pointed at the target and controls the missile by the departure of the axis of scan from some reference axis in the missile has been suggested and should be explored. This technique offers better possibilities for attacks along an interception course than does the method used thus far.

To provide for failure of the signal due to the fluctuating character of radar or for other reasons, the servomechanism[b] must contain a memory element which will keep the missile on course until the signal is restored. Even with such an element in the servomechanism, the cone of vision of the radar receiver must be sufficiently broad to ensure that the target will be contained within it when the signal is restored.

1.2.3 Aerodynamic Problems

A missile has six degrees of freedom: translation along and rotation about the axes of roll, yaw, and pitch. Rarely will it reach a state of complete equilibrium. Bomb-like missiles are, in general, still under acceleration along the roll axis at the instant of impact. Lanchester[1] has shown that a glider with control surfaces fixed in the neutral position does not fly a straight line under the propulsion of gravity; rather, there is a periodic increase in speed with a corresponding increase in lift which flattens the glide path. The component of gravity in the direction of flight being reduced, the glider slows down, loses lift,

[b] In this volume terms involving the word "servo" have a special significance beyond that usually ascribed to them in aircraft-engineering practice:

1. *Servo link*, a mechanical power amplifier by which signals at a low power level are made to operate control surfaces requiring relatively large power inputs (e.g., a relay and motor-driven actuator).
2. *Servo system*, a closed feedback loop comprising the intelligence device, automatic pilot if any, the amplifying link, and the missile itself.
3. *Servomechanism*, the feedback loop exclusive of the missile itself.

This convention follows the principle suggested by Warren Weaver. (See *Fundamental Theory of Servomechanisms*, LeRoy A. MacCall, with foreword by Warren Weaver, D. Van Nostrand Co., New York, 1945.)

and consequently assumes a steeper glide path until sufficient speed has been acquired for the cycle to repeat. Thus the actual glide path is a sinuous curve about a downward-inclined axis. Since the lift varies with the square of the speed and nonlinearly with the attitude of the control surfaces with respect to the wind stream—angle of attack—the curve is not a sine wave. Lanchester called it a phugoid. The phugoid period in seconds is about one quarter of the missile velocity in feet per second. Glide bombs have a phugoid period of about 88 seconds. Time constants of angular motion are considerably shorter, ranging from a fraction of a second for rotation about the roll axis to a few seconds for yaw and pitch. Efforts to analyze any missile statically and to design a servomechanism based on the assumption of equilibrium conditions must fail.

In the steady state, i.e., after equilibrium is established, a glide bomb with properly actuated control surfaces flies rectilinearly along a path which is inclined downward by an angle whose tangent is the ratio of drag to lift and at a constant speed proportional to the square root of the wing loading. The glide bombs designed under this project have a maximum lift-drag ratio of approximately 7 and a flying speed in the vicinity of 230 mph.

In conventional aircraft, change in lift is accomplished by deflecting an elevator so that the wing and consequently the entire structure undergoes a change in angle of attack. Were such a design applied to a homing glide bomb, the axis of scan would be tangent to the life of flight for a single elevator setting only. In glide bombs using this type of control, attempts have been made to compensate for varying angles of attack by a feedback link from the elevator which adjusts the angle between the axis of scan and the axis of roll. Such compensation can be made approximately valid under conditions of equilibrium, but are applied only with great difficulty under transient conditions. As has been pointed out, a steady-state, static equilibrium rarely is obtained with missiles.

In the glide bombs of the Washington Project the problem was solved by the use of *elevons*—full-span control flaps on the trailing edge of the wings. Deflection of the elevons varies the lift of the wing from approximately zero to a large positive value. Proper location of the center of gravity of the missile and a fixed tail structure provide moments from the downwash which balance the moments produced by the flaps. The result is a missile which, in the steady state, maintains its angle of attack constant within 1 degree for the normal operating range of the controls and within 4 degrees for full elevon excursion.

In lieu of a rudder, differential operation of the elevons sets up a roll which in turn produces a component of wing lift normal to the line of flight. This lift, applied to the mass of the missile, produces a centripetal acceleration.

The dynamic analyses of the performance resulting from these methods of control are outlined in Sections 1.4 and 1.5.

1.3.4 Interdependence of Controls and Correlation with Intelligence Coordinates

The controls which affect the moments about the three axes of a missile are not independent. Thus rudder action produces a slight rolling moment in addition to the yawing moment which changes the heading of the missile to the right or to the left. There follows a larger rolling moment because of the reduced lift of the wing, whose absolute speed is decreased by rotation about the yaw axis. Similarly the ailerons produce a yawing moment in addition to their primary roll moment. The roll moment resulting from the yaw may either add or subtract from the roll produced by the ailerons directly. The interaction of controls in pitch with yaw and/or roll are small.

Homing devices and television are essentially two-dimensional intelligences, i.e., they give indication as to the azimuth and elevation of the target with respect to the axis of scan. Radar offers the possible addition of a third coordinate, the slant range, but no embodiment of this principle has been applied to missiles. The servo system has to take into account this discrepancy between two-dimensional control and the three-axis control problem which the preceding paragraph showed to be inherent in aeromissiles.

Furthermore, roll of the missile, since the axis of roll in general is neither coincident with nor exactly parallel to the axis of scan, has an effect on the apparent position of the target with respect to the axis of scan and therefore on the error signal. Pitching and yawing have similar but reduced effects. These effects are subject to quantitative analysis in the idealized case but are difficult to generalize. (See Chapter 7 for a more complete three-axis development of the dynamics of the Pelican family of missiles.)

The fuller discussion of these interactions between the elements of the servo system in Chapter 12 indicates the possibility of their reduction. Homing missiles can be made to work with the interaction present. Further aerodynamic and servo-system research looking toward the possible elimination of interaction is urged.

1.2.5 Stability and Hunting

Like any feedback loop, the servo system consisting of the homing missile and its controls will be unstable if phase and gain relationships around the loop are not kept within appropriate limits. In general, instability will result in angular hunting about the three axes of the missile; in extreme cases of instability the missile may turn completely over and fall in a spin. A hit by a missile flying with a sustained hunt is purely fortuitous, depending upon the amplitude of the oscillation and its phase at the instant of impact; if the amplitude of hunt can be kept small, the miss will be small.

The source of instability lies, as has been indicated, in the phase-gain characteristic of the loop. As the error signal crosses zero, the control surfaces should cross their neutral position. The lag between these events permits an input of energy into the system which must be absorbed by aerodynamic damping. The amplitude of hunt will build up until the cyclic energy input is equal to the energy dissipated in damping.

Two methods of reducing the hunt have been applied. An electric phase advancer can be designed which will reverse the error signal *before* the error is actually zero. Such an advance permits the control surfaces to pass their neutral position as the target comes on course, or even to lead that event. The latter situation corresponds to overdamping and is inherently nonoscillatory. This correction is secured at the cost of considerable attenuation of the error signal and requires a correspondingly increased gain in the receiver amplifier. A second method has been used with success. A rate gyro measures the angular velocity with which the missile comes on course. The indication of this gyro biases the flight-control equipment responsive to the radar so that the moment exerted on the missile toward true course depends not only upon the error in heading but also upon its first time derivative. By making the component of moment which is dependent upon the derivative of error sufficiently large, the system is rendered nonoscillatory.

No aspect of the design of homing missiles is more important in achieving final accuracy than the property of dynamic stability. Serious study of Chapter 12 and the references cited there is urged.

1.2.6 Moving Targets and Wind

If the target is in motion with respect to the mass of air through which the missile flies, the missile will attack the target along a pursuit curve. W. B. Klemperer in Appendix A has shown that a missile with finite maneuverability cannot in general hit a point target unless the ratio of the speed of the missile to the speed of the target lies between 1 and 2. It is obvious that except for a level, head-on attack the missile will be unable to overtake the target if the ratio is less than unity. If the ratio is in excess of 2, except for a level, head-on attack or a stern chase, the curvature of the pursuit curve becomes infinite, requiring an infinite maneuverability on the part of the missile.

Three-dimensional analysis of the pursuit problem is extremely difficult; no complete study of it seems to have been made. An idealized solution has been made for glide bombs under the direction of the Applied Mathematics Panel of the National Defense Research Committee. It shows that against ship targets[3] the miss due to pursuit-course curvature is very small if the azimuth of the target at launching is about 145 degrees with respect to its path.

A solution to the problem may lie in a computer which will cause the missile to lead the target and to fly a rectilinear interception course. A servo system within a servo system is implied, and a nice adjustment of the phase-gain relationship is required. Dryden indicates in Chapter 12 that such a computer amounts to positive feedback and that instability may result. Doubtless, inept choice of parameters in the design of such a computer can lead to failure. The techniques learned in the development of fire-control equipment, however, provide powerful tools for the attack on this problem.[c]

Errors of alignment of the axis of scan with the tangent to the flight path give rise to errors analogous to those due to the pursuit curve. If the angularity between the line of flight of the missile and the axis of scan—the *bore-sight error*—is constant, the projection of the trajectory is a logarithmic spiral with

[c] A study of *Aiming Controls in Aerial Ordnance* by George A. Philbrick, STR Division 7, Volume 3, Part I, is recommended.

infinite curvature at the point of impact. With finite maneuverability in the missile, a miss proportional to its minimum turning radius and to the square of the bore-sight error will occur. So far as the Division is aware, no analysis of the combination of these effects has been published; such an analysis is seriously needed. In this project the effect has been minimized by reducing as far as possible variations in angle of attack and by careful alignment of the axis of scan with a fixed reference axis in the missile to avoid bore-sight error.

1.3 AERODYNAMIC FEATURES[3]

The glide bombs developed under this project consist of high-wing monoplanes of laminated-wood, monocoque construction. The wing loading is approximately 70 psf, and the three sizes (8 ft, 350 lb; 10 ft, 1,000 lb; and 12 ft, 2,000 lb) are substantially homologous. (See Figure 1.)

Control is obtained from elevons which operate in conjunction for control in pitch and differentially for control in roll. Turning moments are derived from roll. A fixed empennage with twin disk-shaped fins stabilizes the missile in yaw and pitch; the position of the empennage with regard to the center of gravity of the whole assembly and the decalage between the wing and stabilizer provide nearly constant angle of attack.

The model with the 8-ft wing span was tested at an airspeed of 90 mph in the NACA wind tunnel at Langley Field. The following tabulation presents the significant characteristics of the structure at trim. The data were obtained by allowing the missile to assume an attitude in the plane of the yaw and roll axes such that the pitching moment (C_m) was zero. Direct observations of change in attitude gave the variation in α, the angle of attack. Lift and drag were measured in the usual manner. Longitudinal stability at trim ($\partial C_m/\partial \alpha$ when $C_m = 0$) is not directly reported as a function of elevon angle, δ. It is determinable, however, from the data reported, and Section 1.4 shows the important application of this function to the study of longitudinal hunting.

The flattest glide angle (8.0 degrees) which is derived from a lift-drag ratio of 7.11 is equivalent to 1.35 miles of range for each 1,000 ft of descent. Extension of the operation to the absolute limits leads to failure, however, since the departure from linearity of the C_L/C_D vs δ characteristic is great, and more particularly because the angle of attack is not con-

Flap angle δ (degrees)	Lift Coefficient C_L	Drag Coefficient C_D	Steady-state glide angle* $\cot^{-1} C_L/C_D$ (degrees)	Angle of attack α (degrees)
−20	0	0.062	90	4.1
−15	0.03	0.053	60.4	3.7
−10	0.08	0.048	30.9	3.5
− 5	0.15	0.046	17.1	3.5
0	0.23	0.048	11.8	3.8
5	0.34	0.054	8.9	4.4
10	0.46	0.066	8.1	5.3
15	0.59	0.083	8.0	6.2
20	0.72	0.110	8.8	7.5

*Referred to horizontal flight.

stant. Within the range $\delta = -10$ degrees to $\delta = +5$ degrees, the variation in α is only 0.9 degree. In practice the missile was dropped at a range to require a glide-path ratio of 3.5 to 4.0 ($\delta = -4$ degrees to $\delta = +5$ degrees). In the region reasonably adjacent, C_L/C_D vs δ is essentially linear.

While the full excursion of the elevons to the position of flattest glide ($\delta = 15$ degrees) cannot be successfully utilized for stretching the operating range of the missile, the implication that mechanical limits can be set on their movement (say at −10 and +7 degrees, which represent the limits of approximate linearity of L/D vs δ) would be wholly false. Since a differential elevon action is superimposed on joint elevon action for combined turn and change of glide-path ratio, the full excursion may be required.

No tests were made to determine α with $C_m = 0$ when combined differential and joint displacement of the elevons is applied. It may be that there is concealed here a considerable variation in angle of attack which vitiates the accuracy of the missile. Further studies appear to be indicated to explore this field. Moreover the dynamic application of steady-state data from the wind tunnel is a matter which strongly demands further inquiry.

1.4 LONGITUDINAL STABILITY OF GLIDE BOMBS

1.4.1 Analytical Studies[4]

The stability characteristics of a glider are those qualities which determine its motion after a small deviation from an initial condition of equilibrium. Longitudinal stability limits these properties to those which determine translation along the axes of roll and yaw and rotation about the axis of pitch. It is the group of characteristics which, when taken together with those of the homing device, the automatic pilot, and the servomechanism, defines the performance of a homing glide bomb in the range sense.

The conditions of equilibrium in flight are defined by:

$$\begin{aligned} W \sin \gamma + \tfrac{1}{2}\rho S V^2 C_D &= 0 \\ W \cos \gamma + \tfrac{1}{2}\rho S V^2 C_L &= 0 \\ \tfrac{1}{2}\rho S V^2 C_m &= 0 \end{aligned} \tag{1}$$

where[5] W is the weight of the missile,

S is the effective wing area,

V is the velocity of the missile,

ρ is the density of air,

γ is the downward inclination of the flight path, and also

m is the mass of the missile,

B is its moment of inertia in pitch,

q is the velocity head,

Q is the attitude of the missile, and

c is the mean aerodynamic chord.

After a small displacement in V, γ, C_D, C_L, and C_m —as by operation upon them by the increment Δ— these equations become:

$$\begin{aligned} W \cos \gamma \Delta\gamma + \tfrac{1}{2}\rho S V^2 \Delta C_D + \rho S V C_D \Delta V &= mV \\ -W \sin \gamma \Delta\gamma + \tfrac{1}{2}\rho S V^2 \Delta C_L - \rho S V C_L \Delta V &= mV\dot{\gamma} \\ \rho S c V C_m \Delta V + \tfrac{1}{2}\rho S V^2 c \Delta C_m &= B\ddot{\theta} \end{aligned} \tag{2}$$

In his classical solution of these equations Lanchester[1] considered the glider as flying in a conservative field, i.e., no drag, and considered only the case where the control surfaces are fixed. In the present study the development is extended to include the major effects of drag and the motion of the elevons which comprise the control surfaces of the glide bombs of the Washington Project. In arriving at an analytical solution which defines completely the motion of the missile in the plane of the yaw and roll axes the following simplifying assumptions are made:

1. Angular velocities and accelerations have a negligible effect on C_L and C_D, and therefore
2. C_L and C_D are functions of α and δ only.
3. The relationship between C_L and C_D on the one hand, and α or δ on the other is linear.
4. $\Delta\alpha$, ΔV, q, $\dot{\alpha}$, δ, and $\dot{\delta}$ are considered small but appreciable. Terms containing products of two or more of them are considered negligible.
5. Static characteristics as measured in the wind tunnel are considered to hold in the dynamic or transient state.
6. The servo system is ideal, i.e., linear and without phase distortion.

Now if:

$$v = \frac{\Delta V}{V}$$

$$L = \text{acceleration due to lift} = \frac{\tfrac{1}{2}\rho S V^2 C_L}{m}$$

$$D = \text{acceleration due to drag} = \frac{\tfrac{1}{2}\rho S V^2 C_D}{m}$$

$$M = \text{angular acceleration in pitch} = \frac{\tfrac{1}{2}\rho S V^2 C_m}{B}$$

$$\begin{aligned} L_\alpha &= \frac{\partial L}{\partial \alpha}, \quad L_\delta = \frac{\partial L}{\partial \delta} \\ M_\alpha &= \frac{\partial M}{\partial \alpha}, \quad M_\delta = \frac{\partial M}{\partial \delta}, \quad M_q = \frac{\partial M}{\partial q} \\ M_{\dot{\alpha}} &= \frac{\partial M}{\partial \dot{\alpha}}, \quad M_{\dot{\delta}} = \frac{\partial M}{\partial \dot{\delta}}, \end{aligned} \tag{3}$$

we obtain:

$$\begin{aligned} L\Delta\gamma + 2Dv + D_\alpha \Delta\alpha + D_\delta \delta + V\dot{v} &= 0 \\ -D\Delta\gamma + 2LV + L_\alpha \Delta\alpha + L_\delta \delta - V\dot{} &= 0 \\ M_q(\dot{\gamma} + \dot{\alpha}) + M_\alpha \Delta\dot{\alpha} + M_\delta \delta + M_{\dot{\alpha}}\dot{\alpha} + M_{\dot{\delta}}\dot{\delta} & \\ - \ddot{\gamma} - \ddot{\alpha} &= 0 \end{aligned} \tag{4}$$

There is nothing in equations (4) that requires linearity or absence of phase distortion in the servo loop. Such limitation is required for the analytical solution. The limitation can be expressed:

$$-\delta = K(\Delta\theta + c'\dot{\theta}) \tag{5}$$

where K and c' are factors of proportionality. Equation (5) is a fundamental equation of an idealized servomechanism; it requires that the elevon displacement be proportional to the error in heading and to its first time derivative.[d] After inserting equation (5) in equation (4) a solution is obtained which gives, independently of the value of K, a short-period, highly damped oscillation. This is the so-called *rapid incidence adjustment*, and its independence of K shows it to be unaffected by servo design.

In addition to the short-period oscillation, there is a motion whose character is dependent upon K. If K is small, this motion is a long-period oscillation similar to the phugoid of Lanchester but damped; if K is large, the motion is not oscillatory and may be either regenerative or degenerative.

If $(\partial)(L/D)/(\partial\delta) > 0$, then the motion will be degenerative or stable; if $(\partial)(L/D)/(\partial\delta) < 0$, instability may result. Such a situation sometimes arises when the glide bomb is launched at too low a speed or

[d] See Chapter 4 for a further discussion of the idealized control regime for a missile guided by full-span flaps.

when too flat a glide angle—excessive range—is attempted.

1.4.2 Solution by an Electromechanical Analogue

The establishment of the equations of motion of a glide bomb and their solution for the case where control is effected through an ideal servomechanism led to a broader study with more realistic servomechanisms through the use of an electromechanical analogue. This technique proved so powerful in attacking such problems that it is discussed at some length in Chapter 11. The applications of the principles of dynamic similitude to the design and the details of construction of the table are discussed there.

The analogue consisted of a table free to rotate about a vertical axis but with damping provided for that motion (see Figure 2). The inertias of the rotating system, the damping factors, and the compliances are adjusted so that oscillation about the vertical axis corresponds to the pitch oscillation of the missile about its horizontal axis. A pitch gyro (see Section 1.6) is mounted on the table, and its output fed to a computing circuit. The computing element in turn actuates the servo link, whose output is spring-loaded to correspond to the hinge moment of the elevons.

The output of the servo link, both as to velocity and displacement, is returned via the computing circuit as a feedback to the table. Thus the system comprises a closed loop with all the elements of the missile system except the automatic homing device. Several types of gyros and strengths of bias coils (see Section 1.6) were tested, together with a very large number of servo links. Typical curves are shown in Figure 3.

1.5 LATERAL STABILITY OF GLIDE BOMBS

The problem of lateral stability is not so simple as that of longitudinal stability. The reason is suggested in Section 1.2.4, where the interrelation between aerodynamic forces and moments was described. Three principal modes of motion are considered: sideslip velocity, roll velocity, and yaw velocity. These are closely interrelated and are in turn sensitive to elevon displacement, attitude in pitch, and inclination of the flight path.

A complete analysis of the problem is beyond the scope of formal mathematics although a study with simplifying assumptions can be made rewarding; in Appendix B Skramstad has made such a study. Even with the assumption of linearity of response, constant air density, and the overwhelming preponderance of certain design properties such as roll damping, the dynamic equations lead to a quintic for the evaluation of the roots.

In two-winged missiles the roll damping is large. Unless the servo system introduces a positive feed-

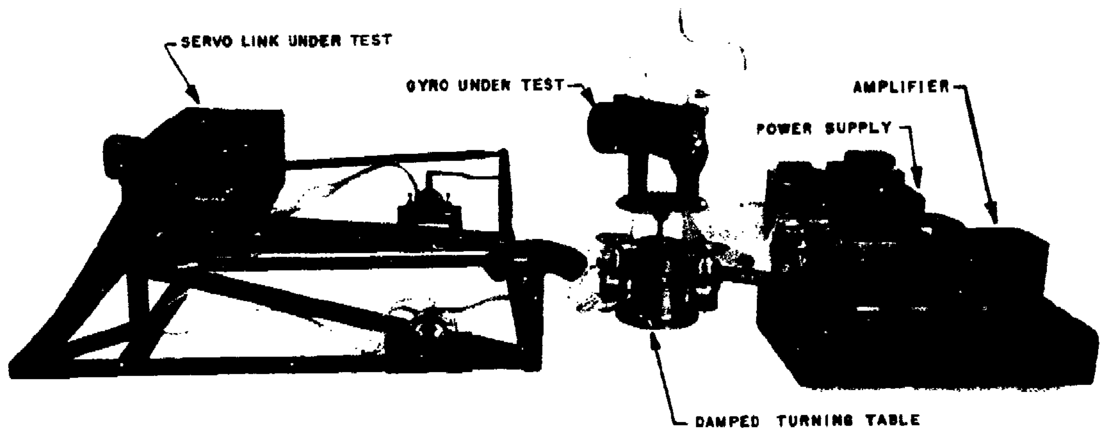


FIGURE 2. Flight-test table and accessories.

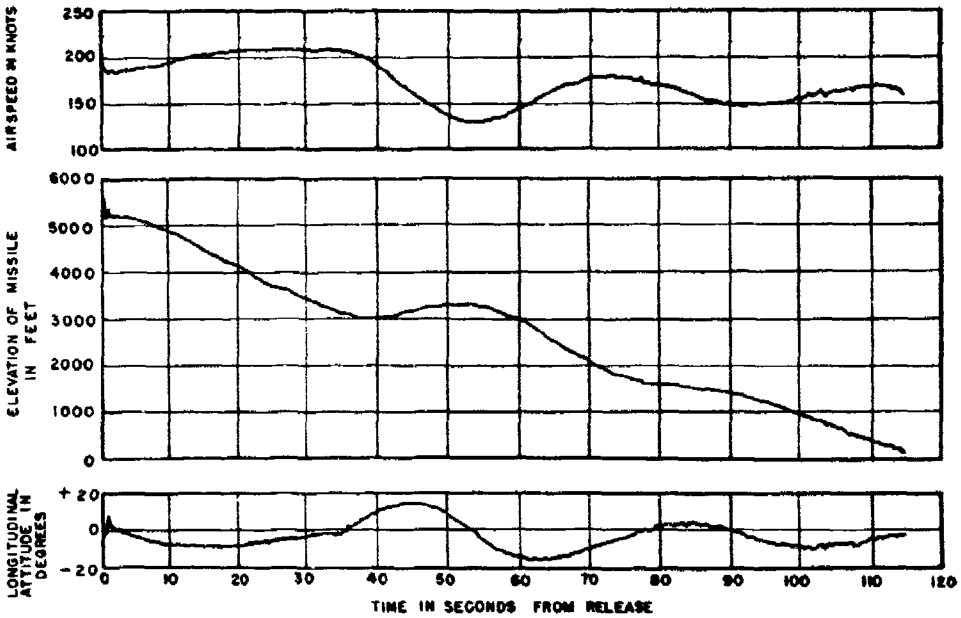


FIGURE 3. Longitudinal oscillation of Pelican in flight.

back, the assumption of roll-damping predominance is valid. Under this circumstance the motion of the missile after a perturbation in roll, yaw, or sideslip breaks down into three components:

1. A rapid exponential subsidence of the disturbance which, for the Pelican family of missiles, has a time constant of about 1 second.

2. A slower exponential factor, which may be either regenerative or degenerative. This component expresses the spiral stability of the missile: if it is degenerative, the missile is spirally stable; if it is regenerative, the missile is spirally unstable. The glide bombs of the Washington Project were spirally stable, although the margin of such stability was small.

3. An oscillation whose period is determined largely by a yawing moment due to sideslip and whose damping is determined largely by a yawing moment due to rate of yaw. The Washington Project's missiles have a period of oscillation in yaw of approximately 1 second and a time constant of about 1.67 seconds.

Simulation was invoked in the analysis of the airframe–automatic-pilot links of the servo-system chain. In the early phases of the program an analogue model was constructed wherein roll and yaw were studied separately, with corrections applied to the results to take their interrelation into account. In the final work the entire servo system including the homing intelligence was simulated. (See Chapter 7.)

The necessity of an automatic pilot (see Section 1.6) had been established. Its performance about the roll and yaw axes was dictated by a rate gyro whose axis of rotation was inclined to the roll axis of the missile so that it was sensitive to both rate of bank and rate of turn. Thus roll and bank of the complete servo system were doubly interrelated: through the fundamental aerodynamic properties of a two-winged

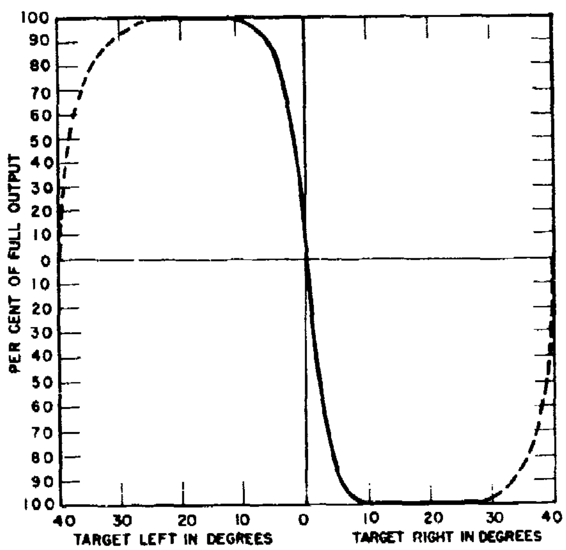


FIGURE 4. Radar homing signal versus error in heading.

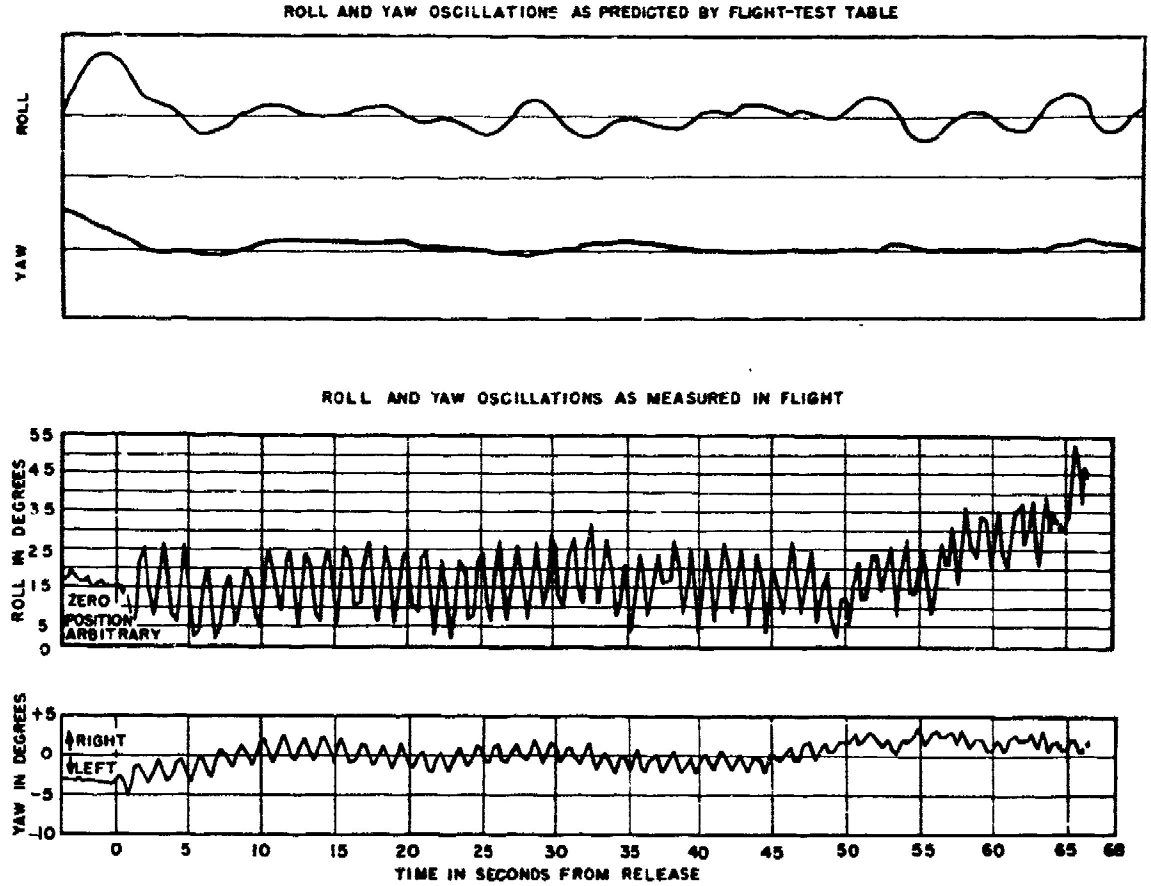


FIGURE 5. Output curves of flight-test table compared with flight tests, roll and yaw.

missile and through the coupling of the rate-of-bank-and-turn gyro.

The coefficient of coupling effected by the gyro depends upon the inclination of its rotational axis to the roll axis. This angle of inclination was varied to determine its optimum value. Runs were made with the inclination angle at values intermediate between 2.5 degrees and 20 degrees. At 2.5 degrees the yaw oscillation was negatively damped; at inclinations of the gyro greater than 20 degrees the system was over-damped and too sluggish. A value somewhat under 15 degrees was found most satisfactory in flight tests.

The radar-homing equipments (see Section 1.7) were designed to give an error signal which is proportional to the error in heading for relatively small errors and is constant at larger errors. The error angle at which the signal saturates is adjustable (Figure 4). Exploration of the effect of varying the saturation angle, called radar width, on the simulative flight table showed that a radar width of ±6 degrees was most suitable (Figure 5). This value also gave the most satisfactory performance in flight.

1.6 AUTOMATIC PILOTS[6]

1.6.1 General

The initial flight tests on this project were made without automatic flight-control equipment. The experience of toy-model builders was a strong force leading to the belief that automatic stabilization would not be required. This hope proved to be false in spite of the inherent stability expected from the high-wing design.

The fundamental decision to be made in the design of the automatic pilot was the choice between free gyros and rate gyros. The free gyro provides a reference in space which—if the frictional forces in the pivots and take-offs are minimized—remains well fixed. Thus the datum from which a free-gyro-controlled automatic pilot controls is absolute, and the whole assembly possesses memory. Loss of control signal, either from the radio-control link or from temporary failures of an automatic homing system, will not result in departure from course beyond the tolerances of the gyro.

In the rate gyro the problems of take-off friction are very easily solved since the whole structure is spring-restrained about the axis where movement results in contact closure. It is relatively simple to make contact friction small compared with spring tension. As the free gyro holds the attitude of the missile fixed, so the rate gyro holds its first time derivative fixed. If the rate gyro could have a zero tolerance or dead band, an ideal situation, the results would be identical. In a practical embodiment, the rates of departure from desired attitude can be successfully small if the control signals are reasonably continuous.

These considerations, together with the considerably more plentiful supply of rate gyros, led to their selection. It is interesting (see Chapter 7) that a successor investigator reversed this decision, free gyros having in the meantime become much more readily available.

1.6.2 Basis of Design

From the outset two rate gyros were used. One has its rotor axis parallel to the axis of yaw and is free to precess, against spring restraint, in response to pitching; its action is thus substantially that of a rate-of-climb indicator. The other gyro is mounted in the plane of the yaw and roll axes, with its axis inclined to the latter axis by approximately 15 degrees (Figure 6); it is thus primarily sensitive to rate of turn but also has a secondary sensitivity to rate of roll. Quantitatively the effectiveness of the instrument as a rate-of-turn indicator is 97 per cent and a a rate-of-bank indicator 25 per cent.

Electromagnets actuate the gimbals to close contacts which control the servo link. Thus if the "down" contacts are closed by its magnet, the elevons are deflected upward (the direction of decreasing lift) until the rate of pitch produces a precessional torque on the gimbal sufficient to overcome the magnetic pull.

Similarly if the "left" contacts are closed by solenoid action, the left elevon is deflected upward and its mate downward until the rate of roll and the rate of turn, biased respectively by the sine and cosine of the angle of inclination of the gyro rotor, produce a precessional torque sufficient to overcome the magnet force of the gyro coils.

On loss of control signal in pitch, the missile will be restrained, except for gyro tolerances, to zero rate of pitch and will therefore continue along a substantially constant glide-path angle. On loss of control signal in azimuth, the turn-sensitive component of precessional torque will right the missile at a rate permitted by the roll-sensitive component. Thereafter the glider will—again neglecting tolerances in the gyro—fly a straight course.

In the television version of the glide bomb, relays in the output circuit of the radio-control receiver energized, at a fixed current value, appropriate electromagnets for "up," "down," "right," and "left" control. Thus the bombardier had the option of imparting to the missile *fixed rates of correction* in range and in azimuth. The amount of correction was governed by proportioning the ratio of time-on to time-off. Skilled pilots did not always make the most successful control bombardiers.

The output of the homing radar receiver is single-valued in current as a function of error through a considerable range. At a "left" error of about 20 degrees, the output is 8.0 ma direct current. With a 20-degree "right" error, the output is equal in the reverse sense. For approximately 6 degrees adjacent to zero, the response is linear from -8.0 ma to $+8.0$ ma. Thus, under radar control the servo system operates to give a rate of return to true course proportional to the error in heading. In order to reduce yaw hunting, a third gyro sensitive to rate of yaw was later added to make the system inherently non-oscillatory. All three gyros are shown in Figure 7.

1.7 RADAR-HOMING CONTROL—RHB CONTROL[7,8]

1.7.1 General Principles

The all-weather property of a microwave makes it an attractive agency for the control of a guided missile. The directional property of radar (Radio Direction and Range) suggested, even before the formation of the Division, that the signals reflected from a water-borne target could be used to guide a pilotless aircraft to impact with exact accuracy. The *radar-homing bomb* [RHB] was conceived as applicable to powered drones, gliders, and to glide bombs. Within

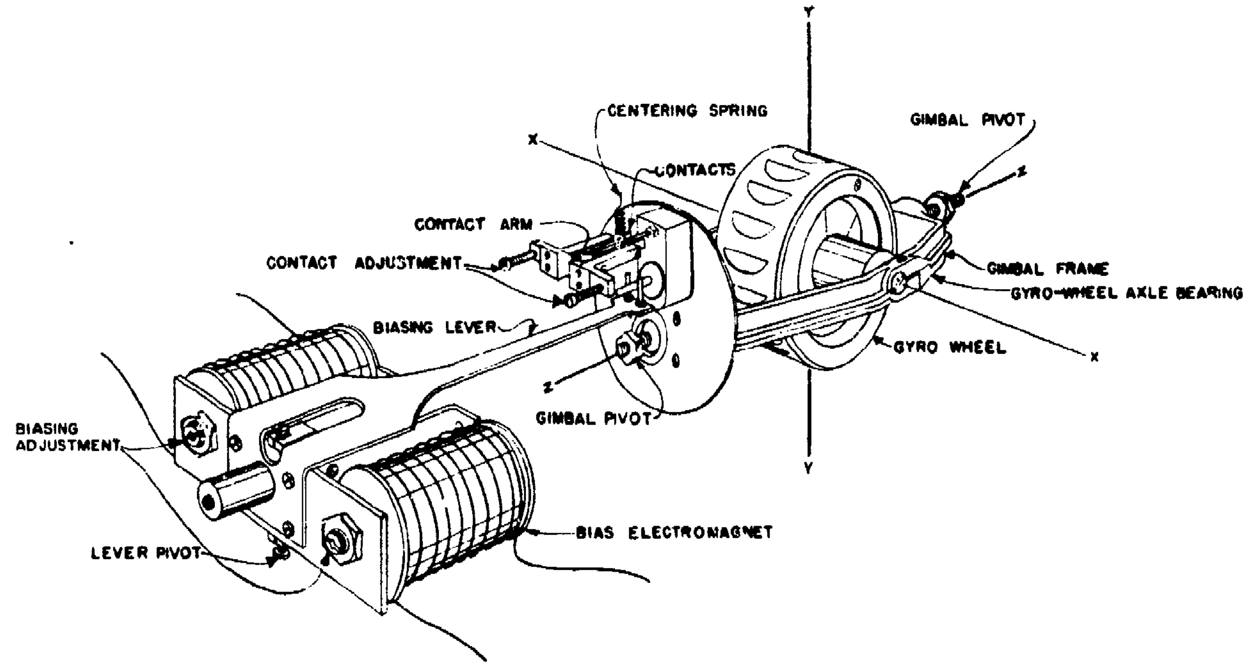


FIGURE 6. Rate gyro for glide-bomb automatic pilot.

the Division, only its application to glide bombs of the Pelican family was prosecuted.

Military targets in general do not emit radio waves; it is, therefore, necessary to illuminate them with radio radiation if a missile is to home on them through the agency of radar. In RHB the target is illuminated by the standard radar search equipment in the carrying aircraft. The equipment consists of a powerful transmitter which emits a narrow beam of short-wave trains of very high intensity. The reflections

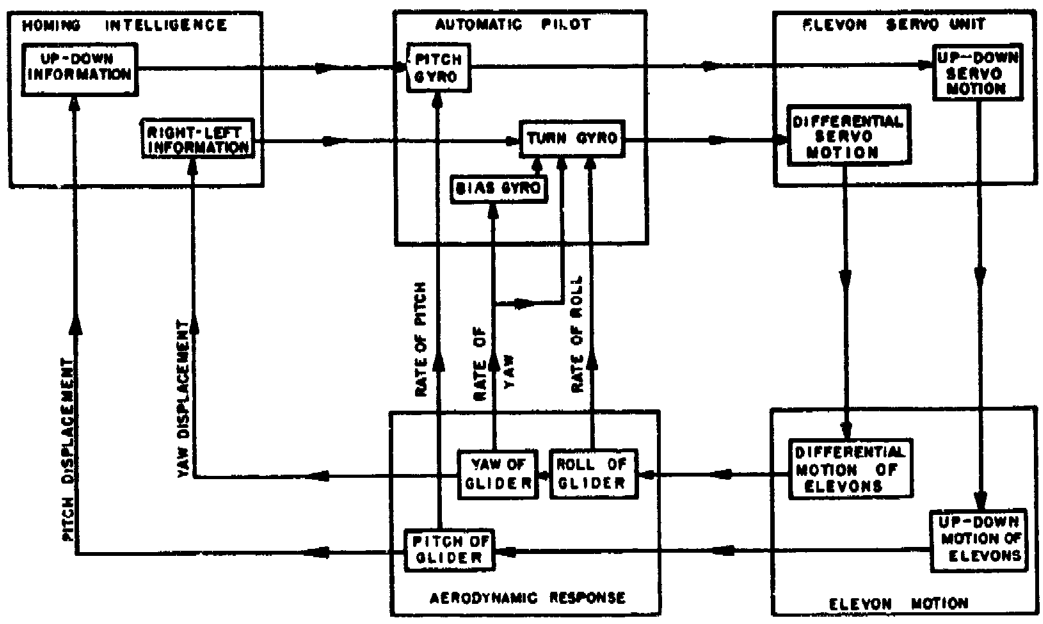


FIGURE 7. Block diagram of glide-bomb control system.

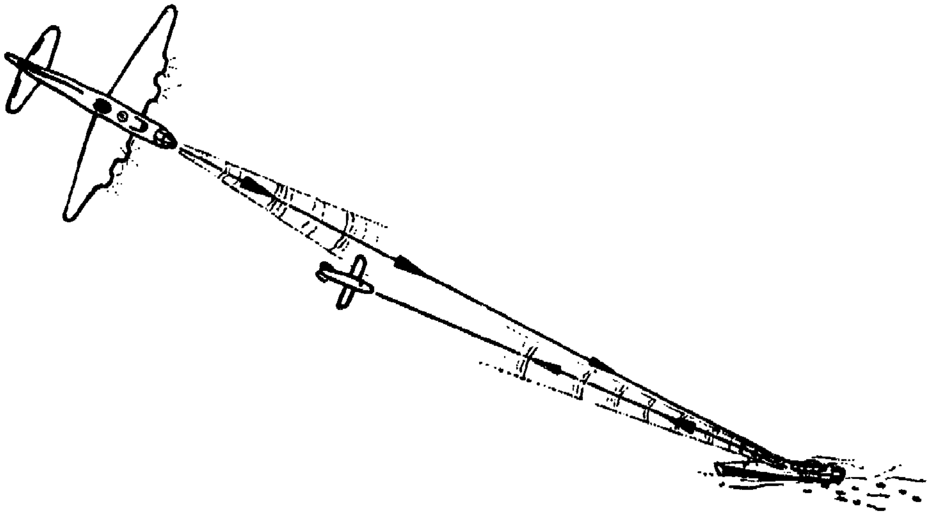


FIGURE 8. RHB attack.

from the target are picked up by a receiver in the missile. The output of the receiver actuates the automatic pilot (Figure 8). The wave trains or pulses occur at a frequency of about 800 per second and are 0.7 microsecond long. The illuminating radiation thus consists of a series of pulses in space, each 740 ft long and separated by 233 miles. The quasi-optical property of the radar frequency, 3,000 mc, provides directional information as to the target's location, and the pulsed character of the illumination provides means of determining its range.

The energy radiated from the illuminating transmitter is focused into a narrow beam (approximately $\pm \frac{1}{4}$ degree to half-intensity) by the antenna structure. Within the field thus illuminated, every object returns some reflected or scattered energy; the study of the energy reflected from various types of targets and from their typical backgrounds is basic to the design of successful radar-homing systems.

1.7.2 Target Contrast

Although all military targets will return a radar echo, it may be impossible for the receiver to resolve the desired signal from the multiplicity of echoes from the objects which surround the target. This is especially true of land targets. Even for water-borne targets there may be considerable clutter from the ocean near the target, particularly when an appreciable sea is running. This is in addition to the very large "altitude" signal which is returned from the ground or sea directly beneath the receiver and which the receiver must be designed to reject.

In the microwave range the resolving power of a radar receiver increases with increasing frequency. Qualitative studies were made by the Radiation Laboratory. The findings in the 3,000-mc band indicated that the resolving power of the receiver was increased if the incidence angle of the illuminating beam was high. Extension of these studies by the MIT group under Division 5 was made against a ship illuminated at depression angles (the complement of incidence angle) between 2 and 11 degrees. These tests showed that nearly all the energy scattered from the ship target lies in the sector extending from the sea to a plane some 45 degrees above the incident beam. The energy is distributed in azimuth on the illuminated side of the ship in a roughly uniform pattern. Homing on a reflected signal at approach angles steeper than 50 degrees is therefore marginal; above 70 degrees it is impossible.

These studies were extended and made more quantitative in the 10,000-mc band. The energy returned from the target and from the clutter was evaluated in terms of the cross-sectional area of a spherical reflector which would return the same echo. This area is defined as

$$S_a = \frac{16\pi^2 r_1^2 r_2^2 P_r}{P_t G_t A_r}$$

In the foregoing:

r_1 is the range from the receiver to the target.

r_2 is the range from the transmitter to the target.

P_r is the peak received power.

P_t is the peak transmitted power.

G_t is the transmitter antenna gain.

A_r is the effective area of the receiver antenna.

Values of S_a were determined for targets ranging in size from LST's to 10,000-ton Liberty ships and for the sea clutter through a broad range of roughness. The receiver and transmitter in these experiments were at the same location. As a function of depression angle the equivalent cross-sectional areas are:

Depression Angle (degrees)	Equivalent Cross-Sectional Area (sq ft) Target	Sea Clutter
20	10^4 to 10^5	Negligible
30	10^4 to 10^5	Negligible
40	10^4 to 6.5×10^4	7 to 1.5×10^3
50	10^3 to 2×10^4	15 to 1.6×10^3
55	250 to 10^4	40 to 5×10^3
60	Negligible	200 to 1.6×10^4
70	Negligible	4×10^3 to 6.4×10^4

Similar studies are required for land targets.

Successful homing operation is not to be expected at depression angles close to 50 degrees, the limit of resolution from clutter given in the foregoing table. The fading character of radar will make range tracking at such angles of dubious reliability.

1.7.3 RHB Receiver

The energy returned from the target is detected and measured by a superheterodyne receiver located in the missile. The local oscillator consists of a klystron tube with a tunable cavity. The signals from the antenna and from the local oscillator are combined in a crystal mixer to produce heterodyne beats which are then amplified. The seven-stage i-f amplifier operates at 30 mc; it is tuned to this frequency but with sufficient band-pass to prevent undue distortion of the 0.7-microsecond pulses. A detector passes the envelope of the pulses which is amplified and, after operation of the tracking system, commutated to provide directional data to the automatic pilot (Figure 9).

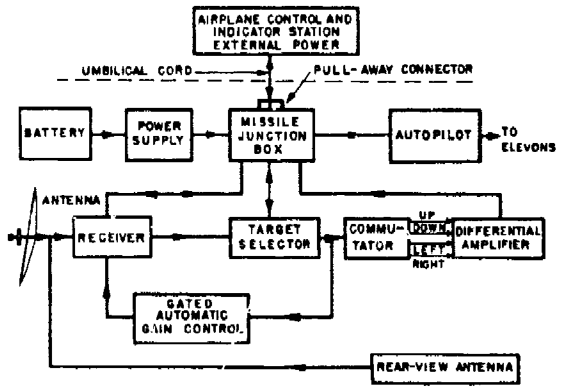


FIGURE 9. Block diagram of RHB receiver.

Fundamental information as to the direction of the target is obtained by a scanning antenna. A disk dipole is located at the focus of a 12-in. diameter parabolic reflector of 3.6-in. focal length. The "beam-receptor" character of this antenna system yields a signal which is down 50 per cent when the source is ±11 degrees from the axis of the reflector. The reflector rotates at 1,800 rpm about an axis which is inclined to its optical axis by 5.5 degrees. Thus, during one revolution of the antenna 26⅔ pulses are received from the target. If fading is neglected, the signal strength during a scanning cycle will depend upon the bearing of the target with respect to the axis of rotation of the reflector—the axis of scan. For a target on the axis of scan the returned signal is constant; for small error angles the variation in signal strength over a scanning cycle is approximately sinusoidal. The envelope (Figure 10) is integrated over quarter-cycles, and the total received energy in diametrically opposite quadrants, when amplified, operates to bias the rate gyros as shown in Section 1.6.

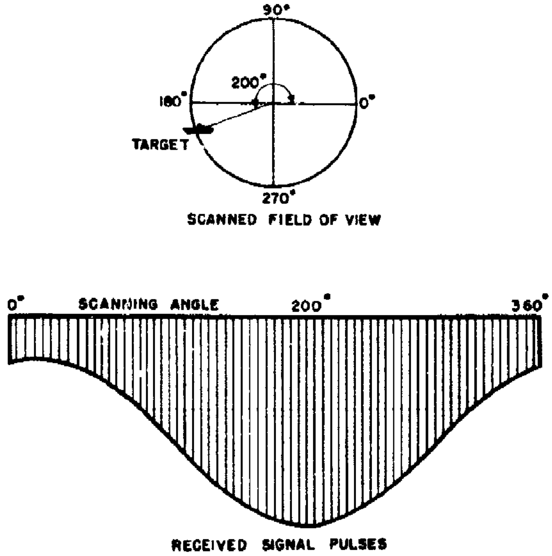


FIGURE 10. Conical scanning process.

Within the illuminated field there will generally be several reflectors. For a homing attack to be successful one target must be selected and the attack pushed home on it. One method of eliminating all but the desired signal would be to make the beam sensitivity of the receptor extremely narrow. This would require an antenna reflector too large to be carried in the missile and might result in complete loss of the target when the motion of the missile is made erratic by gusts. Pulsed radar provides a practicable method for range tracking.

Range discrimination is essential in any event in radar-homing glide bombs because of the large amount of energy returned from the ground or sea, which is always the biggest target in the field. At ranges of 5 miles or more, and with the smaller antennas required for missiles, as much energy is received from the ground or sea directly below the missile as from an average target; this altitude signal must be rejected by the receiver. In glide bombs, since the altitude is always less than the range to the target, a range discriminator makes it possible to eliminate the altitude signal. The target selector provides range discrimination by "gating" the desired signal, i.e., allowing the differential amplifier to receive signals only at the exact time that echoes from the desired target are received. It also, through a memory circuit, adjusts the time of operation of the gate circuit to the range of the target, i.e., to track in range.

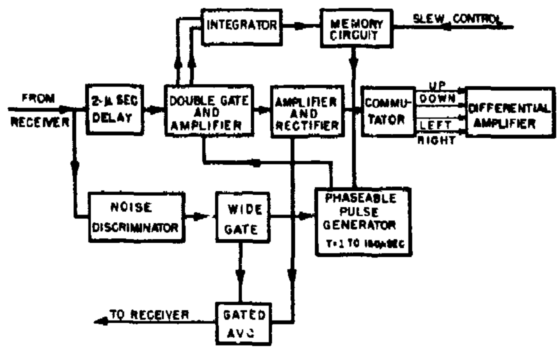


FIGURE 11. Block diagram of range-tracking circuit.

Synchronization is accomplished by starting the tracking circuit (Figure 11) with the reception of the main pulse from the transmitter. The receiver normally is at full sensitivity. Upon reception of the main pulse via the rear-view antenna a negative pulse is applied to the grids of the first and second stages of the i-f amplifier; this biases the receiver below the noise level and prevents the reception of any signal until the first echo. This main gating pulse is about 200 microseconds wide.

Within the main gate are two narrow gates, each 0.6-microsecond wide with a 0.2-microsecond overlap yielding a total gate of 1.0 microsecond. The double gate is tripped by a single-cycle multivibrator at a time after the main pulse equal to the transit time from the missile to the target and back. The time of tripping is determined by the rate of discharge of a condenser in the memory circuit. Were the range to decrease at a constant rate, it would be necessary only to have the double gate traverse the wide gate at a constant rate. The function of the double gate is to adjust the tracking rate so that the target echo will always be centered within it (Figure 12). If the rate of tracking is too fast, the portion of the echo lying in the second 0.6-microsecond gate will exceed that in the first, and the voltage against which the multivibrator condenser discharges will rise, and vice versa. With 3,000 mc there are 2.1 adjustments of the memory circuit in each 0.7-microsecond pulse. Time constants of the memory circuit are such that, should fading cause loss of synchronization, the memory circuit will track at the correct velocity for several seconds.

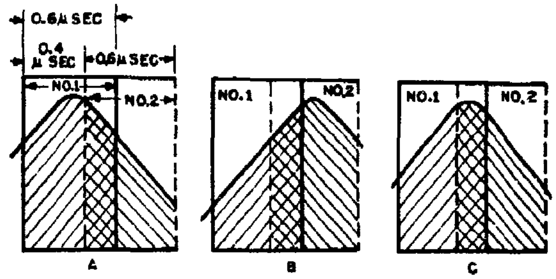


FIGURE 12. Operation of double-tracking gate. (A) phaseable pulse tracking too slowly—excess of energy in Gate No. 1; (B) phaseable pulse tracking too fast—excess of energy in Gate No. 2; (C) phaseable pulse correctly synchronized—equal energy in both gates.

A second function of the narrow gate is to apply an AGC voltage to the i-f amplifier. This voltage is so adjusted that a strong signal is held to half the saturation level of the output stages. The AGC must not be so fast that the 30-c modulation will be obscured with consequent loss of directional information. AGC over a range of about 5.3 db is required to accommodate the increase in received power due to the operation of the inverse square law as the missile approaches the target.

1.7.4 Maximum Range

RHB receivers (Figure 13) have a threshold sensitivity of about 10^{-12} watt; 10^{-10} watt gives a reasonable margin for satisfactory range tracking. The relation between range and received power is given by:

$$r_1 r_2 = \frac{P_t D_t^2 D_r^2 S_a}{64 P_r \lambda^2}$$

where r_1 is the range to the transmitter in feet;
- r_2 is the range to the receiver in feet;
- P_t is the transmitter output in watts;
- P_r is the echo signal strength in watts;
- D_t is the diameter of the transmitter antenna reflector in feet;
- D_r is the diameter of the receiver antenna reflector in feet;
- S_a is the equivalent spherical cross-sectional area of the target in square feet.
- λ is the wavelength in feet.

At the dropping point r_1 and r_2 are identical. With airborne search equipment the transmitter output is approximately 30 kw. D_t and D_r are 2.5 ft and 1 ft respectively. With 3,000-mc radar—λ about $1/3$ ft—a safe maximum range for RHB against a Liberty ship is about 27 miles.

1.7.5 Tests with RHB

The basic development of RHB was carried out by MIT Radiation Laboratory under Division 14. Laboratory prototypes were procured by them for initial tests in powered aircraft and in glide bombs (Pelican). When procurement by the Navy Bureau of Ordnance was instituted, the project was turned over in its entirety to Division 5. A few of the personnel associated with the project formed the nucleus of a new MIT radar group operating at the National Bureau of Standards under Contract OEMsr-240. Too much credit can hardly be proffered to Division

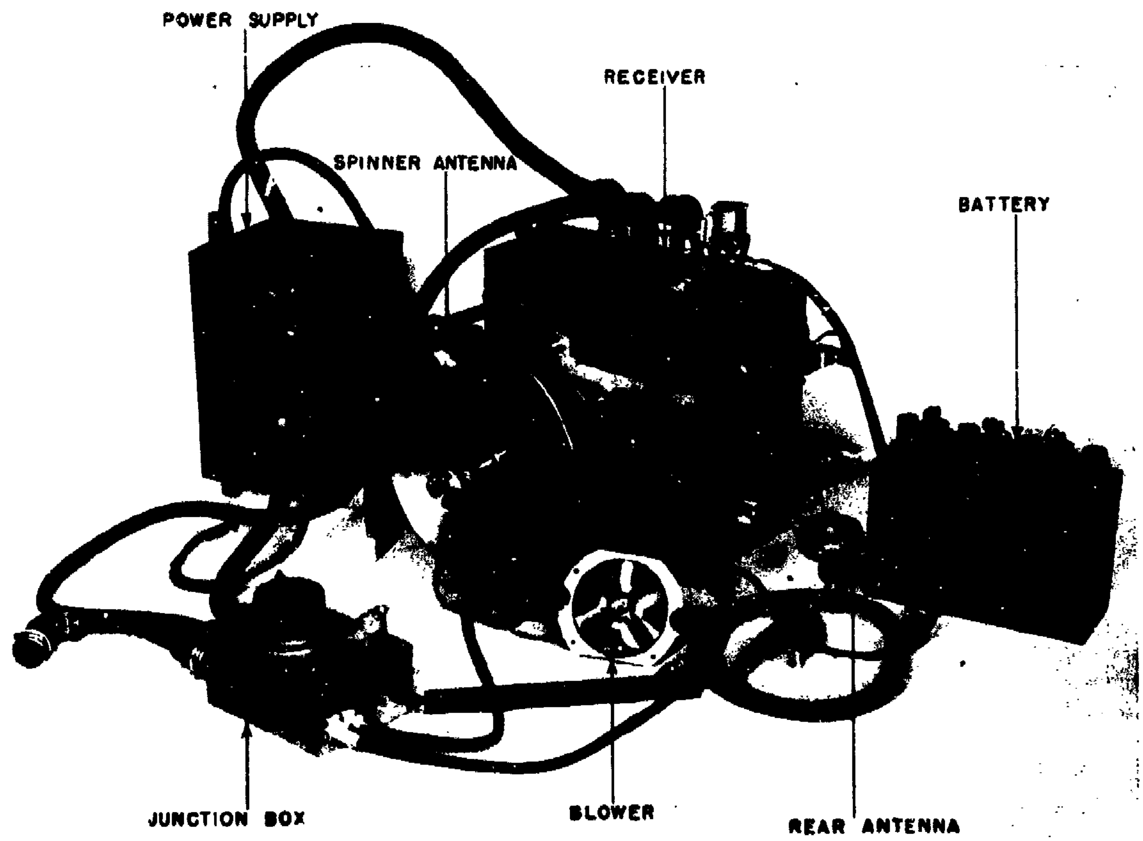


FIGURE 13. Receiver and power supply for RHB Pelican.

14's group for boldly undertaking a difficult venture and completing the basic research in approximately 19 months.

Early tests on RHB were in an AT-11 airplane with a human servo link. The target area was illuminated by a large truck-borne radar search equipment stationed on a hill overlooking a portion of Boston Harbor. The output of the RHB equipment lighted four signal lights by which the pilot flew the airplane at selected ship targets. To passengers the accuracy seemed great; cold analysis of the motion picture records indicated that the airplane was not on true course for a high percentage of the time.

Neither the Division nor the Navy realized the extent of the work remaining to be done. The entire problem of adjusting the response rates of the airframe, the automatic pilot, and the radar equipment remained to be solved.

When laboratory model-shop prototypes became available, an experimental range was established by the National Bureau of Standards and the Navy Bureau of Ordnance. Here testing continued against beacon radiators and reflectors suspended from barrage balloons. Faulty construction of the model-shop equipment masked the results of the tests. Instrumentation (see Chapter 8), though well conceived, was not always adequate to establish conclusively which links of the servo loop failed.

It was not until a complete radar laboratory was established and staffed with some twelve scientists and engineers, supported by technicians made available from the Navy, that a measure of consistent success was obtained. Defects in the radar equipment which seemed trivial in the laboratory were wholly frustrating in the field. A third gyro sensitive to rate of yaw had to be provided to damp out oscillations. Everyone associated with the project had to learn that the automatic control of a glide bomb is a more difficult task than the combined operations of interpreting a radar scope and flying an airplane.

Ultimately, consistent scores of 50 per cent hits from 11 miles were attained against a 10,000-ton ship.

1.7.6 Self-Synchronous RHB

The original RHB used the signal received directly from the transmitter as the synchronizing impulse. In all RHB's, precautions must be taken to insure that sufficient energy is received. When the target is illuminated from an aircraft, the missile may not remain within the beam because of evasive action of the aircraft or because of the difference in the speeds of the missile and aircraft. Hence the transmitter must be equipped with an additional nondirectional (or at least a very-broad-beam) antenna to ensure the radiation of some energy in the direction of the missile. Likewise the directional characteristics of the receiver antenna are such that little energy is received from the rear, which is the direction of the transmitter. It is necessary, therefore, to provide a rear-view antenna on the missile to ensure that sufficient energy is received directly from the transmitter to synchronize the range selection gate.

The second system derives its synchronization from the reflected signal; hence the equipment is termed self-synchronous. Actually a very stable low-frequency oscillator is built into the receiver and an identical oscillator is used to control the pulse rate of the transmitter. The frequency of the receiver oscillator is automatically adjusted to that of the received pulse rate. The self-synchronous RHB was developed primarily because it offered a means of securing homing intelligence all the way into the point of impact with the target. Both the Pelican and the Bat (see below) experience difficulties at close ranges because of the coincidence of the initial pulse with the returning echo. Pelican requires the reception of the direct transmitted pulse for synchronization, and Bat cannot make use of the echo when its transmitter is operating. The self-synchronous RHB, however, derives its synchronization from the echo only, and it can exclude the initial pulse, which is transmitted from many miles behind the receiver. A few experimental models of radar-homing equipment with this method of synchronization have been built and tested.

1.8 RADAR-HOMING CONTROL—SRB CONTROL[9]

The receiving system used in RHB was used substantially unchanged in the *send-receive bomb* [SRB] (Figure 14). The basic change was that the missile Bat carried the transmitter as well as the receiver (Figure 15). The whole equipment was developed by the Bell Telephone Laboratories under direct contract with the Navy Bureau of Ordnance. The Division rendered consulting service through its radar group established for the engineering development of RHB.

Successful operation was required at ranges of 7 miles with continuing tracking in to 100 yd. The

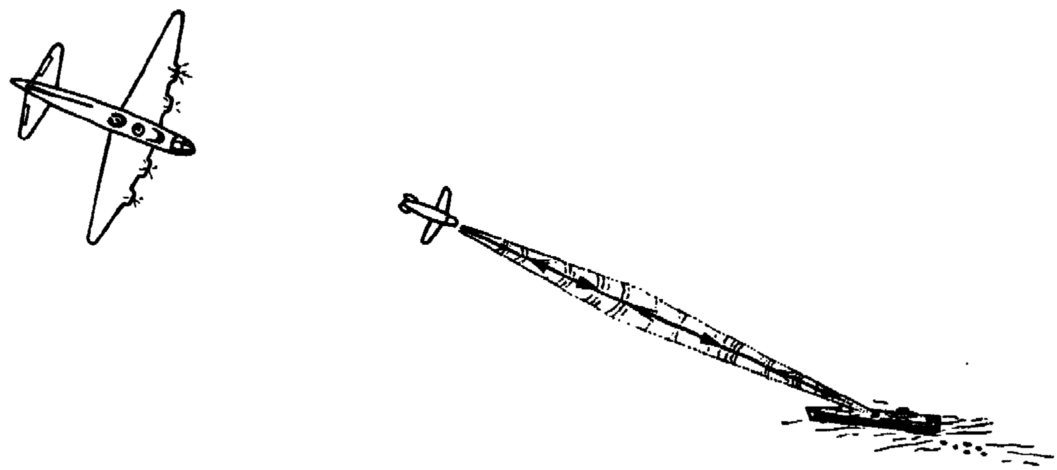


FIGURE 14. SRB—Bat attack.

fourth-power law that such a system follows requires an AGC system with a range of 120 db against large cargo vessels; this requirement was met only with difficulty.

AGC was applied from the second and following stages of the i-f amplifier, the first stage being omitted to avoid pickup of noise on the AGC leads to the grid. The high loads on the first stage at close ranges gave rise to shock-excited spurious signals which persisted as "ringing," distorting the true signal in the tracking gate. The frequency of the transmitter drifted with altitude changes, and the directional

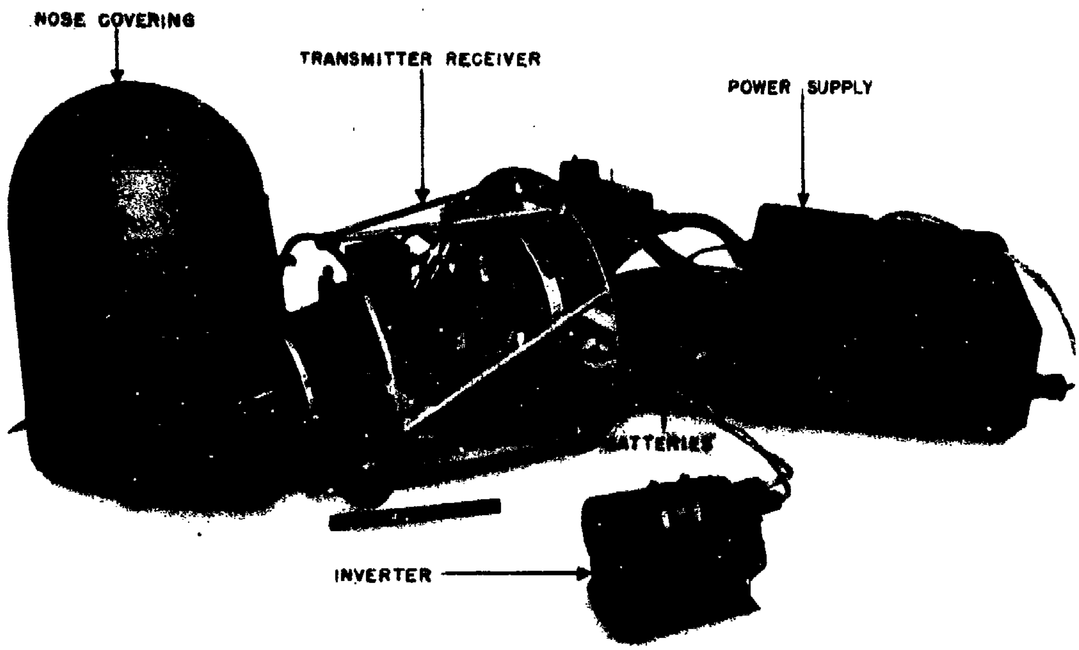


FIGURE 15. SRB—Bat radar equipment.

response of the equipment was distorted because of change in loading impedance as the reflector rotated.

The ghost signals arising in the i-f amplifier were eliminated by an engineering compromise in the Q of the circuit so that the ringing would be more damped, still leaving sufficient band-pass to avoid distortion of the 0.7-microsecond pulse. The master oscillator was pressurized to prevent frequency drift with altitude changes, and equipment within the missile was rearranged to eliminate the squint caused by change in output impedance during scanning cycle.

As in the case with RHB, defects in the equipment which seemed of little importance in the laboratory loomed large in the field. It was only by the complete cooperation of the Navy, its contractors, the Bureau of Standards, and the contractor of the Division that the project reached successful combat use.

1.9 SERVO LINKS[10]

The use of full-span elevons results in larger hinge moments than would ensue from the use of airplane-like control surfaces, elevators, and a rudder. The requirement of constant angle of attack, which required this design, was, however, deemed to be inflexible; indeed, all experience of the Division indicates that its importance cannot be overestimated. A severe requirement was therefore placed on the designers of the servo link: to produce a mechanical power amplifier of very high gain with a minimum of phase lag.

The initial attempt used a continuously running electric motor. Four jaw clutches imparted to the two elevons motion to increase or to decrease the lift of each, independently of any motion which might be taking place on the part of its mate. Thus, if the following table shows the action of the four clutches:

	Increase Lift	Decrease Lift
Left Elevon	Clutch No. 1	Clutch No. 2
Right Elevon	Clutch No. 3	Clutch No. 4

an increase in rate of turn to the right would be executed by energizing No. 1 and No. 4, a decrease in glide-path angle by energizing No. 1 and No. 3, and so on. Flight tests showed that such a system imposed on the radio-controlling bombardier a task not likely to be successfully accomplished. Indeed, two flight tests resulted in such prompt failure that the decision was made immediately to interpose automatic flight-control equipment between the teledynamic signals and the servo link. (See Section 1.6.)

The next design was successful. Here the continuously running motor with the four jaw clutches is retained, but the connection to the elevons is through a linkage so ingenious as to merit particular explanation. The four clutches now perform missile functions rather than elevon functions. In Figure 16 the four small pinions, R, L, U, and D, are driven through the clutches; R and L initiate the turning forces, and U and D the pitching forces. The whole linkage is supported by two heavy fixed members A. Suppose a "down" signal to be called for in the absence of any turning signal. The appropriate clutch will engage, bringing pinion D up to speed; this will drive the pitch sector say in a counterclockwise direction, and with it the pitch-input link. In the absence of any turning signal, the turn sector is stationary and holds rigid all the horizontally hatched system, including H_R through E and F. Thus H_R, B, C, and the pitch-input link operate as a four-bar linkage, and the right-elevon output arm translates circularly, the stud moving counterclockwise about O_4. A connecting-rod from the stud raises the right elevon. The rotation of the pitch-input link is transmitted through D to the internal jackshaft, which in turn gives through B′ and C' a counterclockwise rotation to the left-elevon output arm about O_3'. Now if the radii about O_1 and O_3' are equal and large compared with the arcs of travel, the motion of the elevons will be nearly identical.

An exactly similar procedure covers turn. Suppose a "right" signal is called for, resulting in a clockwise rotation of the turn sector. Then the turn-input link, through C' and B', gives a clockwise rotation to the external jackshaft, which in turn, through D, E, the bell crank H_R, B, and C, rotates the right-elevon output arm clockwise about O_3. Similarly, the stud on the left-elevon output arm will revolve about a suppressed axis O_1'. Again, if the radii about O_3 and O_1' are equal and large compared with the arcs of travel, the motion of the elevons will be very closely symmetrical.

Within the limits of linearity indicated above, these motions are subject to geometric superposition. In any event, departure from strict kinematic rigor is probably unimportant. Any rate of roll introduced by slight inequality of elevon action resulting from a pitch signal would be corrected by the automatic pilot. (See Section 1.6.)

This scheme for a servo link was considered a temporary expedient to provide a means of flight-testing the glide bombs without delay. It was recognized that the linkage was elaborate and not readily adapted to quantity production. Nevertheless, after a most exhaustive exploration of other forms of links involving hydraulic and pneumatic media of transmission, the linkage just described remained the basic method. The other designs were tested on the roll hunt table (see Section 1.5) and showed greater time lags resulting in more hunting, were deficient in output, or were too heavy for airborne equipment of this type.

In the production version the sector-driven shafts were replaced by jackscrews, and the jaw clutches were replaced by positive-acting clutch gears similar to those used for controlling and quickly reversing the longitudinal feed on an engine lathe. These changes together with a general rearrangement of elements, produced a design which had somewhat better performance and was adapted to mass production.

In another contract (see Chapter 7) the entire servo system was reviewed, and the automatic pilot was combined with the amplifying servo link.

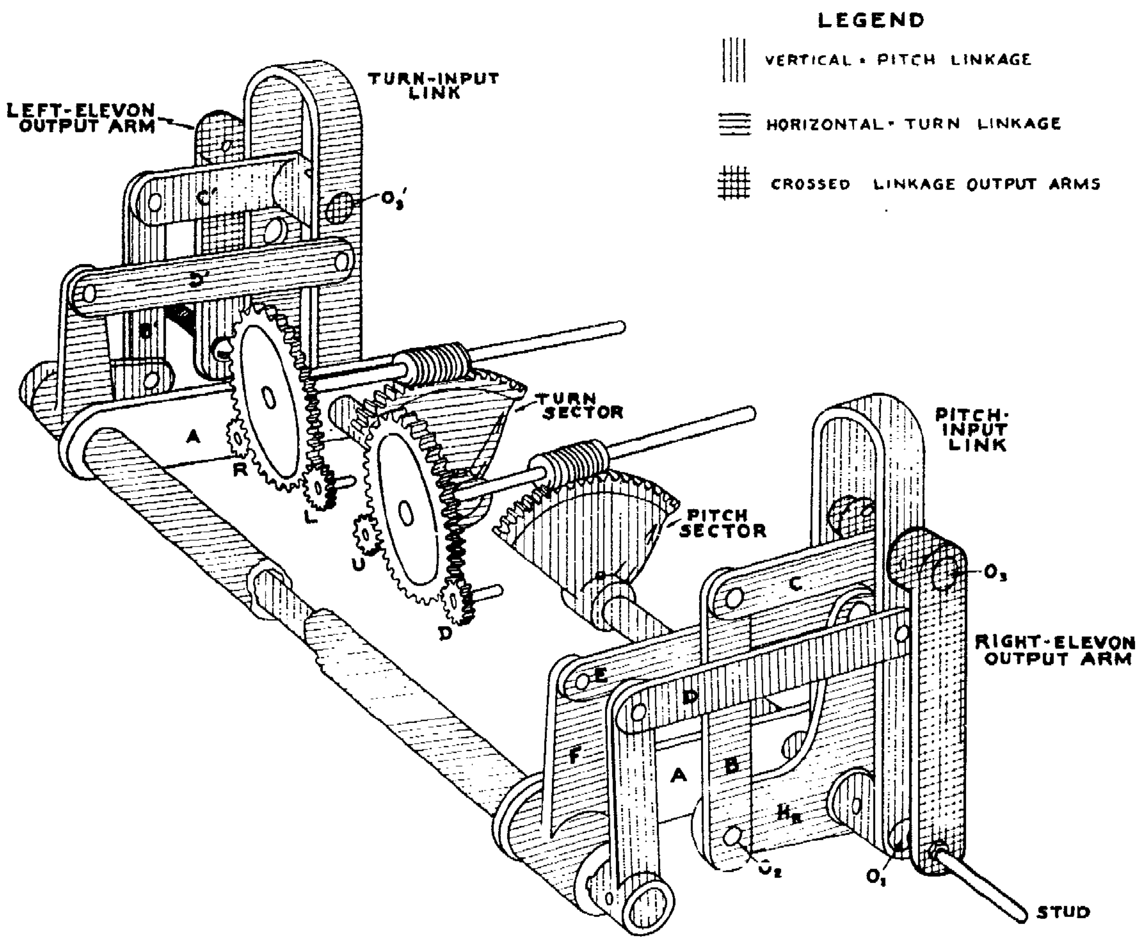


FIGURE 16. Schematic drawing of elevon drive linkage.

Chapter 2

AZON AND RAZON

2.1 INTRODUCTION

The glide bombs discussed in the preceding chapter have a lift-drag ratio of about seven. The long range implicit in this ratio, approximately 13 miles from an altitude of 10,000 feet, yields relative invulnerability to antiaircraft opposition and is achieved by the use of large control and supporting surfaces. Thus increased range is obtained at the expense of ease of carriage. Aircraft carrying glide bombs are limited in their load to two or, at most, three missiles. The aircraft requires modifications to permit the carriage of the missiles; carrying them externally impairs in a measure the performance of the aircraft and clearly marks the airplane for a special attack by enemy pursuit ships. For this reason NDRC undertook the development of a guided missile which could be carried within standard bombardment aircraft, be hung on standard bomb racks, be produced by modifying standard bombs, if possible, and which would require for its control the minimum of specialized equipment in the carrying plane.

2.2 GENERAL

In order to achieve this objective it was early realized that the bomb must provide the major portion of the lift and that steering forces must be provided by the bomb casing itself through yawing and/or pitching it in the wind stream. A well-established agreement between the Army Ordnance and the Army Air Forces had decreed that bombs carried within aircraft should have no protuberances which extend beyond the smallest square prism which circumscribes the body of the bomb. The designers of aircraft for the AAF, on the one hand, designed all bomb racks so that bombs fulfilling this requirement could be carried safely; Ordnance, on the other hand, undertook to see that all bombs were built to this specification.

Within these bounds each group of designers had flexibility, but the limits were held rigid. The Division accepted these limitations and only after exhaustive study within them attempted to secure a relaxation at the expense of reducing the bomb load.

The implications in this restriction are powerful. Any wings or supporting surfaces may have a span not exceeding the diameter of the bomb casing by a factor greater than the square root of two. In order to have an appreciable area their chord must be great—several times their span—so that their aspect ratic is much smaller than normal. The provision of a long lift surface forward of the center of gravity impairs the weathercock stability. It was finally found that the gain in lift due to such "wings" was so small in comparison with their cost in stability at trim that they were abandoned, the bomb body itself developing the major portion of the lift.

This simplification did not, however, produce a solution which was obviously of great promise. A bomb casing in itself is not an aerodynamic structure of highly desirable profile. It is a form that would be no more than tolerable to the designer of a dirigible airship, and such aircraft do not contemplate speeds of 550 mph—approximately the impact velocity of a dirigible high-angle bomb from 15,000 ft.

The basic art applicable to the problem was meager. Dryden[1] had made studies at the National Bureau of Standards on the fundamental aerodynamic properties of standard bombs. Beyond this work, however, neither the Division nor its contractors found much evidence of quantitative work which would indicate a probability of making standard bombs dirigible. There had been considerable speculation, but the most informed opinion from aerodynamic advisers was definitely negative. The question of adequacy of lift from such a wing as a bomb casing has already been mentioned. The problem of exercising adequate control during the thirty-odd seconds of flight seemed difficult. The problem of determining what control to apply, granting the physical possibility of applying it, seemed insurmountable.

It may well be questioned why the Division undertook the project in the face of such negative advice. The desirability of converting near misses into hits—of compressing to within the dimensions of the actual target the relatively large number of craters that cluster about the center of impact with normal distribution—seemed of great importance to the Division chief. However, had he had access to data on actual bombing errors and known that it was necessary to get the amount of control that finally proved feasible, it is doubtful if he would have recommended carrying the project through.

In general there were two approaches to the problem of controlling the bomb. In the first method the bomb was made to home on the target. This was planned with television and manual steering through a radio link or with an automatic homing device. The automatic homing devices which were considered utilized (1) light actuating a photosensitive system, (2) heat actuating a thermosensitive system, and (3) radar homing, actuated by microwave reflections from the target. It was realized that a homing system must operate with its axis of scan parallel to the tangent to the flight path. Consequently, the use of pivoted

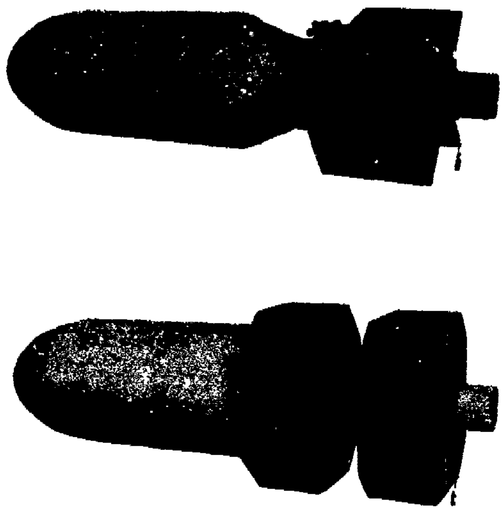


FIGURE 1. Production models of Azon and Razon.

vanes to align the television camera or the automatic homing receptor was contemplated.

The second method contemplated a direct-sight method of control. In this method the bomb was to be controlled along a trajectory such that it continuously eclipsed the target from the point of view of the controlling bombardier.

The first approach involves much more complicated control equipment. The second implies, as will be seen in Section 2.3, a much wider departure from the conventional parabolic trajectory. Each method found embodiment in a weapon standardized for combat. Felix, the automatic heat-seeking high-angle bomb, is discussed in Chapter 3. Azon, a high-angle bomb visually guided in azimuth only, reached combat in the Mediterranean, European, and Burma Theaters of operation. Razon, its two-coordinate counterpart, was in production for use in the Asiatic Theater as the war closed. Production models of Azon and Razon are shown in Figure 1.

2.3 TRAJECTORIES

Controlled high-angle bombs have two types of trajectory. For the homing type, the path is closely rectilinear when the target is motionless in the air mass; when there is target motion with relation to the air mass, the path becomes a pursuit curve. This type of trajectory is treated in Chapter 3.

For visually guided bombs, the trajectory should be analyzed from two points of view. In the azimuth component, the trajectory does not usually require much curvature to effect the necessary corrections, and the problem of parallax, especially if the target is long in the direction of the bomb run, is not acute. It is the problem of parallax in the range sense which recommends the eclipse technique. If the controlling bombardier could estimate continuously the distance from the bomb to the ground and its first few time derivatives, he could doubtless be trained to steer a Razon in both coordinates as readily as an Azon in one. If, however, he keeps the bomb and target continuously collinear with his own point of view, he is assured of a hit even if he has no idea of the time of impact. Eventually, the bomb will reach the ground; if it is continuously in the bombardier's line of sight to the target, it will be on the target at impact.

If this principle is adhered to throughout the flight of the bomb, the release will take place exactly at the target's zenith since in the first instant the bomb is directly beneath the airplane. With a drop from 20,000 ft and a speed of 150 mph, if collinearity is to be delayed for approximately 10 seconds, the drop should occur 2,000 ft before the target is directly beneath the airplane. If collinearity is to be delayed for approximately 24 seconds, the drop should occur 4,000 ft before the target is reached. In the case of the drop with the 10-second collinearity, some 30 seconds of control time would remain; for 24-second collinearity, about 16 seconds would be available for steering. A normal drop for an uncontrolled bomb would take place about 7,000 ft in advance of the target.

Thus, in the eclipse method of range control all the forward velocity of the bomb must be killed, and during a goodly portion of its flight the bomb actually regresses in the range sense. Figure 2 shows the three trajectories discussed in the preceding paragraph as projected on the vertical plane containing the path of the aircraft. It also shows the trajectory of a perfectly aimed, unguided bomb (Curve A).

The increase in curvature of the controlled trajectories, as compared with that of a standard bomb, is a measure of the amount of control force which has to be applied. This technique, therefore, requires considerable maneuverability of the missile—not an ideal application for an airframe constrained to fit within the smallest square prism circumscribing the body of the bomb. Furthermore, it is undesirable to have the release point for guided bombs materially different from that of standard bombs because the miss, if control is lost, would be gross.

Several methods have been suggested for combating the problem of excessive curvature in the trajectory resulting from the eclipse technique. One of them (used by the Germans in Hs 293, a visually guided glide bomb) is to have a rocket propel the missile out in front of the aircraft so that collinearity can be established early without excessive trajectory warping. A second, tried by the Division's contractors,[2] involved decelerating the airplane so that it would drop behind the missile. This was accomplished by putting the bomber into a climb with minimum throttle. In order to get a retardation promising success, it was necessary nearly to stall the ship out. This method was used by the Germans in guiding FX-1500, a visually guided high-angle bomb. Soon after their success in sinking the *Roma*, the use of FX-1500 was abandoned when all the aircraft equipped to carry and control it were destroyed in a mass bombardment. Little data on the efficacy of this technique is, therefore, available.

The Crab modification to the standard Norden bombsight provided a good solution. The problem was placed before the Fire-Control Division of NDRC by the Director of OSRD. The solution is discussed more fully in Section 2.6 and at length in the Summary Technical Reports of Division 7, NDRC. The assumption was made that the time of flight of a Razon could be estimated. Then a partially silvered mirror was inserted in the optical train of the bombsight. The image of the falling bomb is projected into the field of view so that it appears superposed on the terrain at the point it would land if no further control were added. If the drop is perfect, the bombardier sees the bomb exactly on the target and makes no correction. Thus the departure from a normal trajectory is minimized. The residual range error after perfect steering is equal to the error in estimating the time of fall multiplied by the forward velocity of the bomb at impact.

2.4 ROLL STABILIZATION

At the outset of the project two modes of control were proposed, each of which implied its own peculiar type of roll stabilization. One system, which has been uniformly attractive to newcomers in the field, involves a system of cylindrical coordinates. The axis of the system is tangent to the trajectory. In this system no attempt is made to prevent roll, only to restrict its rate to a reasonably low value, say 0.5 revolution per second. Only one set of control surfaces is provided for steering. Ailerons for restricting and controlling the rate of roll are also provided, usually in a plane normal to that of the steering surfaces. The method is to roll the bomb so that a plane normal to the plane of the steering surfaces contains the target, the bomb, and the aircraft. The bomb is then given an angle of attack to produce a resultant of lift and gravity and, consequently, an acceleration in the direction in which correction of the trajectory is desired.

Viewed from a fixed frame of reference in the bomb structure, lift can be produced only in a single plane, normal to the axis of roll and to the steering surfaces. If a turn to the right is required, the bomb is rolled until the steering surfaces are vertical and then the bomb is yawed. If a dive is called for, the bomb is rolled until the steering surfaces take the position of conventional elevators and then the bomb is pitched.

In the second system the location of the three principal axes of motion remains unchanged, but the bomb is closely coupled to them. Two steering surfaces are provided: the rudder operates in the plane of the roll and yaw axes, the elevator in the plane of the roll and pitch axes. This system, therefore, operates in simple Cartesian space.

The cylindrical-coordinate control has the advantage of not requiring absolute roll stability. Only a rate gyro is required which can be made sufficiently sensitive to hold the roll velocity to any desired value. At the outset of the guided-missile program free gyros, which are absolutely essential if the Cartesian system of control is to be employed, were difficult to procure. Further, a wind-driven or unpowered free gyro with two frames is sure to tumble if the bomb is pitched through 90 degrees and then yawed through

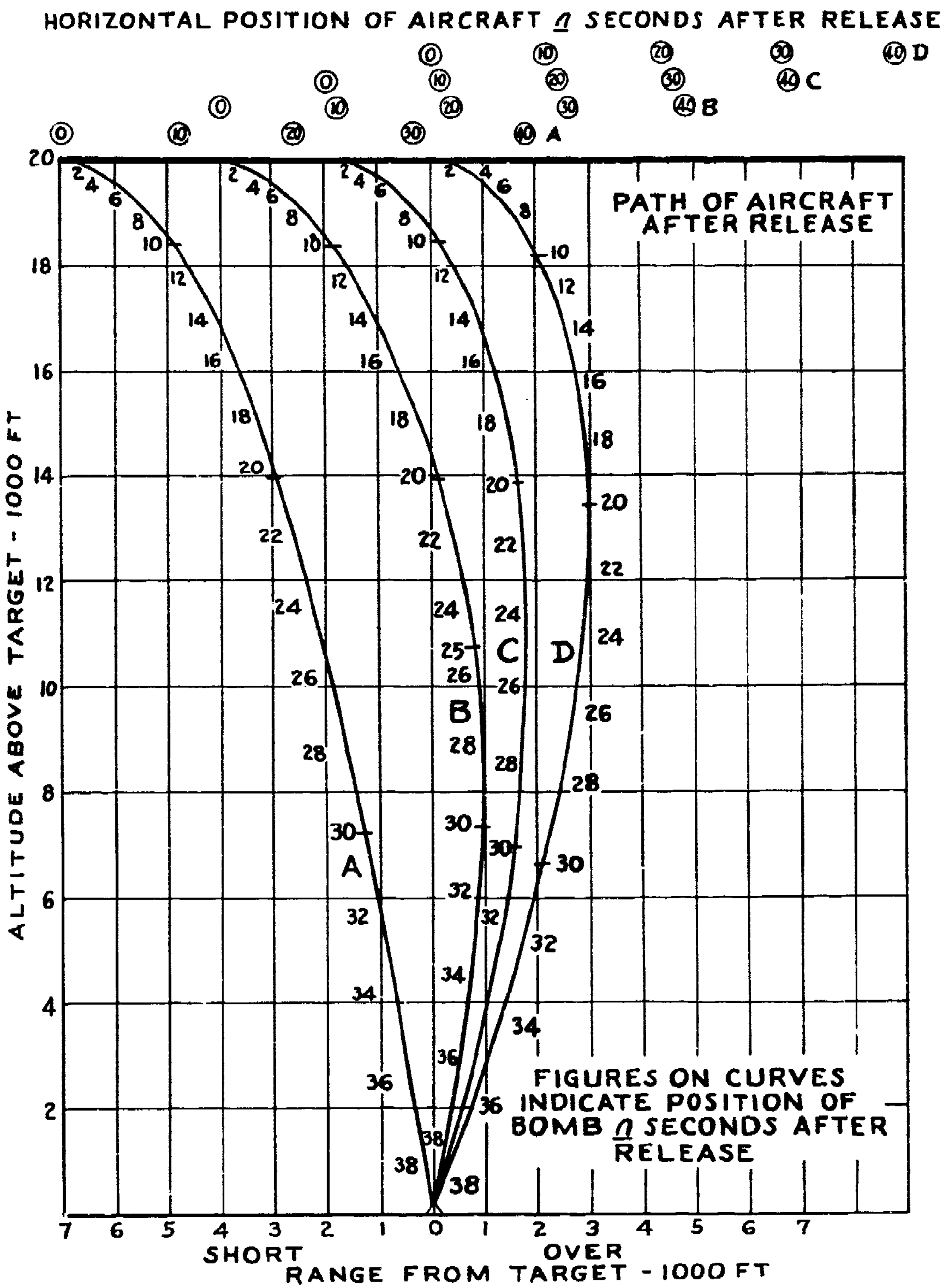


FIGURE 2. Profiles of eclipse trajectories compared with perfect uncontrolled bomb.

90 degrees. Perhaps this property of the free gyro could be circumvented by providing more than two gimbal frames but even if it were, all sense of right-side-upness would be lost after such a maneuver as the one just described. After a 90-degree dive the "top" of the bomb would point forward. A succeeding turn to the right would place the rudders horizontal with the "top" of the bomb on its left.

The summation of these advantages led the investigators strongly toward the cylindrical-coordinate system of control. Not only MIT and Gulf Research and Development favored it for the high-angle bomb, but Douglas strongly favored it for Roc (see Chapter 4), and Polaroid for Dove Eye (see Chapter 3). It was also strongly urged for the Jeffries[3] bomb under development by the British. It has been treated at length in this report as an example of exploration which the Division found unprofitable. *The Division's experience all points to the conclusion that it is much better to plan trajectories which will not involve successive turns approaching 90 degrees about the axes of yaw and pitch than to try to provide a stabilization system which will tolerate them.*

2.4.1 Origin and Nature of Roll Torques

Roll torques occur in all bombs. They are deliberately provided in some German bombs by designing in a screw asymmetry to arm the fuze and in the British Tallboy (a 12,000-lb, deep-penetration bomb) to improve stability about the yaw and pitch axes. In bombs manufactured in the U. S., it is never purposely provided, but the difficulty of holding manufacturing tolerances within limits which will eliminate casual screw asymmetries is so great that in general all standard bombs in flight have a random roll velocity.

Induced Roll Torques. Induced roll torques arise in dirigible bombs from the application of control about the axes of yaw and pitch. Such induced roll torques occur with conventional control structures when yaw and pitch are applied simultaneously. They appear to arise from three sources:

Consider a bomb which has been pitched. Such a bomb has an angle of attack at the elevators. If it now be yawed, one elevator will lose lift because of the reduced speed of the elevator on the inside of the turn. This torque is probably small and should be transient in nature, occurring only during the period while the bomb is approaching its trim attitude. All rotation thereafter is at an axis so remote, certainly not less than 2 miles, that any differential velocity in the lift surfaces is wholly negligible. This property can be disclosed only by transient studies in the wind tunnel.

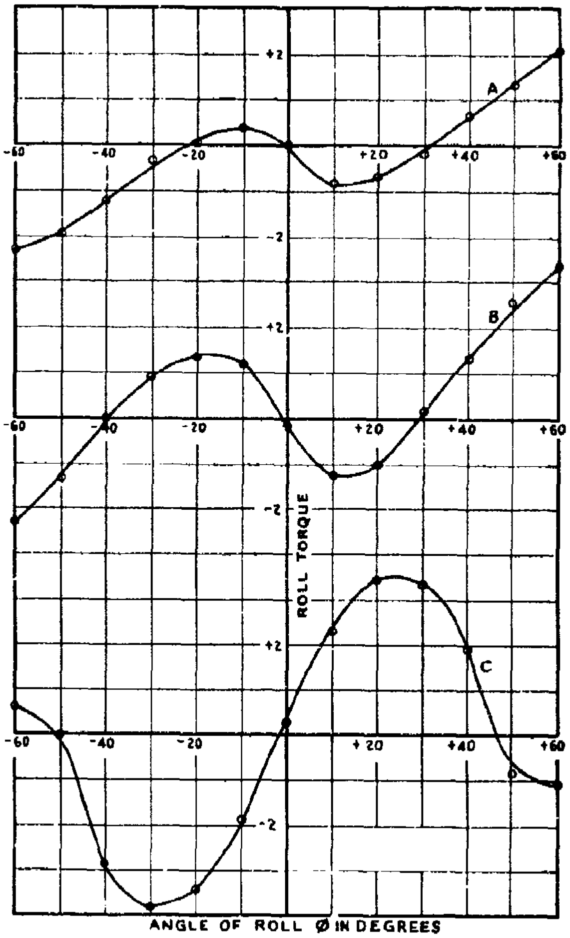


FIGURE 3. Roll torques in cruciform bomb as function of roll angle.

A flat plate in a wind stream tends to orient itself so that it is perpendicular to the direction of flow. So long as the plate is parallel to the wind stream, it is in a state of unstable equilibrium and but little force is required to hold it there. If a bomb is pitched without yaw the plane of the rudders is parallel to the wind stream and only slight aileron power is required to maintain the roll orientation. If a pitched bomb then be yawed, there is a torque as both the rudder and elevator attempt to attain a position normal to the wind stream. This torque disappears when a roll attitude is reached which places the structure 45 degrees away from the desired orientation.

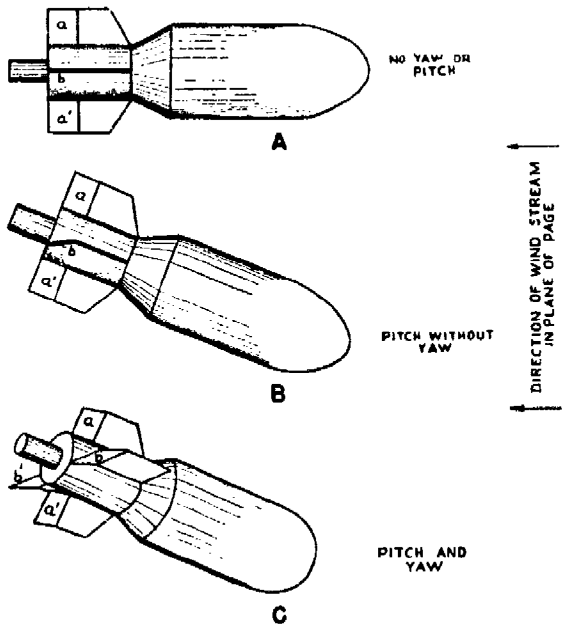


FIGURE 4. Drawings of cruciform bomb in attitudes of no yaw or pitch, pitch, pitch and yaw.

Figure 3 shows the variation of roll torque with roll attitude as measured by MIT in the wind tunnel. In these curves the unit of roll torque is the maximum restoring torque that could be developed by the ailerons planned. The slope of the curve at zero roll, as well as the value of roll torque at that orientation, is of crucial importance, a negative slope indicating stability and a positive slope instability. Thus Curve A (pitch only) and Curve B (yaw only) show roll stability; Curve C (simultaneous roll and pitch), however, shows marked instability.

The third source of induced roll torque arises from shadowing of the control surfaces by the body of the bomb. Figure 4A shows a bomb without yaw or pitch. The rudders a, a' and the elevators b, b' are parallel to the wind stream which is in the plane of the drawing. They therefore produce no torque. In Figure 4B the bomb has been pitched so that the lower rudder a' is shaded by the bomb casing. Since the rudders are parallel to the wind stream, no roll torque is developed in spite of the asymmetrical exposure of the rudders to the wind. In Figure 4C both yaw and pitch are applied. Now in addition to the lower rudder a' the remote elevator b' is shaded by the bomb body. Further, both the rudder and elevator planes are inclined to the wind stream so that the asymmetrical exposure of each results in a roll torque.

The torques developed by shading are in opposition. The excess exposure to the wind of the upper rudder produces a counterclockwise moment; that from the exposure of the elevator in the foreground produces a counterclockwise moment. Figure 5 is a contour map of the roll torques produced by simultaneous yaw and pitch. As might be expected from the preceding two paragraphs, two pairs of orthogonal axes define the attitudes producing zero roll torque. Displacement in pitch or yaw alone results in stable equilibrium. Equal displacement in yaw or pitch results in zero roll torque, but the equilibrium is unstable.

While the torques measured in the wind tunnel show requirements three times in excess of those planned, this is not the whole story. Flight tests showed that torques at least three times greater than those measured could be developed, because of autogyration once a roll velocity is established.

2.4.2 Reduction of Roll Torques

The discussion in Section 2.4.1 as to the origin and nature of roll torques points clearly to the method of their minimization. It is to produce a structure which is symmetrical about any plane passing through the axis of roll. A dirigible high-angle bomb having such a configuration was designed by MIT[4] and is shown in Figure 6. Lift is obtained by the forward shroud which is placed so that its center of lift is substanti-

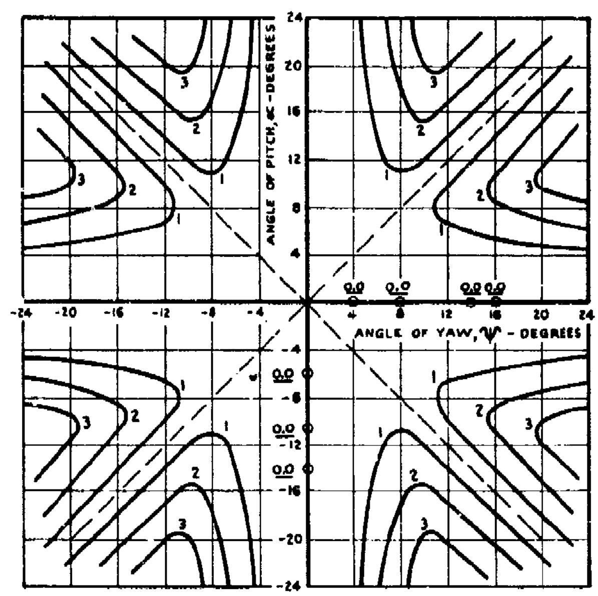


FIGURE 5. Contour of roll torque as function of yaw and pitch.

ally at the center of gravity of the missile. Stability about the yaw and pitch axes derives from the outer of the two empennage shrouds. The inner empennage shroud, capable of being rotated about axes parallel to those of yaw and pitch, serves as a rudder and elevator.

This design was fully tested in the wind tunnel at MIT and was found to develop no roll torques at any combination of pitch and yaw attitudes. It was flight-tested at Eglin Field in February 1943[5] and developed no tendency to roll in spite of being violently pitched and yawed during its flight. In addition to exceeding the permissible compass for standard stowage by a very wide margin, however, it had intolerably large values of hinge moment, with the corresponding implication of excessive power requirement.

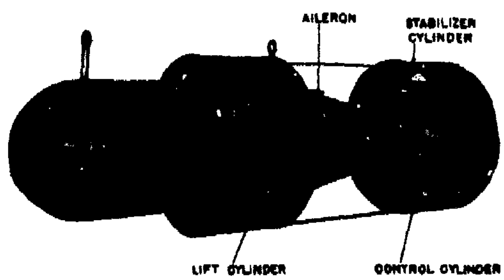


FIGURE 6. MIT cylindrical-fin bomb.

A design to establish a working compromise between minimum roll torque and tolerable hinge moments was worked out by Gulf (Figure 7) which became the prototype for the Felix (high-angle heat-seeking bomb). (See Chapter 3.) This bomb proved completely stable in roll and had adequate maneuverability.[6] Power from small battery-powered motors was adequate to operate the control surfaces.

A second method of minimizing roll torque lies, of course, in the limitation of the control of the bomb to motion about only one of the axes of yaw and pitch. From the point of view of roll alone it is immaterial which axis is selected. For the purposes of developing a useful weapon, problems of sighting necessitate the selection of azimuth or yaw as the single component of control.

The problem of roll stability, then, confronted the Division with the choice between one-axis control and exceeding the limits which had been set on the overall size of the missile. Both solutions were accepted. As the Azon development was pushed to completion, studies were made to determine how seriously extensions of portions of the control structure beyond the smallest square prism circumscribing the body of the bomb would vitiate the military usefulness of Razon and Felix. The compass of Azon was held within the limits originally established. In April 1943, at the completion of the studies just described,

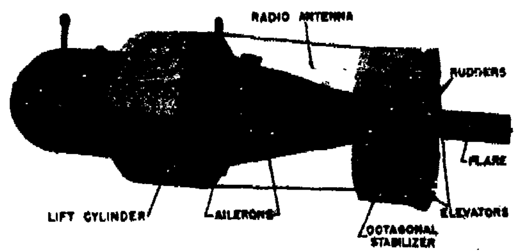


FIGURE 7. Gulf octagonal-fin bomb.

the maintenance of such limits for bombs with two-axis control appeared to the contractor to be hopeless,[a] and further efforts in that direction were not made. This opinion was not unanimously shared by the Division. The cam-controlled drop reproduced in Figure 13 (see Section 2.9) was successfully roll-stabilized with 10-degree deflection of the elevators and a simultaneous regime of rudder deflection ranging from 5 degrees right to 10 degrees left. Further studies in this field might well be rewarding.

2.4.3 Gyro Developments

The decision to abandon a cylindrical-coordinate control in favor of a Cartesian coordinate system (see Section 2.4) implies, as already shown, the requirement of a free gyro to control the ailerons. Such a gyro alone, however, can produce nonoscillatory roll stabilization only with difficulty. MIT therefore developed a system involving a free gyro to determine the roll orientation and a rate gyro to damp the roll oscillations.

Consider a free gyro with contacts on the outer gimbal frame to close two pairs of contacts with a dead band of $\pm\phi_0$ between them. Thus one contact was closed if $\phi > +\phi_0$; if $\phi < -\phi_0$, the other contact is energized. Similarly, the rate gyro has two contacts separated by a dead band of $\pm\dot{\phi}_0$. If

[a] See Chapter 13 for further comments by the contractor's project director.

$\phi > +\phi_0$, one set of contacts closes; if $\phi < -\phi_0$, the second set of contacts closes. The contacts on the free and rate gyros are interconnected through relays to give aileron action in accordance with the following schedule:

$\phi < -\phi_0,\ \dot{\phi} < -\dot{\phi}_0$	CW[b]	aileron action
$\phi < -\phi_0,\ -\dot{\phi}_0 < \dot{\phi} < \dot{\phi}_0$	CW	aileron action
$\phi < -\phi_0,\ \dot{\phi} > \phi_0$	No	aileron action
$-\phi_0 < \phi < \phi_0,\ \dot{\phi} < -\dot{\phi}_0$	CW	aileron action
$-\phi_0 < \phi < \phi_0,\ -\dot{\phi}_0 < \dot{\phi} < \dot{\phi}_0$	No	aileron action
$-\phi_0 < \phi < \phi_0,\ \dot{\phi} > \dot{\phi}_0$	CCW	aileron action
$\phi > \phi_0,\ \dot{\phi} < -\dot{\phi}_0$	No	aileron action
$\phi > \phi_0,\ -\dot{\phi}_0 < \dot{\phi} < \dot{\phi}_0$	CCW	aileron action
$\phi > \phi_0,\ \phi > \dot{\phi}$	CCW	aileron action

As the program advanced, this basic conception of a free and a rate gyro was maintained, although the contact arrangements were altered to give different schedules of aileron action. The initial gyros were air driven. The wheels were enclosed in a sealed cover which was connected with the vacuum line in the airplane. Jets to drive the wheels drew air from the surroundings through vents in the covers.

Figure 8 shows the motion of the free gyro in reference to the bomb structure as an Azon is released and falls. The Azon is carried in standard bomb racks with the rudder and elevator fins inclined to the vertical by an angle of 45 degrees. The position of the bomb and of the free-gyro frames for this condition is shown in Figure 8A. As the bomb falls it must be rolled so that elevator and rudder become parallel to the desired orientation of the pitch and yaw axes. Simultaneously, the bomb noses down as it proceeds along its parabolic trajectory. This change, together with the changing orientation of the gyro, is shown in Figures 8B, 8C, and 8D. Figures 8E

[b] CW (Clockwise), CCW (Counterclockwise).

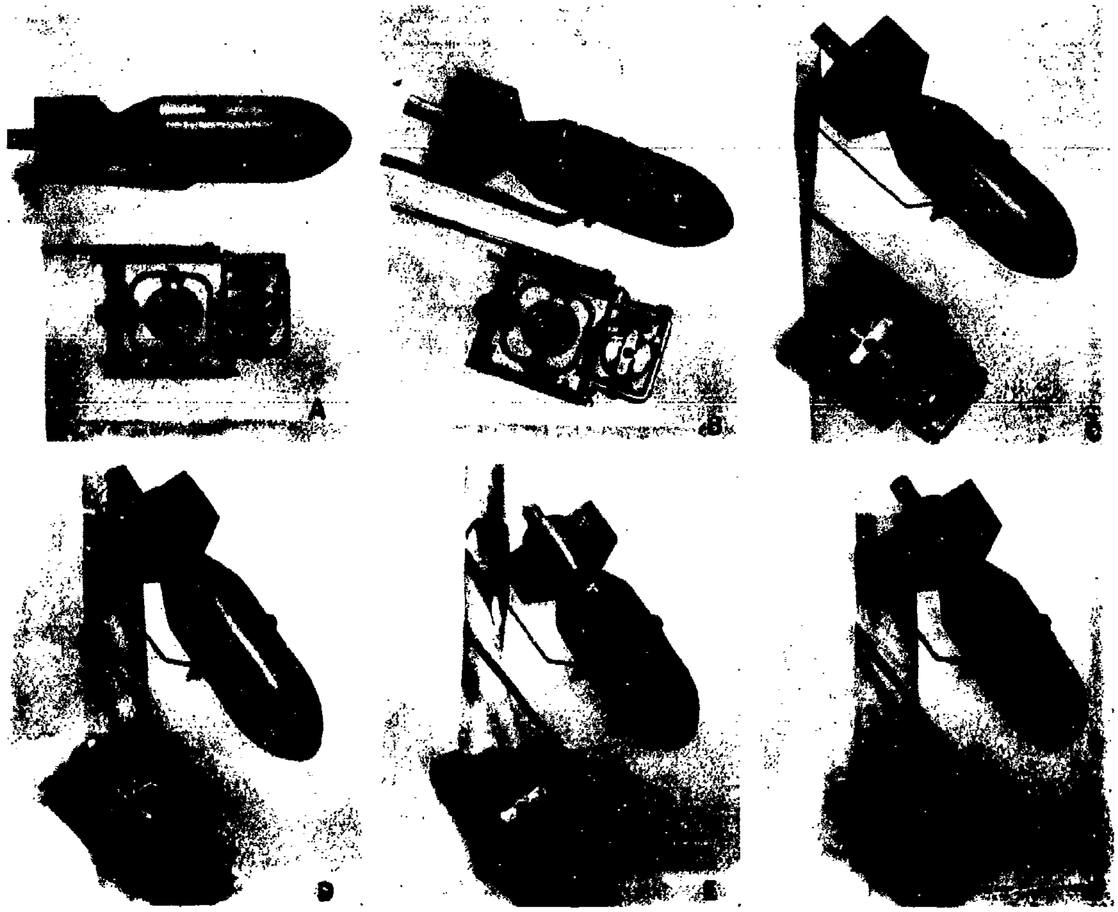


FIGURE 8. Action of free gyro during Azon drop.

and 8F show relationship of the gyro gimbal as the bomb is yawed to the right and to the left.

In its final form, the gyro assembly was electrically driven from the 24-v battery in the bomb tail. The dead band was removed from the free-gyro contacts, which were made movable and coupled to the rate gyro so that the position of the free-gyro contacts, which control the ailerons, is biased by the rate of roll. Under this arrangement there is no neutral; that is, the ailerons are always operating to produce either a CW or a CCW roll torque. The schedule now becomes much more simply stated:

$$(\phi + k\dot{\phi}) < 0 \text{ CW aileron action}$$
$$(\phi + k\dot{\phi}) > 0 \text{ CCW aileron action}$$

The factor k must have the dimensions of time and is set at 0.5 second. In addition an overriding rate-of-roll contact is provided which limits the roll velocity to $\pm \dot{\phi}_{max}$, which was arbitrarily set at ± 36 degrees per second.

The roll motion of the bomb can now be defined. If the displacement from correct roll orientation is in excess of 18 degrees, the bomb will return to $\phi = +18$ degrees at an angular velocity of -36 degrees per second. From this position it will continue along the regime

$$\phi = 18e^{-2t}$$

The foregoing idealizes the action of the ailerons by assuming absence of time lag in their operation as $(\phi \pm 0.5\ \dot{\phi})$ changes sign. This time lag is present largely on account of the time constant of the solenoids which operate the ailerons. It introduces a roll hunt of approximately 2¼ c. The amplitude of the hunt is proportional to the square of velocity and reaches approximately 3 degrees at the end of a 15,000-ft drop.

.5 LIFT AND MANEUVERABILITY

It was explained in Section 2.3 that the attainable trajectory of a dirigible bomb is determined by the transverse lift which it can be made to achieve. Indeed, in the steady state the performance of such a missile is completely determined by two dimensionless coefficients: the lift coefficient C_L and the drag coefficient C_D. These are the well-known coefficients of the aerodynamicist and are defined by:

$$C_L = \frac{\text{Lift}}{\frac{1}{2}\rho V^2 A} \quad \text{and} \quad C_D = \frac{\text{Drag}}{\frac{1}{2}\rho V^2 A} \qquad (1)$$

where ρ is the air density, V the velocity of the missile in the air mass, and A is an area function. In this chapter A is the cross-sectional area of the bomb body—a confusing choice to the aircraft designer, who usually uses this symbol to denote wing area, but convenient here in that it makes the various values of C_L and C_D directly comparable, irrespective of the areas of the control and lift surfaces which the course of the research brought under examination.

The drag coefficient is not of great significance in the visually guided bomb. It limits the terminal velocity and increases the trail angle,[c] thus influencing the sighting problem in the range sense.

The total lift attainable divided by the mass of the bomb gives the maximum attainable transverse acceleration. It is more usual to divide by the weight, however, and express the acceleration in "times gravity" (g's).

$$\text{Acceleration} = \frac{\frac{1}{2}C_L'\rho V^2 A}{W} \text{ in } g\text{'s} \qquad (2)$$

where C_L' is the maximum attainable value of C_L. This is a convenient measure of the maneuverability of a missile, but it is tied up with the air density and the velocity. A still more useful measure is the minimum turning radius. A radius of curvature, R, requires a centripetal acceleration.

$$\text{Centripetal acceleration} = \frac{V^2}{R} \qquad (3)$$

Setting equation (2) equal to equation (3) and solving for R:

$$R = \frac{W}{\frac{1}{2}\rho C_L' A g} \qquad (4)$$

The acceleration due to gravity g is inserted to preserve the dimensional integrity. This parameter is still a function of ρ and it is usually given as a sea-level value.

The most useful parameter which could be established to define the performance of a visually guided bomb of the Azon or Razon type would be the corrigible error. This is a "judgment" figure however, involving an estimate of the skill of the bombardier in recognizing the sense of his error and making the appropriate correction. A convention could be established defining the "correction coefficient" of a guided

[c] Trail angle is the angle between the line of sight from the aircraft to the bomb and a vertical through the aircraft. This definition assumes constant rectilinear flight by the aircraft after release and neglects changes in air density.

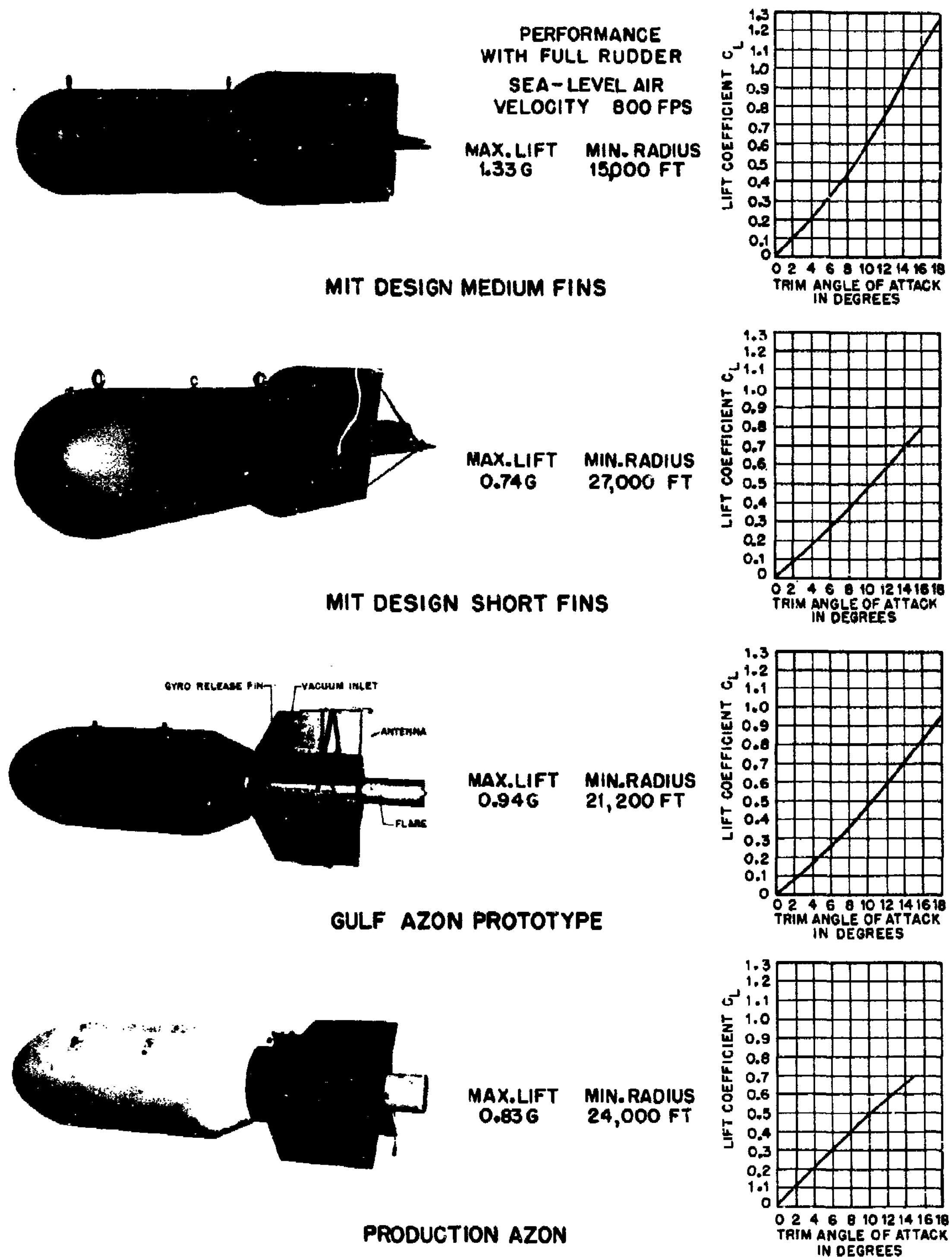
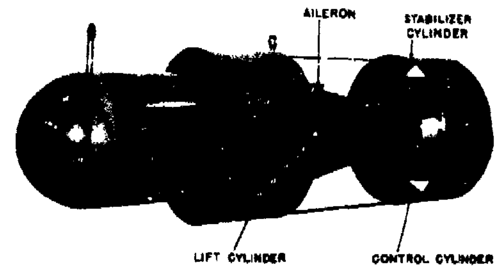


FIGURE 9. Developmental evolution of Azon and Razon.

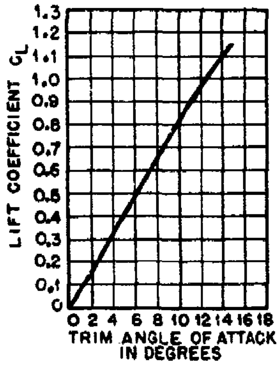


PERFORMANCE WITH FULL RUDDER

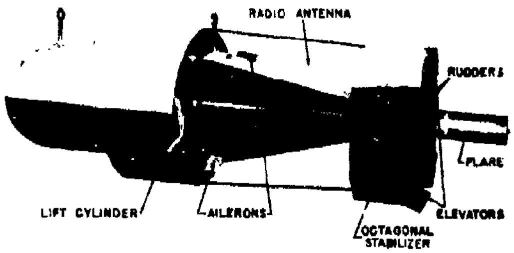
SEA-LEVEL AIR VELOCITY 800 FPS

MAX. LIFT 1.27 G

MIN. RADIUS 15,700 FT

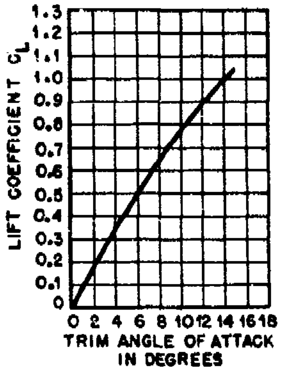


MIT CYLINDRICAL FIN

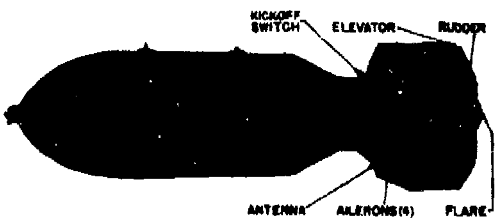


MAX. LIFT 1.31 G

MIN. RADIUS 15,200 FT

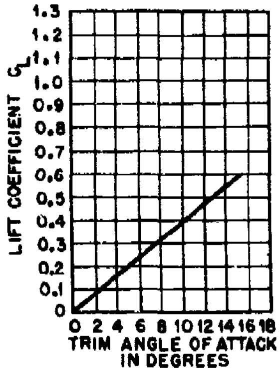


GULF OCTAGONAL FIN

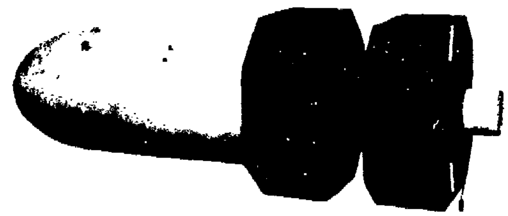


MAX. LIFT 0.67 G

MIN. RADIUS 29,800 FT

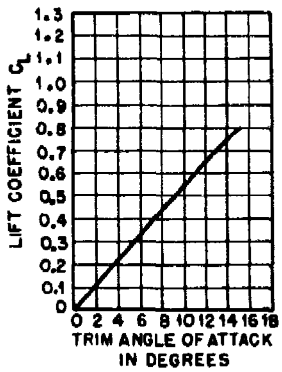


RAZON MK 1



MAX. LIFT 0.97 G

MIN. RADIUS 20,500 FT



RAZON MK 4

FIGURE 9. (*Continued*).

bomb as the deflection of the point of impact due to full control in the last n seconds in a drop from h feet. The computation of such a coefficient is, however, transcendental and requires the use either of step-by-step integration or some such aid as the Rockefeller differential analyzer. The MIT group working on this project and the associated group working on Felix used point-by-point computations until the method was established. Thereafter, they used the differential analyzer most effectively.

Figure 9 shows several of the models of dirigible bombs that were tested as the program advanced and the various parameters which define their maneuverability.

2.6 SIGHTING AND PARALLAX[d]

Section 2.3 explains the ruse by which the problem of parallax in range steering is circumvented. Several descriptions of the Crab attachment to the Mark 15 bombsight have been written. That of the Gulf Research and Development Company[7] is brief and clear. It is quoted in its entirety:

> In a standard uncontrolled bomb, the angle subtended by the target and bomb with the airplane[e] closes to zero at impact time at an almost linear rate. Thus, the fundamental requirement of the sighting device is that it provide a means by which the angle subtended by the bomb and target can be compared continuously with one which closes to zero at impact time at a constant rate.
>
> In the Norden bombsight a mechanism exists which provides just such a motion in the tracking mirror which closes the angle subtended by it at the release of the bomb and the Trail Angle of the bomb at impact in exactly the time of fall of the bomb as put into the bombsight through the Disc Speed setting. The details of the mechanism by which this result is obtained are too involved to describe here; a description can be found in the technical literature describing the sight.
>
> Two adaptations of the Norden bombsight were built for utilizing this mirror motion, one by the contractor involving a double cross-hair method, and another by the Franklin Institute involving a double mirror arrangement similar to that used in a ship's sextant. In the contractor's version, an auxiliary cross-hair at the eyepiece reticle is moved across the field by the regular sight mechanism in a manner such that at the end of the assumed time of fall the moving and fixed cross-hairs of the sight are coincident. Hence if, by steering, the bomb is held on the moving fiducial, and, by precessing the vertical gyro, the fixed fiducial is held exactly on the target, then the proper steering criterion is attained.
>
> This arrangement suffers from limitations in the field of view of the Norden telescope, which, even after permissible modifications, allows steering during only about the last 12 seconds of flight. Furthermore, if the synchronization of the cross-hair on the target is not perfect, then the bombardier has the additional worry of having to continually precess the gyro in order to hold the fixed cross-hair on the target.
>
> Both of these objections are eliminated in the adaptation worked out by the Franklin Institute,[f] Philadelphia, Pennsylvania, in which there are split lines of sight, one to the bomb and one to the target. If the angle between the two lines of sight is caused to converge at the proper rate, reaching zero angle (i.e., coincidence) at the end of the assumed time of fall, a perfect drop would show the bomb eclipsing the target throughout its flight. In the case of an imperfect drop, any deviations of the bomb from a perfect eclipse position can be corrected by control applications. Analysis will show that, except for errors in predicting the time of fall and errors in the mechanism reproducing this time, all normal sighting errors (e.g., improper range synchronization or leveling errors) can be eliminated by steering.
>
> The Franklin Institute adaptation was named the Crab sight (sometimes called Crab No. 1) and was used in all drop tests. For the line of sight containing the target, the normal moving mirror of the sight is used, and it simply continues to track the target until the bomb hits. For the second line of sight, a small mirror is mounted on the telescope objective so as to reflect into view a line of sight slightly rearward of the vertical. The second line of sight will reflect the bomb image into the field, since in a normal drop the apparent position of the bomb is always slightly rearward of a true vertical line extending from the airplane. The bombardier sees two fields of view, one including the area around the target, the other including the terrain directly below the airplane.
>
> Before the Crab sight was tested in flight, there was some concern about the possibility of the confusion which might exist in trying to identify the target and the bomb in the two overlapping fields of view. In practice, there is little difficulty. A red filter in front of the bomb mirror is of some value, but even more important is the fact that the scenery reflected into view by the small fixed mirror (called the Crab mirror) is always moving, although the flare itself is relatively motionless. Thus, it is necessary merely to concentrate one's attention onto the relatively stationary flare image and scenery around the target. The exact arrangement of parts can be seen in the photographs shown in Figure 10.
>
> For a technically more exact description of the Crab sight, reference is made to Figure 11. In this figure, the variation of the angular position of the target with respect to the vertical, θ, and the Trail Angle, ϕ, for the case of a perfectly dropped standard bomb is shown. Since the airplane is assumed to fly along an unaccelerated[g] path after release of the bomb, the value of $\tan\theta$ must obviously decrease at a linear rate. The variation of $\tan\phi$ can be found in making a complete trajec-

[d] See also *Aiming Controls in Aerial Ordnance*, G. A. Philbrick, Vol. 3, Part I, of the STR of Division 7, NDRC, and the 15th Bi-Monthly Report to NDRC of Division 5.

[e] More exactly the quantity $(\tan\theta + \tan\phi)$ closes to zero at a linear rate, where θ is the angle subtended by a line to the target with the vertical, and ϕ is the angle subtended by a line to the bomb with the vertical, also known as the trail angle.

[f] Operating under contract with Section 7.2, NDRC.

[g] In practice this is difficult to accomplish precisely because of the sudden change in weight of the airplane which occurs when a bomb is released.

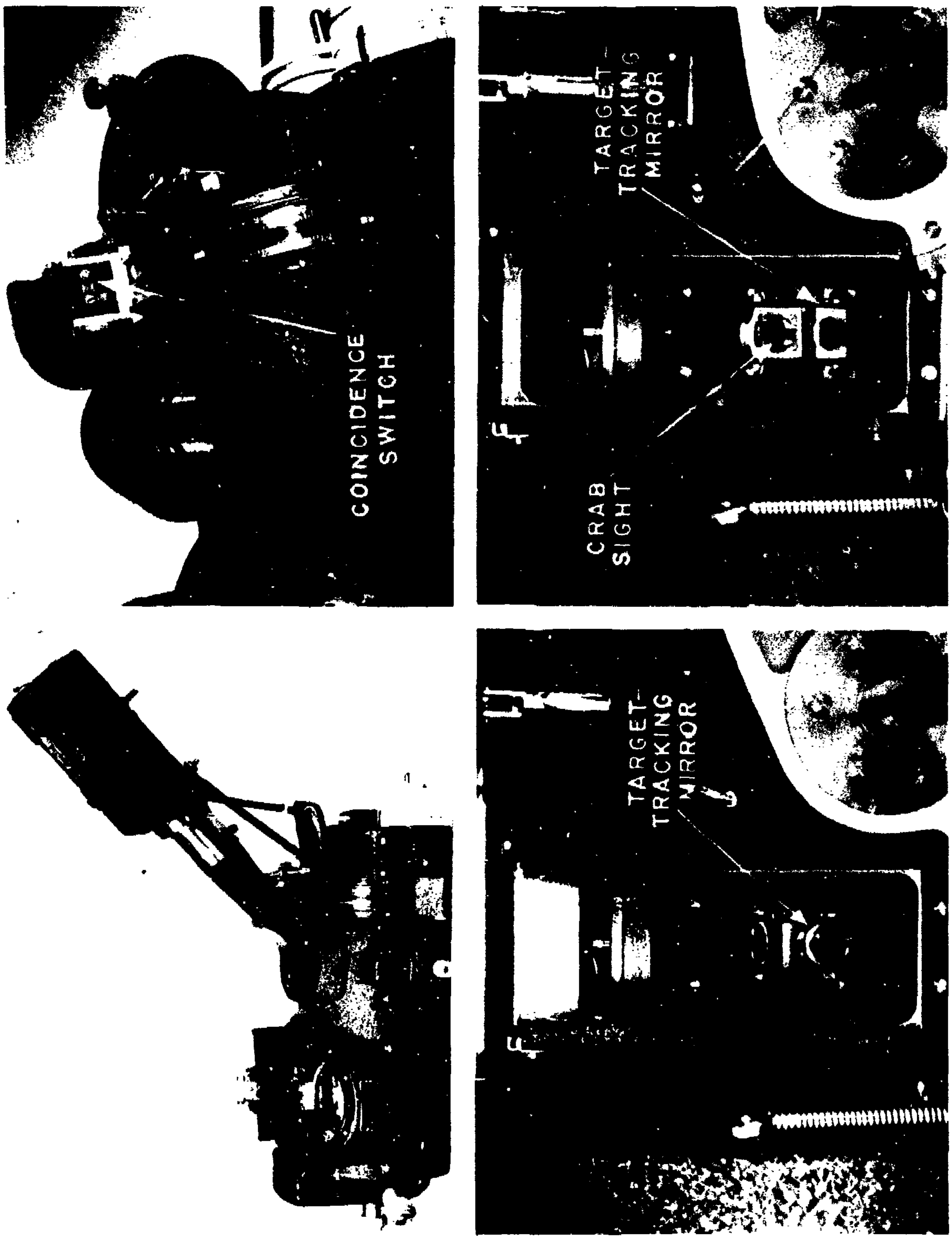


FIGURE 10. Crab sight. Crab attachment in place on Mark 15 bombsight.

tory calculation, which shows that, in general, for a bomb dropped from 15,000 ft. altitude the Trail Angle will start out at release with a value approximately two-thirds its final value, toward which it gradually increases during the flight. This rate of variation of the Trail Angle is shown in Figure 11.

In the lower curves shown in Figure 11, the position of the target and of the bomb in the field of the bombsight telescope are plotted. Since for the case shown it is assumed that the synchronization is perfect, the target appears squarely in the

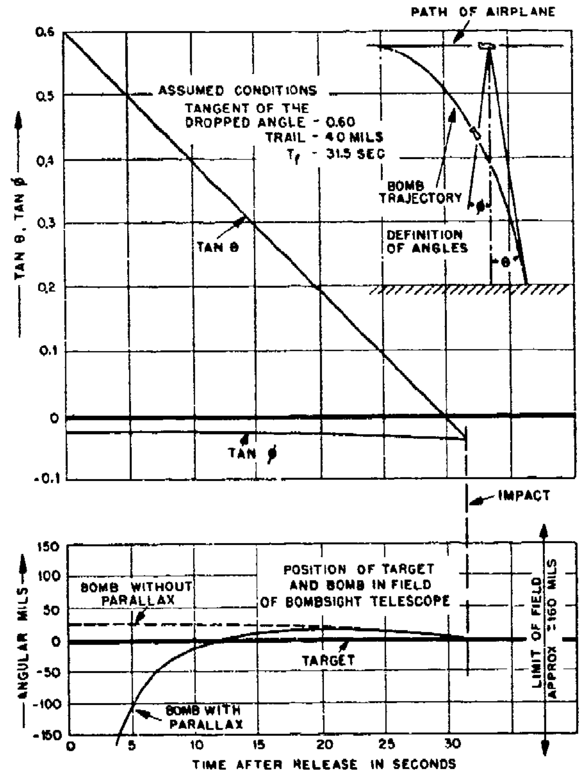


FIGURE 11. Angular relationship in Crab-sight use.

center of the field throughout the flight. The position of the flare varies, however, for two reasons: first, because of the variation in Trail Angle, and, second, because of parallax which results from the fact that the bombsight is not mounted directly over the bomb bay but a considerable distance ahead of it (24 ft. in a B-17). Thus, the bomb appears to have a much larger Trail Angle early in flight, as is indicated in Figure 11. Near the end of flight this variation in position of the flare image is negligible, so that for all practical purposes the bombsight will indicate no error for a perfect drop.

The residual errors, other than those of steering in Razon, are thus due wholly to errors in estimating the time of fall. This time, in addition to being a function of altitude of the release and of the target, is also dependent upon the total amount of steering to which the bomb is subjected during its fall. A large number of drops were made to establish empirically the relationship between time of fall and steering (Figure 12). It was found[8] that steering in the direction to decrease range, i.e., "down" elevator introduces no increase in time of fall. This is because the warping of the trajectory more nearly into line with gravity counteracts the increase in drag due to rudder deflection. If, then, Δt is the increase in time of flight due to steering, $\Sigma(t_u)$ is the totalized time of "up" elevator, and $\Sigma(t_r)$ is the totalized time of rudder application:

$$\Delta t = a\Sigma(t_u) + b\Sigma(t_r) \tag{5}$$

where a and b are the empirically determined constants.

Jag (Just Another Gadget) is a device developed to insert this correction into the bombsight. To a reasonable approximation it is accomplished by subtracting from the tracking mirror's angular velocity an incremental velocity proportional to Δt. The probable error of Razon in range without Jag[8] is estimated at 10 mils. Jag will reduce this by about two-thirds.

2.7 RADIO

The problem of providing a suitable radio link for the remote control of missiles was a major activity of the Division and is covered comprehensively in Chapter 6.

The initial work on the Azon-Razon program used a radio having two r-f carriers. These were pulsed by a commutator keying circuit. The ratio of time-on to time-off of the pulse on one carrier was determined by the position of a rudder-control stick. An integrating circuit following the detector in the receiver caused the servo link to make the rudders assume a position corresponding to that of the rudder-control stick. A similar chain produced proportional control of the elevators. The r-f section of the receivers were superregenerative for compactness; the gain was adjusted so that the final stage saturated with the lowest expected signal.

The field tests at Eglin Field in April 1943 showed that although proportional control was available it was not used; that is, the controlling bombardier put the rudders hard over, adjusting the amount of error correction by the timing of full rudder commands. (See also Chapter 10 for remarks about on-off versus proportional control and simulative methods of their analysis.) Accordingly, the standard RC-186 trans-

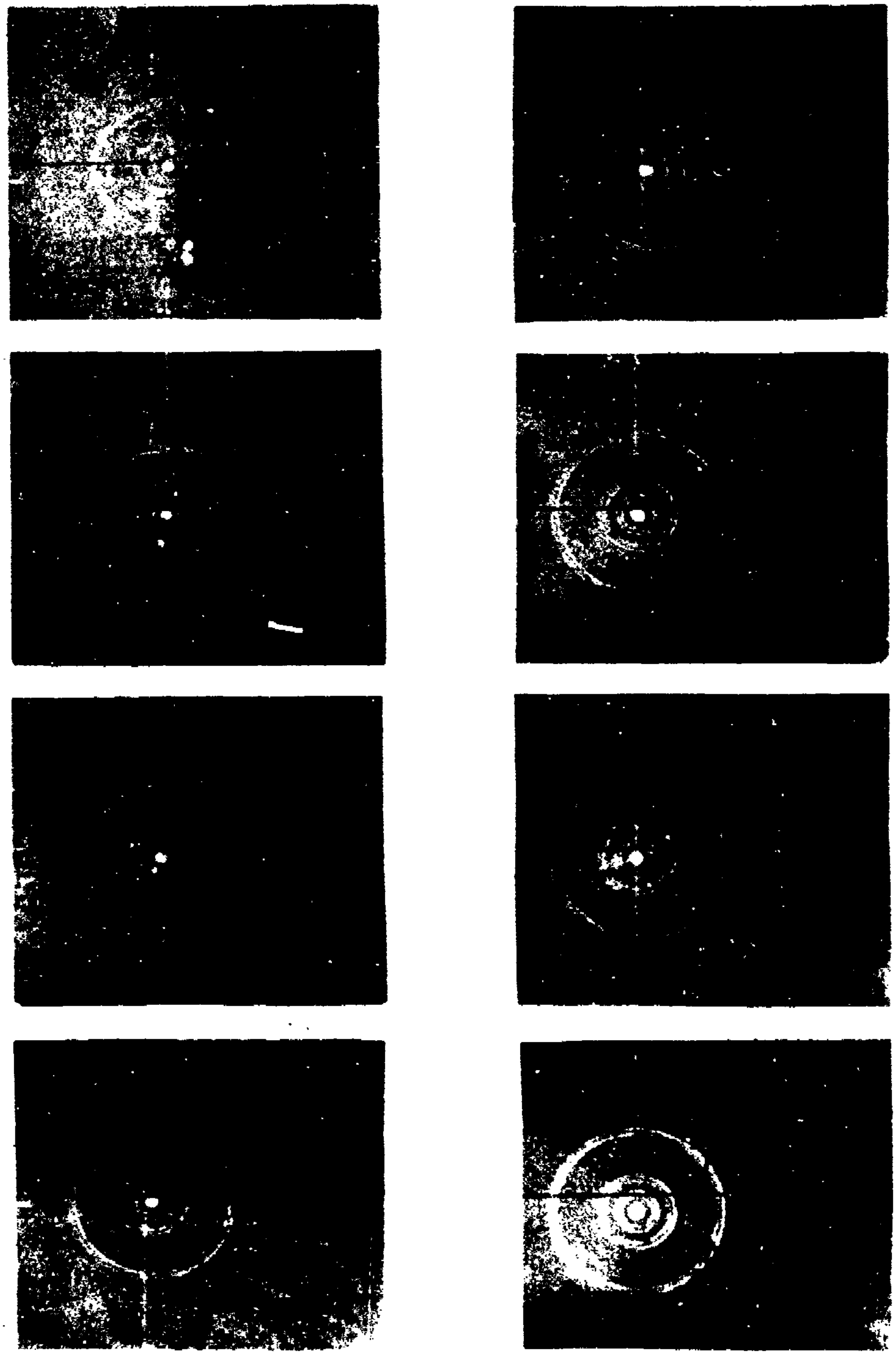


FIGURE 12. View of target and Razon through Mark 15 bombsight equipped with Crab attachment.

mitter having six audio tones was employed on all further work with an on-off modulation—two tones with Azon, four tones with Razon.

A super-regenerative receiver with a resistance-capacitance filter in the audio end of the circuit operated two relays giving "right" and "left" signals to the rudders.

This receiver, with minor changes for production, went into combat as standard equipment for Azons. It was considered deficient in selectivity and stability and was suspected of being subject to false operation from microphonics occurring in the Azon tail. The Army had, however, instituted procurement and they were available.

In order to obtain a more reliable radio for Razon, the Division, through Contract OEMsr-240 with MIT, procured the design of a sharply tuned, crystal-controlled superheterodyne receiver with a tuned transformer for audio selection. Some forty of these receivers were used in the Razon development program. After the initial difficulties were overcome, they were fully reliable. Other activities of the Division in developing a suitable radio for control are discussed in Chapter 4 and in Chapter 6, which is concerned with the radio problem in general.

2.8 ACCESSORY COMPONENTS

2.8.1 Servo Links

Since the Azon and Razon are manually controlled, the servo-link problem is a simple one. This is not to say that all missiles can always be manually controlled through simple servo links. In this case, it developed that the dynamics of the servo loop had phase-gain relationships such that a human operator was able to cope with its response readily without introducing serious hunting.

This was not fortuitously achieved. An engineering sense was developed by Gulf which led them to choose bomb designs having only a moderate compliance and a reasonably low natural period about the pitch and yaw axes. Periods of 1 to 2 seconds were found to result in bombs relatively easy to steer. Lower periods obtained with higher compliance resulted in bombs which got out of control; higher periods produced bombs that "felt too stiff."

A simple 24-v geared motor, standard in the aircraft industry, formed a very satisfactory servo link.

2.8.2 Flares

In order to follow the bomb during its flight a pyrotechnic flare was mounted on the tail. Reliable ignition was an annoying but not a profoundly technical problem. It was solved by using electric ignition of a time-delay powder train, which in turn fired the flare 8 seconds after the ignition circuit was energized by the bomb release. This is not wholly foolproof. One plane was burned up when a flare-equipped bomb dropped on the taxi strip before take-off; another was seriously burned in the air when a bomb hung up in the bomb bay. The flare-energizing circuit should be closed by a contact on the tail fuze, which depends for arming on travel for several hundred feet through the air.

The use of colored flares and selective filters on the Crab sights for mass attacks was studied in cooperation with Division 16 and Division 11. Wesleyan University, under their contract with Division 11, experimented with various color formulas.[9,10] In general, the results were not too successful. Most pyrotechnic color formulas are subtractive, as are filters. Thus, a bombardier using a red filter, for example, would hardly distinguish between a white flare and a red one. Actually, it was found that a bombardier had no trouble concentrating on his own bomb even in tight formations with all flares white.

2.8.3 Fuze Arming

The detonation of standard general-purpose bombs is accomplished typically by two fuzes, one in the nose and one in the tail. These fuzes are armed by wind vanes driven by the wind stream after the bomb has been released. An arming wire, which is withdrawn on release of the bomb, pins the wind vanes and prevents their rotation from drafts in the bomb bay.

It is perfectly simple to apply the standard nose fuze to Azon and Razon. This was done. The tail fuze presented a more troublesome problem since the mechanism in the tails prevented the use of windstream arming. Electric arming motors were suggested and tried. It was conceivable that failures of the circuit would cause the bombs to arm before they were released and this system was, therefore, deemed unsafe.

A cup-anemometer drive to be mounted on the side of the Azon or Razon tail was offered by the Air Technical Service Command. This was tested with some misgivings since the trying experience of the Division with roll stabilization raised doubts as to the possible introduction of screw asymmetry in the structure with the anemometer on one side. Fortunately, these fears proved groundless, and this system was applied to both bombs.

2.9 FIELD TESTS

The program of developing a guided bomb finds its most active phases at the testing ranges. Much can be done in the laboratory; as we have seen, the wind tunnel is a most necessary tool in establishing the course along which an investigation may proceed. For the great bulk of the work, however, actual drop tests form the only technique so far established for developing and proving a design.

For such work the Division relied almost entirely upon the military. In the program on glide bombs (see Chapter 1) the Navy Bureau of Ordnance furnished facilities. For the Azon and Razon program, the field testing was done at establishments of the Army Air Forces. It is impossible to say too much in appreciation of the cooperation rendered by the officers of the Air Technical Service Command and its predecessor group, the Air Materiel Command. In spite of being short of aircraft and range facilities for the multiplicity of projects that they had in hand, they arranged to share what they had with the Division, sometimes at the expense of their own projects. It was not until December 1944 that suitable facilities with aircraft, ranges, ground transportation, and maintenance and shop facilities were established at Wendover, Utah, in which the Air Forces group charged with the development of guided missiles had a vested interest. Theretofore, they had worked—and the Division perforce with them—as more-or-less welcome guests of Ordnance Department at Aberdeen, Md., the AAF Proving Ground Command at Eglin Field, Florida, the Fourth Air Force at Muroc Lake, California, and at Tonopah, Nevada.

The early work at Aberdeen was concerned chiefly with the development of nose cameras for recording the performance of the bombs,[11,12] with early roll-stabilization experiments, and with preliminary tests with 100-lb bombs to establish qualitatively that reasonable deflections of the trajectories could be obtained from small control surfaces.

The work at Eglin started in December 1942 with a series of bombs controlled by clock-driven cams. The trajectories of these bombs had been computed on the Rockefeller differential analyzer using data from the Wright Brothers wind tunnel at MIT. The work was plagued by mechanical failures which masked the significant data. Out of 10 drops 7 failed to stabilize in roll. From the remaining 3, however, important facts were learned. As shown in Figure 13 the radius of curvature was less than expected and, as described in Section 2.5, the lift and maneuverability were therefore greater. Two of the three bombs which were successfully roll-stabilized were deflected along one coordinate only.

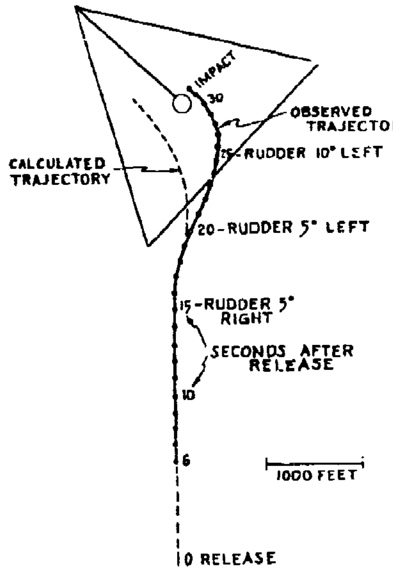


FIGURE 13. Comparison of calculated and observed trajectory of cam-controlled bomb.

The work was continued in February of 1943 with twelve more bombs, two of which were of the MIT cylindrical design referred to in Section 2.4.2 and shown in Figure 6. These bombs were all radio-controlled and while the average of success was not much greater than in the December tests, that of one drop, Figure 14, was great enough to stimulate considerable interest in Azon.

Characteristically, the Division questioned whether the single successful drop of Figure 14 was not an accident—the final accuracy of 20 ft rather than the plotted trajectory having been presented. Accordingly, succeeding drops were made in pairs simultaneously released: one standard bomb uncontrolled, and one Azon or Razon to which control was applied (Figure 15). This technique gave an approximate measure of the error corrected by radio control without waiting for the analysis of motion-picture camera records.

A word should be said about the presentation of trajectories. No satisfactory frame of reference has been developed for defining the trajectory of a guided bomb. The logical system would be Cartesian, in which one plane would be the ground, the second would be a vertical plane containing the bombing run, and the third would be a vertical plane normal to the second and containing the target. Instrumentation to yield such projections of the trajectories is

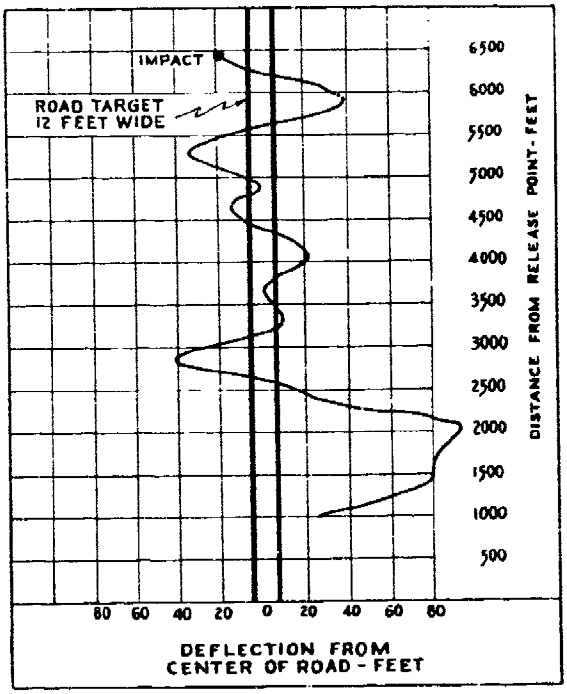


FIGURE 14. First successful Azon drop.

difficult to assemble and to coordinate. Three phototheodolites would probably be a good solution, but the time coordination of three ground stations and an airplane is extremely difficult. In this work the trajectories are presented as ground projections from the aircraft, unaccelerated flight after release being assumed. Such projections are simple to instrument but their true significance is sometimes elusive. A more complete discussion of the measurement and analysis of trajectories is given in Chapter 8.

The development test program of Razon was largely carried out at Tonopah, with final ballistic experiments to establish the constants for Jag performed at Wendover.

2.10 PRODUCTION ENGINEERING OF AZON AND RAZON

However competent a development program may be, it is inevitable that changes in the design are required to suit the techniques of mass production. Contracts OEMsr 1081, 1258, and 1415 were made with the Union Switch and Signal Company to implement the development of the Gulf Research and Development Company and the research of MIT for combat use. The activities under these contracts are described in Chapter 11.

2.11 AZON IN COMBAT

A squadron of B-17's took the first Azons into combat in February 1944. This group went to the Mediterranean Theater of Operations to join the Fifteenth Air Force. They were accompanied by a Technical Aide from the Division. This group had the usual difficulties which occur when new equipment is introduced into combat. The radio receivers (see Chapter 6) particularly gave trouble. Nevertheless, successful missions were flown against the Ancona-Rimini railway bridges, locks and bridges at the Iron Gate on the Danube, and other targets. One spectacular success was the demolition of the Avisio Viaduct south of the Brenner Pass. This viaduct was a key route for personnel and supplies supporting the German defenses in Italy.

As a result of this success a heavy procurement program of Azons was instituted, and a second squadron, B-24's, was prepared for the Tenth Air Force in the China-Burma-India Theater. At the suggestion of the Division, this squadron was diverted in April 1944 to the European Theater of Operations (ETO) to join the Eighth Air Force. They were successful in demolishing bridge targets in Normandy both on the Seine and Loire. Figure 16 is a strike photograph of a bridge at Tours successfully attacked on June 6, 1944. The number of craters adjacent to the bridge is testimony to the preceding unsuccessful attempts against this target.

Production orders were again increased and a major training program established. This program was completely cancelled in July 1944.

In November 1944 the Division was requested to send a technical representative to Burma to assist an Azon squadron stationed there with the Tenth Air Force. This squadron was sent out to replace the one which had been diverted to the Eighth Air Force in the

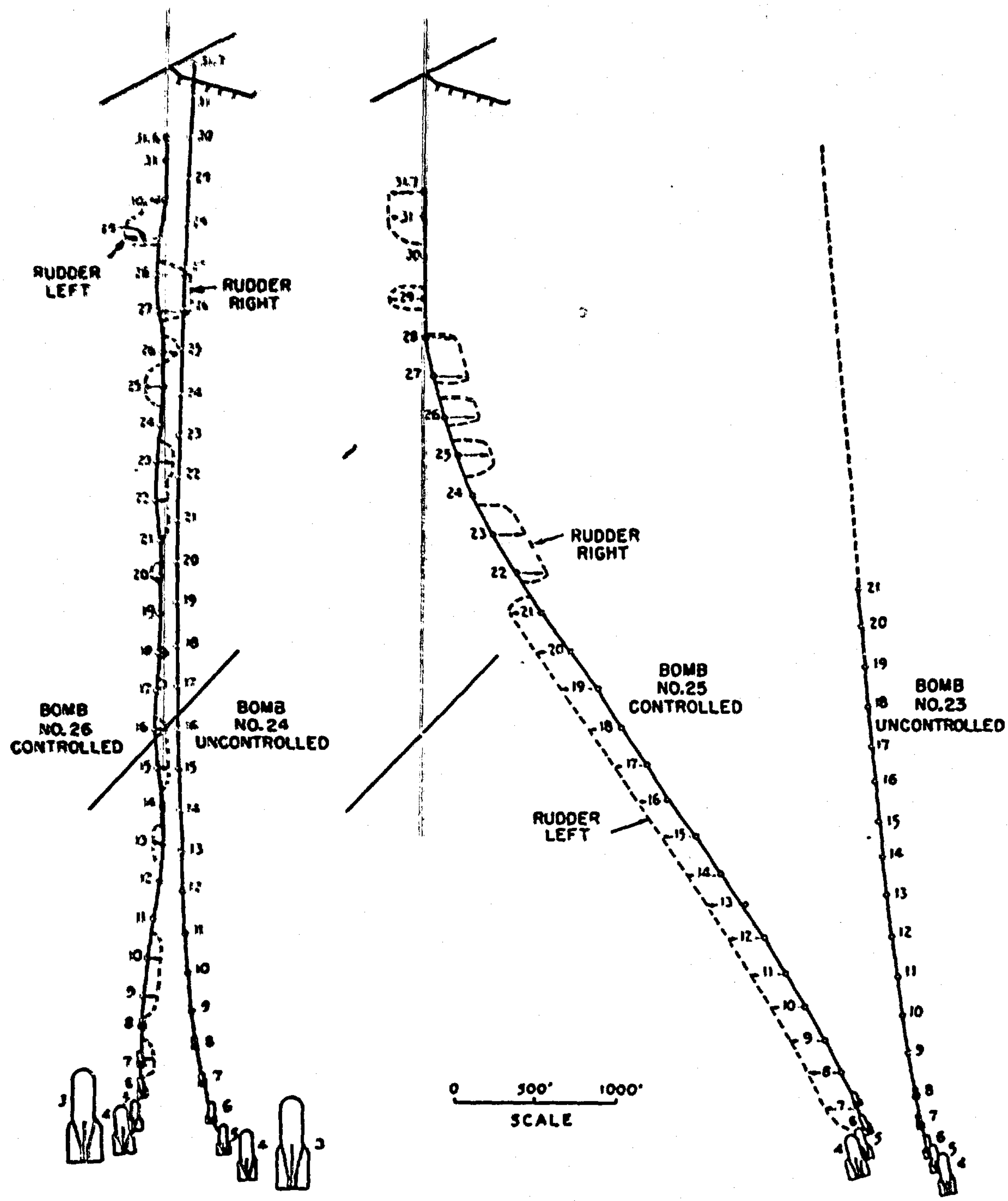


FIGURE 15. Two Azon drops with uncontrolled reference bombs.

ETO in the preceding April. They had gone without the knowledge of the Air Communications Officer, within whose responsibility guided missiles rested. This squadron succeeded in cutting all Japanese lines of communication in Burma during December 1944 and January 1945. (See frontispiece.)

Expedited action was requested for additional Azon control equipment for half the heavy-bomber strength in the CBI Theater, and the production program was reinstituted.

It is not clear why the Azon program was cancelled in the summer of 1944. There seems to be no question that the system whereby bombardment groups received credit for tons of bombs dropped rather than for targets destroyed seriously biased theater commanders in favor of mass salvos as against aimed single drops. This system, together with the basis for award of decorations, has been harshly criticized by the Air Forces Evaluation Board of the Pacific Ocean Area.[13] A study to learn why the Azon program was

FIGURE 16. Bridge at Tours demolished by Azon.

terminated and to make recommendations as to the future policy concerning this missile was made by the Guided-Missile Subcommittee of the Joint Committee on New Weapons and Equipment of the U. S. Joint Chiefs of Staff. The results of this study have not been made available to the Division.

2.12 TARZON

As the war closed the Division had under way the development of Razon-like controls for the 12,000-lb British Tallboy, a deep-penetration bomb. Work had not progressed to a point which would justify reporting it here. It is covered in the final report[14] of the contractor who is continuing to serve in a consulting capacity on the project, which has been transferred to the Air Forces.

2.13 RAZONS AGAINST ARMORED TARGETS

The increased deck armor of capital ships makes them nearly invulnerable against attack with 1,000-lb GP bombs. The large specific gravity of the armor-piercing or semi-armor-piercing bomb, however, makes it an unpromising missile for control in the Razon manner. Furthermore, the pitching and yawing required for control would reduce the striking velocity which is the missile's strength; also, there is a high probability that such a bomb would strike obliquely, losing its armor-piercing power.

The Division requested Division 8, Explosives, to study the possibility of using the Munroe effect of a shaped charge in a 1,000-lb GP bomb casing. Their study and scale-model tests indicated that such a bomb could defeat 11 in. of armor without loss of blast effect. Full-scale firing tests were made on April 1, 1945, at Dahlgren Naval Ordnance Station. The bomb was statically fired against the target, which consisted of one 11-in. and one 4-in. armor plate and three ¾-in. mild-steel plates. Each plate was separated from the next by an 8-ft air space. Some unfuzed 100-lb bombs were stacked between the second and third plates of mild steel. The jet from the bomb penetrated all the plates of the target and detonated some of the 100-lb bombs.

Consideration was given to the design of a composite bomb having a shaped charge with a follow-through explosive charge. The problem of preventing detonation of the follow-through when the shaped charge is fired will require considerable effort if a solution is to be found.

Chapter 3

FELIX AND DOVE EYE

3.1 INTRODUCTION

THE IDEA of a missile so endowed with properties that it would of itself seek out its target on account of some character inherent in the target has appealed to romancers for centuries. The magic bullet of the *Freischütz* legend, for example, was so charmed that it would inevitably strike the heart of a traitor irrespective of any lack of marksmanship on the part of the rifleman. The radar-homing missiles of Chapter 1 and the photoelectric-homing controls described in later chapters go only part way in meeting this ancient need. In each case the homing action of the missile is determined by reflected energy derived from electromagnetic illumination of the target—in the centimeter wavelengths in the case of radar, in the visible range in the case of the various photoelectric devices investigated by the Division.

Between these two wavelength bands lies the group of radiations generally known as heat. The source of such radiations is inherent in the temperature and surface quality of every object. If, then, a method could be developed to identify a military target by its heat radiation and then to cause a bomb to home on these radiations, a weapon possibly less subject to jamming or camouflage countermeasures might result. This was the objective of the Felix program.

Considerable confusion has been prevalent in discussions of infrared and heat-actuated devices. To aid in reduction of this confusion the Division issued a memorandum to contractors and liaison officers setting forth the properties of electromagnetic radiations from the upper limit of visibility, say 0.80 μ to approximately 20 μ. This memorandum is included as Appendix C of this report, and its careful study by those interested in heat-homing missiles is urged.

The masking of visibility by fog is well known. The absorption of radiation by invisible water vapor is less generally appreciated, although the spectacularly greater visibility of arid areas compared with coastal regions is relatively commonplace. In addition the advent of infrared-sensitive emulsions for photographic work has, for the lay mind, confused the situation by investing in any "invisible light" the property of prodigious penetrating power.

This simply is not the case. The true situation can hardly be stated concisely, and in addition to Appendix C of this report the reader is referred to the work under Division 16, NDRC, at Harvard University.[1] In general it can be said that so far as visible obstructions to radiation such as mist, fog, and clouds are concerned, there is no wavelength radiated by a military target that has appreciably greater penetrating power than the visible band between, roughly, 0.40 μ and 0.70 μ. For haze, smoke, and fine dust there is some gain in penetration from the use of wavelengths which are long compared with the particle diameter.

In addition to the absorption by the agencies just cited there is further attenuation of radiation by atmospheric water present as pure vapor. This absorption is a function of wavelength and is at a high value for radiations adjacent to the visible portion of the spectrum, 0.7 μ to 7 μ. It is in this near infrared region, closely adjacent to the visible, that the common infrared devices—photographic emulsions, photoelectric cells, and photochemical devices—operate. Indeed their generic names suggest their character as being light-sensitive rather than heat-sensitive systems. At very long infrared wavelengths the radiation can be detected and measured[2] by microwave techniques.

The Stefan-Boltzmann law (see Figure 1 of Appendix C) teaches that but little energy is radiated from targets at these short wavelengths. At longer wavelengths (8.5 μ to 15 μ), however, the situation is widely different. At these wavelengths, objects at ordinary temperatures radiate at their maximum energy level; furthermore there is at precisely these wavelengths a "window" (reduction) in the absorption characteristic of water vapor. Figure 1 was obtained simply by multiplying the black-body radiation by the transmission through water vapor given in Figure 2 of Appendix C.

If a bomb is to be controlled by heat radiation from its target, it is in the region of the water-vapor window that the measurements of heat must be made. Other wavelengths will not be received in sufficient quantity both because of their paucity at the source and because of water-vapor absorption. The techniques of measurement in this field have been well explored by astronomers; they consist chiefly of the use of the bolometer, gas thermometers similar to the Hayes cell, and the thermopile.

This introductory point has been stressed because confusion still exists. Even after the full discussions and interchange of reports between groups interested in this problem, one still hears the report that, "The Germans had an infrared detector ten times as sensitive as ours." This is probably not true; even if it is true, it is not particularly significant as regards guided missiles. In every case where the attention of the Division has been drawn to such detectors, they did indeed have a high sensitivity but in the near infrared region. They have been photosensitive rather than thermosensitive systems. A similar and equally false comparison could be made between the sensitivity of bolometers and that of the microwave techniques of Dickie.[2] The sensitivity of his method (10^{-16} watt) is many orders higher than that of the bolometers used in Felix. It is of no value to have a sensitivity of detection a hundredfold greater if the energy available at the frequency where the sensitivity is high is a thousandfold less.

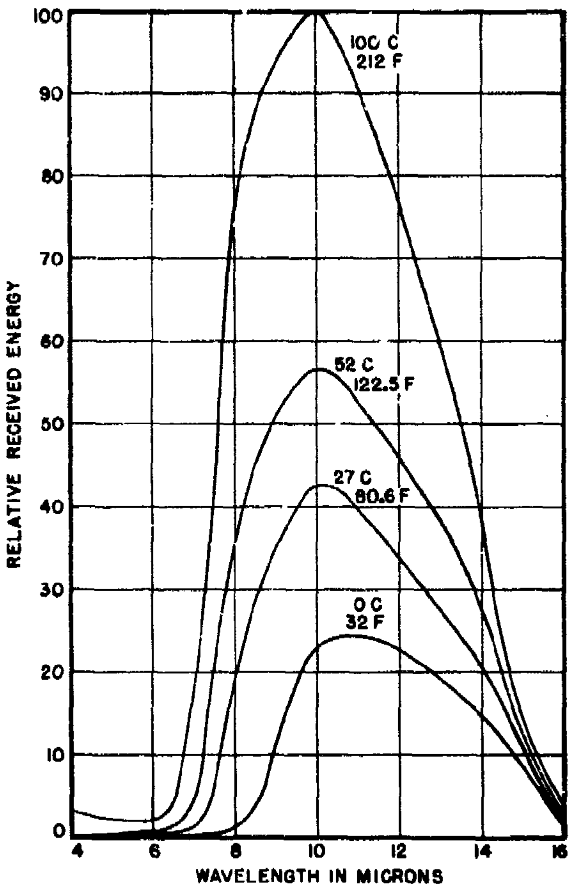


FIGURE 1. Energy received from radiating sources through a water-vapor curtain.

3.2 GENERAL[3,4]

Figure 2 is a photograph of the final version of the Felix bomb as it was produced for combat use. The main structural member was a standard M-44 1,000-lb GP bomb. Attached to the front by the nose-fuze thread was a false nose containing a scanning system to detect thermal targets and to transform the heat signal to an amplified electric signal. A false tail, mounted by means of the fin-lock thread, housed servomotors which operated elevators and rudders in response to the electric signals developed in the nose. In addition, the tail contained a twin gyro unit —one free and one rate gyro—which controlled ailerons to maintain the position of the missile fixed with respect to the roll axis.

FIGURE 2. Felix bomb.

In the initial instant after the bomb clears the bomb bay, its flight is horizontal, headed toward the horizon. Not until some seconds have elapsed will it nose over sufficiently for the roll axis of the bomb to point toward the target (Figure 3). The mechanism, therefore, includes a time switch which keeps the elevators and rudders locked in neutral until the bomb has fallen to a point where the axis of scan intersects the ground in the vicinity of the target. For a drop from 15,000 ft this will be at about 10,000 ft.

Transverse lift is supplied by the body of the missile itself in the same manner as Azon and Razon (see Chapter 2). Such a body of revolution is not an ideal airfoil and considerable angle of attack has to be applied in order to develop sufficient transverse acceleration to correct errors of aim or to follow the maneuvers of an evasive target. The scanning system was therefore mounted on gimbals and connected by cables with the rudders and elevators so as to align the axis of scan more nearly with the tangent to the flight path (Figure 4). This coupling also served as a stabilizing feedback.

The scanning system is discussed in detail in a subsequent section of this chapter. In general, it consisted of an optical bolometric assembly which scanned the terrain in a field of 10-degree radius approximately centered on the point where the bomb would fall with no further control added. The received heat measured by the bolometer while scanning opposite half-fields was compared, and the missile was directed toward the half-field radiating the greater heat. Two channels provided one pair of half-fields in the range sense and another pair in the azimuth sense.

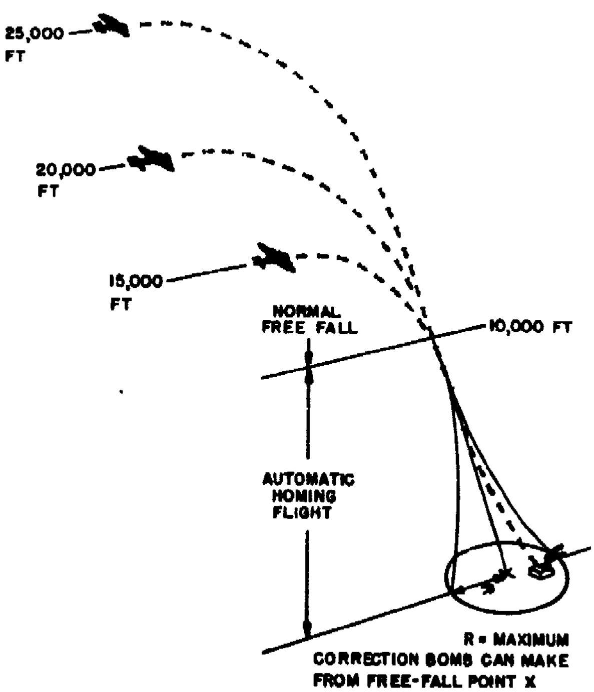


FIGURE 3. Free-fall portion and homing portion of Felix trajectory.

The scanning system contained no intentional dead band where there was no signal for correction in any direction. The servomotors, therefore, were continuously energized for full speed in one direction or the other. Except for the very small interval required for reversal upon instantaneous reversal of armature current, they operated at constant speed to give "up" or "down" elevator and "right" or "left" rudder. Such a system is inherently oscillating.

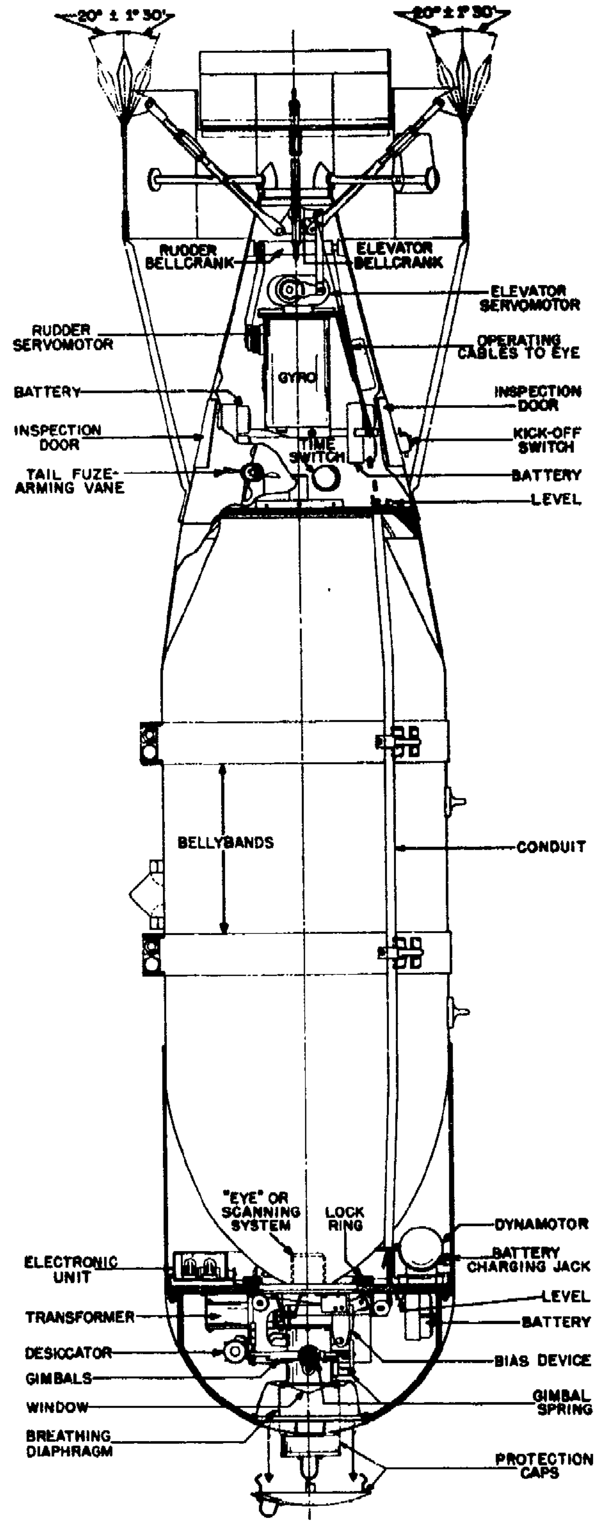


FIGURE 4. Assembly of Felix.

The back coupling from the rudders and elevators to the gimbal-mounted scanning head tended to reduce the amplitude of the oscillations.

3.3 SYSTEM DYNAMICS

3.3.1 The Equations of Motion

The motion of Felix under the control of its homing device consists of two interdependent portions: motion of the center of gravity under the acceleration of gravity and the aerodynamic lift, and rotation about the yaw and pitch axes under the action of aerodynamic moments. Rotation about the roll axis is prevented by the gyro-aileron system as in Razon.

In Figure 5,

- X is the horizontal range of the bomb from the release point;
- H is the instantaneous altitude of the bomb;
- V is the instantaneous direction of the velocity vector whose value is v;
- B is the axis of the bomb in roll;
- α is the angle between the velocity vector and the bomb axis, the angle of attack;
- δ is the elevator displacement with respect to the bomb axis;
- s is the instantaneous direction of the axis of scan;
- ϕ is the angle between the axis of scan and the bomb axis;
- H is the measured error, the angle between the axis of scan and the bomb-target line;
- ψ is the true error in heading, the angle between the instantaneous velocity and the bomb-target line;
- γ is the elevation from vertical of the bomb-target line.

A lift perpendicular to the velocity is developed by the angle of attack set up by the elevator displacement. In the steady state this lift is

$$L = \tfrac{1}{2}\rho V^2 C_L A \tag{1}$$

where ρ is the air density, C_L is the lift coefficient, and A is the area over which the lift is developed. The relationship between C_L and α is linear for small values of α and for airfoils of conventional shape. Although for bombs of this type the departure from linearity is appreciable, it was neglected in this case. A drag in line with the instantaneous velocity is:

$$D = \tfrac{1}{2}\rho V^2 C_D A \tag{2}$$

The relationship between the drag coefficient C_D and α is quadratic. The position of the center of gravity is determined, then, by:

$$\ddot{x} = \frac{1}{m}L\cos(\gamma + \psi) - \frac{1}{m}D\sin(\gamma + \psi) \tag{3}$$

and

$$-\ddot{H} = g - \frac{1}{m}L\sin(\gamma + \psi) - \frac{1}{m}D\cos(\gamma + \psi) \tag{4}$$

where m is the mass of the bomb.

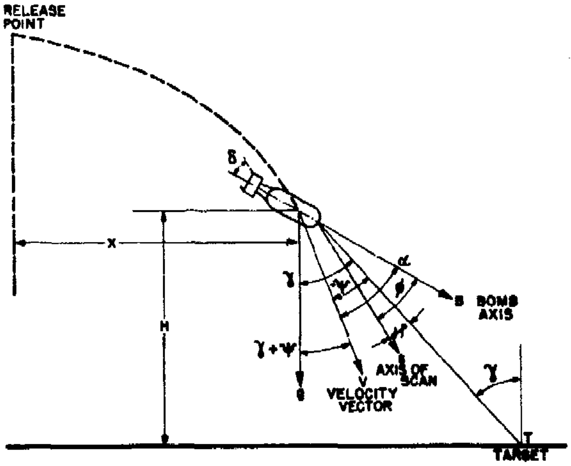


FIGURE 5. Control of Felix in range.

The angle of attack which determines the lift and drag is derived from the rotation of the structure about its center of gravity. The rotation is reponsive to a pitching moment:

$$M = \tfrac{1}{2}\rho V^2 C_M A \tag{5}$$

where the moment coefficient C_M is a function of α and δ. An approximate fit of the steady-state wind-tunnel data is given by:

$$C_M = k_1\alpha + k_2\alpha^3 - \delta \tag{6}$$

The rotation is opposed by an aerodynamic damping

$$R = k_3\rho V \tag{7}$$

The rotary motion then becomes

$$I\ddot{\alpha} + R\alpha - M = 0 \tag{8}$$

The simultaneous solution of equations (3), (4), and (8) defines the motion of the missile.

The solution is complicated not only by the nonlinearity of the relationship between the forces and moments and the corresponding displacements but more particularly by the relationship between $\dot{\delta}$ and the observed error angle H. The elevator motion $\dot{\delta}$

is discontinuous with time. Between the travel limits, $\pm \dot{\delta}_{max}$

$$\dot{\delta} = k_4 \quad \text{if} \quad H > 0 \tag{9}$$

$$\dot{\delta} = -k_4 \quad \text{if} \quad H < 0 \tag{10}$$

Furthermore

$$H = \alpha - \psi + \gamma \tag{11}$$

where H by virtue of the coupling from the servo link is partly proportional to δ and partly a time function developed by the bias device.

3.3.3 On-Off Control

An on-off control is extremely difficult to analyze. The British did considerable work in this field, references to which have been made in various Army reports. In addition the Germans[6,7,8,9,10,11] worked exhaustively on this subject. The differential analyzer at MIT is inadequate to cope with the problem in its entirety. Its use was invoked for simplified portions, but in the main the resolutions were obtained by extremely laborious point-by-point integration and by means of a simulator.

The simulator is described in Chapter 10. It produced solutions of the equations of single-axis rotary motion, including the nonlinearity in the relationships. In the point-by-point integration the complete analysis was made. In each method, however, the assumption was made that steady-state data taken in the wind tunnel is applicable throughout the transient regime.

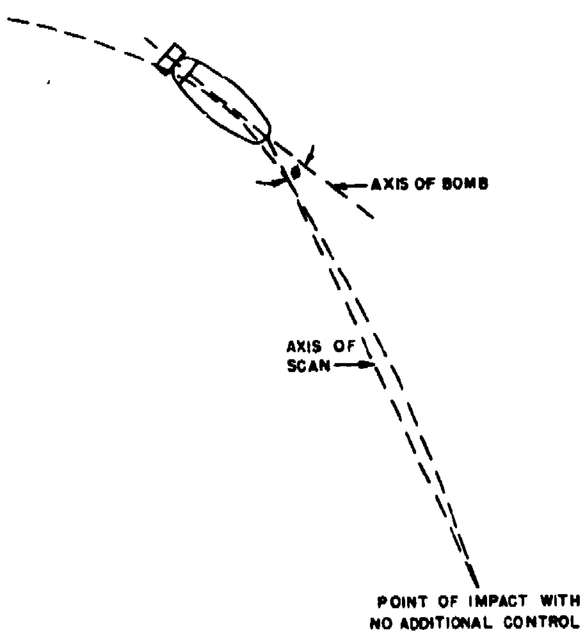


FIGURE 6. Parabolic thinking.

While no thorough quantitative analysis of the dynamics of the Felix system is therefore practicable in this report, a qualitative discussion will be helpful in explaining its operation. An on-off control system such as this one keeps the rudders and elevators in continuous oscillation. If the scanning system were rigidly mounted with axis collinear with the roll axis of the bomb, the whole structure would oscillate, with the roll axis swinging about a line continuously pointed at the target. This would be an extremely inefficient control, since a considerable angle of attack is required to develop the necessary correcting lift, and with the oscillations of the structure the average angle of attack would be continuously deficient. Back coupling causes the rudders and elevators to oscillate about a mean position which causes the scanning system to look continuously at the target. Thus if a correction is called for, the control surfaces will oscillate about a mean position which gives lift in the direction to correct the error. A quasi-proportional control is thus effected. If the back coupling could be made through a linkage which matched the dynamic α-to-δ relationship, i.e., so that the axis of scan was continuously tangent to the flight path—then the measured error angle would become the same as the true error angle,

$$H = \psi \tag{12}$$

and a truly proportional control would ensue, where $\bar{\delta}$ is the mean control-surface displacement:

$$\delta = K\psi \tag{13}$$

Without knowledge of the transient response of airframes, such a design is impossible.

Such a control system, however, would still be wasteful of controllability, especially in the range sense. As the bomb falls in its normal parabolic path, the first glimpse which the scanning system will have of the target would indicate a gross overshoot, even if the bomb were perfectly aimed or were aimed short. In Felix a bias device was added which superposed on the back coupling a range deflection which caused the scanning axis—with the elevators in neutral—to look along a chord of the parabola at the point on the terrain where the missile would fall with no further control added (Figure 6). This system of biasing, known as *parabolic thinking*, was deemed by Gulf[12] to be unnecessary. The deflection between the axis of the scanning system and the axis of the bomb

(ϕ_t) which the bias device inserts is a function of altitude and the range component of airspeed. Since the latter is subject to considerable variation between the points of release and impact, the conclusion of the Gulf investigation was that sufficient accuracy could not be obtained in its estimate to justify correcting for it. The success with the photoelectric high-angle target-seeking bomb (see Chapter 9) supports their conclusion. Further study is needed.

3.4 SCANNING SYSTEM

3.4.1 Bolometer

The requirements for the thermosensitive element in the Felix system are high sensitivity, freedom from microphonics, and low time constant. Thermopiles were tested but found to be inferior to bolometers, although General Motors in an investigation made for the AAF is said to have had some success with far infrared detectors of this type. Bolometers of many types were tested, including the nonmetallic thermistor of Bell Telephone Laboratories. None was more satisfactory than the pure-metal type, nickel or gold. The former was the type finally used in the production design. Work was done with gold bolometers consisting of a single strip of evaporated gold supported on a thin nitrocellulose diaphragm.[13] Although these bolometers worked well in drop tests, they seemed less suited to manufacture than the nickel strip bolometers developed at MIT.

The bolometer element proper consisted of four nickel strips 0.26x0.045x0.00001 in. The nickel strips were manufactured[14,15] by electroplating nickel from a hot (90 C), concentrated solution of nickel ammonium sulphate onto an aluminum cathode. Thickness was controlled by adjustment of the time of current flow. While supported on the cathode the nickel film was cut to the correct width (0.045 in.), after which the aluminum was removed by dissolving it in a 1 per cent solution of sodium hydroxide. The plated cathode, scarred by the cuts in the nickel, was immersed in a shallow bath of the solvent. The nickel strips quickly floated to the surface, borne by the bubbles formed as the aluminum dissolved. The strips were then washed in distilled water and dried flat on paper.

The strips were supported in the bolometer (Figure 7) by springs of phosphor bronze, designed so as to produce a natural period in the nickel strips well above the scanning frequency (32 c). This required a pull of 2 to 3 grams—equivalent to a loading of about 12,000 psi in the nickel. Some damping was provided by making one set of the phosphor bronze springs on one end softer than the other. The nickel strips were hard-soldered to the springs.

The springs were supported on mounting and lead-in wires in a glass-steel press to which a cap of pure silver was soldered. The top of the cap had a diaphragm opening 0.199 in. in diameter, and the whole was covered with a drawn spherical-segment window of pure silver chloride fused to it. To increase the speed of response of the bolometers, the assembly was

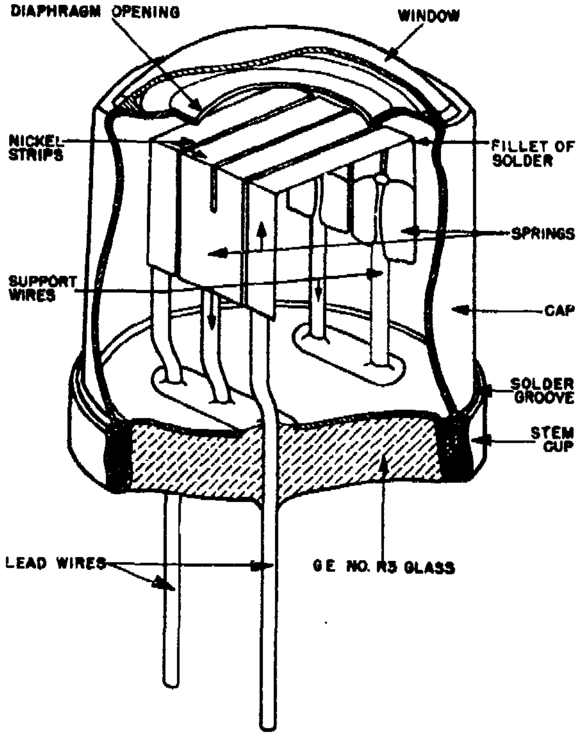


FIGURE 7. Nickel-strip bolometer.

filled with dry hydrogen at approximately 3 mm pressure.

The sensitivity was increased by covering the front surface of the nickel strips with a coating of gold black formed by evaporating pure gold onto the nickel in a low-pressure atmosphere of hydrogen. The technique required nice adjustment since the coating to be effective must have a high absorption in the 8.5- to 15-μ region combined with a low thermal mass. A good coating increases the thermal sensitivity of the bolometer by a factor greater than 5. Too heavy a coating can increase the thermal mass and thus reduce its effective sensitivity. Full instructions are given in Appendix B of the final Felix report.[14]

3.4.2 Optics

The optical system (Figure 8) consisted of a rotating parabolic mirror of approximately 1-in. focal length and aperture of 2⅜-in. diameter. The axis of the parabola was inclined 5 degrees to the axis of rotation, the axis of scan. The two axes, that of rotation and that of the parabola, intersected at the focal plane of the mirror. The bolometer was mounted with its center at the intersection of the axes. The diaphragm in the bolometer assembly (see Section 3.4.1) limits the field which can be projected onto the bolometer strips to a circle 10 degrees in diameter, 5 degrees either side of the parabola axis.

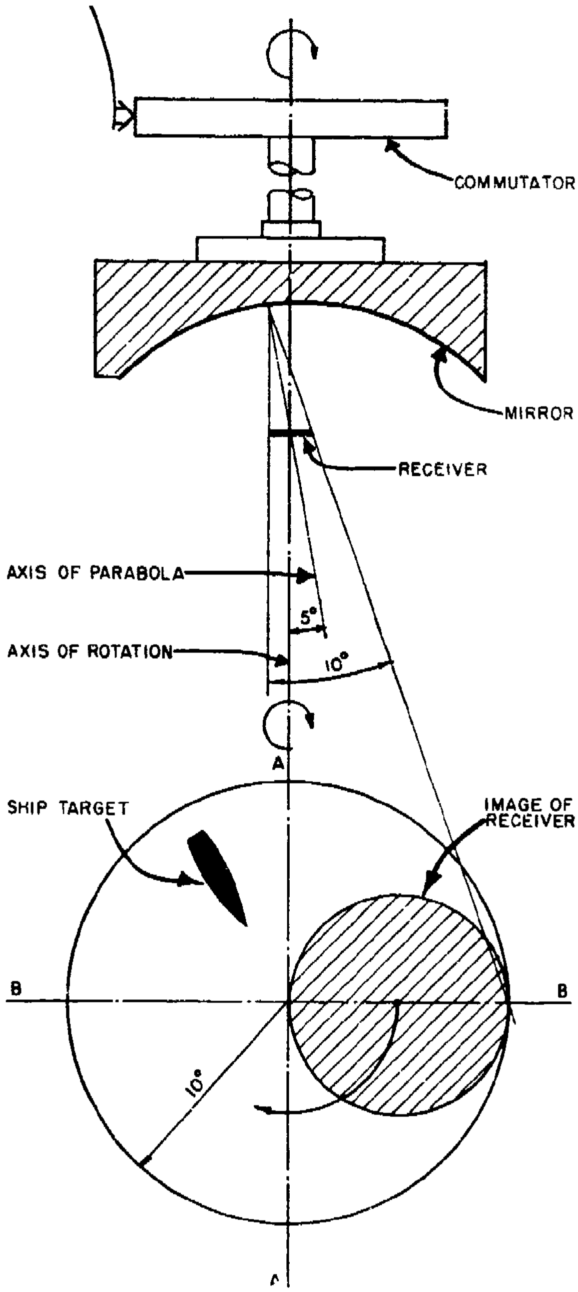


FIGURE 8. Optics of Felix.

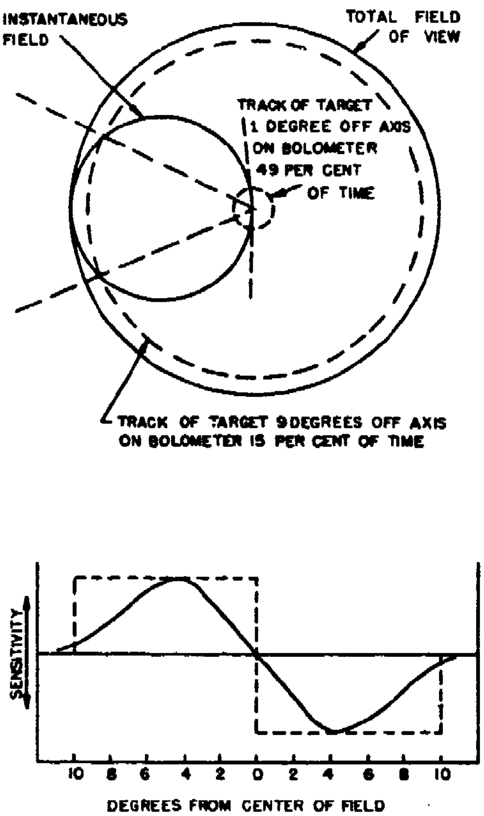


FIGURE 9. Scanning pattern (top); relative sensitivity (bottom).

The combination of the diaphragm and the intersection of the optical axis with the axis of scan assured that no rays more than 5 degrees off the parabolic axis were used. As the mirror rotated, rays parallel to the rotational axis focused at a point which traveled around the edge of the diaphragm aperture. Rays 5 degrees off axis crossed at the center of the bolometer; rays 10 degrees off axis just intersected the edge at a point diametrically opposite to that of the ray incident along the axis of scan.

A simpler way to look at such a system is to consider it in reverse, with the bolometer as a radiator

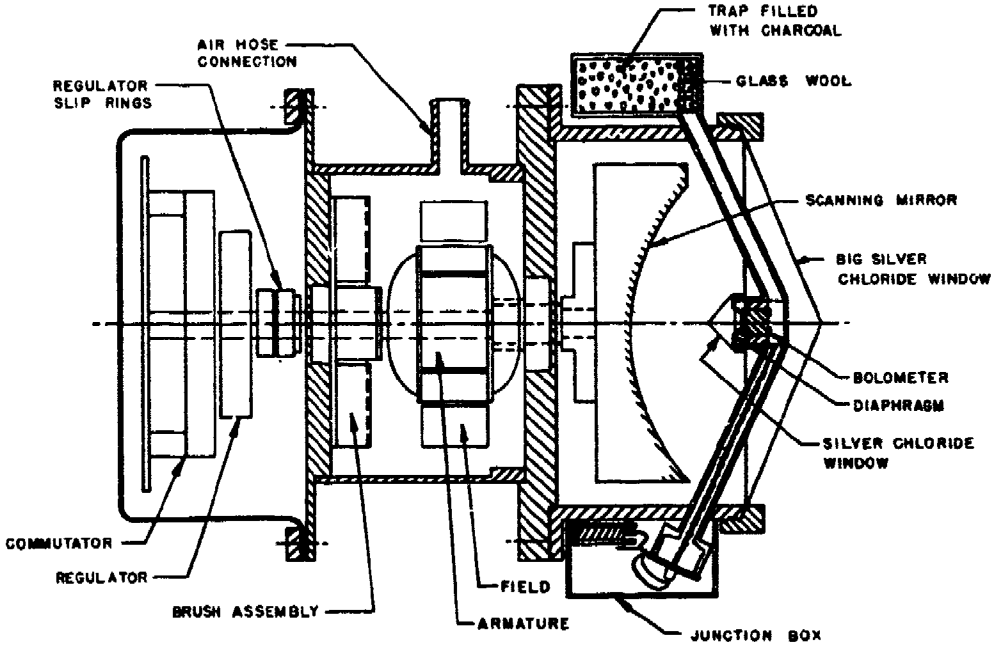


FIGURE 10. Scanner assembly.

rather than as a receptor. Thus an image of the diaphragm is projected on the terrain by the mirror. As the mirror rotates the image nutates—i.e., translates in a circle—about the axis of scan. The distinction between nutation and rotation is important, for if the image of the bolometer diaphragm could be made to rotate (which could be accomplished, for example, by a rotating bolometer) the sensitivity of the system to targets near the edge of the field could be increased by using a cardioid-shaped aperture.

Figure 9 shows the sensitivity of the scanning system as a function of measured error angle. The departure of this characteristic from the ideal square curve (shown dotted) is the result of three causes. The first cause is due to the nutational character of the scanning. The scanning pattern shows the tracks of targets at 1 degree and 9 degrees off axis. It shows that the target near the center is on the bolometer for 49 per cent of a scanning cycle; the more remote target is on the bolometer for only 15 per cent of the cycle.

The second cause is inherent in the optics of a fast parabola, which produces a good image on the axis but a confused one from an object 5 degrees off axis. Schmidt optics could correct this, but mounting a Schmidt corrector plate in such a scanning system presents a serious mechanical problem.

The third cause is the essentially flat character of a hole. This makes the diaphragm aperture, which looks like a circle when viewed from the center of the mirror, appear as an ellipse when viewed from the mirror's edge. With the aperture ratio used (f 0.36) the apparent axes of the ellipse were 10 degrees and 3.5 degrees. As a result, the effective speed of the parabola is much reduced for off-axis rays. The only cure for this would be reduction of the parabola aperture, with consequent decrease in the overall sensitivity. Further, the large parabola served another purpose as a shield for thermal radiations from the scanner case.

Figure 10 shows a cross section of the complete scanning unit. The mirror surface and the bolometer have to be protected against any condensation. This was accomplished by sealing the mirror and bolometer in a dry air space by means of a conical window of 3½-in. base diameter and having an apex angle of 136 degrees. The conical shape and apex angle were so chosen as to prevent any heat from the warmed bolometer or its case from being reflected onto the parabolic mirror and back onto the bolometer strips.

To prevent fogging of the external window surface, the window material, silver chloride, was made ½ mm thick, giving it a low thermal mass. Silver chloride is highly conductive (80 per cent transmission) to wavelengths between 8.5 and 13 μ. It is, however, extremely sensitive to actinic light. In the strong ultraviolet illumination found at altitude it becomes nearly opaque in the visible and partially opaque to infrared in less than an hour. This difficulty was surmounted by coating the windows with silver sulfide in a layer sufficient to reduce the transmission in the 0.4- to 2.0-μ band to about 1 per cent while preserving a transmission in the 8.5- to 13-μ band of 70 per cent. Uncoated windows have a transmission in this band of about 80 per cent.

A second difficulty with silver chloride is its extreme corrosive tendency when in contact with base metals. This was curbed by the use of a nonmetallic gasket between the window and the scanner case.

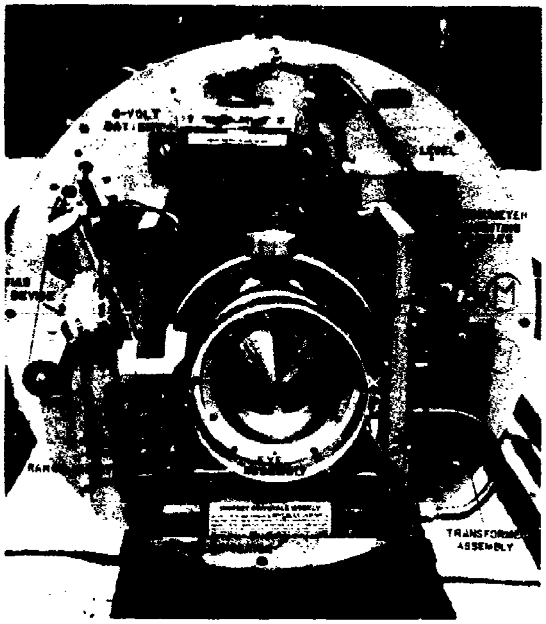


FIGURE 11. Scanning system in place.

The large window was capable of standing a pressure differential of approximately 4 psi, which is less than the sum of the dynamic pressure and the pressure change from high altitude to sea level. An equalizing system was constructed by sealing the bulkhead which closes the back of the scanner compartment, and the annular space between the front of scanner and the nose fairing was closed with a flexible, porous gasket of nylon. Thus the whole cavity housing the scanner (Figure 11) was kept close to the same pressure that existed on the nose of the bomb. The inside of the scanner—the chamber behind the silver chloride window—was connected with this cavity through a large tube containing silica gel as a desiccant.

The remaining elements of the scanning head consisted of the driving motor and the commutator. The motor was of a special design with close tolerances to permit direct mounting of the parabolic mirror on the motor shaft with preservation of optical alignment. To reduce magnetic pickup, the shaft was made of nonmagnetic material (bronze). To prevent change in phase shift as the signal was amplified, the motor was regulated at 32 rps by a centrifugal governor. A double-arm design was adopted to make the governor insensitive to gravity. With the usual single-arm design, the governor tends to cut in and out at scanning frequency whenever the shaft is not vertical. The change in field surrounding the motor caused considerable pickup in the amplifier, which was tuned for this frequency until the double-arm design was adopted.

A commutator of the simple cam and rocker-arm type, mounted on the back plate of the motor, indicated the phase of the bolometer signal. Each of its four contacts—up-down and right-left—was set to close through 165 degrees of rotation; a small adjustment was provided to accommodate variation in phase shift through the amplifier.

3.5 ELECTRONICS AND SERVO LINK

3.5.1 Principles of Operation

The heat signal from the target is intermittently focused on the bolometer as described in the preceding section. When the heat strikes the bolometer, its temperature rises rapidly; as the heat image of the target leaves the bolometer, its temperature falls exponentially until the image falls on it in the next scanning cycle. This fluctuating temperature is accompanied by a fluctuating resistance so that the bridge circuit of Figure 12 is cyclically thrown off balance. The transformer, the primary of which forms two arms of the bridge, serves as an impedance

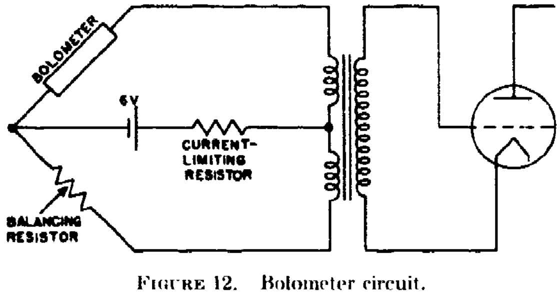


FIGURE 12. Bolometer circuit.

match—about 10 ohms—between the bolometer and the high-impedance grid input of the first stage. Figure 13 represents the temperature change in the bolometer. In addition to providing an impedance match, the transformer, by eliminating the d-c component and blocking the higher harmonics, converts the signal to the approximately sinusoidal form shown opposite the input circuit element in the block diagram of Figure 14. The preamplifier lifts the signal to a usable level and further removes harmonics.

The preamplifier is followed by a twin-triode stage which produces phase inversion, resulting in a two-channel output whose voltages are equal but in phase opposition. The bias on this stage is such as to produce saturation (clipping) for strong signals. A second clipping stage squares up the signal from weak inputs and maintains the amplitude independent of the strength of the input. The output of the phase

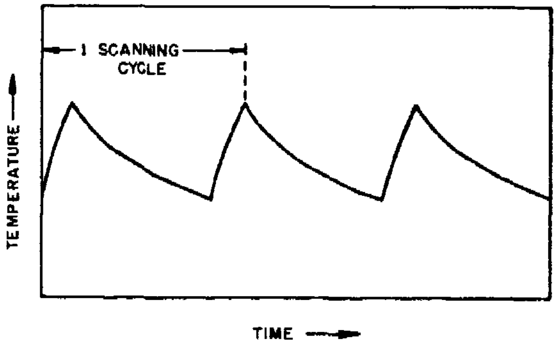


Figure 13. Temperature variation in bolometer.

inverter stage is a pair of chopped waves; the output of the clipper is a pair of square waves.

The signals from the two channels are now analyzed and resynthesized by the commutator. Consider the situation represented by the block diagram of Figure 14 where the target is on course in the azimuth sense but low. At the beginning of a scanning cycle the output of channel A is positive, that of channel B is negative. During the first quarter-cycle the right-left channel receives its voltage through the commutator from channel B (negative). During the half-cycle it receives its voltage from channel A (positive in quarter-cycle 2, negative in quarter-cycle 3). During the final quarter-cycle it receives its voltage from channel B, which has now swung positive. The output to the rudder channel is therefore a balanced square wave of a frequency twice the scanning frequency.

The situation as regards the elevator channel is quite different. At the first instant after the beginning of the scanning cycle it receives its voltage from channel A (positive). This condition continues for the complete half-cycle, at the end of which the voltage supply is switched to channel B, which has now become positive in turn. The commutator output to the elevator, then, consists of a substantially constant positive voltage.

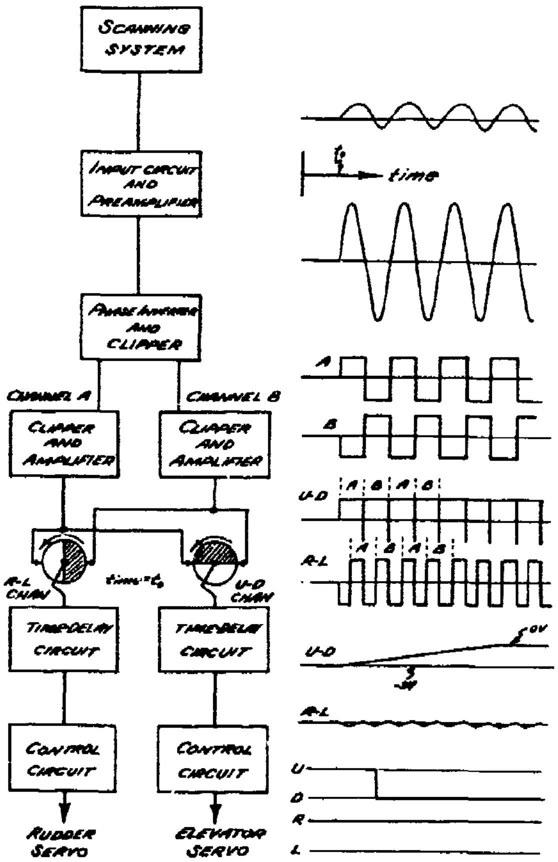


Figure 14. Block diagram of Felix electronic servo system.

The commutator outputs were fed into resistance-capacitance circuits which integrated the voltage over several scanning cycles. Thus, for the condition shown in Figure 14 the input to the elevator-control circuit slowly climbs. When the output of the integrator circuit, amplified by the control tube, reaches the pickup voltage for the control relay, the relay operates. The elevator servomotor reverses, depressing the elevators until the feedback connection to the scanner moves the target into the top half of the field of view, when the whole cycle is reversed.

The input to the rudder-control circuit oscillates at a low amplitude about zero. The relay therefore remains on the "right" contacts. It should be noted that the diagram is somewhat incomplete, for after a few scanning cycles the rudder servomotor would cause the scanner to deflect, bringing the target into the "left" half of the field of view. It is this feedback operation which gives the quasi-proportional control discussed in Section 3.2.

3.5.2 Transformer and Input Circuit

The transformer was of special design, having two 59-turn sections in the primary and 6,500 turns in the secondary. It was wound on a Mu-metal core and provided a net gain of 77 at 32 c. Three cases of Mu-metal and one of copper produced a shielding of 90 db.

The overall size was 1⅞ in. in diameter by 2¾ in. long. The final version of the missile provided more space than this for the transformer. A redesign might have improved both the operating characteristics and its ease of production. Transformer design talent was, however, one of the most critical procurement problems which faced the Division, and the revision of a working design was not undertaken.

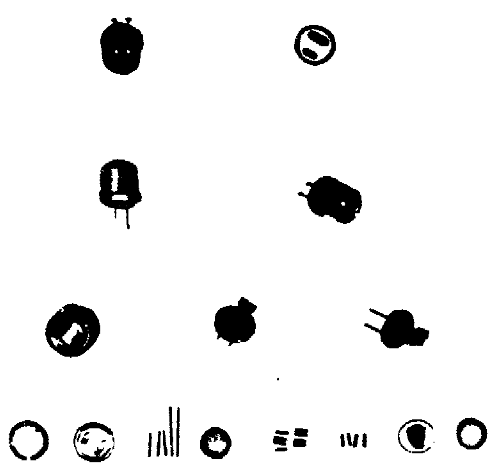


FIGURE 15. Bolometer unit and its components.

The two halves of the transformer primary formed two arms of a bridge circuit; they were balanced to within 1 per cent as to resistance and impedance at 32 c. The bolometer comprised a third arm, which was balanced by a special resistor wound with Hytemco wire, an alloy of high resistivity having about the same temperature coefficient of resistance as the nickel strips. Close balance was essential to eliminate noise and to prevent saturation of the transformer core.

Power for the bridge was supplied from a special 6-v lead-acid battery connected to the bridge by short shielded leads. This portion of the circuit operated at the lowest power level, approximately 1.0 microvolt, and extreme care had to be taken to minimize pickup. The bridge type of circuit reduced somewhat the voltage output available from the bolometer but it reduced the noise by a much larger factor, the overall result of the circuit being a gain of about 50 in signal-to-noise ratio. Taken as a whole the input circuit acted as a broad-band-pass filter, peaked at 32 c and having half-power points at 18 and 60 c. The low cutoff is determined by the transformer itself, the higher limit by a 0.005-μf condenser on the transformer output.

The transformer, series resistor, and Hytemco balance resistor were housed in a heavy iron shield, shock-mounted to guard against microphonics, which constituted an exceedingly acute problem. All connecting wires had to be carefully tested against the production of noise from flexure. Each joint in the primary circuit had to be made so that no conductors touched except within the solder bead of the joint. The sensitivity of the bridge circuit to changes in resistance, one part in one hundred million, imposed these rigorous specifications. Accordingly the entire input circuit (Figure 15), bolometer, resistors, and transformer, was made up as a unit, terminating in a 4-prong plug for connection to the battery and amplifier.

3.5.3 Preamplifier

The preamplifier consisted of two resistance-coupled pentodes with fixed bias. The usual objection to the use of fixed bias, wide variation in tube performance with fluctuations in plate-voltage level, was avoided by stabilizing the plate and screen voltage supply with voltage-regulating tubes. This had the advantage in such a low-frequency amplifier of avoiding large, oil-filled, cathode-by-pass condensers.

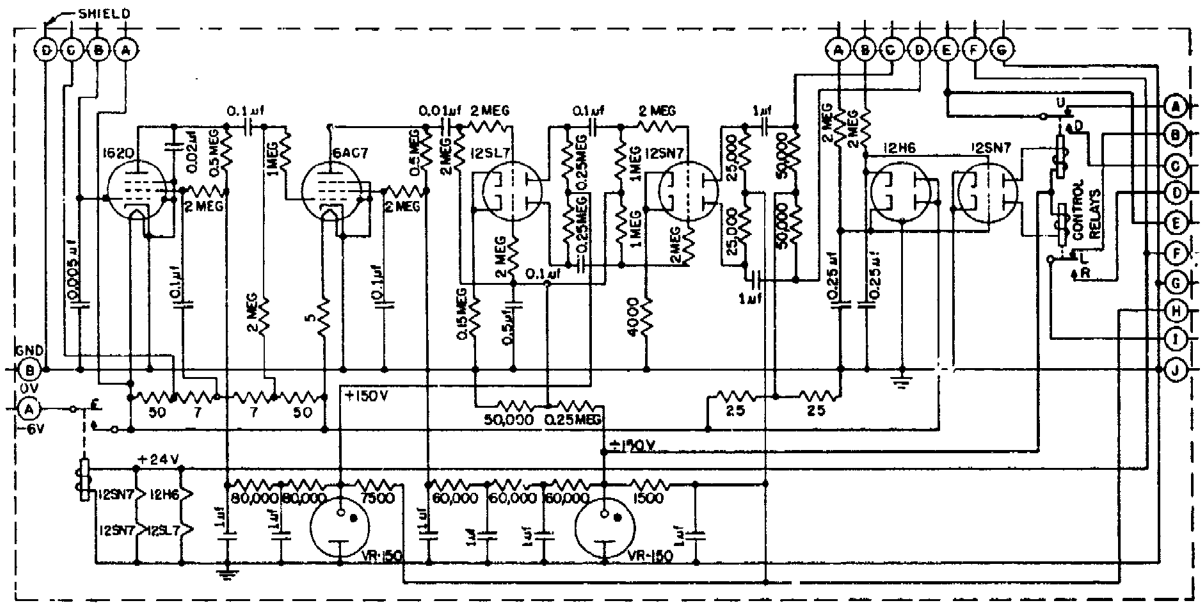


FIGURE 16. Felix electronics.

The band-pass of the preamplifier was approximately 45 c, peaked at 32 c. It is not a particularly narrow band but it is sufficiently narrow to eliminate a large portion of the noise, that above approximately 60 c. It could not have been made much narrower without introducing serious phase shift with variation in scanning frequency.

3.5.4 Phase Inverter and Clipper

Phase inversion was accomplished by a twin triode (12SL7), with the input applied to one grid and a common cathode resistor. The second grid was effectively grounded to voltages of 32 c through a 0.5-μf condenser. Thus the two plate outputs were 180 degrees out of phase. These two plate circuits form the start of channels A and B of Figure 14. The second twin triode (12SN7) of Figure 16 clips or squares the signal. Both the phase inverter and the clipper operate with a positive 26-v bias on the grid, which both stabilizes the operation of the amplifier and prevents overloading and blocking of the circuit from strong signals. This is most important, since blocking even for a fraction of a second would seriously upset the operation of the integrating circuit.

The whole scheme of operation of the electronic servo system is based on phase discrimination. In the preamplifier phase distortion was avoided by making the band-pass wide enough to take care of scanning-frequency variations. The signal level in that portion was so low that danger of phase shift from amplitude distortion existed. In the clipping section, however, the reverse is the case. This section had to have a wide band-pass to produce a square-wave output so that there was no danger of phase shift due to frequency swings. Phase shift from amplitude distortion was avoided only by careful design. Since the very essence of the clipping-circuit operation was a symmetrical distortion of the incoming signal, a careful balance between the positive and negative portions of the square-wave output had to be maintained.

3.5.5 Commutator and Integrator

The action of the commutator has already been described (see Section 3.5.1). It synthesized the signals in channels A and B to produce the control signals for the elevator channel and the rudder channel. Its output was used to charge or discharge a 0.25-μf condenser in each of the two control channels. The high side of each condenser was connected to a grid of the twin-triode control tube which had a 3-v negative bias; a potential shift of 0.5 v at the control-tube grid would cause the relays to operate.

The length of time required for the relays to receive an operating signal depends on the voltage to which the input condenser at the control-tube grid was last charged. It swings during operation between

0 and -6.0 v. The time constant of the input circuit is such as to require about 5 scanning cycles fully to charge or discharge the condenser.

Figure 17 indicates the operation of the system with target motion from the down-left quadrant to the up-right quadrant. This figure assumes that the

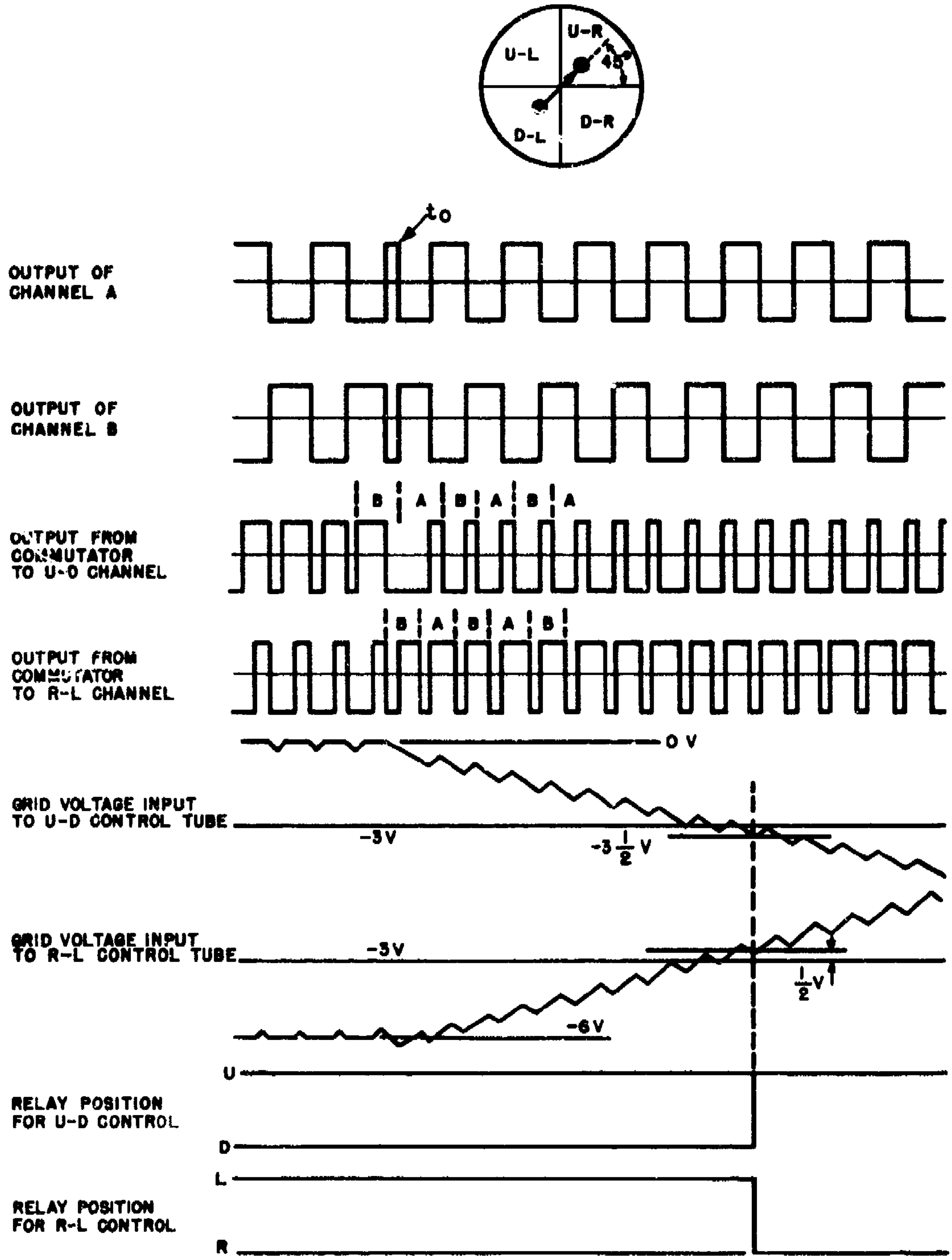


FIGURE 17. Operation of Felix electronic servomechanism with target motion from down-left quadrant to up-right quadrant.

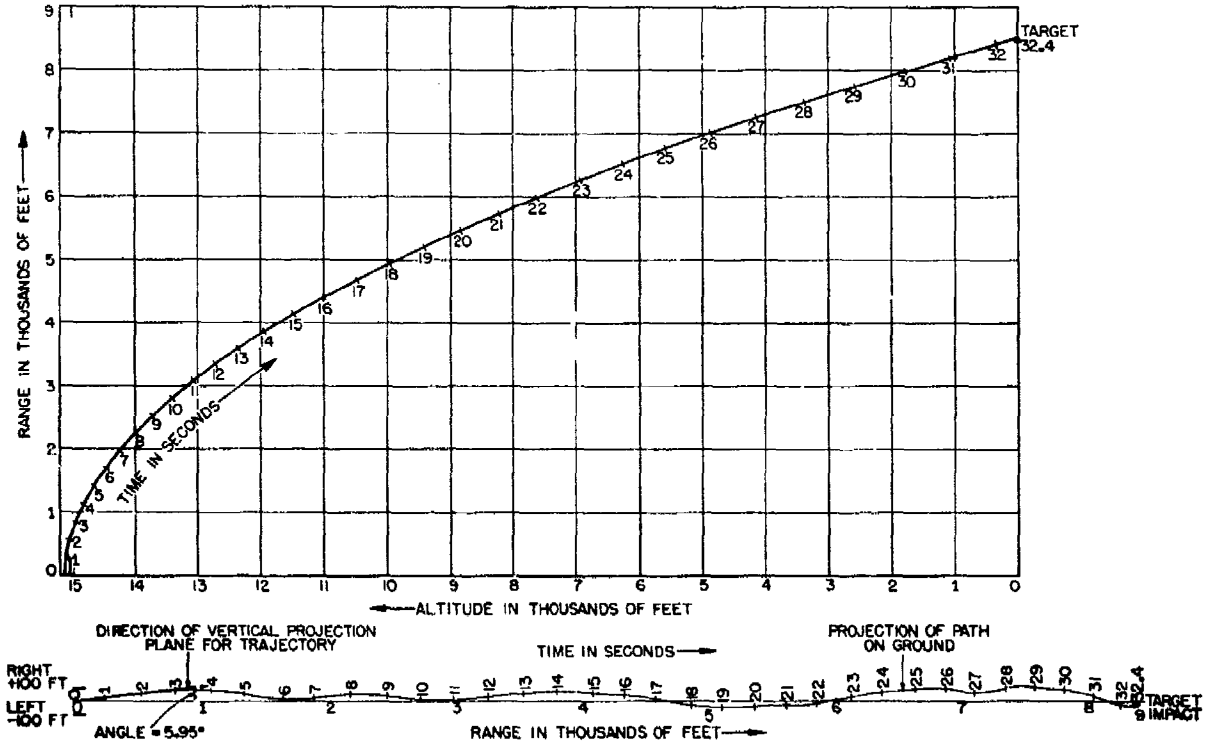


FIGURE 18. Plan and profile trace of successful Felix drop at Eglin Field, January 1944.

target has been in the down-left quadrant for a sufficient interval for the integrating condensers in the elevator channel and the rudder channel to have stabilized at 0 and −6 v respectively. The target is assumed to cross the intersection of the axes at $t = 0$. Ten scanning cycles later the condenser charges have changed sufficiently to cause relay operation.

3.5.4 Servomotors and Feedback

The servomotors controlled by the output relays of the electronic servomechanism were simple 24-v shunt-wound motors. The fields were continuously energized. Their armatures were energized for clockwise or counterclockwise rotation, depending upon whether the control relays happened to be resting on their front or back contacts. As has been already pointed out, this gives rise to oscillation of the control surfaces about a mean displacement essentially proportional to the error in heading.

The motors were geared to give a displacement rate of 12 degrees per second to the elevators; this speed, combined with the time constant of the integrating circuit and the feedback ratio, the ratio of δ to ϕ, determined the frequency of oscillation (about 1.2 c) of the control surfaces.

Increasing the feedback ratio and the servomotor speed or decreasing the time constant of the integrating circuit would raise the frequency of control-surface oscillation. This might result in more stable flight at the expense of a heavier power demand by the servomechanisms. In any case this frequency must be kept reasonably remote from the natural frequency of the missile in pitch, as determined by the partial derivative of the pitching moment at trim and the moment of inertia. The investigators on this project chose to keep the period of control-surface oscillation well above the natural period of the missile. The restricted space in Felix for batteries and servomotors speaks strongly for this choice.

3.6 FIELD TESTS

3.6.1 Eglin Field Tests

The initial tests with an American heat-homing missile were made at Eglin Field in January 1944. Six bombs of a preliminary design were prepared, based on the design of the Gulf photoelectric target-seeking bomb (see Chapter 9). Flight tests had been made with the scanning head with the control relays energizing indicating lights. The results of these tests seemed to indicate promise of control by means of far infrared radiation. The results of the Gulf tests with the photoelectric target seeker indicated that the high-angle bomb had sufficient dirigibility to permit homing control.

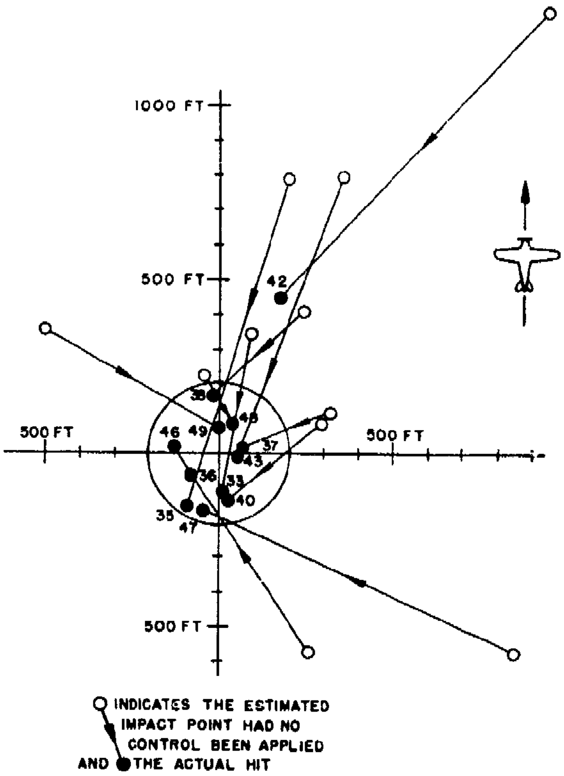


FIGURE 19. Impact pattern of 12 Felix drops, September 1944.

A target was constructed by clearing an 800-ft square area surrounded by scrub undergrowth after the first drop indicated that the regular target at Range 55 was an inadequate radiator. Of the six bombs dropped, two failed to stabilize in roll. The remaining four homed or tried to home on a target which subsequent survey showed to be a heat radiator. One of them made a successful homing-flight landing some 30 ft from the center of the target. The ground projection and profile of its trajectory are given in Figure 18.

These results, while not spectacular, were sufficiently encouraging to enlist the strong support of the Air Forces Communications Officer, who had been given the added duties of serving as senior liaison officer for the Division. Intelligence had disclosed targets of high priority, which later proved to be launching sites for the German V-1; accordingly the Air Forces urged utmost acceleration of the Felix program as a weapon against these well-camouflaged targets, which were known to contain diesel engines and air compressors. It was hoped that this machinery might prove to be a sufficient source of heat to make Felix an effective weapon against them.

Accordingly NDRC accepted in March 1944 the assignment of crashing the Felix program, although it was clearly understood that the targets might prove submarginal and that the chances of proving a combat design within a year were indeed remote.

3.6.2 Tonopah Tests

Two designs were rushed; one, having a cruciform empennage permitting better stowage in bombardment aircraft, was terminated when the experience of Gulf with Razon (see Chapter 2) indicated that roll stabilization with a cruciform tail was hardly to be accomplished. The second design with an octagonal empennage was pushed to completion. Laboratory prototypes were ready for drop tests by August 1944.

The initial target consisted of aluminum foil nailed to panels laid out in the form of a square cross on the desert floor. The arms of the cross were 40 ft by 100 ft, the total circumscribing square being 240 ft by 240 ft. It was hoped to make the bombs home on the sun's reflection from this target; however, it proved to be wholly unsatisfactory. While the signal from the sun's reflection was very large indeed, missions could be flown only in the middle of the day, when the elevation of the sun was approximately the same as the bomb after falling to an altitude of 10,000 ft from a release point of 15,000 ft. The aircraft had to fly directly into the sun in order for the scanner to pick up a good reflection. The greatest disadvantage, however, was that in the middle of the day the air was so turbulent that the bombardier was unable to get a good approach run. Eight drops against this target proved abortive.

A second target was constructed, consisting of 100 rectangular steel plates, each approximately 30 sq ft in area. These plates were mounted so that they inclined 30 degrees from the vertical and were heated to a very dull red heat with 3 oil burners (orchard heaters) per plate. Eleven Felix bombs were dropped

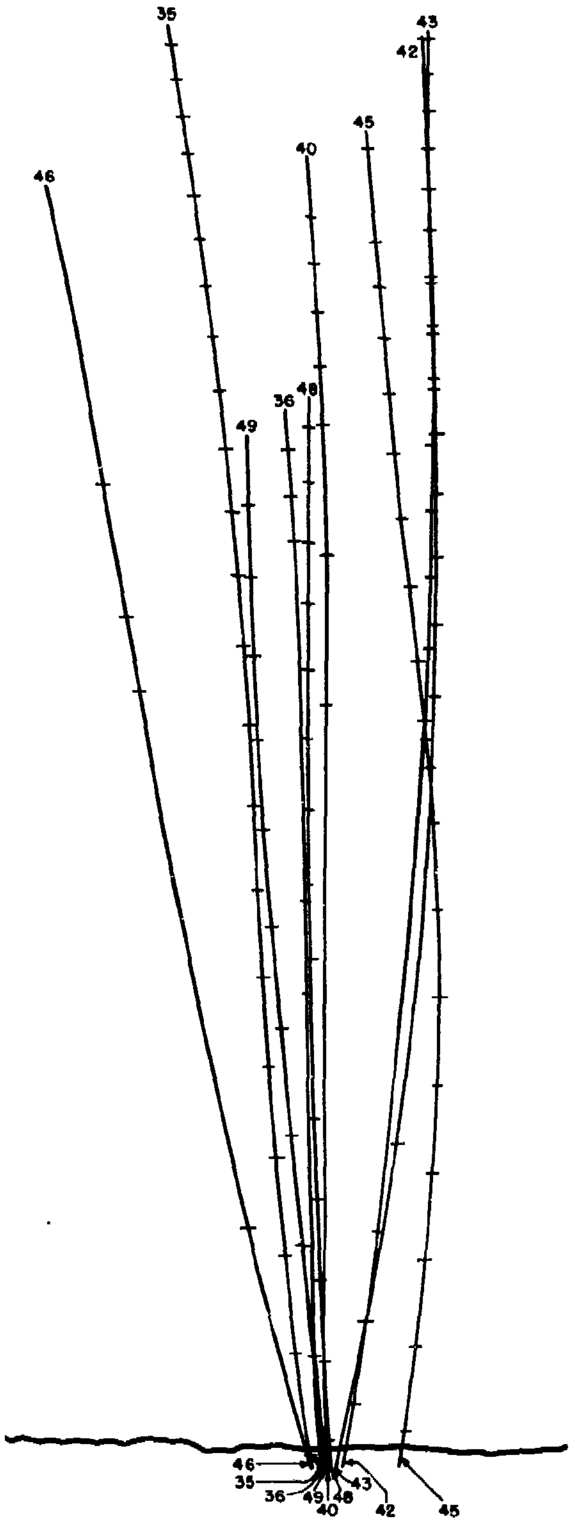


Figure 20. Azimuth traces of Tonopah drops.

at this target. Seven displayed electrical malfunctions. Four made successful homing flights, scoring misses of 100 to 300 ft.

The design was then subjected to an engineering analysis. Longer rudders and elevators were installed, producing a larger angle of attack and permitting the elimination of a troublesome lift shroud. The control relays were redesigned and housed in a hermetically sealed case. The rudder deflection speed

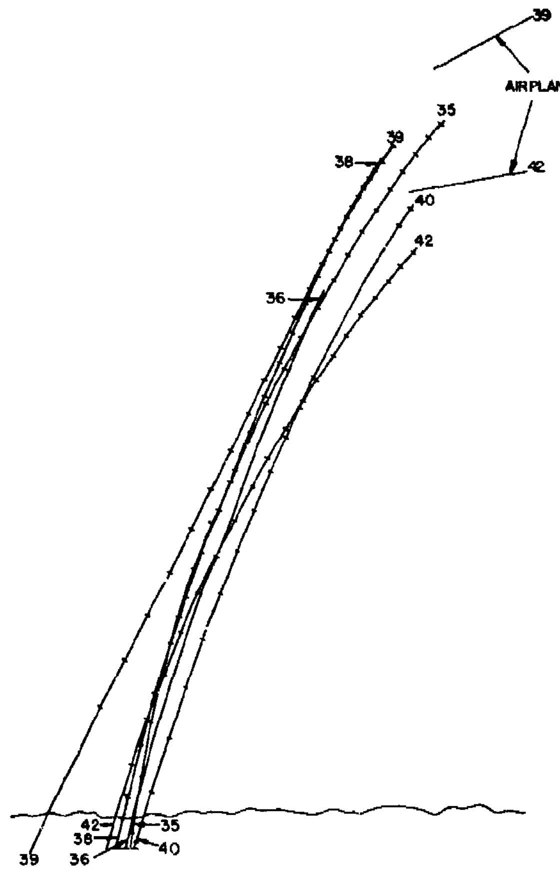


Figure 21. Profile traces of Tonopah drops.

was reduced about 30 per cent to a final value of 12 degrees per second to remove the range of forced oscillation from the vicinity of the natural frequency of the bomb. The feedback coupling mechanism was simplified and the bias device to provide parabolic thinking was introduced. The integrator stage was added to the amplifier.

Sixteen of these bombs were tested in September 1944. Twelve of the sixteen homed successfully, producing the impact pattern shown in Figure 19. Composite plots of the azimuth and profile traces of the trajectories are shown in Figures 20 and 21.

As a result of these reasonably successful tests the designs were released to the manufacturer for a preproduction order of 100 units.

3.6.3 Ocala Tests

The preproduction units from the manufacturer were desired by the Air Forces Board for evaluation at Orlando, Florida. The Division was reluctant to release the initial units from a new supplier for this purpose; accordingly a compromise was worked out whereby the initial phase of the test program to check the manufacturing design would be carried out by the Division's contractor.

It was now obvious that the design of a heat target was a critical element of the testing program. The Division undertook to construct a target to simulate thermally an operational target in which the Twentieth Air Force had a strong interest. Figure 22 is an aerial photograph of the target constructed at Ocala range near Orlando. The target consisted of eleven areas cleared of vegetation to represent the eleven buildings of a Japanese aircraft-engine factory. Oil burners similar to those used at Tonopah were installed to augment the reradiated solar energy. Surveys made in November indicated adequate contrast from the surrounding vegetation.

The tests began on December 27, 1944. It was immediately apparent that a great many defects had crept into the manufacturing procedure and that inspection methods adequate to detect them had not been developed. The hope that any of the preproduction units could be made available for evaluation soon seemed naïve. Too much credit cannot be extended to the Air Forces Board for their patience during the working out of the initial production grief. Such difficulties always arise, even in a program not carried forward at the pace of this one. Nevertheless under the drive of war it is impossible not to hope that each program may be an exception to the rule.

The principal difficulty was from moisture. The terminal board of the transformer proved to be hygroscopic, and a new design had to be developed. The umbilical switch had inadequate clearance and had to be modified. The silver chloride window assembly gave trouble, as the presence of grease, dirt, dents, or

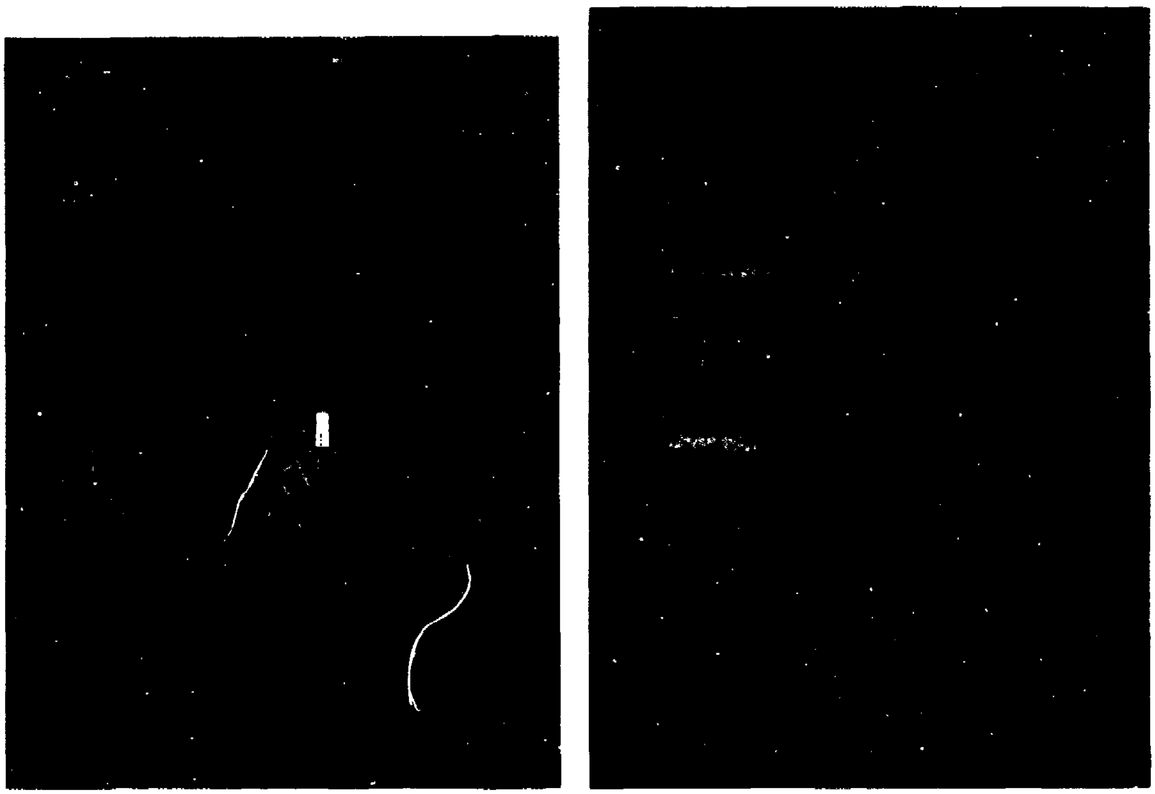


FIGURE 22. Target at Ocala: at 10,000 ft (left); at 2,000 ft (right).

irregularities could cause a "built-in signal." Methods of shop and field inspection had to be developed to eliminate defective windows; manufacturing methods were improved and inspection tightened up. The compound used to seal the eye and the window was found to be deliquescent. The condition was bad on the ground; it was probably worse at an altitude.

The major source of trouble was associated with the excessive humidity in the Orlando area. This is spectacularly worse than the atmosphere at Tonopah, where the preceding tests had been run. It is not worse, however, than the test specifications that airborne electronic equipments are supposed to meet nor, indeed, worse than conditions in the Southwest Pacific combat area. Too much emphasis cannot be placed on the importance of careful climate testing of all components and of the complete assembly before field trials are attempted. The temptation to neglect them is sometimes almost irresistible, but succumbing to this temptation can result only in an overall loss of time.

The support of the Air Forces was, however, unswerving. In the face of the unsatisfactory tests they urged the Division to work out a mass-production design and ordered 1,000 units under a transfer of funds to NDRC. Accordingly the investigators undertook to select another target which would prove satisfactory in Florida summer weather. Further, they strongly urged that only production units be used in evaluation tests.

3.6.4 Channel Key Tests

The target finally selected was Channel Key (Figure 23), located about one mile northwest of the Key West Overseas Highway. While this target was relatively weak in comparison with some of the industrial targets which had now been surveyed (see Section 3.8), it was believed that its contrast with the surrounding water would make it a satisfactory target. Permission for its use was obtained, not without difficulty.

Only results with the production unit will be reported here. Thirty-one individual releases were made. Twenty of these made successful homing flights, landing on the target after making observable corrections. Of the eleven failures, five were due to failure of the bomb shackles to release or to neglect on the part of the bombardier to energize the warm-up circuit to bring the amplifier tubes up to temperature before release. The difficulty with bomb shackles dogged the Division's entire program and, indeed, is said to have been the cause of much bombardment inaccuracy in combat.

One test was of outstanding interest. Eighteen Felix bombs were released simultaneously from a formation of nine B-17 airplanes flying in loose line—abreast in elements of three. Although the average spacing of the aircraft in line was supposed to be 400 ft, the extreme right-wing ship was about 2,500 ft on the flank of the target. Figure 24 shows an approximate map of the trajectories of the eighteen bombs.

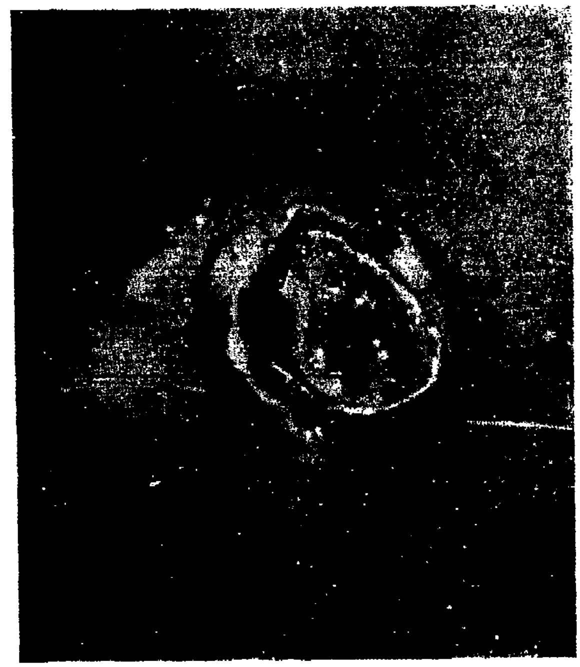


FIGURE 23. Channel key.

Fourteen homed well, their impacts forming three distinct clusters corresponding to three observed heat centers on the target. Figure 25 is a plot showing the errors corrected.

In the closing weeks of the war the Twentieth Air Force headquarters placed an order for a squadron equipped and manned to take Felix into combat. Their assembly was incomplete as the war ended.

3.7 DOVE EYE[15]

Under urgent representations from the Navy Bureau of Ordnance the Division undertook with the Polaroid Corporation the development of a quantitative heat-homing scanner. The contractor's organ-

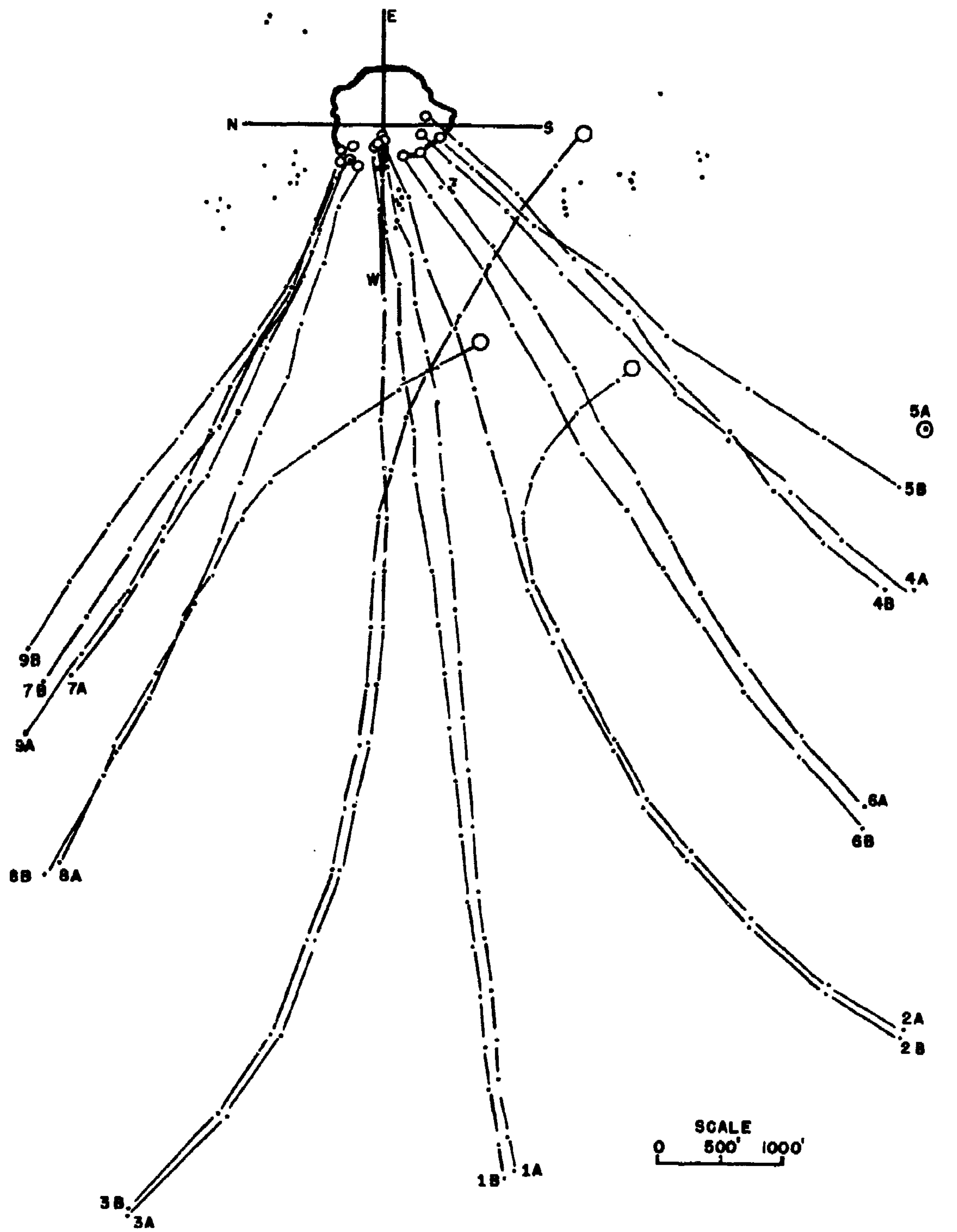


FIGURE 24. Plot of traces of bombs as observed from lead plane.

ization was eager to develop a complete heat-homing missile. The strong belief of the Division, however, was that the war was much too far advanced to initiate the development of a completely new missile system at that time (early 1944). The Navy Bureau of Ordnance, however, did sponsor such a development with Polaroid Corporation so two projects were carried forward cooperatively, the Navy Bureau of Ordnance administering work at Polaroid on the missile structure and its aerodynamic control surfaces and servo links, the Division administering the development of a quantitative heat-homing scanner (Dove Eye). At the close of the war development was still incomplete and the project was turned over to the Navy Bureau of Ordnance even in advance of the preparation of a definitive report.[17] This section, therefore, is of necessity general rather than specific in treatment.

From February 1944 on, the Dove Eye was conceived as an infrared detector which would report the angular velocity of a line from the bomb to the target relative to any stabilized line in space. This derivative would be used to effect the minimum aerodynamic acceleration necessary to convert a miss into a hit. Minimum departure of the missile from its normal free-fall path would be necessitated, particularly if the aerodynamic control system used were continuous and proportional.

The first derivative-taking Eye was built and operated during the first three months of the project, but because of inherently poor discrimination and loss in threshold sensitivity, it was abandoned after successful laboratory tests in favor of the present lock-on Eye. This "moving-grid" eye obtained the derivative by interposing a moving orthogonal grid between the target heat flux and the thermistor bolometer receptor. Angular velocity of the target relative to the Eye showed itself as a frequency shift.

The final "lock-on" Eye obtained the angular velocity of the line of sight from the bomb to the target by continuously pointing along that line. The optical scanning system and detector was mounted on the rotor housing of a free gyro, with the axis of scan collinear with the spin axis of the gyro. Since the Eye was made to point at the target by precessing the gyroscope, the magnitude of the torque required for precession was proportional to the angular velocity of the line of sight.

In greater detail, the optical system consisted of a 2-in. clear aperture spherical mirror with a thermistor bolometer mounted at the focal plane. The mirror was displaced horizontally so that its optic axis was 9.5 mm from, but parallel to, its spin axis (unlike the 5-degree inclination of the Felix unit). The mirror, detector, optical system housing, and initial amplification stages were mounted on the gyro casing of the free gyro, and the mirror was coupled—through reduction gearing—to the gyro rotor. The rotary motions of both gyro and mirror were coaxial. The gyro rotor, gimbal mounted, was precessed in two planes by two sets of electric torque motors, one motor at each gimbal axis termination.

During operation the Eye attempted to point at the target. If the target was not at the line of sight,

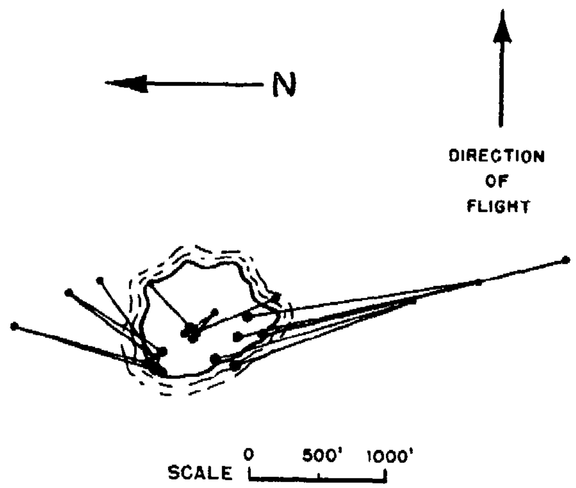


FIGURE 25. Errors corrected by Felix in nine-plane mission.

but within the field of view, a signal was initiated, its phase in the scan cycle indicating the position of the target. The pulses from the detector, after suitable amplification and commutation, were used to drive the torque motors so as to precess the gyroscope and cause the Eye to point at the target. At all times the total voltage across the torque motors was proportional to the angular velocity of the line of sight relative to the fixed line; this voltage, measured, served also to effect aerodynamic control.

The heat-sensitive element used in the Dove Eye was the thermistor bolometer, initially selected in 1944 because of its availability, the ease of manufacture of its odd-shaped detectors, its acceptable sensitivity threshold, low microphonics, and low time constants. Although suitable evaporated-metal bolometers were produced in connection with the project, and successfully used in laboratory lock-on tests of production-type Dove Eyes, all the guided missiles used in homing tests with Dove Eye were provided with thermistor bolometers.

The thermistor bolometer used was cruciform, to give a nearly circular field of scan. The length of each of the four legs of the cross equaled the displacement of the mirror spin axis from its optic axis. The ceramic legs of the cross were mounted on a quartz backing, and the whole detector hermetically sealed in a silver capsule for moisture protection. A silver chloride window, suitably filter coated and induction welded into the front of the silver capsule, admitted desired wavelengths while excluding those near and below 1.0 μ.

By June 1946, better than 30 per cent of the Dove Eye units dropped from an altitude of 20,000 ft at a heated hulk target hit within 50 ft of the target, even though the bombsight was set with a fixed error of approximately 20 mils.

3.8 TARGETS AND TARGET SURVEYS

3.8.1 Target Discrimination

The chief problem in the development of any homing missile is one of target discrimination. This point

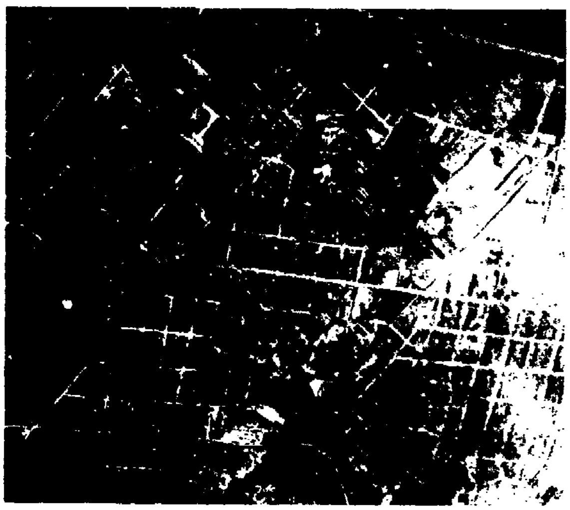


FIGURE 26. Industrial target.

was stressed in Chapter 1 in connection with radar-homing glide bombs and it is discussed in broad generality by Dryden in Chapter 12. The problem is particularly acute in thermal-homing missiles such as Felix and Dove. So long as the background surrounding the target is uniform, no ambiguity exists. Thermal scanners of any type developed thus far are difference-measuring devices, but they are sensitive to very small differences even though the gross heat fluxes compared are large.

In the Tonopah tests discussed in Section 3.6.2, the total thermal flux radiated from the heated target was well under 5 per cent of the total flux from the field of view. Yet so long as the tests were carried out before dawn, when the desert floor was at a uniform temperature, troubles with target discrimination were minor. After sunrise, however, areas of the terrain warmed at irregular rates, and these irregularities produced signals which masked the desired signal from the target.

Marine targets are normally considered to have a very uniform background; however, even the ocean surface can have thermal gradients of sufficient magnitude to cause difficulties. Military targets on land, present a much different aspect. Such targets, for example, as that shown in Figure 26, are, in the main, industrial and are likely to be surrounded by a heavily built-up area.

The presence of the many discontinuities in the thermal array presented by a typical land target has the effect of introducing noise into the signal received.

The effect of noise can be minimized, however, by integration or smoothing. This corrective measure was involved in each of the thermal homing devices developed by the Division. In Felix the integration to suppress noise was accomplished in the thermal receptor itself by making it large enough to subtend a 10-degree field of view. In Dove Eye the same end was accomplished by an integrating element in the circuitry. The case favoring one of these techniques over the other is not clean-cut. Direct thermal integration as in the Felix manner can be accomplished only at the expense of increasing the time constant of the bolometer which was already marginally large. Circuit integration, the method used in Dove Eye, introduces a phase shift in the servo-system loop which may be seriously injurious to the accuracy of the missile.

3.8.2 A Target Survey Instrument[18]

In order to determine the suitability of specific targets, the Heat Research Laboratory of MIT developed a quantitative target-evaluation instrument. This instrument consisted of a standard Felix scanner mounted in a metal case with a telescope and a

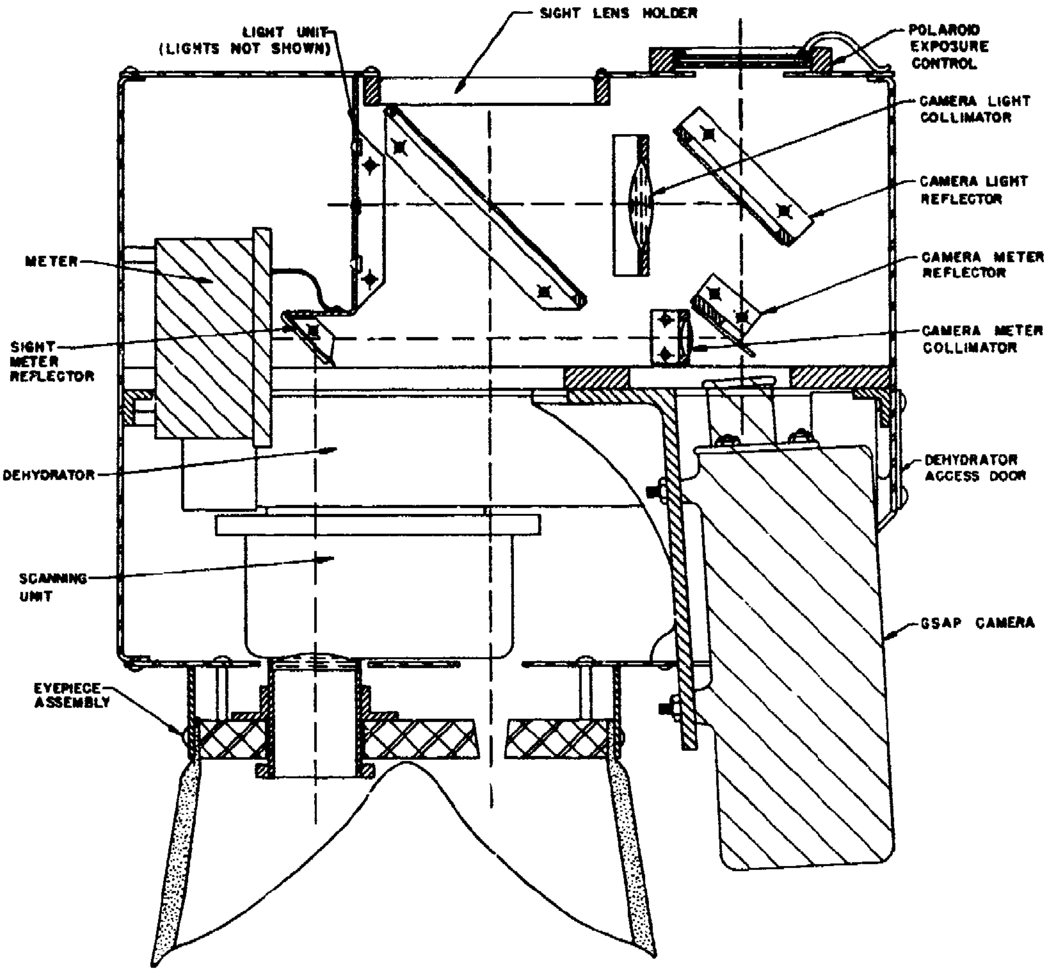


FIGURE 27. Section of target survey head.

GSAP camera. The telescope, the camera, and the scanner were all mounted with their axes parallel; all had a 10-degree field. The amplifier associated with the scanner was in a separate case with the necessary batteries. Batteries and amplifier were connected with the surveying head by cables, and the surveying head (Figure 27) was provided with a gimbal suspension to permit traversing and swinging in elevation.

In addition to photographing the terrain surveyed telltale lights connected so as to show the operation of Felix rudders and elevators were reflected by partially silvered mirrors onto the film. Further, a meter with a logarithmic scale was connected with the amplifier so that its scale reading indicated the heat flux received in watts per square centimeter; this meter was also photographed. The operator observed the meter with one eye while sighting the survey head and observing the telltale lights with the other eye (see Figure 28).

This instrument (Figure 29) will evaluate with some precision whether any particular target is a

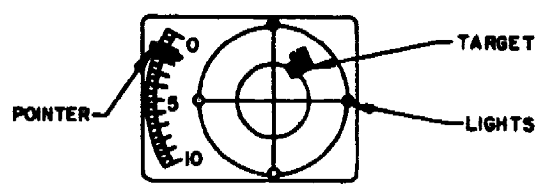


FIGURE 28. Typical frame from survey instrument.

satisfactory objective for an attack with Felix. The target-survey report[18] discusses fully the appropriate techniques for the use of the instrument. With its careful use the successful application of Felix should be assured.

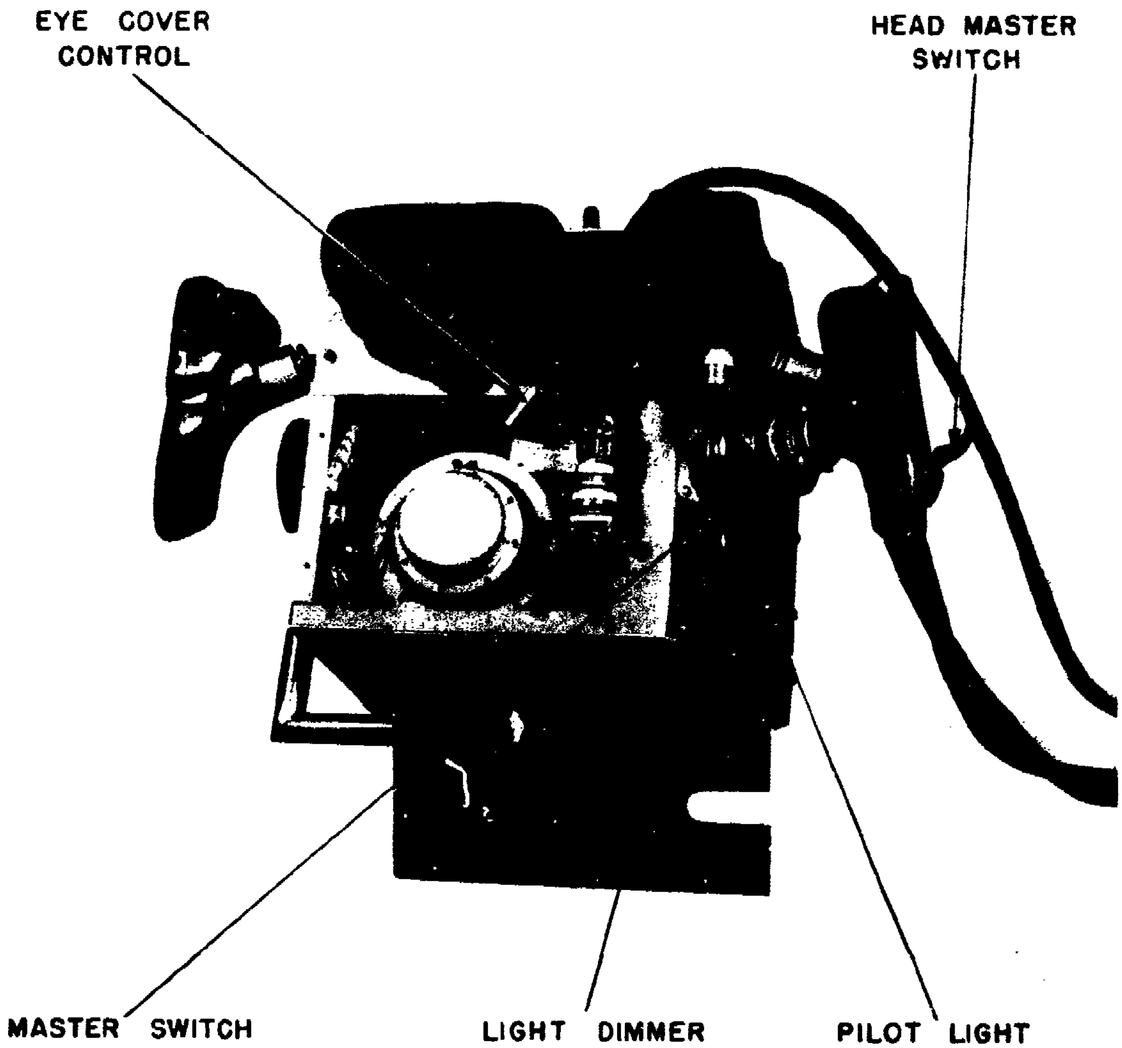


FIGURE 29A. Surveying head, rear view.

It is hardly to be expected that a technician with an instrument would accompany each combat mission and advise the commanding officer as to appropriate thermal targets. Rather it is conceived that many thermal reconnaissance missions will be flown in company with photographic reconnaissance. The parallel analysis of these missions, especially if some of the photoreconnaissance be in color, will develop a target "heat-evaluation lore" so that analysts will be able to predict from photoreconnaissance data what targets can profitably be attacked with heat-homing bombs.

3.9 FUTURE PROSPECTS FOR HEAT-HOMING MISSILES

The program of the Division in Felix suggests further work which may be done in this field. Future missiles in the main will probably not be powered by gravity; instead, jet propulsion in the transsonic and

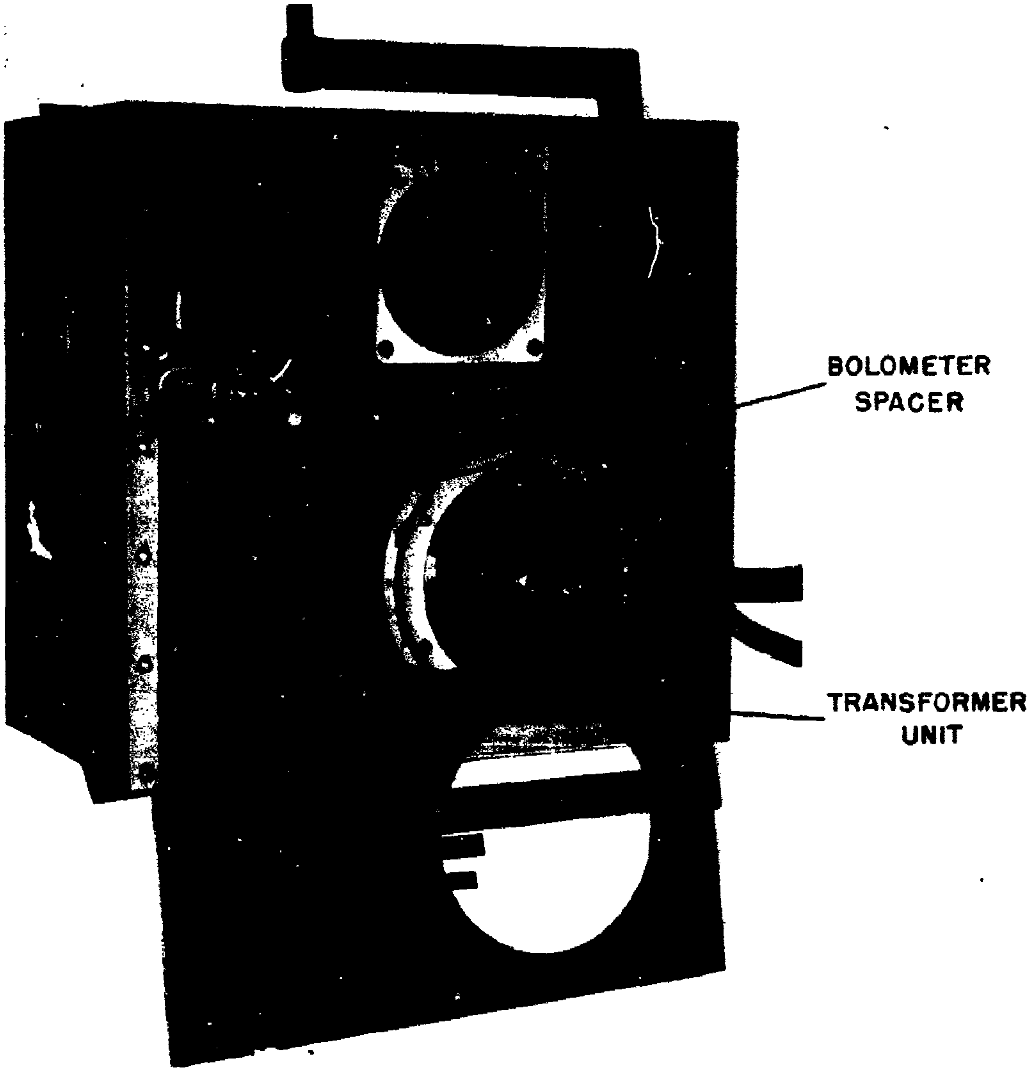


FIGURE 29B. Surveying head, front view.

supersonic ranges may be employed. Problems of higher speed pose new problems in the field of heat detection. Scanning speeds must be increased so that the distance traversed by the missile during a scanning cycle will remain negligible in comparison with the distance remaining so long as additional corrections are likely to be required. This implies the requirement for developing heat receptors of continuously decreasing thermal time constant. The bolometers of the Felix program were small; heat detectors of supersonic missiles may have to be minuscule.

Sensitivities, particularly differential sensitivities, need to be increased. The relative thermal signal received from targets and from a fairly cold background has been discussed. A better method of evaluating the heat from a specific target is needed. The comparison of the total heat radiated from an area containing the target with a similar area from which the target is absent is like measuring the weight of a truck driver's hat by comparing the weight of the truck with the driver hatless or covered.

While the preceding section indicated that promising heat targets need to be large in area, one possible exception may exist. In the field of antiaircraft guided missiles, particularly in clear weather, the contrast between the heat radiated by a jet-propelled missile and by the empty sky may well be sufficient to produce satisfactory homing control.

In the entire field, however, no item for further study is more important than the exhaustive quantitative survey of all possible targets, including their backgrounds, which it may be desirable to attack with heat-homing missiles.

Chapter 4

ROC AND ITS CONTROLS

4.1 INTRODUCTION

THE DIRIGIBLE HIGH-ANGLE bomb in its direct-sighted version (Chapter 2) and in its heat-homing version (Chapter 3) resulted from a conservative approach to the guided-missile problem, requiring relatively minor new aerodynamic knowledge or art. The glide-bomb program (Chapter 1) was also an extension of more or less conventional methods to a new problem. The Roc program adopted a less inhibited view of the problem. It was hoped that thereby a broader application of the missile to various tactical situations might be attained.

The original concept was of a radar-controlled bomb, the all-weather character of this agency of control being most attractive. Later, difficulties in radar resolution at the selected approach angles forced the decision between revision of the fundamental aerodynamic design and the adoption of a different control means. In this dilemma the Division selected the latter alternative. As the project terminated Roc emerged as a television-guided, radio-controlled bomb.

The program was hampered throughout by difficulties in system coordination. The Division's contractors in the radar and other control fields were located on one side of the continent, while the overall design of the missile was on the other. This separation placed a burden on the program which was carried only at the expense of its retardation. Further, for the first two and a half years of the program all radar development was lodged in a separate division of NDRC (see Section 1.7), which was itself heavily loaded with programs of high priority so that a forthright attack on the radar problems which the Roc program faced was impossible. By the time the Division had established its own radar group under Contract OEMsr-240 (Chapter 1), the promise of success with Pelican and with Bat seemed not to warrant the diversion of effort of its very limited personnel away from the glide-bomb program.

4.2 GENERAL[1]

The aim of the program was to produce a missile whose inherent aerodynamic character provided the necessary properties for pilotless control. Only the minimum of mechanical devices to correct for aerodynamic inadequacy or redundance was permitted. Thus the use of an automatic pilot was not only avoided but shunned.

4.2.1 Roll Stabilization

The experience of model-aircraft builders spoke strongly for the design of a missile inherently stable in roll without assistance of a gyrostabilizer. These experimenters, however, used the axis of gravity as a fixed reference, and, in general, maneuvers of such aircraft were limited to directions not greatly differing from perpendicularity to gravity. True, loops are sometimes executed but at speeds and radii which require the net lift of the wing to be positive or dorsal. With negative or ventrally directed wing lifts, models usually turn over.

The permissible dynamics of guided-missile flight are seriously limited if the control system is constrained to use gravity as a reference to prevent roll. Guiding in vertical dives then becomes impossible. The alternatives are, of course, a gyro system to preserve a fixed frame of reference or else a missile which is indifferent to its roll attitude. The latter attack to the problem was adopted and led to a design symmetrical about any two orthogonal axes normal to the axis of flight. Such a structure can develop a lift in any transverse direction. From the point of view of its ability to maneuver, it is inconsequential what roll attitude obtains at any instant.

4.2.2 Bankless Turn

The banking of a homing missile in order to correct a course error in yaw can create an apparent error in pitch. Further, if there is a combined yaw and pitch error such that the target appears to be in either of the top two quadrants of the field of view (i.e., requiring flattening of the angle of glide) there is a positive feedback which can induce sustained oscillations. Such oscillation was not reported by investigators of the Washington Project. This is not a clear indication, however, that this effect would be negligible with another missile.

The symmetrical structure indicated as a solution for the problem of producing indifference to roll also permits turning without banking. Since lift can be produced in any direction transverse to the line of flight, it follows that moments can be set up and sustained about any axis perpendicular to that of roll.

4.2.3 Zero Angle of Attack

Any aircraft which is to be guided needs a reference against which the course may be checked. In ordinary airplanes, landmarks and an altimeter serve for contact flying; the compass lubber mark and the horizon indicator furnish a first approximation in instrument flying. With automatically controlled, pilotless aircraft, a similar reference is needed—for the controlling bombardier if the missile be teledynamically guided, for his electromechanical counterpart if the missile be fully automatic.

The usual practice would be to apply an automatic pilot to the missile, depending on its gyro mechanism to provide a continuing frame of reference. Such practice violates the basic concept of the Roc program, however, which is to make the missile self-sufficient without resort to such adjuncts. Self-sufficiency in this respect can be achieved by maintaining a reference axis in the missile continuously tangent to the flight path.

Then, if the control is through a radio link with television guiding, the bombardier will be continuously advised, by identifying the center of his received picture, of the true direction of flight. The picture center does not necessarily indicate the point of impact, for in general flight need not be rectilinear. An appropriately systematized control needs to be worked out. This problem is not easily solved (see Section 4.6.2), even with full knowledge of the true direction of flight; without such knowledge it is still more difficult.

If automatic homing is applied, the homing system can similarly measure the departure of the target from the true direction of flight, and an appropriate system of control can be designed to apply appropriate corrections. Roc was designed to fulfill these requirements. In the steady state the requirement was well met, the fuselage maintaining tangency to the wind stream within 0.5 degree. During transients resulting from the application of control there is reason to believe that the departure from tangency was sometimes significantly greater. In homing tests with a photoelectric target seeker (see Section 4.5.2), the missile appeared to fly with negligible angle of attack. In the initial tests with television (see Section 4.7.2), there were transient oscillations in pitch. The television version (Roc 00-1000) was radically different in form from the photoelectrically controlled version (Roc-1). In addition, the regime of control was changed. Whether the departure of the angle of attack from zero during the television tests was due to inadvertent loss of aerodynamic damping or to feedback from the changed system of control remains not fully determined.

In an automatically controlled missile the dynamic or transient conditions are of dominant importance. Methods of estimating the transient response in advance of drop tests are at present incomplete; methods of measuring it during drops have been inconclusive.

4.2.4 Radar Control

The original plan for radar control of Roc was to have the missile so controlled that it would fly down the axis of a microwave beam continuously directed from the carrying aircraft toward the target. The missile would then ride down the beam. This plan is attractive because it places the problem of target selection in the hands of a trained operator in the airplane instead of requiring the development of an elaborate mechanism to make and to maintain that selection. It is fundamentally unattractive because the sensitivity of control—here defined as the derivative of field strength with departure from the axis of the beam—decreases quadratically as the missile falls. Thus the control is least sensitive just before impact when it is of crucial importance.

The objection just cited is outweighed by the advantages of simplicity in the missile-borne microwave equipment, which is expendable in quantity. There is a further disadvantage, however, which is scarcely met by any compensating advantage. Beam-borne bombs describe a trajectory exactly similar to direct-sighted bombs in the eclipse method of control if the beam is continuously trained on the target (see Chapter 2, Figure 2). Indeed eclipse bombing is beam control in the visible electromagnetic spectrum, the beam being light originating in the target and terminating at the aircraft. The same arguments which spoke against its use for the dirigible high-angle bomb speak with nearly equal force here. The only mitigating feature in this instance is the presence of reasonably large supporting surfaces, with corresponding reduction in the minimum attainable radius of trajectory curvature. However, the ability of a radar operator to keep a guiding beam continuously on the target is doubtful. Wavering of the beam when the missile is near the end of its flight would give rise to intolerably large requirements of transverse lift. The decision was made, therefore, to design Roc as a radar-homing missile. The radar was to be of substantially the same type as for RHB-Pelican with illumination provided either from the parent plane or from another in the squadron.

To make the corrections to the flight path nonoscillatory, the rate of change of transverse lift was made proportional to error heading and to its first time derivative.

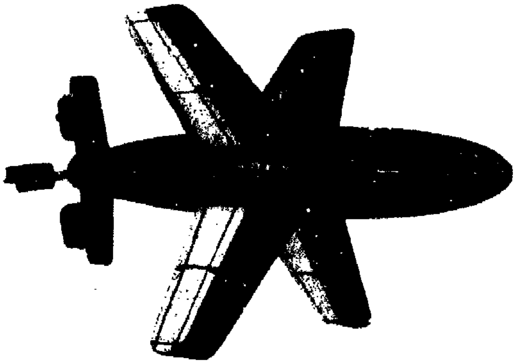


FIGURE 1. Roc-1.

The initial experiments to prove the homing characteristics of the system were made against a strong light source with an improvised photoelectric target seeker. The tests were supposed to be with a full-sized (although not necessarily a fully loaded) missile, which could be the prototype of a combat weapon (Figure 1). However, by the time the tests had been completed, the earlier requirements of the Services for a design utilizing a 14-in. diameter bomb had changed, and the new requirement was for one of 18¾-in. diameter.

In addition, while the experimental program with photoelectric target seekers was proceeding, crucial experiments with radar had shown that reliable homing signals could not be obtained with angles of approach steeper than 50 degrees if the source of radiation illuminated the target at an angle steeper than 11 degrees, both angles being referred to the horizontal.[2] Roc had been designed to fly within a vertical cone having an apex angle of 90 degrees located on the target. The margin between the flattest glide path for Roc (approximately 45 degrees) and the steepest angle for radar homing (50 degrees) left little margin for flexibility, either in design or in use. The requirement of illumination at a flat angle (11 degrees) implied a two-airplane maneuver for attack. The Services found this limitation intolerable.

The requirement of the new payload—the 1,000-lb GP bomb instead of the 14-in. SAP bomb—meant a new design with considerable increase in wing span. Problems of carriage were considerably increased, especially as the Navy insisted that the missile be capable of use with carrier-based aircraft.

4.2.5 Television and Radio Control

Faced with a new design on account of problems of stowage with the 1,000-lb GP payload, the requirement of use with small aircraft, and the approach-angle restriction previously unknown in the use of radar for homing, the Division had three choices: (1) in revising the design to accommodate the 1,000-lb GP bomb in reduced space; aerodynamic changes could be made which would so flatten the trajectory as to make radar homing practicable with

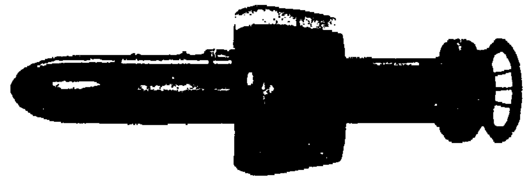


FIGURE 2. Roc 00-1000.

single-airplane tactics; (2) the aerodynamic performance could be left unaltered and a new means of control sought; or (3) the project could be terminated.

While calculations showed that minor revisions of the design would produce an angle of approach flat enough to accommodate radar, this change involved removal of the dive brakes, and it was not known by what extent this would influence the missile in its property of flying continuously tangent to the flight path. The image orthicon had been developed (see Chapter 5), and it appeared likely that a miniature version of small enough compass to fit within Roc could be developed. Accordingly, the contractor accepted the Division's request to continue the project toward television control.

Furthermore, the increased maneuverability of Roc (Figure 2) as compared with Razon—8,000-ft minimum radius of curvature compared with some

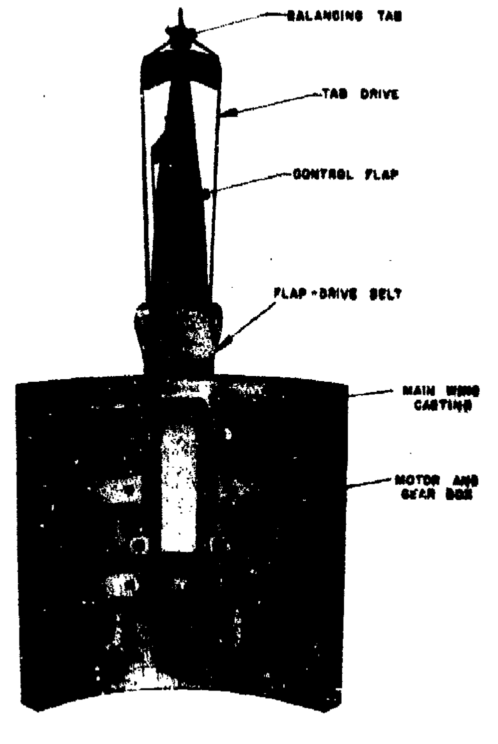


FIGURE 3. Wing assembly for Roc-1 looking radially outwards.

20,000-ft—gave promise of successful application of Roc to the eclipse technique of direct-sight control. This was strongly urged as an interim measure pending the development of Mimo (miniature image orthicon camera and transmitter). Such a program was particularly indicated in view of the fact that while the development of the Crab attachment (see Section 2.6) had been started, its accuracy had not been established. An eclipse technique gives exact accuracy, but it is most difficult to achieve.

As the war closed, tests with television were under way. The direct-sighted version had been abandoned in view of the marked success with Razon when used with Crab and especially with the addition of Jag. Further investigations with Roc and Mimo are to continue under the supervision of the Air Technical Service Command.

4.3 ROC SYSTEM DYNAMICS[3]

The requirement that Roc should be capable of generating lift in any direction and of flying with zero angle of attack led to the embodiment of Figure 1. Cast magnesium wings were constructed with a quadrant yoke at the root such that, when they were bolted together, they formed the central portion of the fuselage. The wing was hollow, providing room

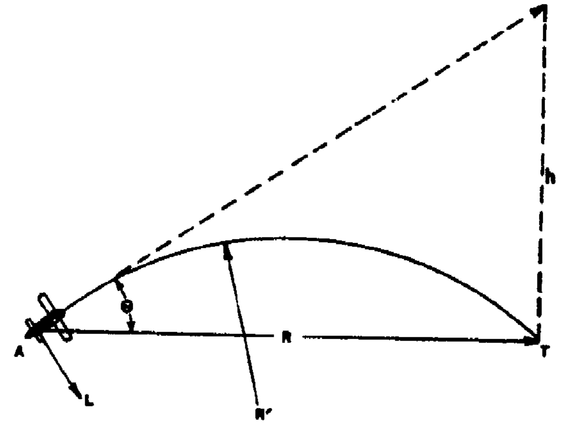


FIGURE 4. Two-dimensional projection of trajectory.

(Figure 3) for a motor and gear box to drive the lift-generating flaps, which extended the full semispan of the wing.

The establishment of a law to govern the control-flap position is the outcome of the solution of the problem of system dynamics. Six degrees of freedom are involved, and the relationships are generally nonlinear. A simplified analysis is, however, rewarding. In his analysis of longitudinal stability of glide bombs (see Section 1.4.1), Skramstad suggested a control regime defined by

$$\delta = k_1\theta + k_2\dot{\theta} \tag{1}$$

This contractor used a method which produced flap operation according to:

$$\dot{\delta} = k_3\theta + k_4\theta \tag{2}$$

There are many control methods possible which will yield the desired result, namely approach toward the target along a pursuit curve without superposed oscillations.

Consider now the two-dimensional simplification of Figure 4. The missile is at A with a velocity V and a course error θ which would result in an expected miss h. A lift L must be generated to reduce h to zero and in a nonoscillatory manner. (Of course it may be impossible to reduce h to zero, a finite lower limit existing for the radius of trajectory curvature R'. That phase of the problem does not concern us here.)

The lift L is balanced by dynamic reactions due to imparting a centripetal acceleration to the missile and an angular acceleration about an axis perpendicular to the flight-path tangent and to the lift L.

$$L = am\dot{\theta} + bI\ddot{\theta} \tag{3}$$

where m is the mass of the missile;
- I is the moment of inertia of the missile;
- a is a constant of proportionality;
- b is an assumed constant relating the restoring moment to the angle of attack.

If

$$am\dot{\theta} \gg bI\ddot{\theta} \tag{4}$$

then the missile can be deemed to behave like a massive particle. Further, if linearity between δ and L is assumed, we can write from equation (1):

$$L = k_1\theta + k_2\dot{\theta} \tag{1'}$$

$$am\dot{\theta} = k_1\theta + k_2\dot{\theta} \tag{5}$$

$$\dot{\theta}(k_2 - am) + k_1\theta = 0 \tag{6}$$

$$\theta = \theta_0 \epsilon^{k_1 t/(k_2 - am)} \tag{7}$$

which is decadent if $k_2 < am$. It satisfies our requirement if θ is small so that

$$\theta = \tan\theta = \frac{h}{R}$$

Similarly with equation (2):

$$\dot{L} = k_3\theta + k_4\dot{\theta} \tag{2'}$$

$$am\ddot{\theta} = k_3\theta + k_4\dot{\theta}$$

$$\ddot{\theta} - \frac{k_4}{am}\dot{\theta} - \frac{k_3}{am}\theta = 0$$

whence

$$\theta_0 = \theta_0 \epsilon^{k_4 t/am} \sin\left(\sqrt{\frac{4k_3}{am} - \frac{k_4^2}{a^2m^2}}\right) t \tag{8}$$

Thus, in the simplified version at least, either flap-control law will yield stable approach to the target with judicious selection of the constants.

In the more complete analysis where angular acceleration in pitch or yaw is not considered negligible, control of the lift by equation (1′) can lead to damped oscillations similar to equation (8). Control of the rate of change of lift in accordance with equation (2′) results in a cubic equation for the roots. The real root can be made degenerative; the other roots are, by proper choice of constants, conjugate and represent a damped oscillation.

The control law of equation (1) thus seems to lead more directly to a stable trajectory than does that of equation (2). However, it also leads to greater driving power for the control flaps. The abrupt appearance of a course error calls for the immediate appearance of lift, with a correspondingly large expenditure of power to overcome the hinge moments at a high rate. Further, while it is impossible to attain instantaneously the flap velocity $\dot{\delta}$ of equation (2) required by the sudden appearance of an error in heading or rate of departure, it is one derivative easier than the instantaneous attainment of a flap angle δ. In summary, it would appear that one system of control leads more readily to the desired flight path but is much more difficult to mechanize. The implication is that time lags will force a greater departure from the idealized program in the case of equation (1) than in the case of equation (2).

One feels that a full exploration should be made of the control possibilities implicit in

$$\sum_{n=-\infty}^{n=\infty} k_n p^n(\delta) = \sum_{m=-\infty}^{m=\infty} k_m p^m(\theta) \tag{9}$$

In equation (9) p is the time derivative operator defined by:

$$p^n = \frac{d^n}{dt^n} \tag{10}$$

Negative values of n and m indicate integrals.[4] The generalized exploration of equation (9) with the quantitative rejection of such terms as are redundant or insignificant might well teach where the best engineering compromise in design of a control system lies. Its generality is extremely suggestive of power in the approach to other missile problems.

It is significant in this connection that in developing controls for the V-2, the Germans[5] used a control regime defined by

$$\omega_0 L + \omega_1 \dot{L} + \omega_2 \ddot{L} = \omega'_{-1}\int E\,dt + \omega_0' E_0 + \omega_1'\dot{E} + \omega_2'\ddot{E} \tag{11}$$

where E is a measurable error function. Moreover, the parameters ω_n and ω_n' were not necessarily constant but were permitted dependence upon error or its correction.

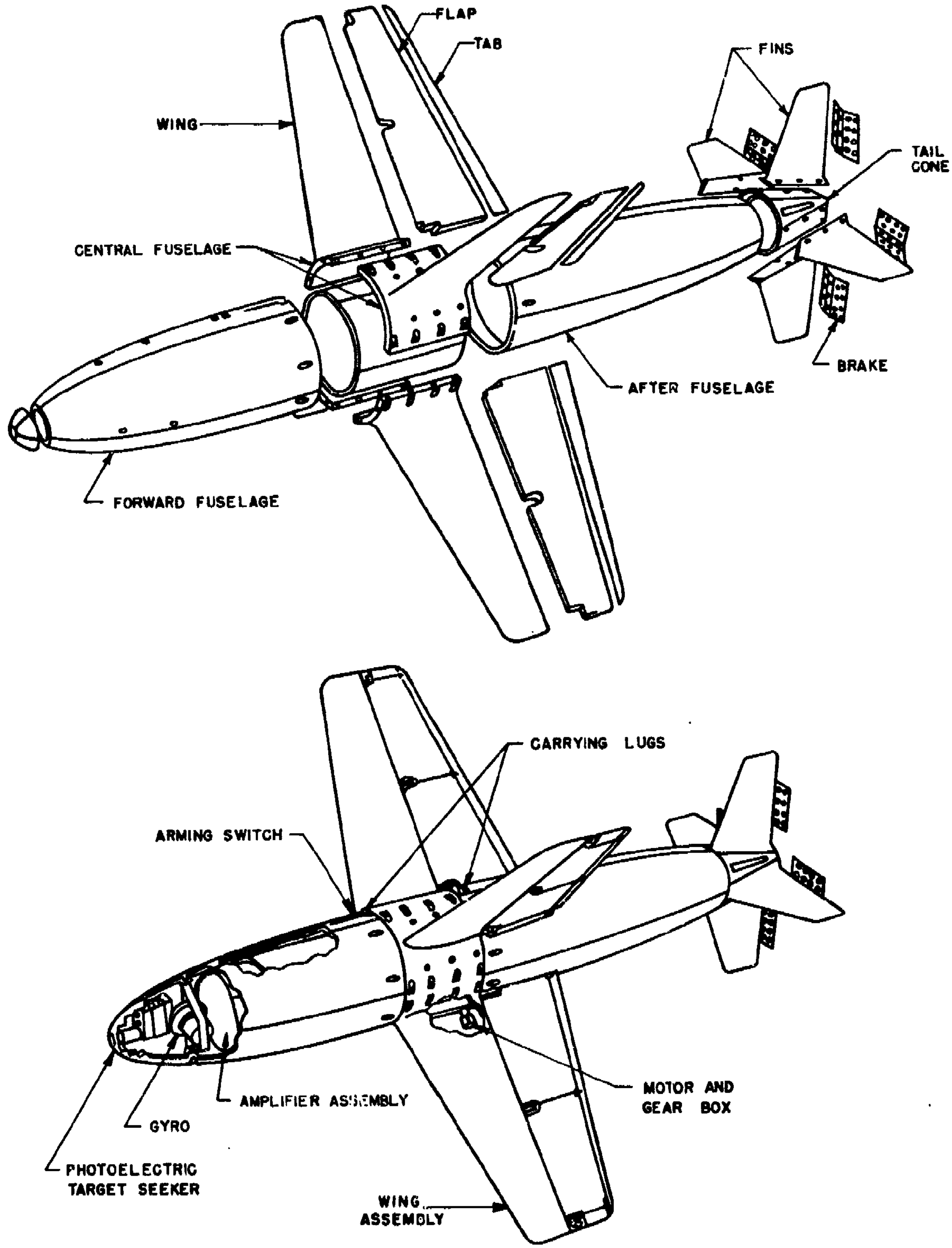


FIGURE 5. Exploded cutaway and views of Roc-1.

4.4 MISSILE DESIGN

4.4.1 Cross-Wing Roc Structure[6]

The final design of the cross-winged version is shown in Figure 5. All fixed members are castings. The wings and central fuselage section are of magnesium; the forebody, afterbody, and empennage are of aluminum or of zinc alloy, depending on the weight of missile desired. In the combat version it was planned that all castings would be magnesium.

The space forward of and surrounding the nose of the payload was planned to house the radar-homing equipment; space abaft the payload was provided for the power supply. In the test birds no payload was used, so that extreme effort to compress the control into minimum compass was not exerted.

The principal dimensions are given in the following tabulation.

Length overall (in.)	95.98
Wing span (in.)	77.0
Effective area of 2 wings (sq ft)	10.95
Weight with payload (lb)	1,300
Wing loading (psf)	119
Test missiles	
Weight without payload (lb)	500–600
Wing loading (psf)	45–55
Flap hinge line (per cent of wing chord)	55
Tab hinge line (per cent of wing chord)	9
Wing system section	
Root	NACA #0011
Tip	NACA #0009
Tail-fin span (in.)	40
Tail-fin area of 2 fins (sq ft)	1.8
Tail-fin section	
Foot	NACA #0009
Tip	NACA #007

The flap is partially balanced, its rounded nose fairing into a recess in the fixed wing placing the hinge line at 55 per cent of the section. The tab at the trailing edge of the flap gives approximately full balance. With the flaps in the neutral position the wing is without camber, and its chord is parallel to the fuselage axis. The tail-fin chord is continuously parallel to the fuselage axis. The empennage is fixed but it is so constructed that the planes of the fins can lie either in or midway between the planes of the wings. The latter configuration gives somewhat better trim stability.

The full-sized missile was tested in the wind tunnel at the Ames Aeronautical Laboratory, Moffett Field, California.[7] This test showed that the missile would fly with substantially zero angle of attack, that a maximum transverse lift of 2,000 lb could be generated in the plane of two wings at 400 mph or of 2,800 lb in a plane midway between two wings. The corresponding minimum radii of curvature with the fully loaded missile are 6,940 ft and 4,950 ft respectively. The brakes hold the terminal velocity to about 500 mph. Rolling torques due to casual screw asymmetries are negligible and are readily killed by differential operation of one pair of flaps.

The flaps are made of molded resin-impregnated Fiberglas in stressed-skin hollow construction. They are hinged on bushed pins at the root and tip. A pin at midspan is supported on open slots to prevent binding due to load deformation of the wing and flap.

The balancing tabs are of molded resin-impregnated veneer. They are supported on knife edges riding in molded saddles, being held in place by the cables that control their angular position with respect to the fixed position of the wing and to the flaps.

The drive for the flap (Figure 6) is an electric motor and gear box, one assembly for each wing. The overall gear and belt reduction, 7,582 to 1, yields a flap speed of 6 degrees per second with a motor speed of 7,582 rpm. The input to the motor is approximately 8 watts, and the overall efficiency of the system is approximately 25 per cent.

The tab is driven through a cable belt. The belt is fastened to a pulley fixed to the wing and concentric with the hinge line of the flap. It is also fastened to a pulley, which is fixed to the tab concentric with its hinge line. Pulley ratios are such that the angular motion of the tab with respect to the wing is 20 per cent of the angular motion of the flap. The angle between the flap and the tab is thus 80 per cent of the wing-flap angle. A slight loss in lift due to the tab is the price for substantial elimination of the hinge moment.

4.4.2 Control System

The basic purpose of the program was to develop a radar-homing missile. In the absence of expendable radar equipment for tests, a photoelectric target seeker was improvised. This target seeker, which is described more fully in Chapter 9, was designed to give an output closely similar to that expected from the radar equipment. For small errors in course, the output of the target seeker is a voltage nearly proportional to error in heading (Figure 7); thereafter it holds nearly constant until the limit of the field of view is approached. For small errors, then, the voltage is proportional to error heading. In order to

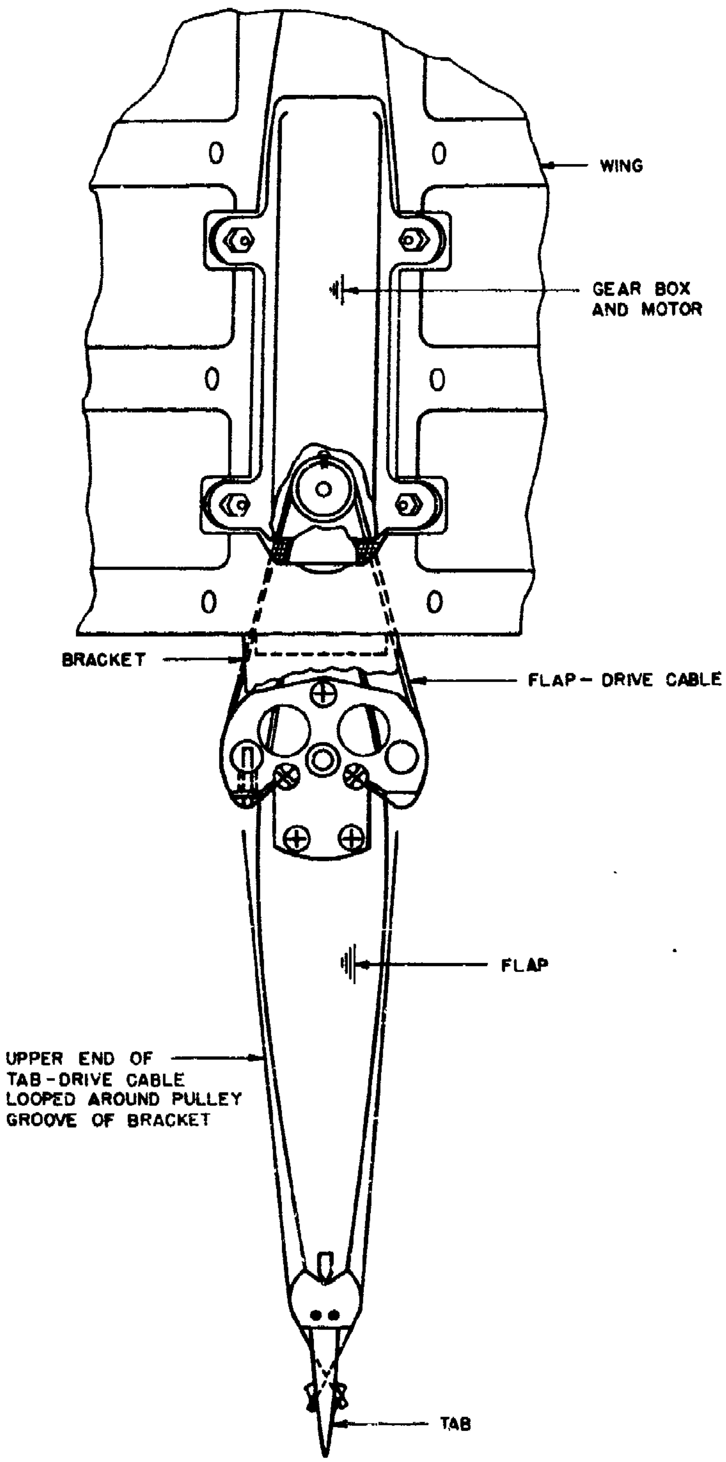


FIGURE 6. Schematic diagram of flap and tab.

apply the control regime selected as a result of the arguments in Section 4.3, this voltage must be made to drive the control flaps at a speed proportional to it and to its first time derivative. Then

$$\dot{\delta} = k_1 e + k_2 \dot{e}$$

since

$$e = c\theta$$

for small values of θ.

Pacific Division of Bendix Aviation Corporation under Contract OEMsr-1002,[8] developed an amplifier to perform these operations. A preamplifier driven by the photoelectric scanner produces a voltage in a two-

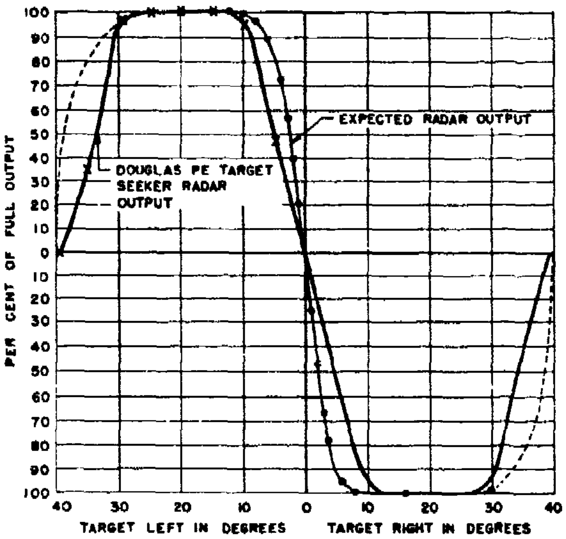


FIGURE 7. Expected output of radar equipments; actual output of Douglas PE target seeker.

channel output such that the voltage level in either channel is zero or

$$0 \leq e_1 = c\theta$$

This voltage is applied to the network of Figure 8. Now if the attenuation of the network is made such that the output e_2 is small compared to the input e_1, then the output of either channel is either zero or

$$0 \leq e_2 = c_1 e_1 + c_2 \dot{e}_1$$

It is not necessary to establish any specific values of c_1 and c_2 since the level of the voltage e_2 can be adjusted in succeeding stages. Their ratio must, however, be established here since it is this ratio that determines the nonoscillating quality desired for Roc's flight. This ratio is determined by R according to the relation

$$R = \frac{8k_1/k_2 - 5.5\sqrt{6.25(k_1/k_2)^2 - 33k_1/k_2 + 30.25}}{2 - 2.1k_1/k_2}$$

In this evaluation k_1 and k_2 are the constants of proportionality in the fundamental Roc control equation. For nonoscillatory approach to the target, the ratio k_1/k_2 should be not greater than 0.2. This requirement results in a value of 0.625 megohm for R in the circuit of Figure 8.

A voltage satisfactorily proportional to error in heading and to its first derivative having been developed, it is necessary to make the flap motors follow this voltage in speed, irrespective of load torque. The output of the differentiator-mixer (approximately 0.3 v maximum) is amplified to about 150 v maximum through two stages of push-pull 6SL7-GT in a Class A circuit. This voltage triggers thyratrons to control the flap motors (Figure 9).

The flap motors are separately excited at 12 v. The armature is especially wound for 100-v d-c average when supplied from a half-wave rectified source. The power supply is a 100-c vibrator and trans-

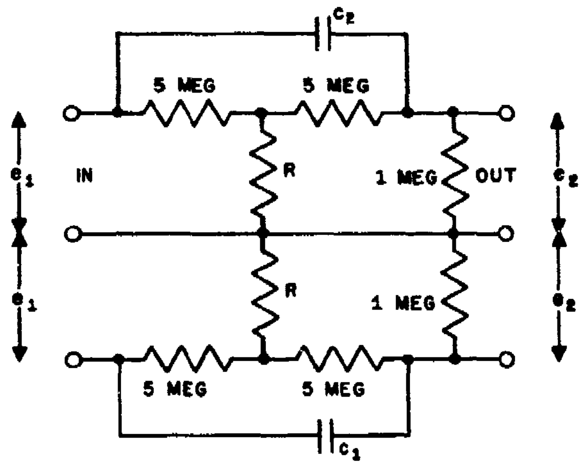


FIGURE 8. Differentiating-mixer network.

former. During the conducting half-cycle, the thyratron will fire if the grid is at a sufficient potential to trigger it. The bias at the instant of firing is determined by the grid voltage supplied by the d-c amplifier and the cathode voltage. Since at this instant no current is flowing, the cathode voltage is equal to the voltage generated by the motor armature and (the motor being separately excited) exactly proportional to its speed. Thus for any grid voltage there is a motor speed which will just prevent firing of the thyratron. At any load torque a sufficient percentage of the half-cycles will pass current to develop the torque at the speed demanded by the grid voltage (Figure 10). Thus the extremely flat speed-load characteristic is achieved. It should be noted that this application imposes a severe duty on the motor. The entire armature circuit floats at an average voltage determined by leakage resistances; it is subject to violent surges when the tubes fire or cut off. It was necessary to insert a 0.001-μf capacitor between the thyratron grid and cathode to prevent surges from becoming regenerative.

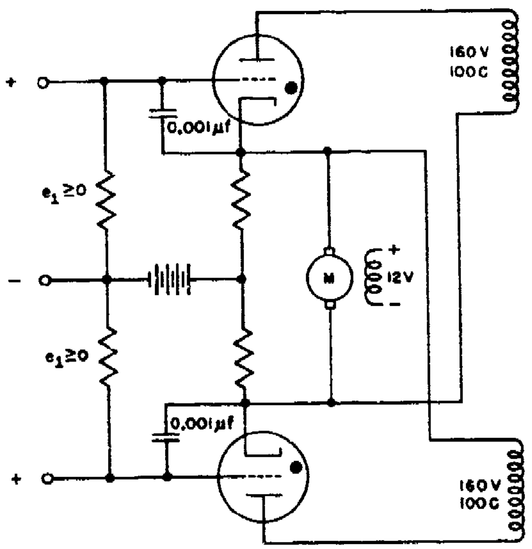


FIGURE 9. Thyratron motor-control circuit developed by Radiation Laboratory, MIT.

One pair of wings is electrically locked in step. This is accomplished by feeding into the d-c amplifier controlling each flap motor a voltage proportional to the difference between its travel and that of its mate. Thus, if one flap gets ahead of the other, its speed is immediately reduced while that of its partner is increased. This circuit maintains identity of the flap displacement within 1 degree—approximately 4.3 per cent of full travel.

The other pair of flaps are purposely allowed to operate separately. A gyro sensitive to rate of roll biases their speed of operation differentially, introducing a differential flap speed of 0.4 degree per second if the rate of roll of the missile is between 0.833 rpm and 2.5 rpm, and a differential speed of 1.6 degree per second if the rate is in excess of 2.5 rpm. Figure 11 shows the electronic control as used for the photoelectric target seeker and as planned for use with radar.

4.5 TESTS WITH PHOTOELECTRIC HOMING

4.5.1 Preliminary Tests

As a proof of the nonoscillatory character of the control regime, a scanning head and the associated electronic apparatus were mounted on a truck and made to home on a strong light. The driving was done on a dry lake, and the driver turned the wheel in such a manner as to match the motions of a flap position indicator controlled by the scanner and amplifier. A control factor for the truck can be defined as the product of the wheel displacement and the corresponding turning radius. For a given air density a

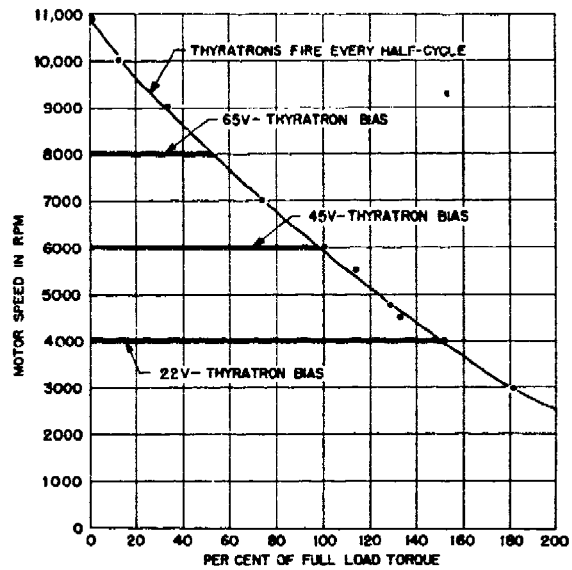


FIGURE 10. Motor speed versus load torques and bias.

similar product of flap angle and turning radius is descriptive of Roc. The ratio of these products is the scale factor by which the driver should relate steering-wheel motion to flap-indicator motion.

This relationship was approximately adhered to. In eight tests the truck homed on the light along a nonoscillatory path. In other tests the differentiator was cut out so that the steering-wheel speed was made proportional to error-heading only. In these tests the course was oscillatory and soon got out of control.

Prior to making drop tests, all apparatus was subjected to altitude and temperature tests. In addition, a test was devised to give a quantitative evaluation of the control system. A small light was mounted on a wheel located in front of the missile and rotating about an extension of its roll axis. Thus, with constant wheel speed the motion in the yaw and pitch senses was simple harmonic, with all its derivatives well known. With small angles of parallax subtended by the wheel diameter, the response of the flaps could be quantitatively checked; for larger excursions of the light, a more involved analysis was required.

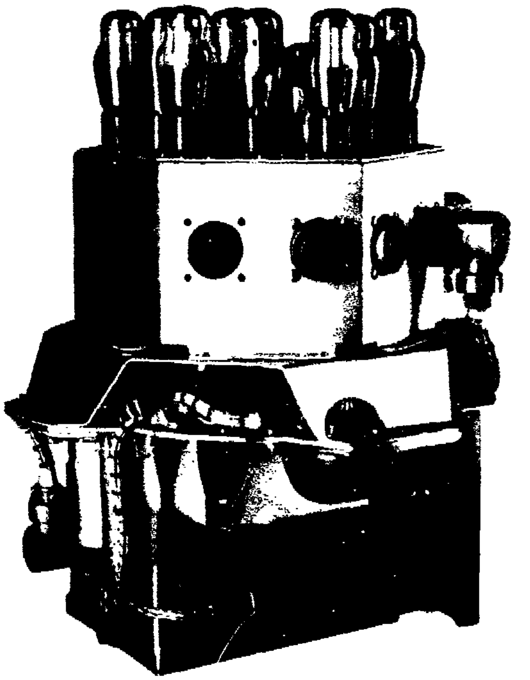


FIGURE 11. Bendix motor-control amplifier.

4.5.2 Drop Tests[9,10]

In spite of the careful preliminary testing, five of the nine missiles dropped failed for various reasons. Drops No. 2, 3, 4, and 5 were successful, the first having failed through malfunction of the arming switch. This uniformity gave rise to an optimism which was perhaps unfounded. The program was then plagued by a variety of minor but frustrating difficulties, and the next four drops failed. This reversal gave rise to a pessimism which was equally false.

The tests were carried out at the rocket range of California Institute of Technology on Goldstone Lake near Barstow, California. The target consisted of an array of 100 battery-powered photoflood lamps supplemented by pyrotechnic flares. The light intensity at the release point, 10,000 ft above the target and average 25-degree lead angle, was approximately 10^{-2} footcandle. The flux entering the scanning eye as the target entered the field of view was estimated at 300 microlumens, approximately 10 times the threshold for operation of the target seeker.

The drops were fully instrumented (see Chapter 8). Misses of 260, 96, 68, and 30 ft were scored. Figures 12 and 13 present the frontal and profile traces of the trajectory of a typical drop as recorded by cameras with open shutters set up approximately

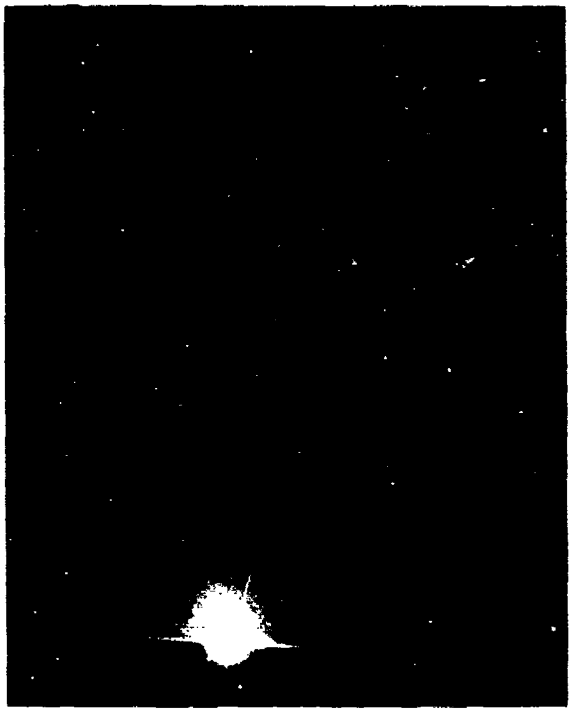


FIGURE 12. Frontal trace of PE homing drop No. 4.

4,000 ft from the target in the plane of approach and 2,000 ft on the flank. A more precise determination of the trajectories was made from the analysis of two phototheodolite records taken from the ends of a carefully surveyed base line. Figure 14 is a reconstruction of the plan and side elevation of the trajectory shown in the preceding photographs.

The trajectory shown in the photographs of Figures 12 and 13 and in the plots of Figure 14 shed interesting light on the dynamics of Roc control. For small errors of heading, the target seeker gives a proportional output. In the azimuthal sense the error in heading was small, and the control response was quantitatively sensitive to it and to its first time derivative. The frontal trace (see Figure 12) of the trajectory reflects this condition, which resulted in non-oscillatory homing.

In the range sense, however, the error is not always small. It starts, of course, at the complement of the lead angle to the target, corrected for the attitude of the airplane at the instant of release. For this drop the lead angle was 19 degrees; the correction for attitude of the airplane was negligible. The initial range error in heading was thus 71 degrees, which lies beyond the field of view of the target seeker. As the

FIGURE 13. Profile trace of PE homing drop No. 4.

target enters the field of view at a range error in heading of about 33 degrees (see Figure 6), the output is in the correct sense but its slope is wrong, producing an increasing signal for a decreasing angle. This results in negative damping until constant output is reached at approximately 21 degrees error. The damping disappears with constant output and only appears in the correct sense after the error has been reduced to 10 degrees. The profile trace (Figure 13) and the side elevation plot of the trajectory (Figure 14) show the resulting overshoot in the initial portion of the flight caused by negative damping during the early phases of the oscillation. The remaining portion of the trajectory after the first swing was well damped.

The experiments were further instrumented by motion-picture cameras mounted on the empennage and pointed forward to record the view "seen" by the scanner. Tangents drawn to the trajectory pro-

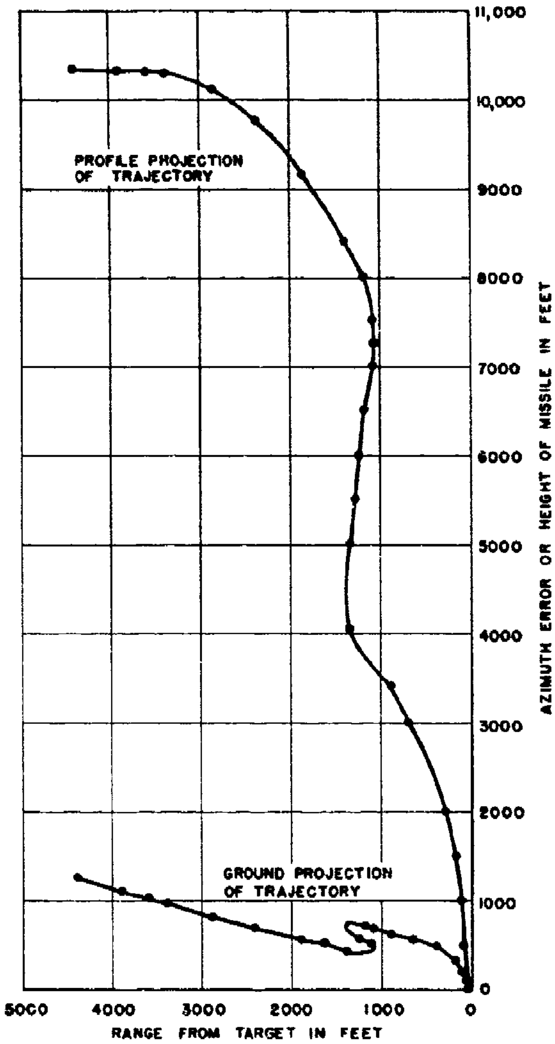


FIGURE 14. Plots of PE homing drop No. 4 from phototheodolite records.

jections derived from the phototheodolite records disclose the instantaneous direction of the missile's flight. The center of the corresponding motion-picture frame shows the spot on the terrain toward which the missile was pointing. A comparison of these data showed that Roc-1 flies with small angle of attack.

This conclusion can hardly be said to be more than qualitatively established. Some of the motion-picture film was lost at impact. In some of the drops one or both of the phototheodolite operators were unable to track the missile. Finally the graphical differentiation of an empirical curve to establish the direction of its tangent is inherently not very accurate.

In addition to the series of nine tests just described, three drops were made of Roc missiles equipped with a photoelectric target seeker developed under Contract OEMsr-1182 by Fairchild Camera and Instrument Company.[11] These drops, marred by flare and gyroscope failures, were inconclusive. The target seeker is described in Chapter 9.

The problem of coordinating the activities of an aircraft crew, two phototheodolite stations, the target operation, several camera stations, and the usual observers from the Division and from the military is not to be underestimated. This experience of the Division's contractor reinforces the conclusion drawn from each of the other programs. An adequate experimental range equipped with good communication, adequate transport, and facilities for the routine collection of formal quantitative records is essential if success in this field is to be quickly attained.

4.6 DESIGN OF ROC 00-1000[12,13]

4.6.1 Structural Design

The tests described in the preceding section demonstrated with some authority that the Roc conception resulted in a system of missile and control which would produce satisfactory homing flight. However, the wing span (77 in.) precludes carriage within the bomb bay; with external carriage there is inadequate clearance on carrier-based aircraft; and finally, the original payload contemplated (the 14-in., 1,100-lb SAP bomb) was considered an undesirable weapon for the bulk of the remaining targets to be attacked. Accordingly, the Division requested the contractor to undertake the development of a missile for carrier-based aircraft. The payload was to be the 1,000-lb GP bomb, and the method of carriage was to permit landing with the missile unexpended on the deck of an aircraft carrier in the event of an abortive mission.

The resulting design eliminated the cruciform wings with adjustable camber and the cruciform empennage. In the new design a cylindrical shroud replaces each (Figure 15). The wing shroud is Cardan-mounted so that it can be rocked to produce lift in any direction normal to the roll axis. The stabilizer cylinder is fixed. Within the stabilizer ring two ailerons were planned to limit the rate of roll; in the final version, however, four ailerons were provided, so controlled as to eliminate roll.

The principal dimensions and the performance constants as determined from wind-tunnel tests[14] are compared with those of the cruciform Roc-1 in the following table.

	Roc-1 Combat Version	Roc 00-1000
Weight complete (lb)	1,300	1,662
Payload (lb)	1,100	1,000
Turning radius (ft)	6,950	7,500
Wing span (in.)	77	48
Wing area (sq ft)	10.95	8.86
Wing loading (psf)	119	188
Length overall (in.)	96	148
Terminal velocity (mph)	450	400
Mean wing chord (in.)	20	30
Tail span (in.)	40	30.6
Mean empennage chord (in.)	8.3	5.3
Ailerons	None	4
Time to apply full control from neutral (seconds)	2.5	1.6
Max. hinge moment main control surfaces (lb-in.)	*	2,170
Wing airfoil section	NACA #0011-Root NACA #0009-Tip	Douglas N_8
Stabilizer airfoil section	NACA #0009-Root NACA #0007-Tip	Douglas 81080-18
Aileron airfoil section	None	Douglas 81080-18

*Balanced by tab.

With the exception of a false nose, the entire construction is of aluminum-alloy sheet, with the bomb itself forming the central portion of the fuselage. A plastic nose section, fastened to the bomb through the nose-fuze threads, houses the television camera. Abaft the bomb a fuselage structure carries the remaining electronic equipment, the power supply, one wing actuator, and the gyro-aileron system.

The wing is of monospar construction with the major portion of the training section permanently attached to the spar. Removal of the nose section and a generous panel of the trailing section yields access to wiring, strut bearing, and the second wing actuators.

The wing is carried by a strut (Figure 16) which is hinged in the fuselage to rock the wing in yaw. A bearing support between the wing and the strut provides freedom for rotation of the wing in pitch. Thus lift and drag are carried by the strut in bending; hinge moments in pitch are carried axially and hinge moments in yaw are carried in bending. The strut is

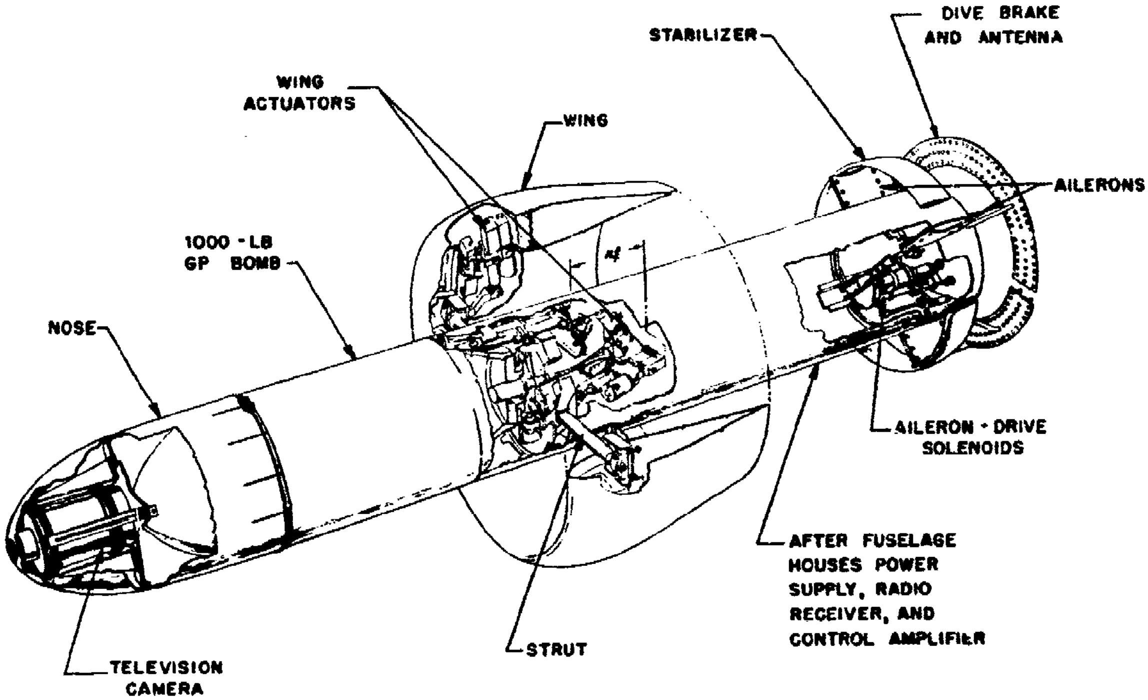


FIGURE 15. Cutaway view of Roc 00-1000.

fabricated of X4130 steel, heat-treated to 125,000–145,000 psi to withstand the foregoing design loads, calculated at 91,200 psi at the critical section.

In the cruciform version (Roc-1) hinge moments of the control flaps are nearly eliminated by balancing tabs. With a movable cylindrical wing this technique is not applicable.

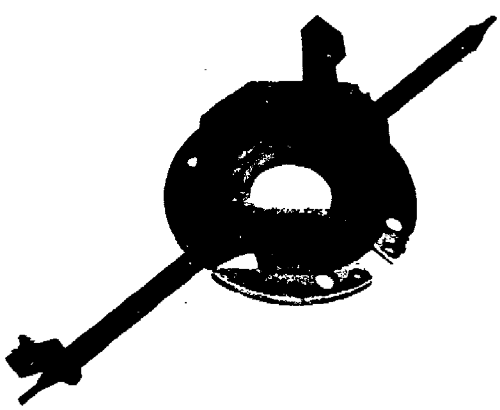


FIGURE 16. Wing strut, Roc 00-1000.

The study to determine the basis of the control system was not complete as soon as the missile design was ready for its findings. There is some argument, in the case of television, for using a quasi-homing control in which the controlling bombardier tracks the received image of the target and in so doing automatically transmits a signal to the missile proportional to the error in heading and to its first time derivative. The possibility that a control system based on the angular velocity of wing incidence, $\dot{\delta}$, might be required, rather than a system based on δ, spoke strongly for using the same electronic computer developed for Roc-1.

The large hinge moments and the use of a single wing, however, imply a much heavier load on the control motor than is the case in Roc-1, the entire power supply for which is passed through a single thyratron rectifier. It became necessary, therefore, to exert extraordinary effort toward high efficiency in the wing actuators. A ball-bearing, thread-nut drive was developed by Western Gear Works having a mechanical efficiency of approximately 80 per cent and an overall efficiency including the motor of about 40 per cent.

The decision of the Division to attempt direct-sight control as an interim means of control, pending the development of a suitable television or automatic homing equipment, made it necessary to develop absolute roll stabilization. This the contractor agreed to undertake although the extrapolation of the experience with Azon to Roc seemed hazardous in view of the greatly increased maneuvers to be required. The same gyroscope assembly developed for Azon and Razon was applied to the aileron control. Aircraft practice suggested a modulating control for the ailerons such that small excursions from a mean position would provide transient roll stability. With the on-off contact arrangement provided from the free gyro, such a control with motor-driven actuators proved wholly successful. A solenoid drive capable of following gyro oscillations up to 5 c was used.

4.6.2 Control System

Control with direct sight or television implies a radio-control link. At the outset of this phase of the program it was not clear what mode of control would be most appropriate. For television, as just explained, the contractor favored the same regime used for automatic homings,

$$\dot{\delta} = k_1\theta + k_2\dot{\theta}$$

the bombardier keeping a reticle superposed on the televised image of the target. The Division felt that arguments such as temporary blocking of the radio signal spoke strongly in favor of a regime expressed by:

$$\delta = k_1\theta + k_2\dot{\theta}$$

Moreover, in view of the success with Azon, which used on-off control, there was strong compulsion to experiment with that system for Roc.

The Division worked closely with Section 7.2 (Airborne Fire Control), which recommended a computer which would steer the missile along a nearly straight interception course rather than along a pursuit curve. Simulative studies[15] with Division 7's contractor at Columbia University disclosed that for the direct-sighted version a link which provided wing deflection proportional to control-stick motion is adequate. For the television version, Douglas constructed a model range with a test cart carrying television and a radio receiver. This model reproduced the missile flight in two coordinates and time. Many modes of control were explored.[16] With the aid of this range and the cooperation of Section 7.2, a computer was developed which resulted in an approximation of a collision course.

The computer projects on the television screen a reticle which moves across the screen at a speed proportional to the wing-incidence angle δ and to the actual reticle position. The actual equation of motion of the reticle is:

$$\dot{\lambda} = \frac{K}{2}\rho\delta + \frac{g}{v}\left(\lambda_0 - \lambda + \frac{\gamma_0}{2}\right)$$

Where λ = reticle position in degrees with respect to the center of the television field of view,

λ_0 = target and reticle position at the time computer is started,

γ_0 = angle in degrees between gravity vector and trajectory of missile at the time the computer is started,

K = $(S/2m)(dC_L/d\delta)$, the aerodynamic response coefficient of the Roc missile,

ρ = the average air density during the effective phase of guided drop,

v = average value of the missile velocity,

g = acceleration of gravity.

In a normal television drop the target appears at the bottom of the screen and moves upwards across it as the missile noses over. The reticle is located near the bottom of the screen. As the target image crosses the reticle, the computer is turned on, which starts the reticle moving up screen in accordance with the above equation. The operator then so manipulates the control stick as to keep the target on the reticle. When the appropriate lead angle is established, the motion of both target and reticle stops.

Various control regimes will satisfy the computer equation. It is necessary only that the control stick feed into the computer a value proportional to the wing incidence attained. With the aid of this computer, runs on the model range showed a tenfold improvement in accuracy (12 ft average miss as compared with 120 ft) over unaided guiding with television alone.

As the project closed, it appeared that the computer renders equally accurate an on-off system of control in which the wing-incidence angle is proportional to the net total time of control, right-and-left control time being taken in opposite sense. This system is much the simplest of those that have any hope of success. It was not tried in drops made under Division sponsorship, although five missiles have been built for this control regime.

It is obvious from the foregoing that it was not until the project terminated that the optimum mode of control which determined the control-link design was established. It appeared obvious that a quantitative radio link would be required, delivering a signal proportional to control-stick deflection. The decision as to whether the wing-incidence angle should be made proportional to the received signal, to the control signal, and to its time derivative, or whether the angular velocity of wing incidence should be controlled, had to be held in abeyance.

The decision having been made to use the same standard transmitter that controlled Azon and Razon, Bendix developed a proportional control link based on it. Two versions appeared. In the first, the carrier which operated in the 100-mc band was continuously modulated by four audio tones. The difference between the degree of modulation of tones 1 and 2 gave the amount of "right" control – "left" if tone 2 was greater than tone 1; similarly the difference between tones 3 and 4 gave quantitative control in range. The signals were received, demodulated, recti-

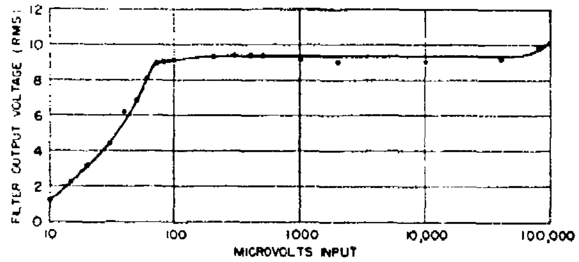


FIGURE 17. Radio receiver AGC characteristics.

fied, and selectively subtracted. If the angular velocity of the wing in yaw or pitch was to be controlled, the difference between the appropriate d-c voltages would be applied to the differentiating and control amplifier exactly as in the case of the photoelectric homing control (see Section 4.4.2). If the angle of wing incidence was to be controlled, a feedback voltage from a potentiometer mounted on wing actuators was applied to the d-c amplifier stage ahead of the thyratron motor control.

The audio tones were 300, 475, 755, and 1,195 c. With all tones on, as in the differential method just described, beat notes are produced between the modulating tones and between their beats. The beat between tone 2 and tone 3, for example, is 280 c, which beats with tone 1 at 20 c. Thus there was a tendency for the wing to hunt at low frequencies.

The extraordinarily flat AGC characteristic (Figure 17) of the MIT-Harvey receiver permitted the use of a simpler system in the second version. Again four tones were applied but never more than two simultaneously. The missile responded to the percentage modulation of each tone – one each for up, down, right, or left. The tones in the up-down regime were selected so as not to produce objectionable beats with those in the left-right regime. Since only two tones were on simultaneously, only one first-order beat could be produced.

The experimental program with the model range described at the beginning of this section showed that, provided a computer was used, simple on-off control of the wing-incidence angle produced accuracy equal to any other mode tried. The final version of the control system, therefore, abandoned the thyratron motor control, replacing it with heavy-duty relays, themselves controlled by the thyratrons.

4.7 TESTS OF ROC 00-1000

4.7.1 Visual Guiding[17]

Some twenty missiles were expended in an attempt to attain high-accuracy direct-sight control. Even with the high degree of maneuverability in Roc as compared with Razon, there can be little hope of successful precision bombardment by this means. The intervention of a computing sight is required, and the parameters of its computation, involving not only the position and velocity of the aircraft with respect to the target at the instant of release but also their whole regime until the instant of impact, are complicated.

The success attained with Razon through applying rigid limitations on the path of the aircraft after release made continuance of the visually guided Roc program unprofitable.

The extension of the bombing run over the target speaks strongly, especially to crews of bombardment aircraft, against the use of Razon or of Roc with the proposed visual guiding. Crab produced a good first approximation to the problem of parallax. It seems clear that a more searching study of the bombsight might yield a solution to the problem of evasive action. Such a program, unprofitable under pressure of war, might well be indicated in peacetime.

4.7.2 Television Guiding[18]

Ten missiles equipped with television were dropped before the termination of hostilities closed the experimental portion of the activities of NDRC. None

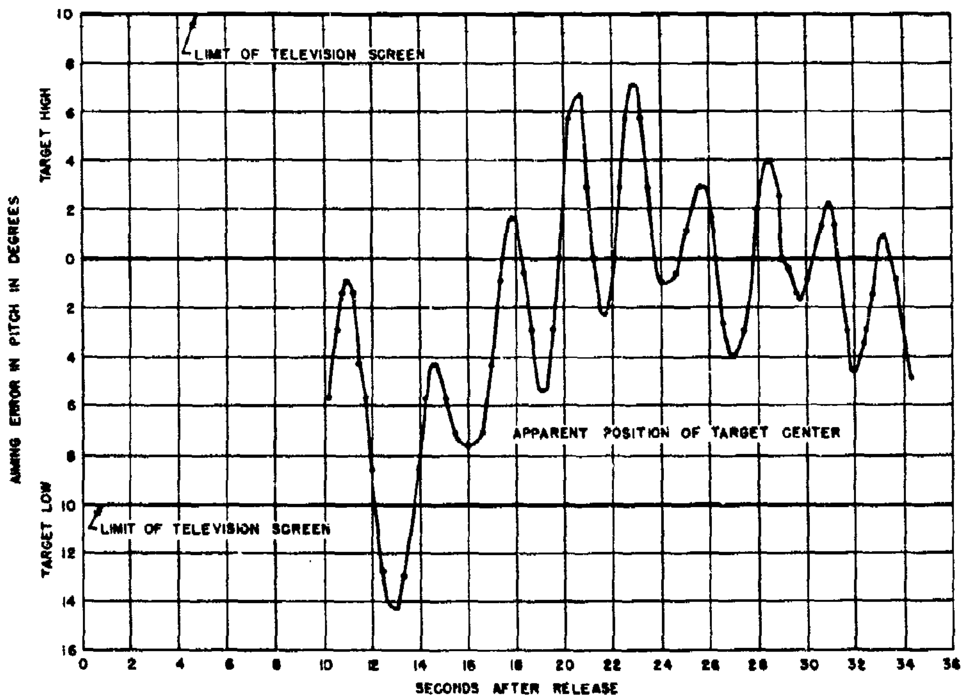


FIGURE 18. Pitch oscillations in drop T-2, pistol-grip aiming.

of these was controlled by the computer regime discussed in Section 4.6.2. In four of the drops the television picture was adequate for guidance. In one of the remaining six the failure of the television was probably due to faulty tuning and is, therefore, hardly to be charged against the television equipment.

In the drops where the television operated satisfactorily, the misses were 69, 266, 119, and 133 ft. In the best of these drops, an aiming device was used consisting of a gimbal-mounted pistol grip. A mirror driven by this grip projected a luminous circle approximately ½ in. in diameter on the television screen. The controlling bombardier encircled the image of the target with this ring. Potentiometers on the pistol grip controlled the radio transmitter. The differentiation in the missile was eliminated, so that the wing followed the control law

$$\delta = k\lambda$$

where λ is the pistol-grip displacement.

The others were dropped without the aid of any computer. The second and third missiles, with impact errors of 266 and 119 ft respectively, were controlled from the airplane with a conventional control stick. The fourth was controlled by two men from the ground, using knob potentiometers.

These scores can doubtless be improved with practice, and plans are established to continue the program in the Air Technical Service Command. The problem of guiding a television bomb, is, however, quite complex. Even with a stationary target and an approach angle near the vertical to eliminate foreshortening, skill is required comparable with that required for precise dead-stick landings through unknown wind strata.

There can be no doubt that the ability of the missile to fly with the television axis tangent to the flight path is vital. Figure 18 shows the apparent oscillations in pitch of the target in one of the tests. These oscillations extend over about 7 degrees of the field of view (20 degrees total) and are typical of most of the drops. Without a reconstruction of the trajectory it is impossible to be certain whether these oscillations of the target image represent hunting of the center of gravity of the missile. Their amplitude and frequency, however, would indicate a curvature in the trajectory hardly to be attained by Roc. It is much more likely that they reflect the failure of the missile to fly with zero angle of attack under transient conditions.

Chapter 1 describes similar difficulties which were encountered in the glide bombs of the Washington

Project. The problem was solved there by adding small correcting elevators, solenoid-operated by a rate-of-pitch gyro. Such a corrective device is probably applicable to Roc. The hasty application of this palliative, however, is obviously not to be recommended in time of peace. Rather, what is needed is a searching examination of the transient behavior of the whole servo-loop system. Techniques are available for such study of all components except the airframe. The extrapolation of steady-state data from the wind tunnel to the transient phase seems to have proved unsound.

Although this project was incomplete at the end of the Division's developmental activities, it has brought out the importance of the basic principles which were postulated for it at the outset. It has also shown their difficulty of attainment and has discovered a need for new aerodynamic study to fill a deficiency in knowledge in this field. As the speeds of missiles are extended through and beyond the sonic range, this exploration of the transient phase of their performance is likely to become increasingly important. A prompt and careful attack on this problem cannot be urged too strongly.

PART II
COMPONENTS AND ACCESSORY ACTIVITIES

Chapter 5

TELEVISION

5.1 INTRODUCTION

The same urge that prompted the Japanese to inaugurate their program of suicide missiles prompted effort in the United States to undertake the development of guided missiles equipped with television. Under the Japanese type of thought, it appeared simple and appropriate to provide a missile with a trained pilot and to expend him against a major target. Under American thinking it appeared that the same objective could be obtained by removing the pilot to a relatively safe location providing him in the missile with television to see the terrain under attack and with a radio link to execute his commands.

Under each culture it was realized that such missiles are expensive, but as the Japanese were prepared to expend trained personnel against major targets, so it seemed appropriate for our Services to expend major logistic effort against targets of crucial importance. The solution of the problem was less simple than either nation realized. The efforts of the suicide pilots were not uniformly crowned with success, and for exactly similar reasons (see Chapter 4) efforts at remote control of missiles with the aid of television had not been successful as the war closed. The problem of flying a missile by remote control is not easily solved.

An attack with such a missile can logically be divided into three phases.

There is a phase of navigation during which the missile must be directed to the general vicinity of the target. If the missile is of long range, an assault drone, for example, then the information conveyed to the directing pilot by means of the television link must be adequate to give him the same degree of recognition of the terrain which is required in contact flying. Such information is not always available, even with direct vision. The added restriction due to loss of resolution and contrast in television, together with its limited field of view, further increases the problem. Probably television is inadequate for this phase of the attack, and other methods, such as maintaining visual contact between the drone and its shepherd or tracking by radar, would have to be used.

The second phase of the attack begins when the missile is in the general vicinity of the target, which has to be distinguished from its surroundings. This phase of the attack presents a problem with missiles of moderate range (such as glide bombs), as well as with long-range missiles (such as an assault drone). During this phase there must be no compromise with picture quality. The target must be recognized early; otherwise, course errors may develop which will be so great by the time positive identification takes place that subsequent correction of them is impossible.

In the third and final phase of the attack the purpose of the television is to give the controlling pilot continuous knowledge of the course of the missile and the error which is likely to take place, so that he can continuously correct the error by the application of appropriate controls. This phase of the attack presents a problem in a missile such as Roc (see Chapter 4). Navigation to the vicinity of the target is made by the bombardier before release. For an attack of this nature, demands on television are at a minimum; the bombardier having identified the target, he is much more likely to recognize it when it appears on the screen than in the case when its appearance on the screen represents his first view of it. Thereafter, his problem is simply to see that the target is properly positioned on the screen to insure an accurate hit. The problem of properly positioning the image of the target proves to be a difficult one. Even with missiles such as Roc, which fly with zero angle of attack, an attempt to keep the target centered on the receiver screen leads to failure; some type of lead computer is required. For missiles with an angle of attack which varies with the amount of course correction required, the problem is even more difficult.

The Division concentrated its efforts in the field of television-guided missiles on the high-angle dirigible bomb and on Roc, after early experiments with Robin indicated but little promise of successful use of a television-guided bomb during phase 2 (see above) of an attack.

In addition to developing television for its own missiles, the Division cooperated with the AAF in the application of television to their glide bomb GB-4[1] and with both the Army and Navy in the application of television to other military uses. Because these activities were not a primary divisional responsibility, they are not reported here.

5.2 GENERAL CONCLUSIONS

The experiments indicated that television was generally practicable for use as a guiding agency for a wide variety of vehicles, within limitations which are discussed in this chapter.

The general reliability of the television system for all conditions under which it is to be used is imperative. The great complexity of television apparatus and the compactness necessary for military applications make this requirement difficult to meet, but the indications were that after enough effort had been put on a given television system it could be made reasonably reliable in production models. This effort had to be exerted again for each new system developed.

It was found essential to the successful use of television on guided missiles that the role which it is to play be carefully considered in planning the operational tactics with the missile. In particular, it is easy to underestimate the picture quality which is needed to carry out a given steering operation, especially in the early stages of the maneuver. Furthermore, television viewing is extremely susceptible to weather conditions.

General navigation with television was not found to be feasible. The field of view is too narrow, and a good quality picture (even with a high-grade system) is not enough to permit general recognition of terrain over a wide area. An ability to move the camera about under control of the operator was found helpful in some applications. The extent to which limited navigation is practicable was, however, not studied extensively by the Division.

There is a second stage in the maneuver during which it is necessary to find the previously unseen target. It is to aid guiding at this stage that the best quality of picture consistent with the other requirements of the television system is needed. The better the picture, the less conspicuous a target and surrounding terrain it will be possible to identify. Even conspicuous targets and terrain are not too easy to recognize at this stage with television equipment of weight and compass permitting its carriage in a guided missile.

The third stage consists in guiding the missile to the target. Here the requirement on quality is not particularly severe, and the principal requirement is adequate functioning of the system.

It was found that after a good television picture is obtained it is still necessary to study carefully how to steer the missile by it. This difficulty is usually underestimated. Airborne missiles are in general not so easy to guide as automobiles for example.

For accurate steering it is necessary that the picture should show either the instantaneous heading or the ultimate destination of the vehicle on the terrain with no further steering changes. The best method for insuring this characteristic appeared to be to incorporate it in the design of the vehicle, i.e., to make the missile axis continuously tangent to the line of flight. Of the other methods studied, it could only be said that it is not enough to compensate for yaw without taking account of large transient oscillations in the yaw when the bomb is undergoing steering changes.

Indications were that severe wind would influence marksmanship, and that automatic computation for this and target motion would probably be desirable. Only a beginning was made in the study of a computer to correct for these factors.

Skill and practice in the art of guiding from the television picture appeared to be necessary, in the stages of development of the apparatus used, to secure accurate hits. A trainer was developed (see Chapters 4 and 10) to assist in this. The radio link which carries the television must be carefully designed, with the following considerations in mind:

1. It is easier to build equipment for the longer wavelengths, but these give more trouble with antenna directivity. Enough work was done with systems of 1,000 to 2,000 mc to indicate that these are generally practical, but more work is necessary to obtain a wholly adequate link from them.

2. The power output of the system must be large enough to obtain good signals at the receiver. The problem of jamming was not considered extensively, but some immunity to it was developed in the course of the work.

3. The directivity of the antennas (transmitting antenna on the missile and receiving antenna at the control point) must be broad enough to permit maneuvering both of the vehicle and of the control point (when on a plane) to permit continuous transmission without loss of signal in extreme angular positions. The directivity must, however, be narrow enough to eliminate paths involving ground reflection. In particular, in a fast-moving, medium- or high-angle missile the forward radiation must be kept down to a very low figure. A sufficiently low forward radiation was not obtained in the work of the Division with high-angle dirigible bombs and with Roc.

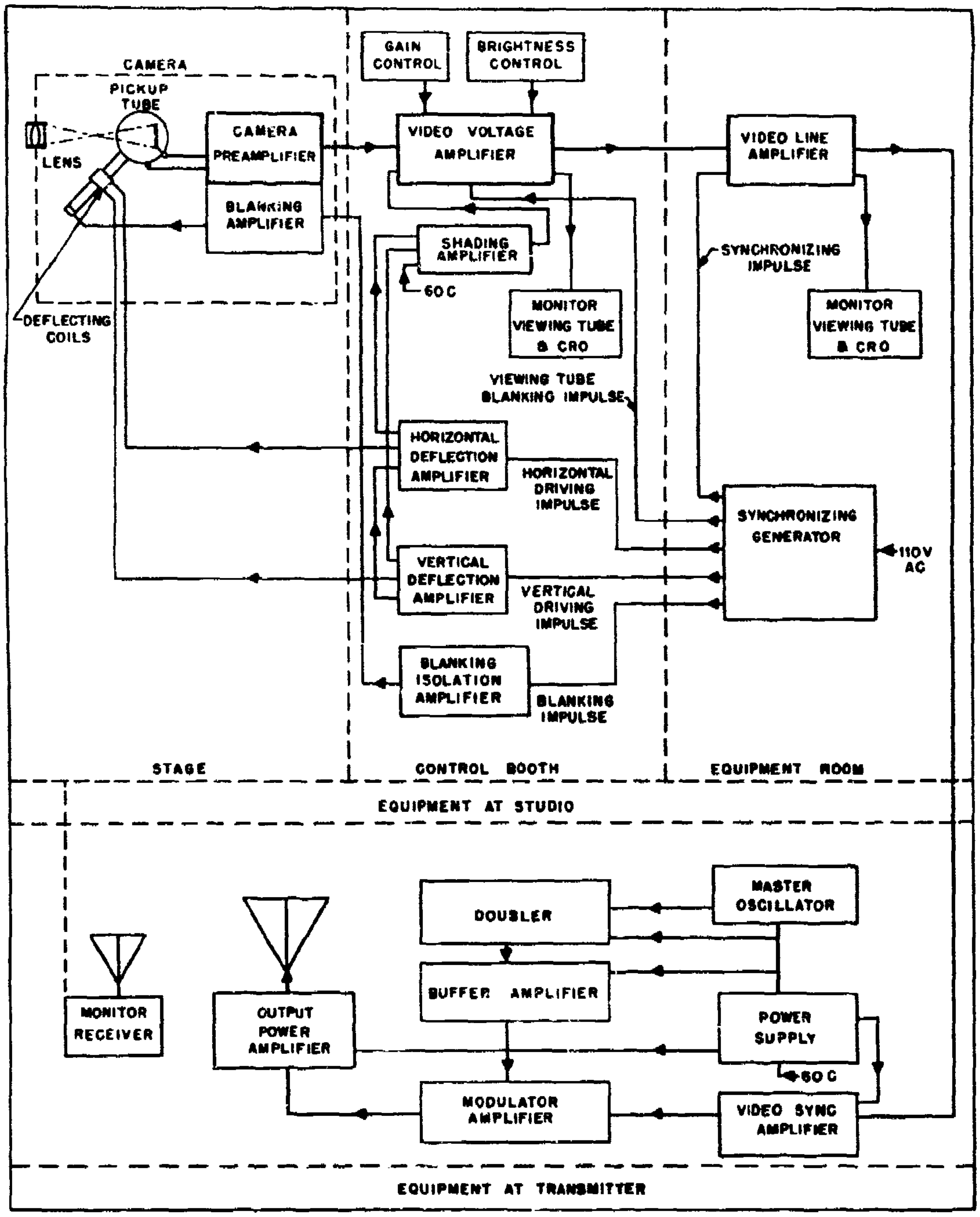


FIGURE 1. Block diagram of one video transmission channel.

4. As between amplitude and frequency modulation, the former is not easily practicable in the higher frequency range, i.e., 2,000 mc. Frequency modulation will usually give the better results when spurious multipaths are kept sufficiently down and the signal is strong. The amplitude modulation system, however, is generally simpler and lighter and does not fail so abruptly under adverse conditions.

The different systems of television tested were found, with certain exceptions, to be not too far different. The Iconoscope was found to be a good all-around pickup tube. The Image Dissector pickup tube is less sensitive than the others but permits somewhat simpler circuits. The Image Orthicon is extremely sensitive but more complicated.

Infrared sensitivity in the pickup tube gives only a slight advantage in seeing through haze, and this advantage vanishes completely as the haze becomes thicker and turns into fog. This refers to radiation about 1 micron in wavelength. There appears to be no advantage in utilizing immediately longer wavelengths, because of water-vapor absorption. No studies were made with television using much longer wavelengths.

5.3 THE STATE OF TELEVISION AT THE BEGINNING OF THE PROGRAM

5.3.1 Television Equipments and Circuit Arrangements

From its earliest experimental stages television has captured the American imagination. Even during the early days of mechanical scanning, the public refused to believe that television was not "just around the corner." Indeed, the feeling was not uncommon that television was being viciously withheld from the public by a selfishness of the large corporations not easily understood or explained. By the outset of the war, however, experimental telecasting of pictures was regularly taking place in several cities. New techniques in UHF transmission, the advent of the storage camera tube, and the cathode-ray presentation tube were the major factors which had made such experimental telecasting possible. In spite of these developments, however, there was no commercial broadcasting of television programs in the same sense that sound programs had been on the air fifteen years earlier.

The equipment for broadcasting television programs[2] was not simple. Figure 1 shows a typical block diagram of the equipment required for such experimental broadcasting as was then practiced. This equipment was installed at the Radio City studio of the National Broadcasting Company and at a transmitting station in the Empire State Building. In aggregate the weight was several tons. The power requirement was in excess of 100 kilowatts, and during all broadcasts the entire equipment was under the continuous supervision of more than a score of competent technicians.

As the cuts indicate, the results with this equipment were wholly satisfactory. Figure 2 shows a test chart to be transmitted from the television station and a photograph of the picture received on the viewing screen at a location approximately 45 miles away. The equipment was adjusted to have a scanning frequency of 525 lines interlaced and 30 frames per second. The test chart was illuminated at a level of 800 footcandles and the camera was equipped with a lens of $f/4.5$. Transmission was on a carrier of 51-25 mc, employing vestigial sideband transmission in a channel 6 mc wide.

The equipment indicated in Figure 1 is typical of several prewar television installations in the United States, and the results shown in Figure 2 are typical of prewar television transmission generally. The problem of applying television to guided missiles was to compress the equipment shown in Figure 1 to the compass permitted by the missile geometry, or to develop alternative equipment of smaller compass. Of equal importance and even more acute was the problem of improving the reliability of the equipment so that its satisfactory operation when unattended would be assured. Thus equipment of several tons had to be reduced to not over 150 lb, with increased reliability and no serious compromise with quality of picture transmission.

Quality of picture transmission is not readily definable. It consists, essentially, of perfect synchronism in scanning between the camera and the receiver. Loss of synchronism in horizontal scanning results in a sidewise drift of the picture; loss of synchronism in vertical scanning can cause the received picture to drift vertically. Phase displacement of the scanning will cause improper framing of the picture. Simultaneous loss of synchronism in both the horizontal and the vertical sense will result in destruction of the picture, "tearing." Continuous and perfect synchronization, then, is necessary to receive any picture at all. A picture having been received, its quality is perhaps best defined by four properties: (1) resolution, (2) contrast, (3) brightness, and (4) flicker.

1. Overall resolution is measured by the number of horizontal lines which can be distinguished in the received scene. This value corresponds to the screen fineness of the photoengraver. It is not expressed in lines per lineal dimension in the case of television, however, on account of the varying degree to which the received picture may be magnified. The resolution obtained is dependent upon many factors, a few

of which are: the resolving power of the optical system of the camera, a quality of the photosensitive element akin to photographic grain, the density and distribution of secondary electrons in the pickup tube, the width of band-pass in the radio sections of the transmitter and receiver, and such characteristics of the presentation tube as fineness of focus of the electron beam and the qualities of the phosphor on its screen. Figure 2 shows overall resolution in the

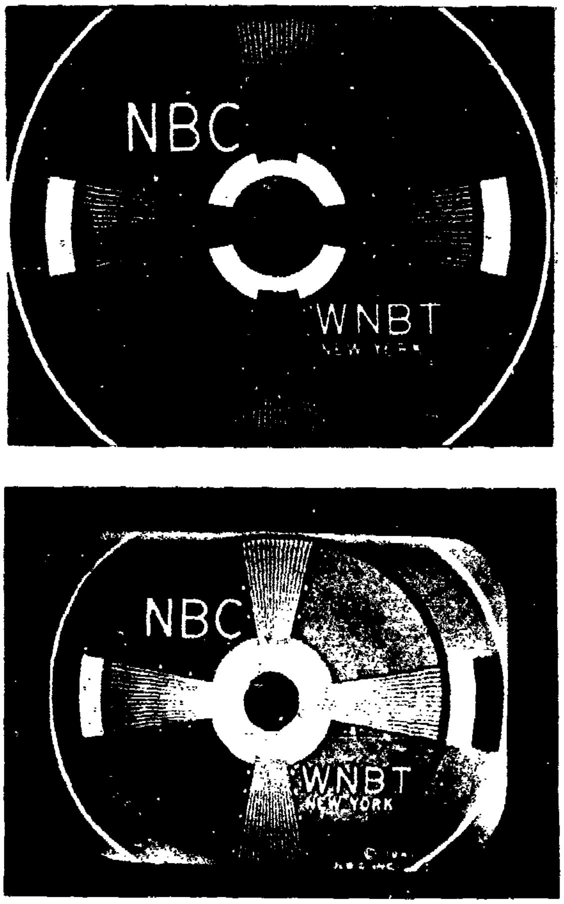


FIGURE 2. Resolution chart for testing television transmission (top); photograph of received picture (bottom).

received picture of 184 lines. This quality was never equaled in the missile-borne television equipment developed by the Division. About the minimum resolution reasonably tolerable is 120 lines, and with such scanning most of the picture's detail is lost; 240 lines represent about the lowest limit of satisfactory resolution when any detail is required; 480 lines give a resolution roughly comparable to that obtained from the usual 16-mm amateur motion picture. The foregoing criteria are due to Engstrom;[3] they have not been standardized by the industry.

2. The maximum contrast obtainable is determined by the characteristics of the presentation tube. Within the limits set by the presentation tube the contrast is determined by the video gain between the

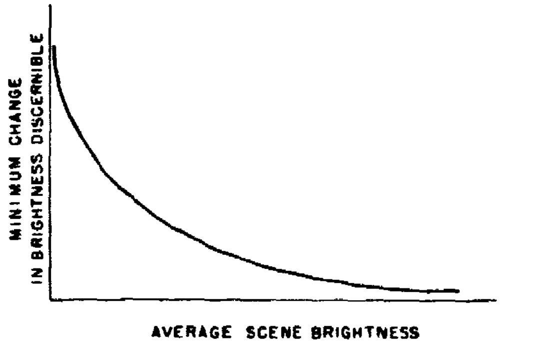


FIGURE 3. Change in brightness threshold with scene brightness.

camera and the modulator of the transmitter and between the second detector of the receiver and the viewing tube. Suppose an image is to be transmitted of a perfectly black and perfectly white checkerboard. The portions of the photosensitive surface on which the black squares are projected will receive no light, and therefore develop no signal to the video amplifier. The white squares will excite the photocathode and develop a certain voltage level. With a

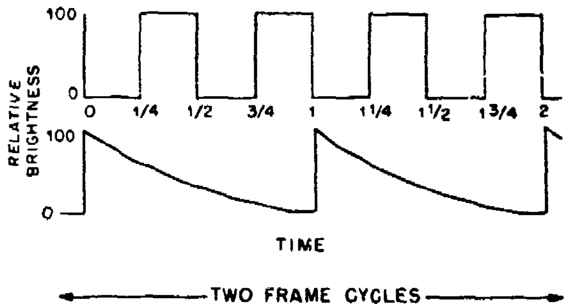


FIGURE 4. Screen illumination for intermittent pictures: motion pictures at 24 frames per second (top); television at 24 frames interlaced (bottom).

very low gain the difference between the blackest black and the whitest white, one definition of contrast, is very small; with a considerable video gain the contrast can be considerably increased. Contrast is also affected by the received-picture brightness. Figure 3 indicates a characteristic of the typical eye in resolving halftones. It shows that unless the highlight brightness of the received scene is adequate, loss of contrast will result, irrespective of video gain. The quantitative incorporation of this characteristic into design awaits further study.

3. Brightness of the received picture depends upon the characteristics of the phosphor screen, the impressed voltage, and a number of other characteristics of the presentation tube and its associated circuits. This dependence is, of course, based on the assumption that the received signal is of sufficient strength to drive the tube to its full capability. Prewar tubes had a brightness level too low to be adequate for phase 2 of a guided-missile attack (see Section 5.1). The work on cathode-ray oscillograph tubes of increased brightness for radar applications was of great benefit to the television program.

4. Flicker is also a function of brightness. Direct transference of motion-picture experience to television is unsafe: the 24 frames standard for modern motion pictures is inadequate to prevent objectionable flicker in television. This is partly due to the difference in the illumination characteristic of the viewed presentation: in motion pictures the screen is fully illuminated during the entire exposure; with television there is an exponential degradation of the highlights, starting immediately after a picture element has been scanned (Figure 4).

High-quality television is obtained by 60 repetitions per second of the scene on the presentation screen. The use of 500 scanning lines and 60 frames, however, requires a band-pass of about 20.4 mc. The use of interlacing—scanning alternate views of the scene with alternate numbered scanning lines—cuts the required band in half while preserving the resolution and freedom from flicker.

5.3.2 Camera Tubes

Two types of photosensitive tubes were used for the pickup of television scenes for prewar broadcast. The first type was the nonstorage type. This represented a development from the earliest phases of television, when mechanical scanning was employed and elements of the scene were successively allowed to register on the cathode of a photoelectric cell. The output current was amplified and modulated the carrier wave.

In the more modern version (the Image Dissector) the photocathode is enlarged so that the entire scene is focused on it. A potential applied between the cathode and an anode produces an electron current emanating from the cathode. In space cross section this current corresponds in intensity to the level of illumination on each element of the photocathode. An axial magnetic field focuses the electron image. Transverse magnetic fields deflect it horizontally at the line-scanning frequency and vertically at the frame-scanning frequency. A small aperture (0.02x 0.02 in.) permits small portions of the space current to enter an electron multiplier, which develops a signal consisting of a level of current for each 0.0004-sq-in. element of the electron image. Magnification by electron optics between the photocathode and the aperture permits a number of scanning lines greater than the quotient of the vertical dimension of the optical image or the photocathode by 0.02 in. A large number of stages in the electron multiplier yields a usable sensitivity.

The other general class of tubes was known as storage tubes.[4] In these devices the photosensitive surface consisted of a mosaic cathode. A scene focused under such a cathode caused charges to be built up on each picture element by the emission of photoelectrons. An electron gun in the envelope scanned the photosurface horizontally and vertically under the influence of magnetic fields. This electron beam knocked secondary electrons out of the mosaic in varying amounts, depending upon the number of photoelectrons already emitted. The mosaic was backed by, but insulated from, a conducting plate. Thus the changing charge on the mosaic-backplate condenser formed a signal which was used to modulate the carrier. The tube, the Iconoscope, is characterized by high resolution and good contrast at scene-brightness levels much lower than were permissible with the Image Dissector or with mechanical scanning. It was in production at the beginning of World War II in considerable quantity.

The Iconoscope has an unfortunate characteristic known as shading—the appearance of dark areas in the received picture which sometimes spread to cover the entire viewing screen. The cause of the phenomenon is the formation of clouds of secondary electrons released by the mosaic. The mechanism is not wholly understood nor has a completely satisfactory cure been devised.

To correct these and other difficulties, a revised type of tube was under development at the outset of World War II; this tube was known as the Orthicon. In this structure a decelerating anode was located adjacent to the photosensitive cathode so that the electrons of the scanning beam impinged on the photosensitive surface at substantially zero velocity. Thus no secondary electrons were emitted. Further, the "stored" photoelectrons emitted by the photomosaic during intervals between the passages of the scanning beam were more effectively used, so that the sensitivity of the Orthicon was about four times that of the Iconoscope.

The sensitivity of a television camera is conveniently expressed by the average intrinsic brightness of a received scene which will result in an acceptable signal for modulating the carrier. The following tabulation gives the relative thresholds of operation of the foregoing tubes with lenses of equal *f* number. Equal *f* numbers give an equivalent basis for comparison of absolute sensitivities without regard to the logistic effort involved in their procurement. Certain tubes require a long-focus-length lens which for the same *f* number is more difficult to procure.

	Scene brightness required[64] (candles per sq ft)
Image Dissector with electron multiplier	10^3
Iconoscope	1.0
Orthicon	0.25
Scene illuminated by bright sunlight	10^4
Moonlight	5×10^{-3}
Threshold of human eye	10^{-7}

5.3.3 Transmission Links

All television broadcasting at the outset of World War II followed the conventional UHF AM practice. Specifically the frequency channels assigned were in the 40- to 60-mc band. A channel of 6-mc width was assigned to each transmitter. The original practice of double sidebands of 2 to 2.5 mc had been superseded by a single sideband of 4 mc in the interests of better resolution.

In military applications of television, however, it was recognized that not all the refinements normally invoked in experimental television having commercial application in mind could be employed. Specifically, interlaced scanning was eliminated, with consequent increase in flicker. A concession in picture detail was made by the reduction of the number of scanning lines from about 500 to 350. The frame repetition rate of 30 per second was raised to 40 in partial compensation. The resulting required bandwidth was approximately 5 mc.

The usual transmission techniques available in experimental television could not, in general, be applied directly to military uses. Some of the work on radio relay was, however, applicable. Initial allocations of frequency were in the vicinity of 100 mc. This was soon changed to 300 mc and by the end of 1943 the only frequencies available for television work were in the vicinity of 800 and 1,800 mc.

5.3.4 Receivers

The typical television receiver in 1939 consisted of a superheterodyne circuit in the 40- to 60-mc band with the necessary bandwidth designed into the i-f amplifier. Intermediate frequencies were rectified in a second detector and amplified in a video amplifier; the resulting output was applied to the control grid of a cathode-ray oscilloscope. A pulse transmitted with the video signal at the beginning of each scanning line triggered a local oscillator, whose outpat deflected the electron beam horizontally across the screen; at the end of the line-scanning period a blanking pulse returned the line to its original position. At the beginning of each frame another pulse, transmitted with the video signal, started the electron beam downward across the screen, but at a much slower rate; at the end of the frame a blanking pulse returned the beam to its position at the upper left-hand corner of the picture. A series of pulses, then, deflected the electron beam at more or less uniform velocity across the fluorescent screen of the tube so that the electron screen "painted" the tube in narrow horizontal lines closely placed together. In the absence of any video signal, the pattern received consisted simply of the horizontal lines. With very close scanning, these lines merged so that the received pattern was a clear illuminated rectangle.

Introduction of a video signal produced an alternating component in the velocity of the cathode ray so that the brightness varied from point to point along the line and among the lines. In this manner the received picture was produced.

The presentation of any recognizable picture on the viewing tube was always dependent, then, upon the proper reception of the synchronizing and blanking pulses. Noise in the circuit from static or other sources readily produced pulses of a magnitude comparable with the synchronizing and blanking pulses. Under these circumstances, the picture was destroyed.

5.4 THE APPROACH OF THE DIVISION TO THE PROBLEM

5.4.1 General Overall Engineering

Even before the formation of the Division, preliminary work had been undertaken by NDRC and by the Services toward the development of compact, expendable television-transmitting equipment for missiles and for other purposes. The first responsibility of the Division in regard to television was to coordinate these activities. The compromise of picture quality, particularly in resolution, with compactness of equipment was in some cases made ill-advisedly, and a major initial step of the Division was to reduce all television activities to a comparable basis of 350 lines and 40 frames sequentially scanned.

A second major overall activity of the Division in the television field was to improve the reliability of the equipment through the application of sound engineering principles. A great many detailed problems, minor individually but frustratingly important in the aggregate, were solved. One of significant importance was the elimination of crosstalk between the horizontal and vertical sweep circuit in the camera and in the receiver. No single activity contributed more to the reliability of airborne television equipment than the application of proven engineering principles to the design of equipment already in advanced development.

5.4.2 Comparison of Camera Equipments

An attempt was made to rate objectively the several pickup tubes available at the beginning of the Division's program and to establish objective rating standards for future camera tubes which might be developed. This proved to be impractical, however, and the comparison of the overall camera equipment—optics, pickup tube, scanning equipment, and video amplifier—was undertaken. This was a continuing project;[6] the contractor's report is recommended for study to all those interested in the application of television to military problems. Sensitivity of various equipment was measured and the performance of the equipment from threshold to a highlight brightness of about 1,000 foot-Lamberts explored. No objective measure of contrast similar to the *gamma* of the photographer was known. Contrast was rated as good, low, or high. Brightness of the received picture and flicker were not assessed.

An attempt at a quantitative evaluation of contrast was made by measuring on a cathode-ray oscillograph the video output of the camera when scanning a strip of white blotting paper on a matte background and also by measuring the variation in signal developed by light transmitted through a translucent gray scale having ten logarithmic steps from 2 to 0.2. In the latter test certain of the conversion equipments show perceptible linearity between the logarithmic density of the translucent gray filter and the signal strength developed. It appears that further work along these lines might reasonably be expected to yield an objective contrast rating.

The importance of using objective, quantitative methods of evaluating television performance can hardly be overemphasized.

The several camera equipments were also rated as to blocking, shading, and distortion. Spectral response was taken by measuring the response at various levels of illumination at a color corresponding to 5,400 K and with the following filters.

Wratten	47 Blue
Wratten	61 Green
Wratten	29 Red
Wratten	88A Near-infrared-passing
Aklo	9780 Infrared-blocking

The performance of the equipments under mechanical vibration at low frequencies was not measured, but each unit was placed in an acoustic chamber and subjected to very high noise levels from a loudspeaker. The noise level in db above 10^{-16} watt per sq cm which produced interference was determined at several audio frequencies from 400 to 3,500 c.

5.4.3 Improvements in Sensitivity

Two approaches are available to improve the sensitivity of television pickup equipment. The aperture of the optical system can be increased, permitting more light to fall on the photosensitive material. This is normally accompanied by loss of resolution, increase in the complexity of the lens system, or both. This is even more true in the case of television than in the case of photography, since the usual photosensitive surface has a broader spectral response than most photographic film, so that color correction in the lenses must be extended into the near infrared region. A second approach to the problem is through the increased sensitivity of the pickup tube itself.

Both these avenues were explored by the Division. Lenses of f 3.5 were customary in television work. Further extension in this direction appeared unprofitable, since the geometry of the camera tubes requires a lens of a considerably greater focal length than would be called for by the diagonal of the projected image. Schmidt optics with an equivalent aperture of about f 0.7 was applied to each of the pickup tubes available.

A major improvement, therefore, of the camera pickup tube itself seemed desirable. Preliminary work had been started before the war on the Image Orthicon[5] tube. This tube was a modification of the Orthicon, in which an electron image was created on a glass target behind the photocathode. Electrons from the photocathode impinged on the target with sufficient velocity to cause the emission of secondary electrons. These electrons were collected on a fine screen, producing a residual positive charge on the target. A rise in the target potential was prevented by the adhesion of some of the electrons of the scanning beam. The insulating property of the target caused the charge distribution, and therefore the capture of electrons from the scanning beam, to correspond to the electron image impinging on it. The electron beam was thus modulated by subtraction at the target. The modulated return beam was collected and amplified by electron multiplication to produce the signal.

The target was made extremely thin (0.2 mil) so that a moderate leakance existed between the front (electron-image) and back (scanned) surfaces. Thus the charge resulting from the loss of secondaries was neutralized in each scanning cycle without production of dangerous voltage stress between the target surfaces.

5.4.4 Television Radio Links

Transmission at Higher Frequencies

At the beginning of World War II, television experimentation for military purposes was at 100 mc. This channel was very early taken over by other communication services, and television was pushed to the 300-mc band. As warfare progressed and communication and radar required more and more of the spectrum, the only bands finally available for television were two—one about 800 mc and the other about 1,800 mc. In addition some work was done on television transmission at 1,200 mc.

Multipath Problems

At the outset, multipath transmission caused considerable difficulty. It resulted in the appearance of vertical bars in the received picture, which could only be accounted for by beating of the signal transmitted over the longer reflected path with that transmitted over the direct path. Considerable analysis of the video signal was made to seek out a source of the beats near the portions of the scene where there was an abrupt change in the video frequency. The major cause, however, proved to lie in a spurious frequency

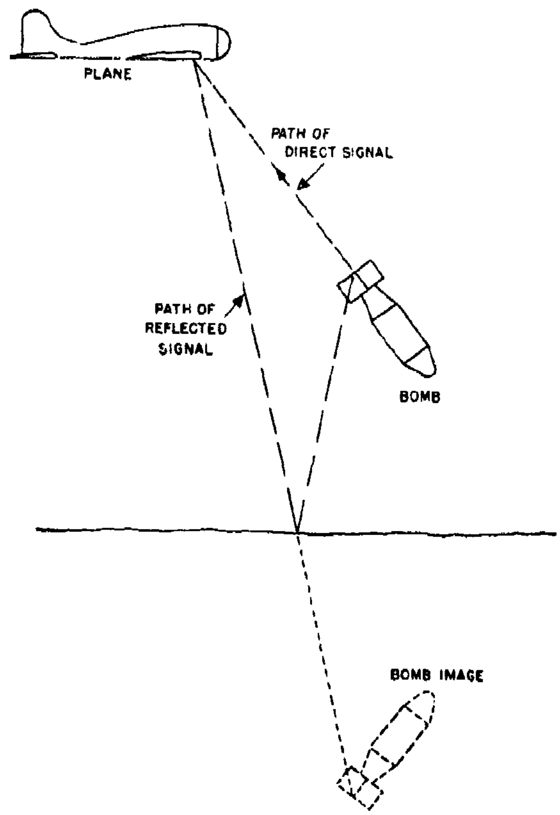


Figure 5. Multipath interference.

modulation of the carrier, resulting from close coupling of the master oscillator with the modulator. To save space the usual buffer stage separating the oscillator from the modulator had been eliminated. The reaction of the modulator on the oscillator resulted in frequency pulling of the order of 100 kc. The restoration of the buffer reduced the spurious FM to the order of 10 kc, well below the threshold at which multipath difficulties are detectable.

Even with a fixed carrier frequency, however, motion between the transmitter and the receiver will introduce a changing frequency through the doppler effect. With missiles of moderate speed such frequency shifts are small, and the effects on picture transmission are negligible. With the high-angle dirigible bomb, however, the bars characteristic of spurious FM were present. (See Section 5.6.2.) In many cases the beating was so pronounced as to cause loss of synchronism and tearing of the picture.

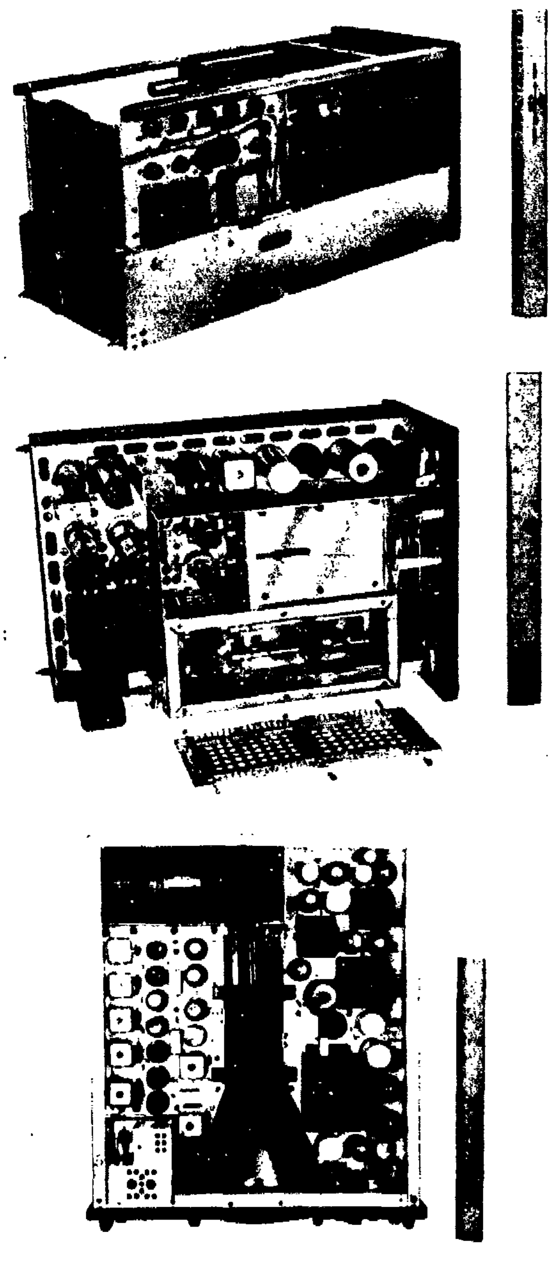


Figure 6. Block III equipment: camera (top), transmitter (center), and receiver (bottom).

The major difficulty which confronted the Division's investigators was beating between the signal from the transmitter in the bomb and the signal from its reflected image (Figure 5). This interference produces bars across the picture whose direction depends upon the relative change in length of the two transmission paths. At the velocities of the high-angle dirigible bomb and Roc, the bars are horizontal and of considerable intensity.

If an application of television to high-speed missiles is to be considered, this problem, as yet unsolved, must receive careful attention. Preliminary work in this direction was done with higher frequencies (1,800 mc) in an effort to eliminate downward radiation from the missile and the image of its transmitter.

Frequency Modulation vs Amplitude Modulation

The pronounced improvement in reception of audio signals when transmitted by FM as compared with AM spoke strongly for the exploration of this type of transmission for video signals. The Division's contractors made comparative tests with both types of transmission at 300 mc, at 775 mc, and at 1,200 mc. At 1,800 mc the geometry of the tubes in the r-f circuits precludes amplitude modulation.

5.5 SUMMARY OF RESULTS

5.5.1 Equipment Simplification and Improvement[7,8,9,10]

The elimination of crosstalk between the horizontal and vertical scanning circuits and the video amplifier has already been mentioned. It was accomplished largely by cleaning up the wiring of the camera, transmitter, and receiver equipments (Figure 6). This step, in addition to the elimination of spurious FM by the decoupling of the oscillator and modulation in the transmitter, represented a major contribution to the reliability of television at Block I and Block III frequencies (100 mc and 300 mc).

The early models of military television equipments were very discouraging when flight-tested; one cause was the spurious FM already mentioned; the second was low percentage modulation. The correction of the latter difficulty was complicated by the fact that no ready means was available at the outset of the program of measuring percentage modulation at the broad band of modulating frequencies occurring at the transmitter. The accepted practice was to apply sine-wave modulation and to assume that the percentage modulation remained unchanged with the change in waveform of video modulation. A percentage-modulation meter was improved from which the approximate percentage modulation could be scaled off.

The application of appropriate engineering to the production design of the Block III resulted in the elimination of six of the nine operating control adjustments, without loss of ability to select any one of ten channels with a single equipment. The same simplification increased the output power by 39 per cent from 18 to 25 watts. The corresponding increase in range of 18 per cent is perhaps not important; however, the improvement in signal-to-noise ratio at ranges less than the limiting range is very important in reducing the effects of interference.

The r-f end of the receiver was redesigned, with a much improved head-end tuner. The new tuner permitted the use of an r-f stage with an improvement in the ratio of the signal to its image of from 3.5 to 100. The overall result was a 14-db improvement in signal-to-noise ratio.

The receiver scanning oscillators were stabilized, and an improved AGC circuit was developed. The original cathode-coupled multivibrators were replaced by sine-wave oscillators capable of automatic synchronization with the received synchronizing pulses by AFC circuits. With the added AFC and the stabilized oscillators there was no tendency for the received picture to tear, even with loss of synchronizing pulses for several frames. New low-impedance AGC circuits were designed with low time constants in comparison to a line duration, in contrast with the high-impedance AGC circuits which they replaced. They resulted in successful reception of signals through pulse interference, even if the pulse had an amplitude 1,000 times the desired signal, provided the interfering pulse rate was not too close (within 1 or 2 per cent) to the scanning frequencies. The combination of low-impedance AGC and the stabilization of the scanning oscillators with AFC resulted in maintaining protection against 4,000-to-1 pulse interference, even with pulse repetition rates within 0.4 per cent of scanning frequencies. AFC had not been incorporated into production receivers as the war ended; stabilized oscillators and fast AGC improvements were.

A further improvement of about 4 to 1 in allowable peak noise-to-signal ratio was obtained by the use of a keyed low-impedance AGC, which permitted signals to pass through the AGC amplifier only during the synchronizing pulse. This kept the bias constant during the line duration. At the close of World War II, this form of AGC had not been applied to military television receivers, its dependence upon very precise maintenance of synchronism having deferred its application. The use of the keyed low-impedance AGC during periods of poor synchronism resulted in an effect similar to motorboating.

A limiter was applied to the receivers to clip noise peaks to a value only slightly higher than the synchronizing peaks. A second limiter, acting on the video input to the synchronizing circuits, limited the synchronizing-pulse amplitude at strong signal levels, as well as limiting pulse noise to amplitudes equal to the synchronizing pulses with weak signals. This improvement, not available until the close of the program, further reduced the vulnerability of the radio-transmission link to pulse noise near the scanning frequency.

The Iconoscope camera tube is limited in latitude (the range in scene brightness over which fidelity of response is maintained) on account of the clouds of secondary electrons already discussed. To accommodate scenes which change over a broad range of brightness, a lamp was placed behind the mosaic.

The provision of suitably insulated windings for the horizontal output transformer solved the problem of a suitable supply for the Iconoscope cathode heater. In addition to reducing the high-voltage cabling to a minimum, it permitted a simplification in the horizontal deflection output circuit.

A "clamp" circuit was developed which sets or clamps the bias of the output video stage at the beginning of each line and then opens the bias supply circuit for the duration of the line. This results in removing all microphonic disturbances in the preceding video stages and further permits designing the video amplifier so that it is flat only down to line frequency. This eliminates most of the electrolytic filter capacitors while maintaining satisfactory reproduction of scenes that have frequency components below line frequency, e.g., scenes including the horizon.

The limitations of space in the Block III camera prevented its use. In its place an RC network was inserted in the grid circuit of the first video stage. The time constant of this network, the leveling circuit, was adjusted to give approximately the same overall effect as the clamp circuit. Its efficacy was rather less, however, and the clamp circuit was used on the compact equipment, the Orthicon, and the Image Orthicon equipment.

The availability of 6AG5 miniature pentodes at the later stages of the program permitted the design of a much more compact video amplifier. Further saving in space was accomp'ished by the elimination of peaking coils through the use of small capacitors to by-pass the cathode resistors. In spite of the loss of gain per stage due to degeneration at low frequencies, the overall gain of the amplifier strip was preserved at sufficient saving in space to permit the reinsertion of a buffer amplifier without increasing the overall size of the equipment.

5.5.2 Comparison of Camera Equipments[6]

The original plan under this project was to make an objective comparison of television pickup tubes. The intimate association, however, of the pickup tubes with the remaining portions of the camera equipment prevented this objective from being realized. Since the comparisons made, therefore, are between complete camera equipments, they do not lead to a conclusion as to which is the best pickup tube to choose for the optimum design of associated cameras.

Seven camera equipments were tested as follows.

Name	Manufacturer
Block III	RCA
2-in. Orthicon	RCA
Experimental Image Orthicon	RCA
Production Image Orthicon	RCA
Image Orthicon with Schmidt optics	RCA
Vericon	Remington Rand
Image Dissector with multiplier	Farnsworth

The equipments under test were assembled in a single laboratory where they could be compared under controlled conditions (see Figure 7). Lighting of adjustable level and color was provided. The illumination was continuously adjustable from 0.02 to 2,000 footcandles. The corresponding intrinsic bright-

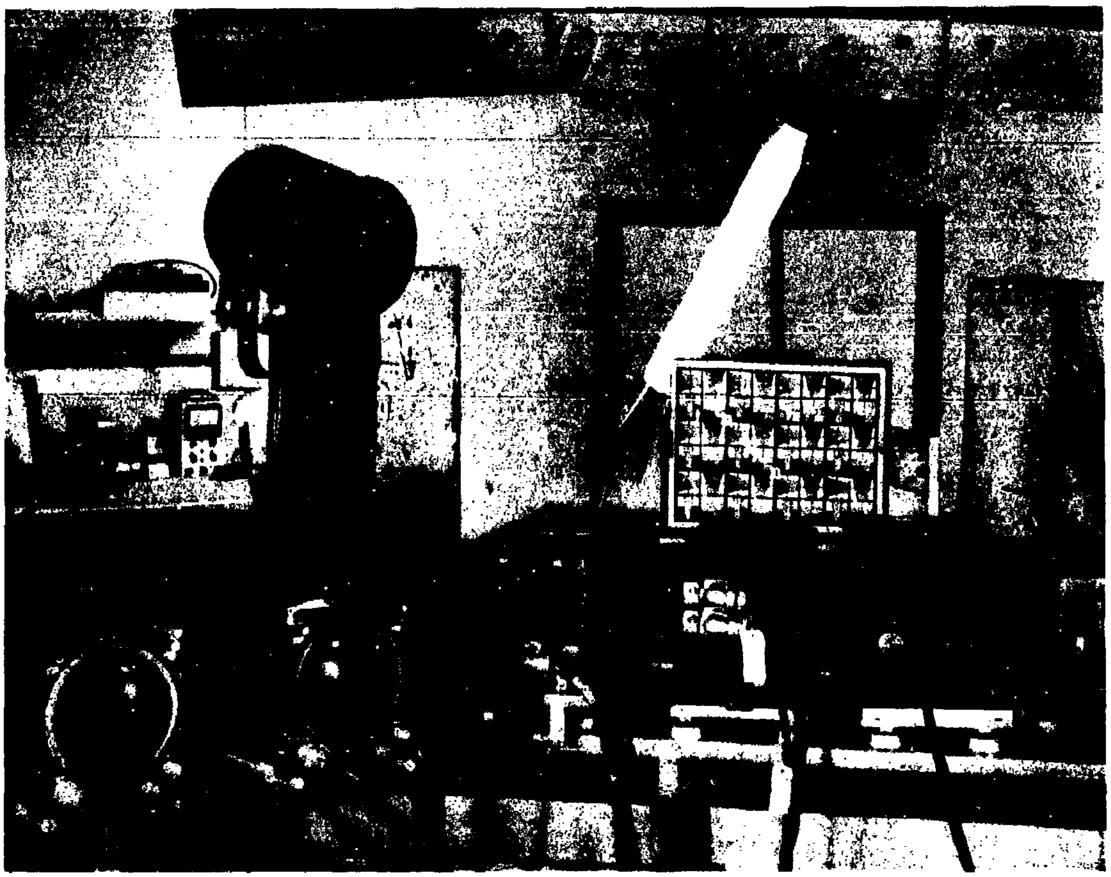


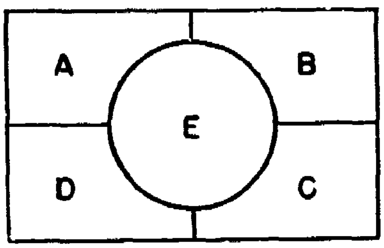
FIGURE 7. Conversion units set up for comparative measurement of resolution and sensitivity.

TABLE 1

Type of camera tested	Block III Iconoscope	Vericon	Image Dissector	2-in. Orthicon	Experimental Image Orthicon	Production Image Orthicon	Image Orthicon with Schmidt optics
Optical system—focal length (cm)	20.3	5.0	23.7	1.7	12.0	8.9	20
f number	4.5	1.9	2.5	1.2	27	3.5	1.0
Threshold sensitivity (ft-Lamberts)	8.2	18.3	175	27	1.5	0.5	0.07
Optimum highlight brightness (ft-Lamberts)	280	210	420	600	12	8.0	0.7
Resolution at threshold							
Area A	130	160	180	100	.....	100	......
Area B	160	140	150	100	.....	150	......
Area C	200	120	150	200	.....	170	......
Area D	200	140	190	130	.....	120	......
Area E	200	200	200	200	200	200	100
Resolution at optimum brightness							
Area A	260	290	200	160	300	200	120
Area B	300	290	170	200	300	190	150
Area C	260	240	170	240	250	180	200
Area D	250	250	200	198	250	180	150
Area E	300	300	240	250	300	260	200
Resolution at high brightness level (ft-Lamberts)	580	580	420*	600*	580	580	250
Area A	260	290	200	100	300	110	120
Area B	300	290	170	200	300	200	150
Area C	260	240	170	240	250	190	200
Area D	250	250	200	198	250	160	150
Area E	300	300	240	250	300	210	120
Contrast at threshold	Low	Low	Low	Low	Low	Low	Low
Contrast at optimum	Good	Good	High*	Good	Good	Good	Good
Contrast at high brightness level	Good	High–Good	to Good*	Good*	High	High	High

*Same as optimum.

KEY TO RESOLUTION AREAS



VIEWING—TUBE SCREEN

ness of the highlights in the scene viewed varied between 0.005 and 500 candles per sq ft. The spectral distribution of the illumination corresponded to a color temperature of 5400 K. Color sensitivity was determined by measuring the response of the camera equipment when viewing scenes consisting of Wratten filters in combination with Eastman logarithmic step gray scales. The entire assembly was covered by a filter of Aklo glass to cut out the near infrared.

Sensitivity and resolution were determined by viewing a standard 18x24-in. black-and-white resolution chart at a distance which covered the photosensitive surface, with the exception of a small margin as recommended by the manufacturers. The test

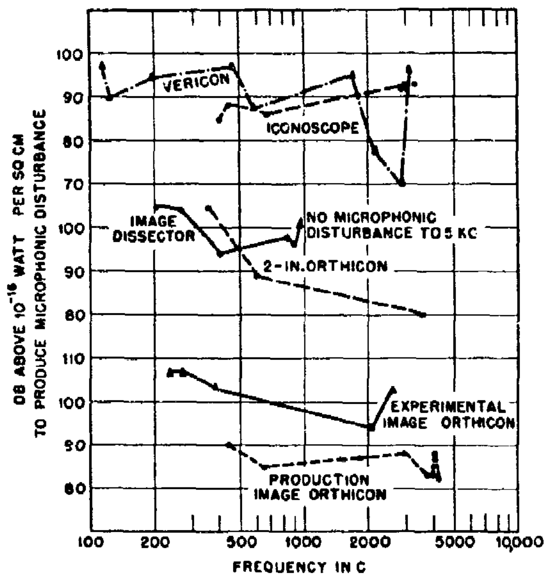


FIGURE 8. Noise level above 10^{-16} watt per sq cm at which microphonics produce serious interference with video signal.

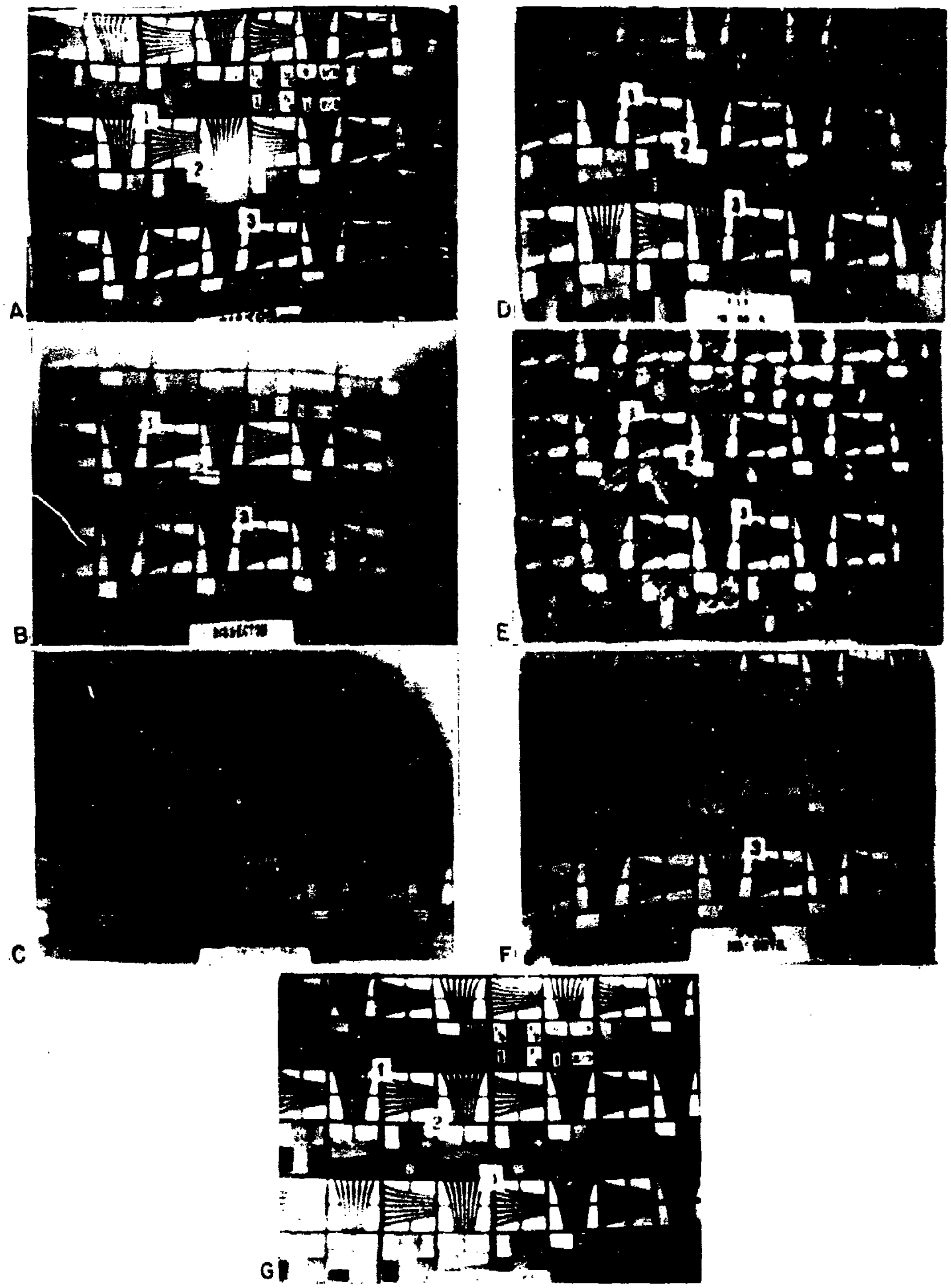


FIGURE 9. Comparison of resolution of camera equipments: A, Vericon; B, Dissector; C, 2-in. Orthicon; D, experimental Image Orthicon; E, Image Orthicon with Schmidt optics; F, production Image Orthicon; G, Block III Iconoscope.

SECRET

chart permits direct observation of resolution between 100 and 300 lines. Table 1 gives a comparison of the observed sensitivity and resolution of the seven equipments.

Contrast was reported as high, good, or low; a quantitative evaluation of contrast similar to *gamma*, well-known to photographers, was not established.

The vulnerability of the camera equipment to interference from audio vibrations was determined by enclosing each equipment in a soundproof cabinet with a powerful loudspeaker. Figure 8 shows the frequencies and noise levels in decibels above 10^{-16} watt per sq cm at which serious interference occurred.

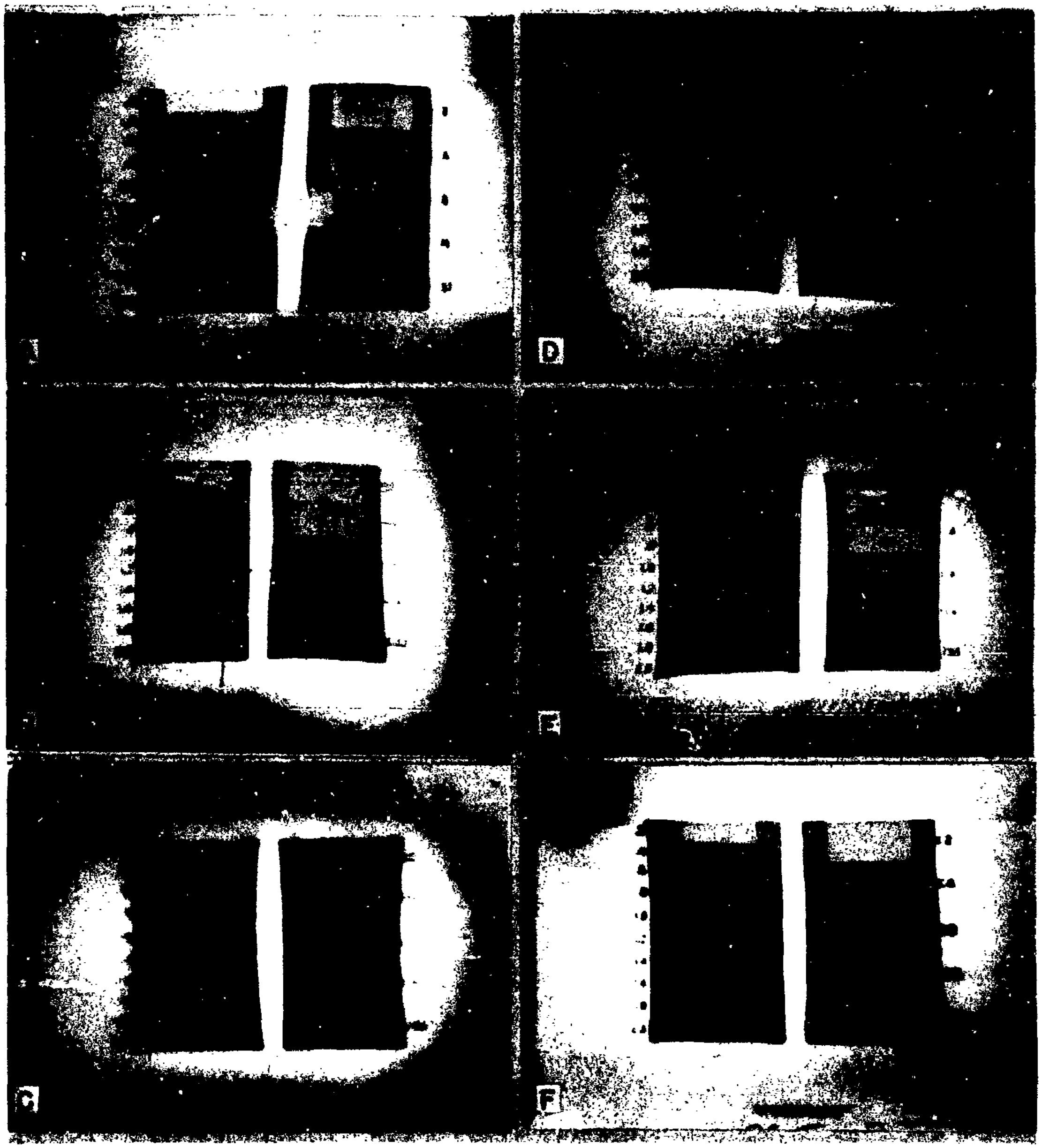


FIGURE 10. Comparison of amplitude linearity of camera equipments: A, Vericon; B, Dissector; C, 2-in. Orthicon; D, experimental Image Orthicon; E, production Image Orthicon; F, Block III Iconoscope.

Table 1, prepared from data presented in Columbia Broadcasting System's report,[6] indicates satisfactory picture reception when the peak-to-peak signal-to-noise ratio is less than unity. This ratio has been recognized as a generally inadequate criterion unless its frequency distribution is specified. Broadly it is found that more random noise is tolerable in the upper than in the lower stretches of the video frequency band.

The Columbia investigation did not attempt to evaluate the data to reach a conclusion as to the best overall pickup tube. The greatly increased sensitivity of the Image Orthicon speaks very strongly in

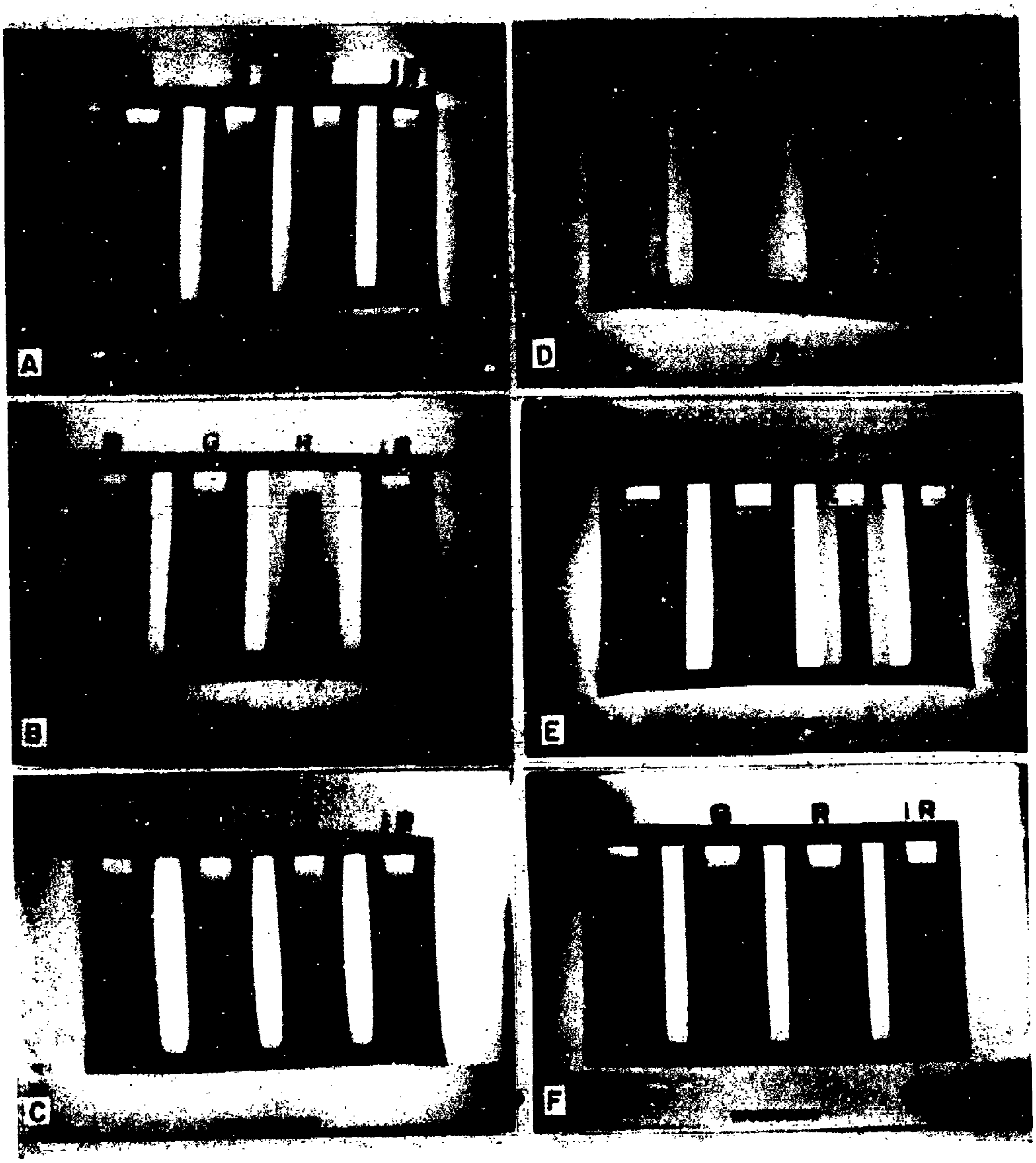


FIGURE 11. Comparison of color response of camera equipments: A, Vericon; B, Dissector; C, 2-in. Orthicon; D, experimental Image Orthicon; E, production Image Orthicon; F, Block III Iconoscope.

its favor. The overall fidelity of its output at any light level, however, is not equal to that of the Iconoscope. In addition, (1) it is more sensitive to fluctuations of supply voltage, (2) it loses contrast range with wide ranges of illumination, (3) it is more susceptible to microphonics, and (4) it has a lower signal-to-noise ratio. This last element does not appear from the work of Columbia because of the limited frequency range over which the noise was studied. The high sensitivity of the Image Orthicon in the near infrared portion of the spectrum, 1.0 μ, is most attractive for certain military operations. This sensitivity was partly lost, however, in the miniature version of this tube. On the whole it appears that the best overall performance is obtained from the Iconoscope, but that for purposes where extreme sensitivity is paramount the Image Orthicon is to be preferred. There are possibilities, also, that for special uses some of the other pickup tubes may be advantageous, although no clear case of such use appeared in the work of the Division. Figures 9, 10, and 11 compare resolution and sensitivity, amplitude linearity, and color response of the conversion units tested.

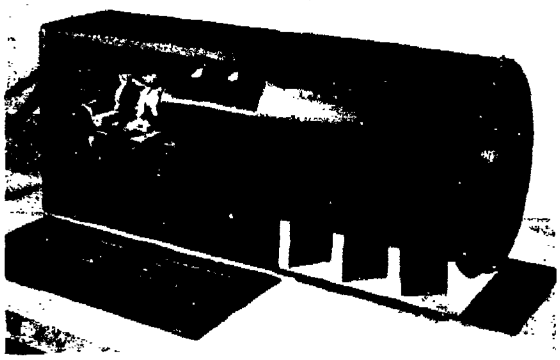


FIGURE 12. Image Orthicon camera with Schmidt optics.

5.5.3 Improvements in Sensitivity

The threshold sensitivity of the Block III camera using the Iconoscope with an f 4.5 lens was of about 8.2 ft-Lamberts. This was typical of the maximum sensitivity available at the beginning of the Division's program. Motion-picture cameras and emulsions were available for work at illumination levels of approximately one-tenth this level, and there was considerable pressure from the Services to get equal television performance. Two approaches to the problem were made, one by the increase in aperture of the optical system through the use of Schmidt optics, the other by the improvement of the pickup tube itself. Schmidt optics applied to the Image Orthicon[11] (Figure 12) showed an improvement in threshold sensitivity

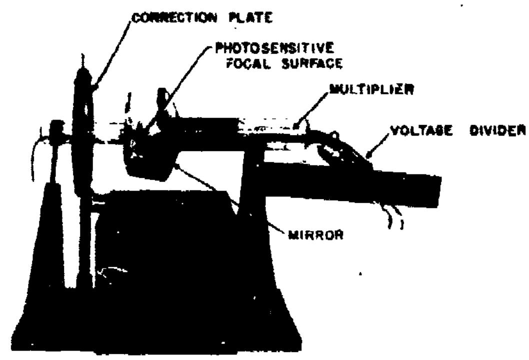


FIGURE 13. Bench test setup for sealed-beam Dissector with Schmidt optics.

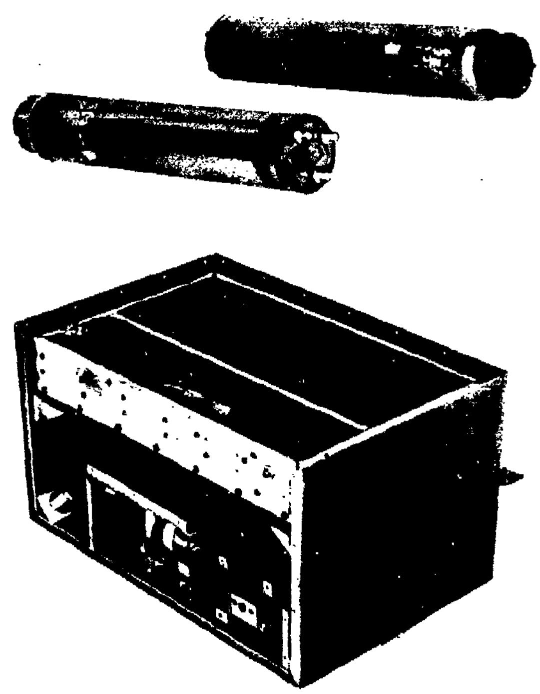


FIGURE 14. Vericon tube and camera (cover removed).

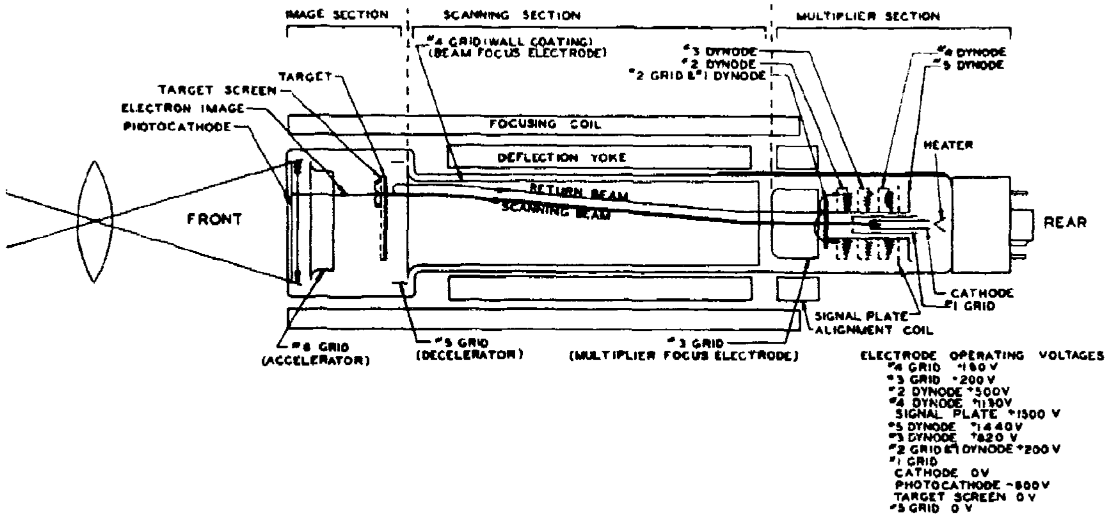


FIGURE 15. Image Orthicon tube with focusing coils and deflection yoke.

as reported in Table 1 of 7 times. The optical aperture for the conventional system was *f* 3.2, and the aperture of the Schmidt system was approximately *f* 1.0. An increase in sensitivity slightly less than the square of the *f* number may be due to losses in the correction plate and Cassegrain mirror.

Experiments were also made in the application of Schmidt optics to the low-velocity Iconoscope[12] and to the Image Dissector.[13] Success with the former was frustrated by the mosaic's charging at even moderate illumination levels. The spherical mirror for the Image Dissector with Schmidt optics was sealed in the envelope of the pickup tube in a sort of sealed-beam construction (Figure 13). The program was dogged with mechanical difficulties and no definite conclusion was reached.

The second method of improving sensitivity was through improvement of the pickup tubes themselves. Development of a small Orthicon-type tube and camera (Figure 14) was carried out by Remington Rand[14] under Contract OEMsr-187. This contractor's version of the tube is known as the Vericon.

The resolution of the Vericon is rather better than that of the Orthicon. Its sensitivity as tested by Columbia (see Table 1) is somewhat higher than the Orthicon, even without correcting for the greater incident light received by the Orthicon in the Columbia tests (*f* 1.9 for the Vericon, compared with *f* 1.2 for the Orthicon). It is rather less subject to microphonics at audio frequencies; otherwise it is substantially similar to the Orthicon.

The most useful gain in sensitivity was accomplished by adding image multiplication and electron multiplication to the Orthicon tubes. Table 1 testifies to the success of this development. A further improvement beyond that noted in the tabulation is the sensitivity of the Image Orthicon to the near infrared. With a Wratten 88A infrared filter, the Iconoscope produced a fair picture, but with rather low contrast and resolution at 1,600 footcandles of illumination. With the same filter, the Image Orthicon produced a picture of slightly decreased contrast at an illumination level of 23 footcandles. With a Corning 9780 filter, the corresponding illumination levels were 785 footcandles for the Iconoscope and 18 footcandles for the Image Orthicon. The Wratten 88A filter is practically opaque to visible light but transmits freely beyond 0.71 μ; the Corning 9780 blocks beyond 0.7 μ but passes freely in the visible range. This increase in sensitivity to the infrared is particularly important in outdoor applications at dawn and dusk, when military application of television may be of particular importance.

The Image Orthicon tube (Figure 15) has been fully described in the public technical press as well as in the contractor's reports.[5,7] Some of the difficulties encountered in its development are worth mentioning. The problem of mounting a 0.2-mil glass target on a supporting ring so that it would be free from ripples was solved[15] by firing a thin section of a blown bubble over a metal ring. At softening temperatures, the glass draws into a tight drumhead by virtue of its surface tension. A carefully controlled heating and cooling schedule was developed to bring the structure down to room temperature while the glass was still under tension and flat.

The target screen consists of fine-mesh wire screen with a high percentage of opening area. A method was developed which produced screens with 1,000 meshes per in. and 40 to 80 per cent open area. A sheet of glass was precision-ruled with the desired mesh and covered with a thin layer of metal. The metal was then removed from all except the rulings. Additional metal was plated onto the lines and the resultant screen stripped off.

An efficient multiplying electrode was designed which would accept electrons from one side, multiply them, and allow the secondaries to pass to the following stage. A "Venetian blind" structure was evolved which was substantially opaque to incident electrons but which provided liberal apertures for passage of the secondaries to the adjacent stage (Figure 16). The efficiency of this structure, 80 to 90 per cent, was sufficient to provide adequate gain from three stages.

"The present limiting factor of the tube's performance is its low signal-to-noise ratio compared with the Iconoscope performance. This low ratio results from the low target capacitance." This conclusion, quoted from the contractor's final report, should be reexamined in terms of the noise-signal-frequency relations discussed above. In any case it appears that the overall efficiency of the tube approaches, as far as sensitivity is concerned, the quantum efficiency of the photosurface.

5.5.4 Radio-Transmission Links

Amplitude vs Frequency Modulation

In an effort to obtain the same improvement in freedom from interference for television that has been obtained with audio transmission, experiments were made with frequency modulation at each of the carrier frequencies with which the Division's contractors were concerned. At all except the highest band (1,800 mc) frequency modulation was inferior to amplitude modulation. Amplitude modulation at 1,800 mc proved impracticable.

At Block I and Block III frequencies,[16,17] it appeared that with the same bandwidth per channel, FM is definitely inferior to AM. This is true even with a stationary transmitter and receiver; with relative motion between transmitter and receiver the picture degradation is even greater. The pictures of Figure 17 show the results of multipath beating. Where large changes in brightness took place, the range of the discriminator was sometimes exceeded. Under such circumstances the swing of the signal carried over onto the reverse slope of the discriminator characteristic, producing a negative image.

Figure 16. Image Orthicon—miniature in foreground and standard size in background.

The comparison of FM and AM at other frequencies is discussed in connection with the development of radio-transmission links at higher frequencies.

Television at Higher Frequencies

The continuing increase in communication density continually drove television into higher and higher ranges of the electromagnetic spectrum. The first work on military television was carried out at about 100 mc. Even before the organization of the Division, this band had to be abandoned, and a band in the vicinity of 300 mc was assigned. During 1943 the 300-mc band was barred to television, and bands were made available at 800, 1,200, and 1,800 mc.

Block X.[18] This program, carried out by Philco under Contract OEMsr-1159, covered the development of a radio-transmission link at 775 mc. Video and synchronizing were provided by a standard Block III camera unit. Two transmitters were developed, one using frequency modulation, the other amplitude modulation (Figure 18). Appropriate receivers were developed for each transmission system; the video end of the receivers (viewing tube, sweep circuits, etc.) were taken from standard Block III receivers.

AM Transmitter. The video signal from the camera unit was amplified through three stages and a driver

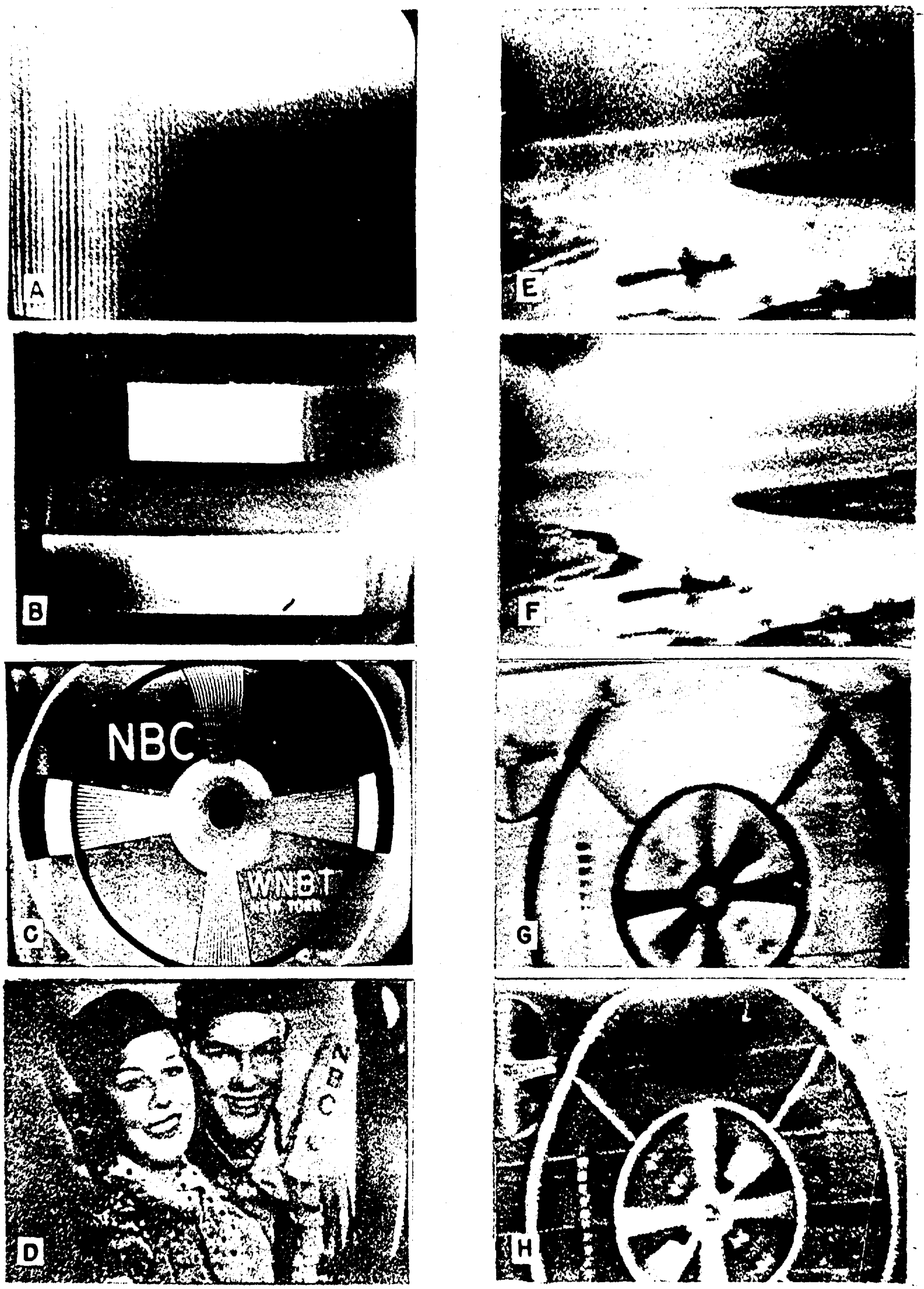


FIGURE 17. Multipath, distortion, and reversal of television pictures in FM transmission at 312 mc. A and B show multipath interference; C shows some distortion; D is a substantially normal picture; E and F are adjacent frames of a 16-frame-per-sec motion-picture record, F being partially reversed; G and H show almost complete reversal.

Figure 19). The output of the driver (modulator) was impressed on the cathode of the final r-f output stage. Synchronizing signals were similarly amplified

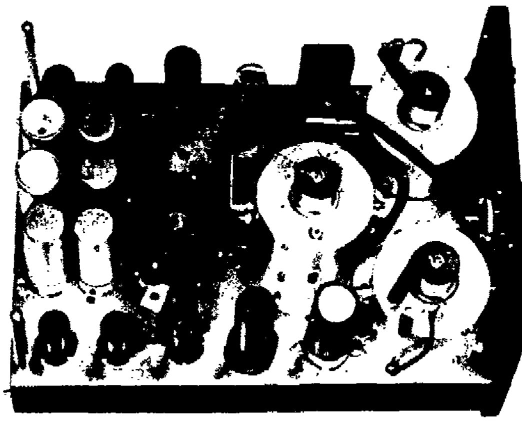


FIGURE 18. Block X AM transmitter.

through three stages and a modulator, rectified, and impressed on the plate of the r-f output stage. The r-f system consisted of a master oscillator, a buffer, and a single output stage. Oscillator, buffer, and output tubes were 2C44 tubes in resonant cavities with small plate and grid trimmers. Degenerative feedback around the oscillator and output provided stable wide-band operation. Interconnection between stages and to the antenna was by short coaxial lines. The antenna consisted of two dipoles driven in phase, with ⅝-wavelength vertical spacing (Figure 20). Two parasitic reflectors, each a quarter-wavelength behind the driver dipoles, assisted in producing an overall antenna gain of 4. The output of the AM transmitter was 4 watts.

AM Receiver. The AM receiver was a superheterodyne with 446-A tubes as the oscillator and mixer (Figures 21 and 22). Its six-stage i-f amplifier had a band-pass of 10 mc, centered at 60 mc; the three-stage video system had a band-pass of 4 mc. Fast (0.01-sec time constant) delayed AGC provided substantially flat output between 150-v and 1,000-v input.

FM Transmitter. The r-f suboscillator of the FM transmitter (Figure 23) operated at 260 mc. Video and synchronizing signals were separately amplified and mixed in a cathode-follower stage, which drives a reactance tube to swing the oscillator frequency through 1⅓ mc. The modulated oscillator was am-

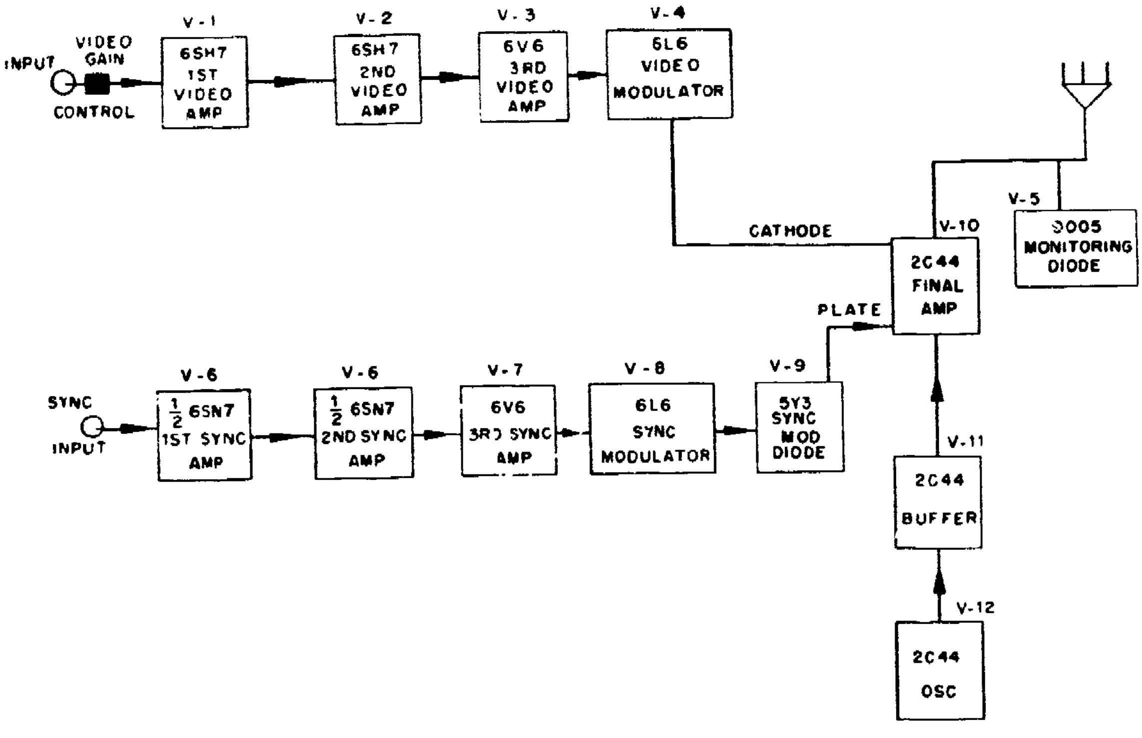


FIGURE 19. Block diagram of Block X AM transmitter.

plified through two push-pull, Type 832 amplifier stages, which drove a cavity-type frequency tripler followed by two cavity-type output stages. The antenna used with this transmitter (Figure 24) was identical with that used with the AM transmitter. An output of 3.5 watts was attained.

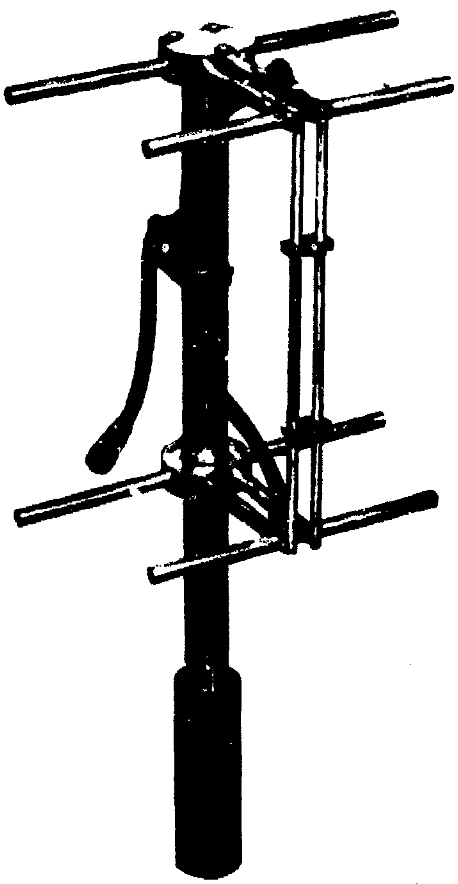


FIGURE 20. Block X AM transmitting antenna.

FM Receiver. The FM receiver (Figures 25 and 26) was a unit similar to the AM unit with such differences in the i-f system as were dictated by the use of frequency modulation. The local oscillator and mixer were identical; they were followed by a total of seven i-f stages, the last two of which were limiters. The i-f bandwidth was 10 mc. The discriminator employed two 9006 tubes, each with its tuned circuit capacity coupled to the last i-f stage. AGC was rather less effective than for the AM receiver, the output rising some 80 percent as the input signal increased from 150 v to 1,000 v.

Flight Tests. Figure 27 shows the comparative picture quality for the two systems, and the following tabulation gives their comparative performance.

	AM	FM
Transmitter power (average)	4 watts	3.5 watts
Range, substantially free of noise	5 miles	2.5 miles
Limit for reliable synchronization	10 miles	5 miles
Maximum range under optimum conditions	32 miles	20 miles

Block XII.[19] The improvement of airborne television equipment by raising the carrier frequency to 1,200 mc was considered. It was hoped that this change would (1) reduce aerodynamic drag by reduction of size of the antenna structure; (2) improve directivity, thus improving the power radiated in the desired direction; (3) obtain more channels and give greater freedom from electrical jamming; (4) result in less interference from ignition and pulse sources. Lack of suitable tubes to permit the design of a broad-band amplifier at this frequency blocked the program. By the time tubes were available (see *Block X* above and *Block XVIII* below), this frequency band was closed to television.

Block XVIII.[20] The Division assigned to the General Electric Company under Contract OEMsr-1172 the task of developing a transmission link in the 1,850- to 2,000-mc band. Originally it was planned that both AM and FM systems would be developed. Initial calculations indicated, however, that even if the carrier was crystal-controlled amplitude modulation of the final stage would produce sufficient variation of the transit angle to give an intolerable amount of phase modulation. These preliminary conclusions were confirmed by AM experiments using tubes of lighthouse construction (ZP464 and L30C). The preliminary work, analytical and experimental, further showed that plate amplitude modulation at the oscillator was a promising method of obtaining frequency modulation (Figure 28). Specifically, 15-mc swing of an 1,850-mc carrier could be obtained with 20 to 30 per cent amplitude modulation. This range of AM was well within the scope of well-designed limiter stages.

The *frequency-modulated transmitter* consisted of a reflex velocity oscillator using a 2K28 lighthouse tube in a cavity tunable to the carrier frequency. Standard 2K28 tubes could not be depended upon to give a 15-mc swing when amplitude modulated 20 to 30 per

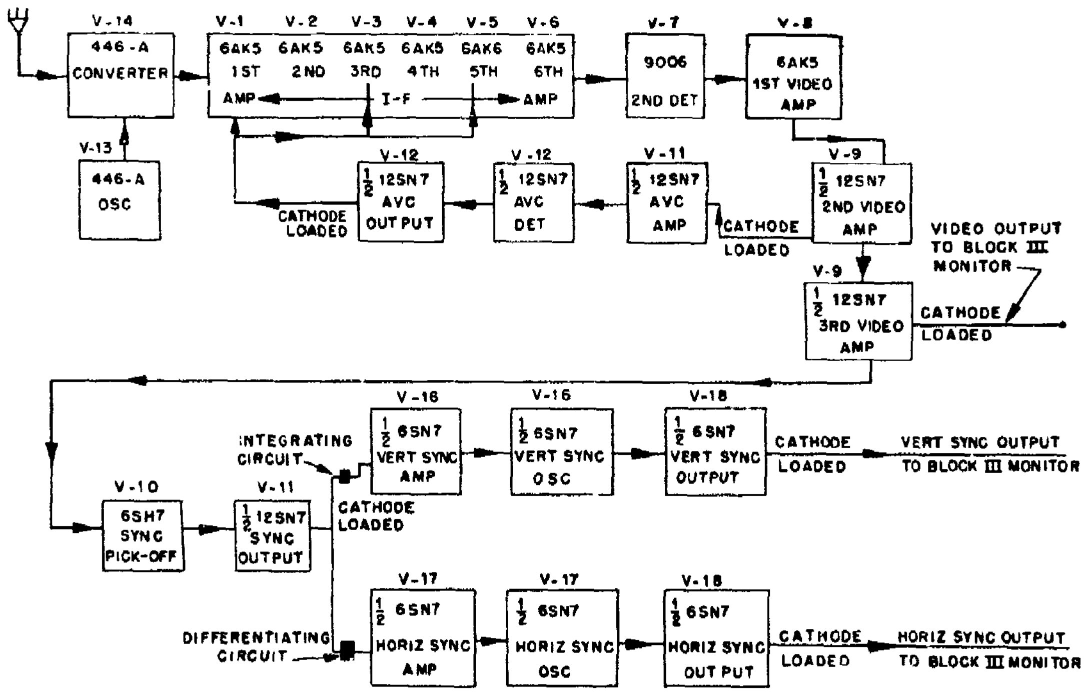


FIGURE 21. Block diagram of Block X AM receiver.

cent; selected tubes, however, would yield at least this degree of frequency modulation.

The video and synchronizing signals were brought separately to two 6AB7 pentodes, with individual gain control obtained through the bias to the individual grids. Joint gain control was provided by voltage adjustment of the common grid-bias potential source. The plates of the 6AB7's were paralleled for mixing the video and synchronizing signals. A 6AG7 stage amplified the combined video and synchronizing signal to 60 volts, peak-to-peak for plate modulation of the oscillator.

Two stages of power amplification, using ZP579's and interconnected with tunable plumbing, supplied the antenna. As originally laid out, the transmitter supplied 5 watts to the antenna; revisions in the cavity and plumbing design doubled the output.

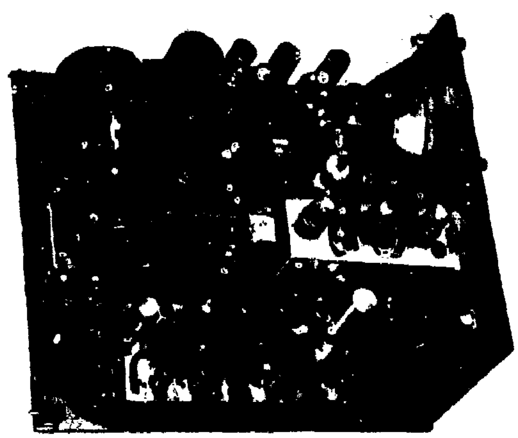


FIGURE 22. Photograph of Block X AM receiver.

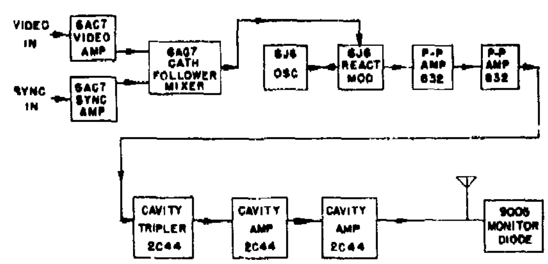


FIGURE 23. Block diagram of Block X FM transmitter.

The transmitting antenna (Figure 29) consisted of five dipoles coaxially mounted and backed by a plate reflector. This array yielded a distribution, in a plane containing the dipoles and normal to the reflector, 20 degrees wide to the half-power points. In a plane normal to the dipoles, the distribution pattern was 120 degrees wide to the half-power points. Figure 29 shows the complete transmitter and its antenna.

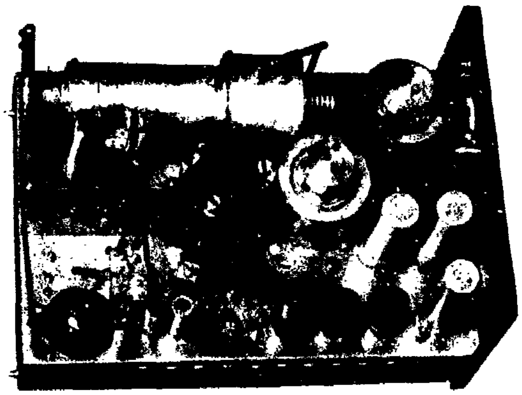


FIGURE 24. Block X FM transmitter.

The *Block XVIII receiver* was a superheterodyne with a GL-466-A lighthouse local oscillator and a crystal converter. The cavity of the GL-466-A had built-in feedback between the anode and cathode resonators to sustain oscillation. The resonators were tunable over a 150-mc range, which was arbitrarily divided into 10 channels of 10-mc width.

The antenna and local oscillator were capacitively coupled to the converter, which consisted of a standard radar crystal cartridge in a quarter-wavelength cavity (Figure 30). The output of the converter was 50 mc, with a 15-mc swing for the video and synchronizing signal.

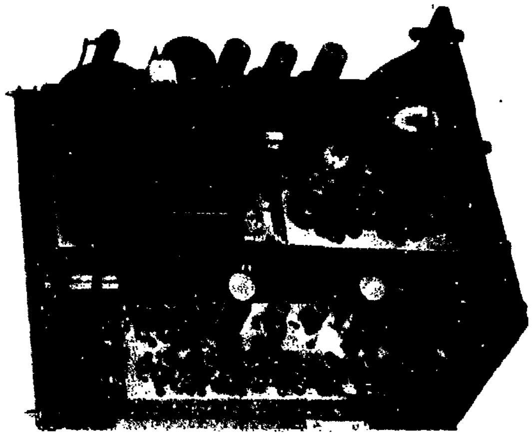


FIGURE 26. Block X FM receiver.

The 50-mc i-f signal was amplified through nine pentode stages using 1852 tubes. The last two stages were limiters to clip noise and remove the amplitude modulation which produced the desired frequency modulation. A 6HG discriminator was 20 mc wide, compared with the maximum frequency swing of 15 mc. This resulted in a loss of efficiency—maximum

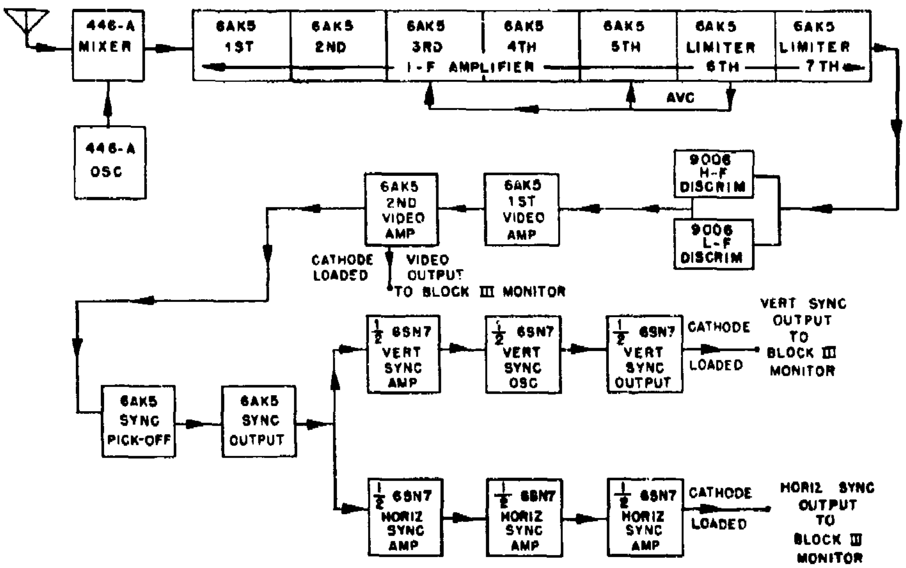


FIGURE 25. Block diagram of Block X FM receiver.

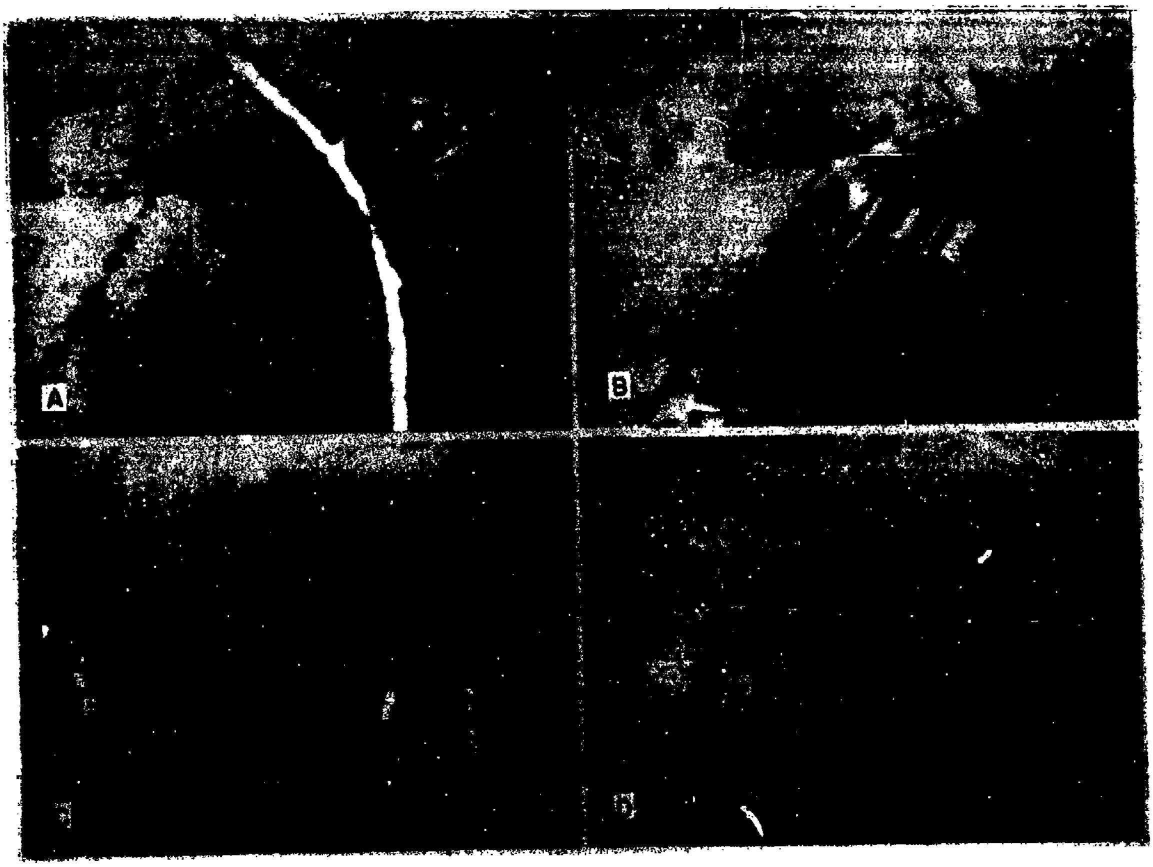


FIGURE 27. Comparison of AM and FM reception: A, AM, 3½ miles; B, FM, 1½ miles; C, AM, 10½ miles; D, FM, 5 miles.

video output from the discriminator, 0.1 v—for the sake of preserving linearity of discriminator action.

Video and synchronizing signals were separated after the second video amplifier stage. AFC by means of phase discrimination with the received synchronizing pulses could be applied optionally to the receiver scanning oscillators.

The antenna (see Figure 31) consisted of five coaxial dipoles. This array gave an omnidirectional pattern in a plane normal to the dipoles. In the perpendicular planes the sensitivity was down 3 db along the 20-degree lines.

Test results showed that reliable picture transmission could be obtained without multipath interference if the received signal was adequate to give good limiter action. In stationary ground-to-ground transmission, limiting action was satisfactory at 6 miles (grazing line of sight) with a 2-watt transmitter output. With a 4-watt output and a 1,200-ft effective elevation of the transmitter, the limiter action was satisfactory at a 12-mile transmission distance.

Plane-to-plane transmission yielded usable signals up to 15 miles with 6 watts radiated from the transmitter. With revised transmitter plumbing, the ra-

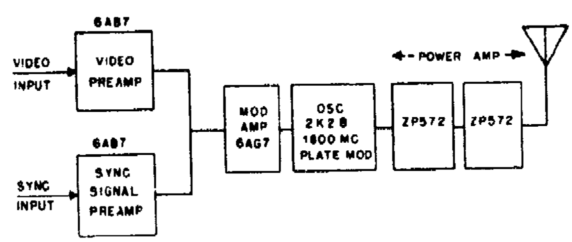


FIGURE 28. Block diagram of Block XVIII transmitter.

diated power was increased to between 10 and 12 watts. Plane-to-ground and plane-to-plane tests with the increased transmitter power were not made. Multipath difficulties were absent when the transmission was short enough to insure limiter action and when the receiver supply voltage (28 volts) was normal. Reduction of the receiver supply voltage to 24 volts produced bars on the received picture similar to Block III multipath patterns. Study of the i-f plate and screen supply was not neglected. It is perhaps not impossible that the reduced voltage cut the i-f gain sufficiently to prevent limiter action.

A *miniature Block XVIII*,[21] utilizing the miniature Image Orthicon, was under development as World War II closed. The possibility of obtaining high directivity from a compact antenna array suggested that television at Block XVIII frequencies might eliminate the doppler-effect difficulties with Roc. The project was terminated at the cessation of hostilities.

5.5.5 Television in Missiles

PRELIMINARY TESTS WITH GLIDE BOMBS

The glide bombs of the National Bureau of Standards (see Chapter 1) were planned for remote radio control with television. The missile consisted of a monoplane airframe with a 12-ft wingspan and a 2,000-lb GP bomb as payload. The empennage structure was fixed, "guiding" being performed by deflection of full-span trailing-edge wing flaps (elevons). Deflection of the flaps changed the camber of the wing, with resultant change in its lift coefficient. Thus the missile flew with substantially zero change in angle of attack with changing glide path (see tabulation in Section 1.3). Turns were effected by differential elevon displacement.

Tests were made of Block I in Robin (Figure 32) in April and July 1943[22,23] In the April tests, transmission was from the missile to a ground station where the radio-control transmitter was located. For such drops as had a very good initial launching, the received picture was adequate to permit recognition of the target at moderate range, about ¾ to 1 mile. It was by no means good enough to permit recognition of the target area during early phases of the flight, 3 to 5 miles. Therefore flights failed in which the combination of launching error and automatic-pilot operation resulted in a heading error in excess of some 15 degrees at a 1-mile range. Those tests whose unguided flight brought the missile within a mile of the target and at a heading which brought the target within the field of view of the camera scored misses of from 100 ft to 500 ft. The ground radio-control and television-receiver station was located about 1,500 ft from the target. Consideration for the physical safety of high-ranking observers may have interfered with the ability of the controlling bombardier to obtain better scores.

With a ground control station the conditions for television are somewhat better than would exist in a tactical situation (Figure 33). Any ground reflections will be directed away from the television receiver,

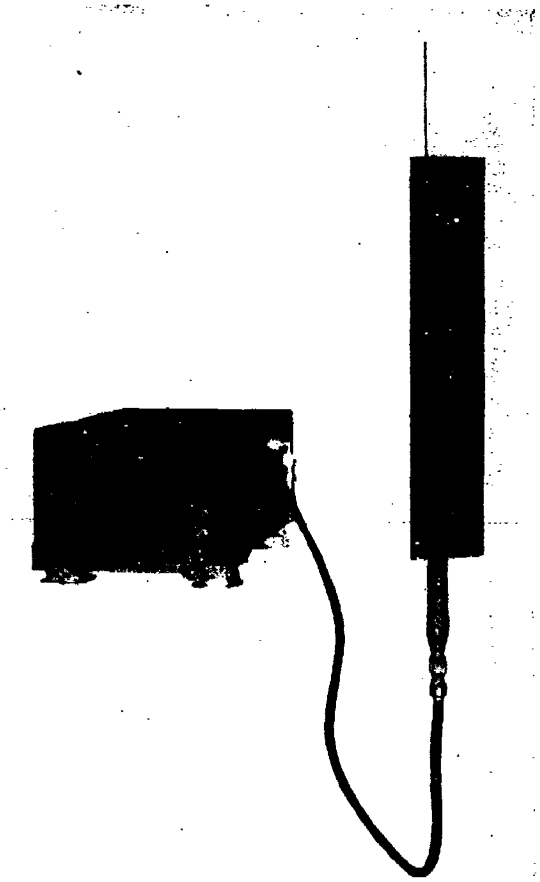


FIGURE 29. Block XVIII transmitter and antenna.

eliminating multipath problems. Further, the absence of severe vibrations, which are inescapable in tactical aircraft, prevent the appearance of microphonic noise generated in the receiver.

In the July experiments the receiver and control station were airborne in the bombardment airplane. The nose housing of the missile had been lined with Ozite to absorb acoustic vibrations, which were believed to have impaired seriously the television per-

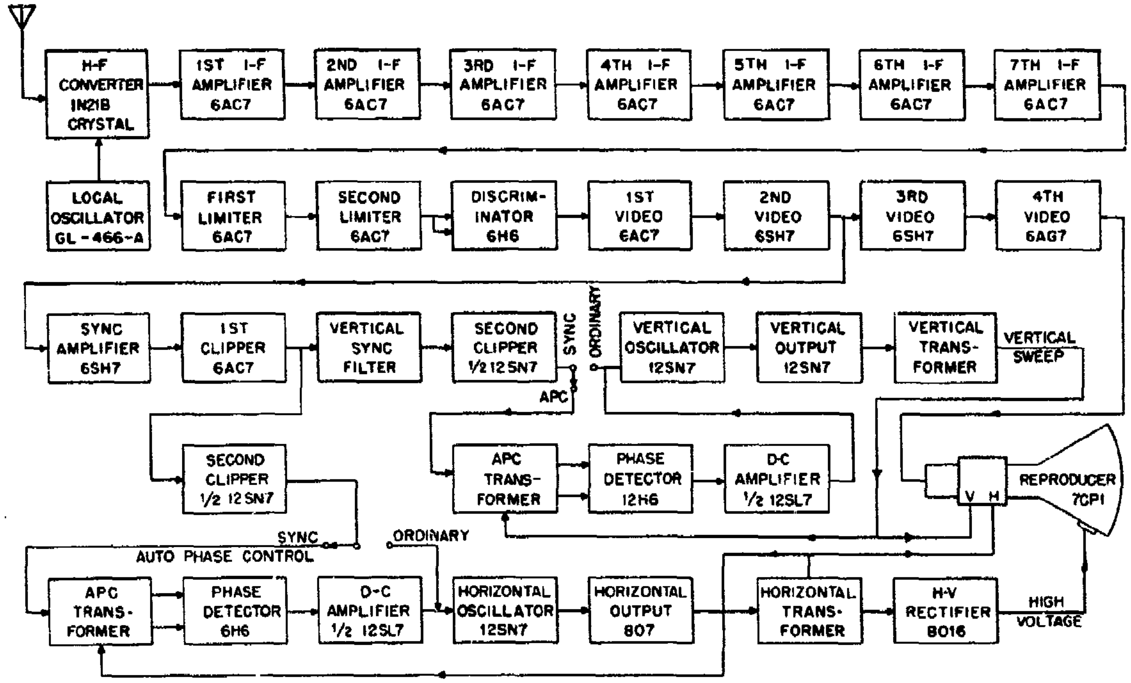


FIGURE 30. Block diagram of Block XVIII receiver.

formance in the April tests. As a further guard against microphonic disturbance originating in the camera-transmitter equipment, the camera-transmitter was covered with acoustic deadening material and sponge rubber. Microphonics were much reduced, and residual disturbance was attributed to microphonics originating in the receiver. The total disturbance was sufficiently severe to cause tearing of the picture. It is not clear whether this interference was due wholly to microphonics or, at least in part, to multipath beating.

At the conclusion of these experiments the Division's work with television-guided glide bombs was terminated. The Navy was much more interested in the application of radar-homing control to this missile—Pelican and Bat (see Chapter 1). The AAF had already under way a glide-bomb program of its own,[1] one version of which was television-guided. The Division served cooperatively on the AAF program and supplied, through its contractor (RCA) under Contract OEMsr-441, consultation services on television aspects of the project.[24] The problem of guiding successfully a television-guided missile has already been touched on. It was particularly acute in the AAF glide bomb GB-4. This missile has a conventional empennage which provides two-axis steering, as in airplane practice. Consequently it flies with a variable angle of attack, and bore-sight errors exist at all but a single elevator setting.

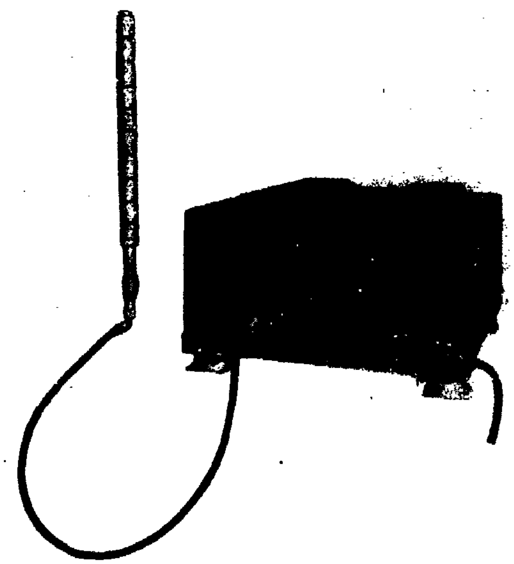


FIGURE 31. Block XVIII receiver and antenna.

Television in Dirigible High-Angle Bombs

The Division's predecessor groups had made contracts with Hazeltine Service Corporation,[25,26] Farnsworth Television and Radio Corporation,[27] and RCA[7,14,28,29] to develop compact television pickup and transmitting equipment of such compass as to be contained within a standard aircraft bomb. None of the contractors succeeded in producing a reliable assembly which would be contained within a 1,000-lb GP bomb and leave space for an appreciable charge of explosive. The equipment would fit in the compass of the standard 2,000-lb bomb with space for approximately the bursting charge of a 1,000-lb GP bomb.

The Hazeltine project compromised resolution and flicker as a concession to compactness. To obtain minimum bulk the scanning frequency was reduced to 210 lines per frame and 10 frames per second. Transmission on a 220-mc carrier was by frequency modulation for the video signal and by amplitude modulation for the synchronizing and blanking pulses. The radiated output was approximately 1 watt.

To compensate for the large variation in angle of attack which a high-angle dirigible bomb undergoes, vanes mounted in the wind stream were coupled to the pickup assembly so as to keep the camera objective continuously aligned with the flight path.

Experiments indicated that the resolution and power output were inadequate and that flicker was at an objectionable level.

The Farnsworth project employed the Image Dissector. Its comparative freedom from microphonics (see Figure 8) and circuit simplicity—thirteen tubes and four controls in the Dissector camera as compared with seventeen tubes and fourteen controls for the Block III Iconoscope—made it attractive for missile application, although its low sensitivity was a drawback. Transmission was at 112 mc, amplitude modulated with a single 4-mc sideband on the basis of 225 lines and 40 frames sequentially scanned.

The transmitter oscillator consisted of two 6C4 triodes in a modified Hartley circuit. The oscillator, plate modulated by the video and synchronizing signals, was transformer coupled to the power amplifier, which consisted of an 832 twin pentode in push-pull. This circuit was able to radiate approximately 10 watts. Plane-to-plane tests produced a received picture with bars characteristic of spurious frequency modulation. The picture was, however, deemed adequate to justify drop tests. Poor weather frustrated the program, and dropping tests were never carried out. Figure 34 shows nose and tail views of a dirigible

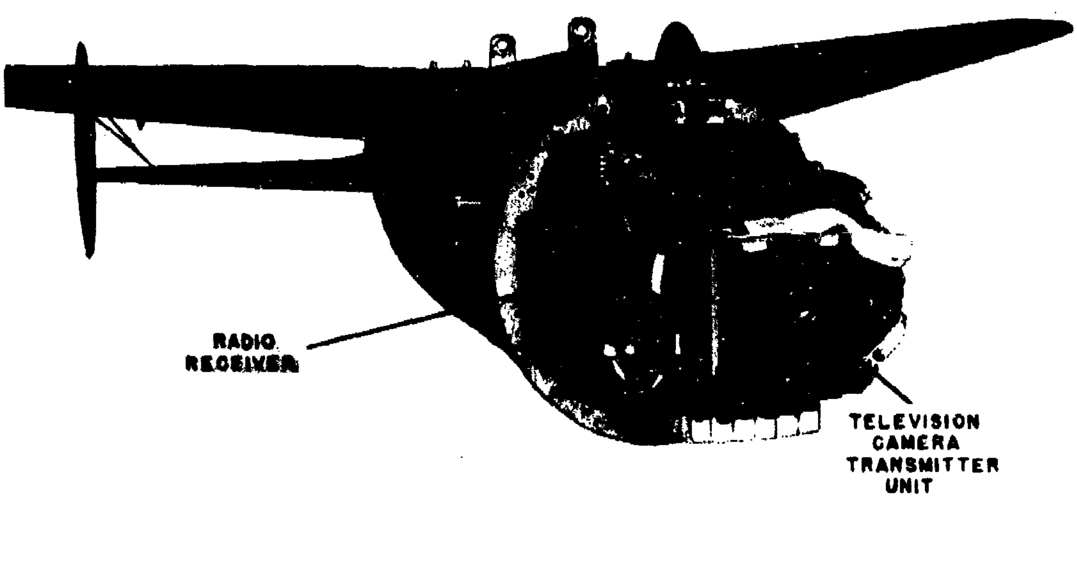


Figure 32. Robin, nose fairing removed.

bomb C equipped with Farnsworth television camera-transmitter equipment.

The *Vericon* equipment (Figure 35) was manufactured by Remington Rand. The camera tube was similar to the Orthicon of RCA (see Figure 14). Its development was undertaken by the contractor because the difficulties in the control of secondary electrons in pickup tubes of the Iconoscope type seemed insurmountable to them.

The 105-mc carrier was amplitude modulated with video and synchronizing signals. Scanning frequency was based on 350 lines and 30 frames per second. The master oscillator was crystal-controlled at 26.25 mc and was followed by two frequency doublers in a 6N7. The video and synchronizing signals grid modulated the power amplifier, two 829 tetrodes in push-pull. The power output was approximately 10 watts.

The resolution obtained by the contractor was rather better than that obtained by Columbia in the comparative study of pickup equipments (Figure 36). The reason for this has never been made wholly clear. The automatic beam-focusing control included in the camera circuit may have been a contributing factor. As in the case of the Farnsworth equipment, drop tests were planned for this equipment but were cancelled on account of poor weather.

Drop Tests. In addition to the foregoing, which were never conclusively tested, the Division had a project with RCA to adapt the Block I, 100-mc, equipment to the guidance of the high-angle dirigible bomb (Figure 37). Preliminary tests were held at Eglin Field in the winter of 1942–43. They showed sufficient promise to justify continuing development work. Further tests with revised television equipment were made at Tonopah Air Base in April and May 1944. While the results as regards television were probably satisfactory, the tests emphasized how different the problem of steering such a missile was, even with wholly satisfactory television performance. In view of the Division's program with Roc (see Chapter 4) and Mimo, work on a television-guided high-angle bomb was shelved.

The Eglin Field experiments comprised drops with three missiles. One was a dummy, provided with a parachute which extended the time of fall from approximately 30 seconds to 6 minutes; this permitted more complete observations of missile-to-plane transmission than could be made with an unimpeded drop. This dummy missile was not equipped either with radio control or gyro stabilization. The other two missiles were laboratory prototypes to explore the possibility of accurate steering.

Preliminary tests to determine radiation strengths and approximate patterns were made by standing the missile on end on the ground and transmitting a video signal to an airplane 15,000 ft above it. These tests

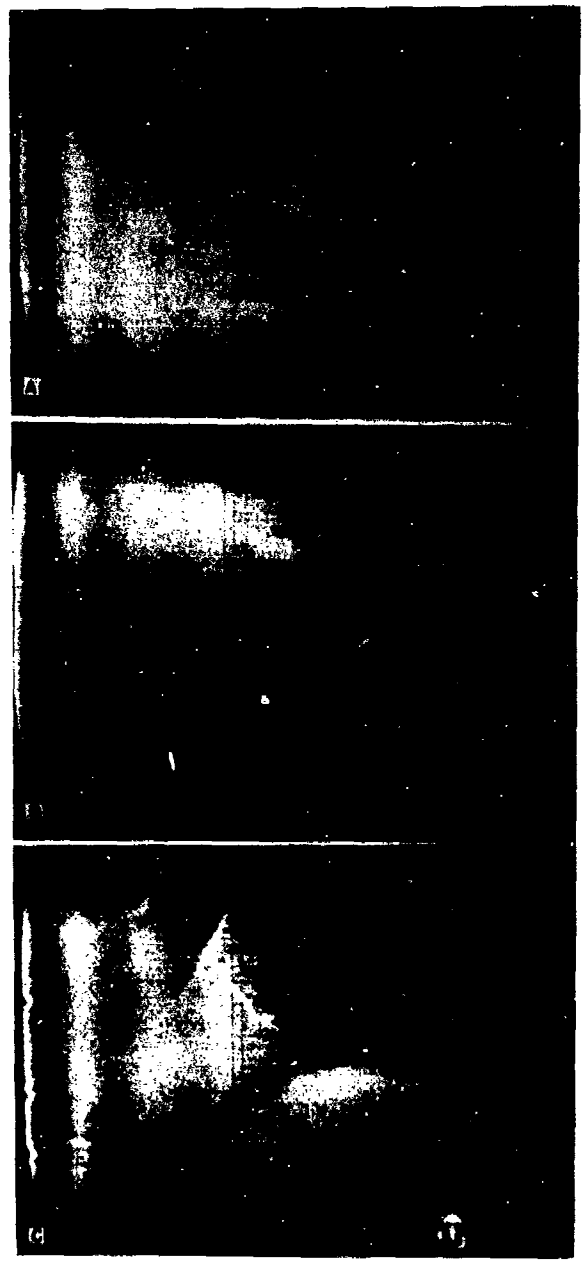


FIGURE 33. Photographs of received picture at ground control station: A, 1 min before impact; B, 30 sec before impact; C, 10 sec before impact. Arrows indicate target.

disclosed that the radiation core from the missile was approximately 37 degrees wide to an undefined minimum signal-strength level. They also disclosed a serious pulse-modulated interfering signal at almost exactly the carrier frequency of the Block I transmitter. This proved to be a nearby radar search station operating at 105 mc. Further work was carried forward by an informal agreement to shut the radar

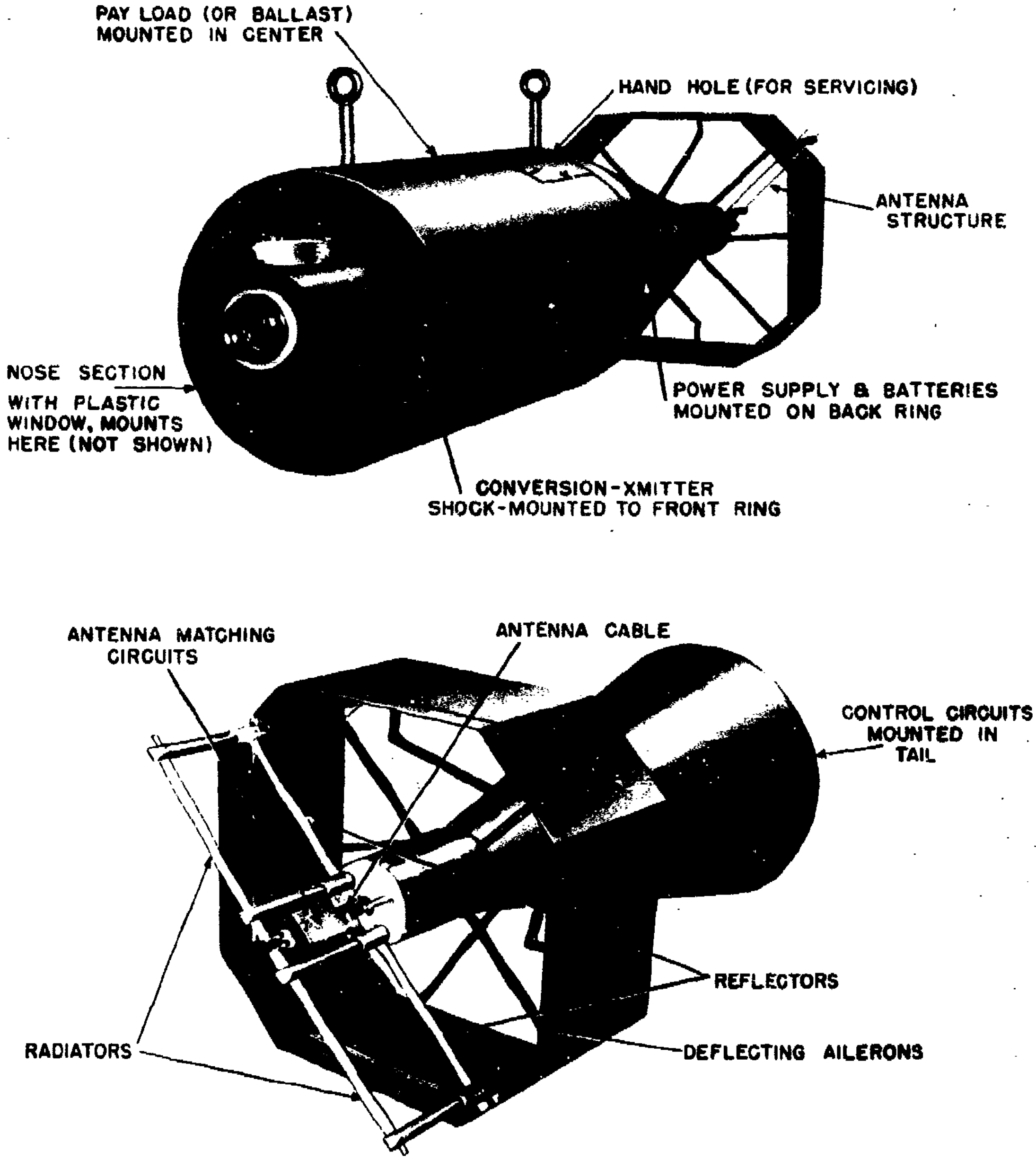


FIGURE 34. Nose (fairing removed) and tail views of dirigible bomb equipped with Farnsworth television camera-transmitter equipment.

station down when it was desired to put the television on the air.

The dummy was dropped with parachute recovery. Picture reception was considered satisfactory, although there was some loss of horizontal synchronism. This the television operator at the receiver was able to correct promptly. The equipment having been recovered undamaged, the dummy was then dropped unimpeded. The trouble with horizontal synchronization continued but was deemed inconsequential.

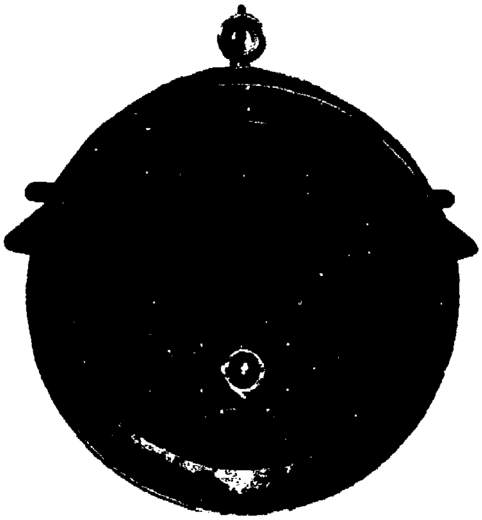


FIGURE 35. Vericon camera installed in dirigible high-angle bomb.

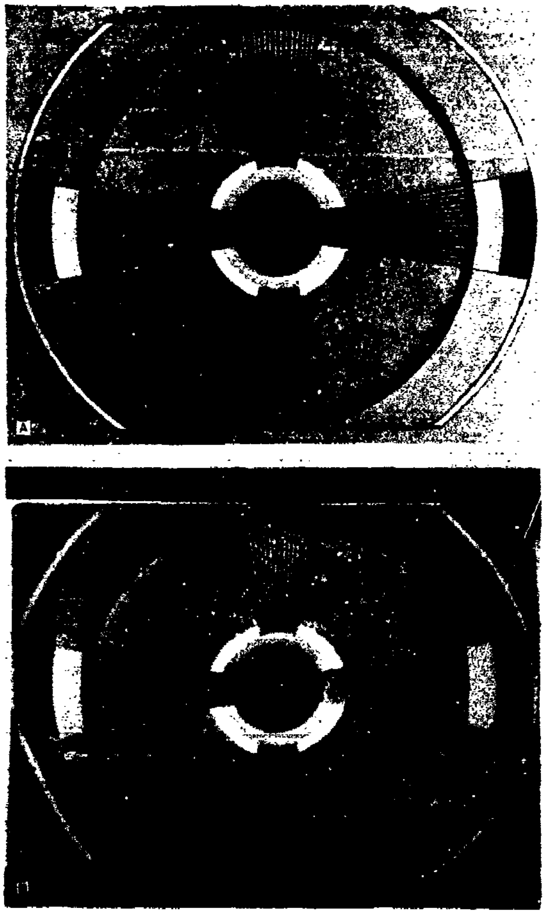


FIGURE 36. A, standard resolution chart; B, picture received from Vericon pickup.

The two prototype missiles were then dropped. The enthusiasm of the investigators was undampened, in spite of a report which stated, "There was a very objectionable white band about an inch wide [out of a viewing screen about 4 inches wide] and two inches down from the top which extended completely across the picture raster." This effect, which had been observed before, was most probably caused by interference with the ground-reflected signal, inasmuch as it was not observed at the ground monitor station. Other difficulties included: (1) horizontal bars due to crosstalk with the radio-control carrier, or possibly to microphonics; (2) vertical bars probably due to multipath; (3) loss of horizontal synchronism due to fluctuation in the battery voltage, as the coverage of the plates by electrolyte varied with changes in the missile attitude.

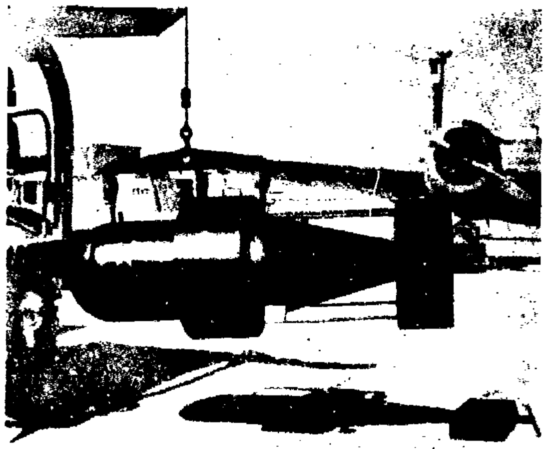


FIGURE 37. Television-guided high-angle bomb.

The *Tonopah experiments* were made with Block I equipment in which the improvements cited in Section 5.5.1 had been incorporated. Clamp circuits were included in the camera-transmitter units. All receivers had a tunable r-f head and low-impedance AGC. Receivers planned for use in controlling the missile had phase-actuated AFC. An antenna of improved gain to increase the radiated power was installed on the bomb (Figure 38). To compensate for varying angle of attack with application of control, stiff wires were mounted vertically and horizontally in front of the viewing screen (Figure 39). With no control signal applied, these wires crossed in front of the center of the screen; upon application of control signal, they moved across the screen horizontally and vertically at a speed proportional to the rate of rudder or elevator displacement. To a first-order approximation (see Chapter 2), this action compensated for changes in angle of attack during steering, and the point of intersection of the crossed wires corresponded to the point on the transmitted image of the terrain toward which the missile was heading. To avoid crosstalk between the control and television signals, the transmitting antenna (Figure 40) for control signals was mounted in front of the bombardier's greenhouse. The television receiving antennas (Figure 41), two parallel dipoles, were mounted under the belly of the ship.

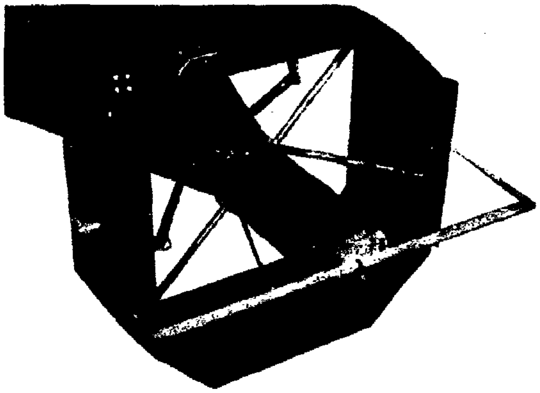


FIGURE 38. Folded-dipole antenna on television-guided high-angle bomb.

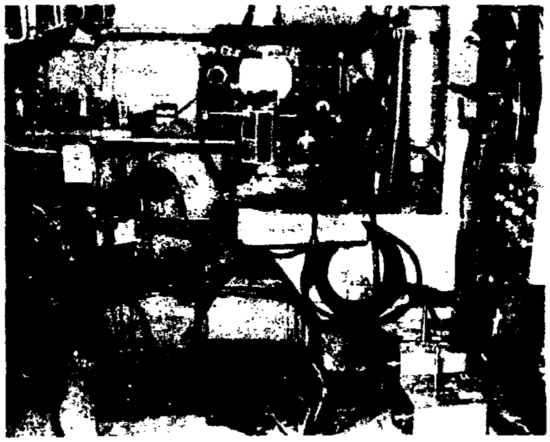


FIGURE 39. Receiver in B-25 airplane showing arrangement of compensating crossed wires on television screen.

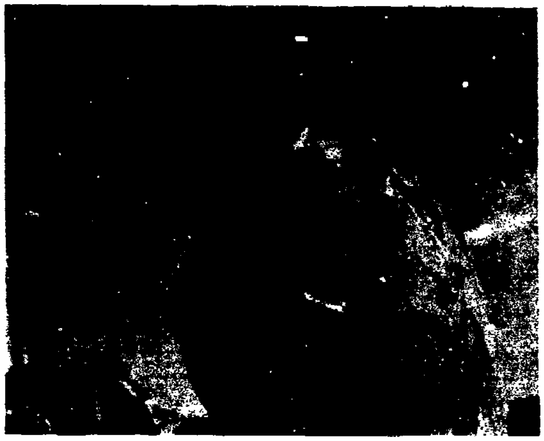


FIGURE 40. Radio-control transmitting antenna.

FIGURE 41. Television receiving antennas.

In addition to the receivers in the plane, a group monitoring station was installed in a blacked-out 2½-ton truck near the bombing range. Reliable radio communication was maintained between the ground monitoring station, the airplane, and the target area. The target consisted of scraped areas on the desert floor—a 100-ft diameter bull's-eye with scoring rings of 200-ft and 500-ft diameter. To improve the low contrast between the scraped target and the general terrain, slaked lime was spread on the bull's-eye and scoring rings. This did not, however, remain in place long on account of the high winds prevailing at that season.

Preliminary to the drop tests, passage tests were made in which all signals which might be on the air during a drop were simultaneously operated. There was no crosstalk, and the received television signal was reasonably free from microphonics. No picture was received since the bomb was enclosed within the bomb bay of the B-25, and the glass window of the bomb was masked.

In the first drop the operator never saw the target, and the miss was 2,000 ft in range and 2,800 ft in

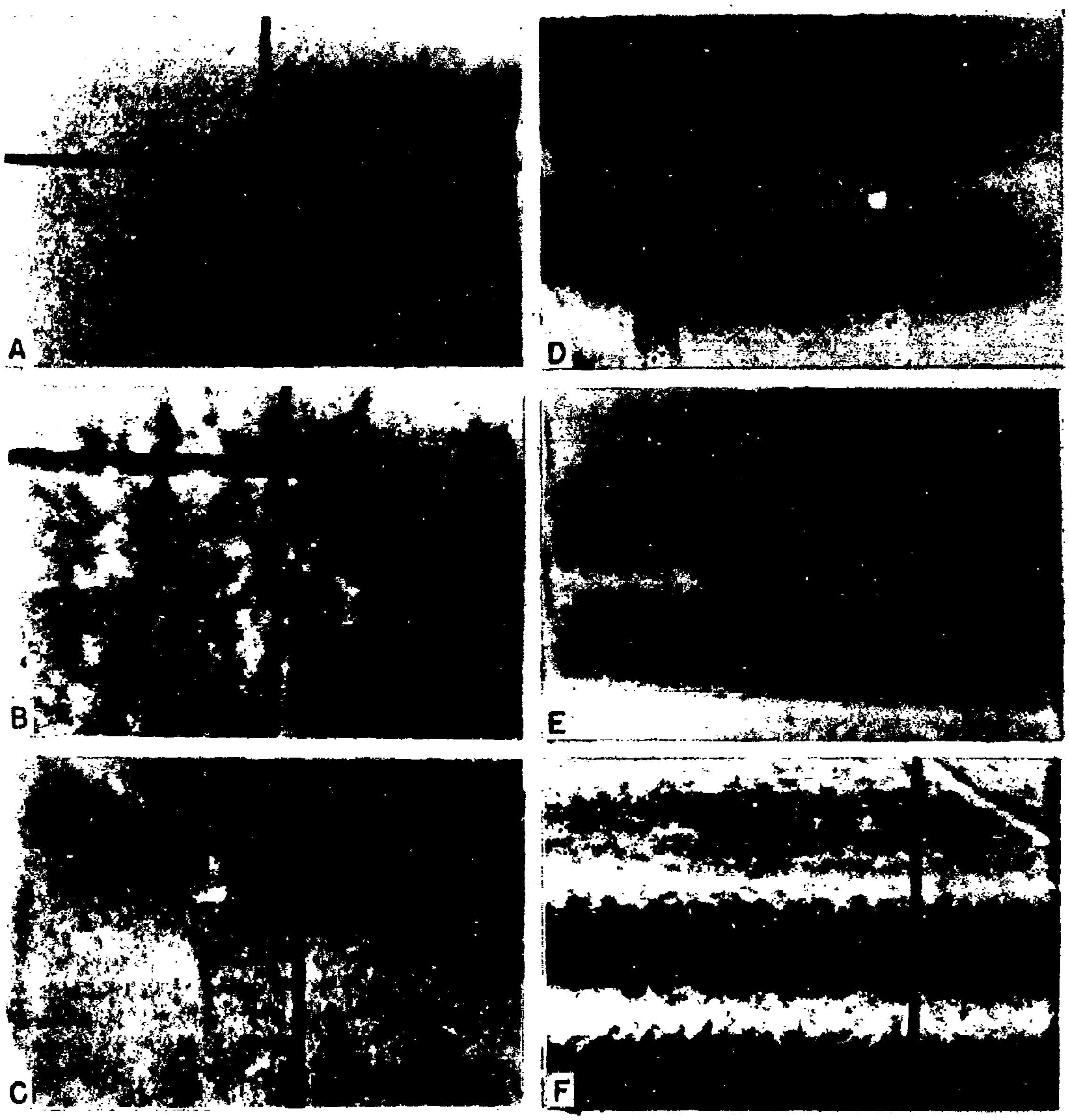


FIGURE 42. Received pictures in airplane: A, B, and C, time of release and altitude not known; D, 21.8 sec from release, altitude 3,860 ft; E, 28.1 sec from release, altitude 1,035 ft; F, 28.8 sec from release, altitude 250 ft.

azimuth. In the remaining four drops the errors were:

	Range error	Azimuth error
Drop No. 2	300 ft	250 ft
Drop No. 3	No record	
Drop No. 4	450 ft	525 ft
Drop No. 5	15 ft	250 ft

It was the consensus that television can produce an adequate picture of the terrain to improve bombardment materially during phase 3 (see Section 5.1) of an attack. The coupled crossed wires, however, are inadequate to compensate for variations in angle of attack. Bars due to interference between the signal from the missile and that from its image (see Figure 5) is a problem as yet unsolved. These bars typically appear about 15 seconds after release, when the bomb velocity has reached some 450 ft per second. They are shown in Figure 42, which is a group of single 16-mm frames from the motion-picture record of the

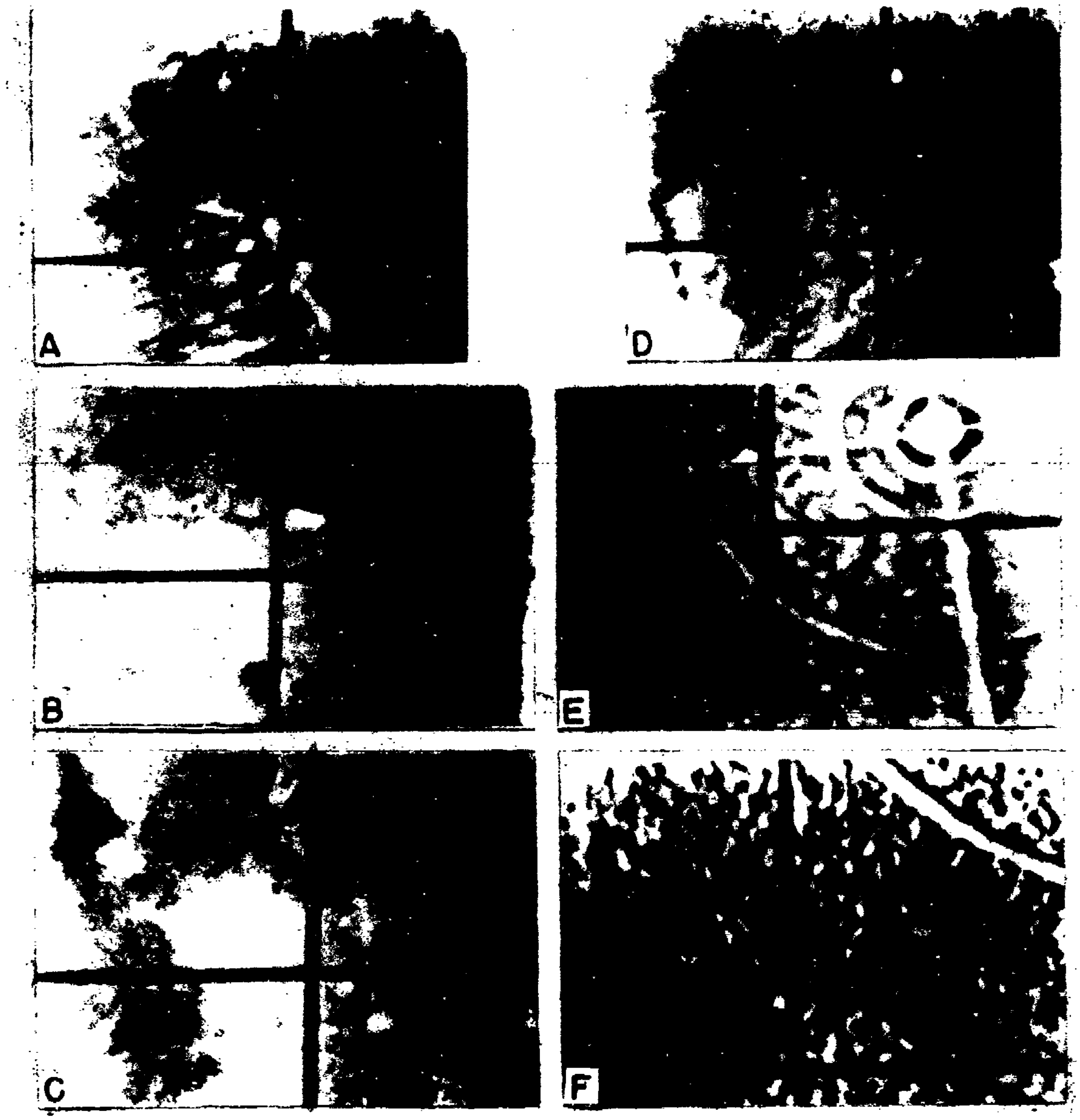


FIGURE 43. Received picture at ground monitoring station: A, 26 frames, 1.06 sec from release; B, 48 frames, 3 sec from release; C, 198 frames, 12.3 sec from release; D, 241 frames, 15.06 sec from release; E, 450 frames, 28.1 sec from release, altitude 1,035 ft; F, 461 frames, 28.8 sec from release, altitude 250 ft.

receiving screen in the aircraft. Their absence from the pictures received on the ground (Figure 43) is striking in comparison.

Even if the interference were not sufficiently severe to threaten to obscure the target and with adequate compensation for variation in angle of attack, the problem of steering is still paramount. If the missile is so maneuvered as to place the target early in the center of the receiver screen it will be impossible to hold it there, as the bomb will have been dived too early and adequate lift is not available with the high-angle dirigible bomb to pull out at the end. A lead computer which takes competent account of the dynamic trajectory of the missile is indicated. The development of such a computer for the high-angle dirigible bomb seems unjustified.

It had been planned to test the Image Dissector and the Vericon equipments during the Tonopah program. The onset of a long period of bad flying weather and the rather definite contra-indications in the results of the Block I experiments recommended a decision against further work with the television high-angle bomb.

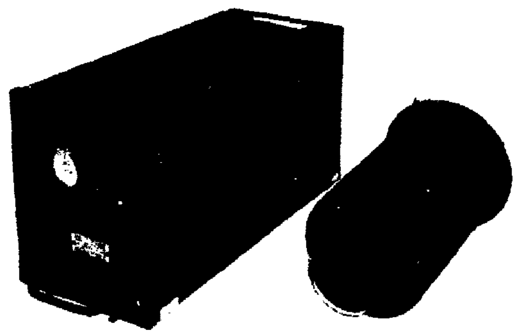


FIGURE 44. Mimo camera (right) compared with standard Block III camera (left).

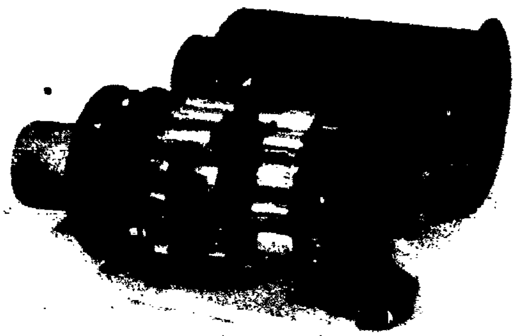


FIGURE 45. Mimo camera, cover removed.

Roc and Mimo Project[21]

The missile Roc, developed for the Division by Douglas Aircraft Company and discussed in Chapter 4 of this report, recommended itself to television guiding during phase 3 of an attack for several reasons. It was designed to fly with the axis of its fuselage continuously tangent to the flight path—zero angle of attack—so that the center of a television image received from a camera-transmitter bore-

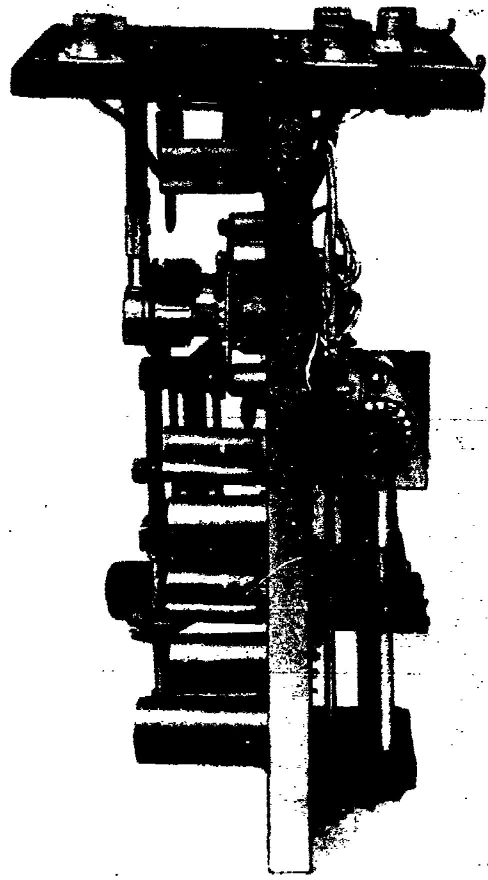


FIGURE 46. Mimo transmitter, side view, covers removed.

sighted with the axis of the missile would continuously indicate the point of impact of the missile with continued rectilinear flight. The normal trajectory was relatively steep—intermediate between the dirigible high-angle bomb and the glide bomb—so that the received picture of the terrain showed little foreshortening. Finally, its maneuverability, which was 7,500 ft minimum turning radius as compared with 20,000 ft for the production Razon, seemed to justify the use of television as a means of guiding, costly in complication and manpower though it was. Accordingly the Division, strongly urged by the Air Technical Service Command, undertook the development of a compact camera and transmitter equipment specifically for this missile. Miniature in compass and utilizing an Image Orthicon-type of pickup tube, it was dubbed Mimo. Transmission was set in the 300-mc band, although that frequency had been preempted by other communication services. The hope of getting a compact transmitter and carrier at 800 or 1,800 mc in time to be of military significance seemed remote.

Camera. The camera utilized a new tube similar in design and performance to the Image Orthicon (see Figure 16). It was, however, considerably smaller, being but 9 in. long overall and 1½ in. in diameter (Figure 44). All leads were brought out to a 17-prong base. This new design was brought out rapidly and smoothly. Except for loss of sensitivity beyond 0.71 μ on account of contamination of the photocathode by gas driven off from the electron cathode, its performance was identical with the larger version.

The entire camera unit (Figure 45) contained a video amplifier, deflection, and synchronizing circuits. The video amplifier contained four stages of 6AK5 miniature pentodes. The third stage had a high-frequency peaking circuit in the grid input to provide substantially flat response out to 4 mc, in spite of the high-frequency attenuation of the Image Orthicon. Beyond the fourth stage, a 6AK5 clipper provided a 0.3-v blanking pedestal for the synchronizing signal.

Both deflection circuits consisted of 3A5 twin triodes, operating as blocking oscillators and discharge tubes. The vertical deflection 40-c oscillator was followed by a 3A5 amplifier output stage with both sections connected in parallel; the horizontal deflection oscillator was followed by a 25L6 output stage. In addition to energizing the deflection coils for the pickup tube, each deflection output tube drove a blanking stage. The output of the horizontal blanking stage supplied a voltage to the clipper to create the blanking pedestal; the output of the corresponding vertical stage was applied to the target of the pickup tube to provide vertical blanking. The output voltages of the deflection circuits were mixed in a twin triode to provide the synchronizing signal.

Transmitter. The entire tube complement of the r-f section of the transmitter (Figure 46) consisted of three 2C43 lighthouse tubes. The master oscillator, which operated at carrier frequency, was tuned with a resonant line and had Colpitts feedback. An adjustable feedback capacitor determined the plate current at the proper level. The output of the oscillator was impressed, through resonant lines, on the grids of two 2C43's in push-pull, which comprised the output power amplifier.

The video and synchronizing signals were mixed at the first-stage grid of a three-stage video amplifier. The output stage, two 6V6's in parallel, grid modulated the power amplifier. When connected to a matching antenna, the transmitter radiated 7 to 10 watts.

Antennas. Four antennas were required for the Roc system. A transmitting antenna was necessary for the television equipment on the missile; this was known as Mimo-Roc. A receiving antenna for the channel was required at the plane; this was known as Mimo-Plane. A receiving antenna on the missile was required for the 84-mc control—Roc; a complementary transmitting antenna on the plane was known as Control-Plane. The Mimo-Roc antenna had to be so designed as to give a radiation pattern which would contain the plane at a bearing of high signal strength for any expected maneuver of the plane or missile. It also had to cut off forward radiation sharply so as to prevent, as far as possible, any signal from reaching the ground to produce multipath, as well as to conserve power. The elimination of downward radiation is tactically important to preserve security as well as being technically important for the reasons just mentioned. The Mimo-Plane transmitter ideally should cut off sharply beyond the limits of the cone originating in the plane which will contain the missile for all practicable maneuvers. The elimination of downward sensitivity of the Control-Roc antenna is an aid against jamming. The requirements of the Control-Plane antenna are similar to those of the Mimo-Plane.

The *Mimo-Roc* antenna (Figure 47) consisted of a tuned dipole mounted at the rear of the missile, with the axis of the dipole arms parallel to the pitch axis of the bomb. The Roc was gyrostabilized in roll by means of ailerons. Therefore its pitch axis is continuously parallel to the ground plane. The radiation pattern from the dipole can then be defined in terms of two orthogonal planes: the azimuth plane is one which contains the axis of the dipole arms and the

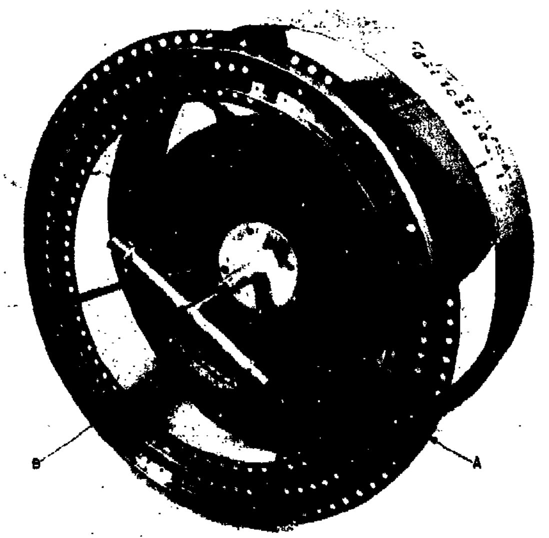


FIGURE 47. Antennas on Roc: A, Control-Roc receiving antenna; B, Mimo-Roc dipole.

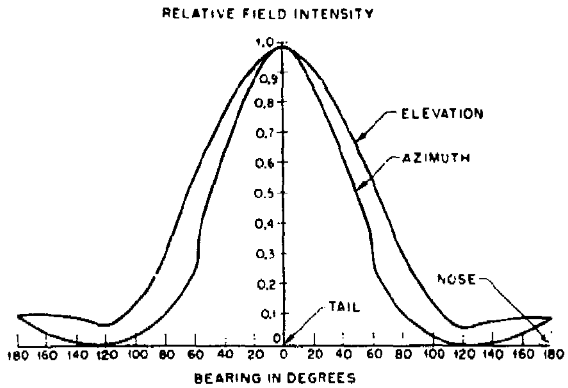


FIGURE 48. Radiation pattern of Mimo-Roc dipole.

axis of its stem; the elevation plane is perpendicular to it and also through the axis of the dipole stem.

It was desired to use the perforated dive brake as a reflector for the dipole. Its size and location were determined by aerodynamic arguments principally to give zero angle of attack at trim. It was also desirable to use the same element as the Control-Roc antenna in view of the need to maintain aerodynamic cleanliness. The problem, then, was to ground the dive brake to the structure at 300 mc but to insulate it therefrom at 84 mc. This was accomplished by building the supporting struts of composite Dural-Bakelite. This construction provided very low capacitive reactance at Mimo frequencies but kept it high at control frequencies.

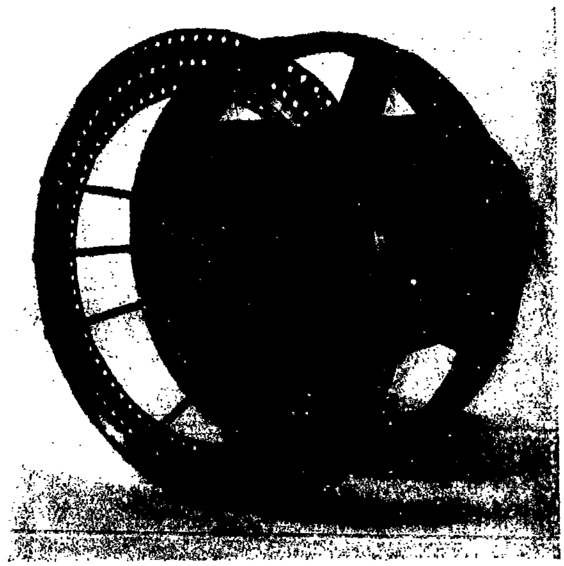


FIGURE 49. Slot antenna for Mimo-Roc with folded waveguide.

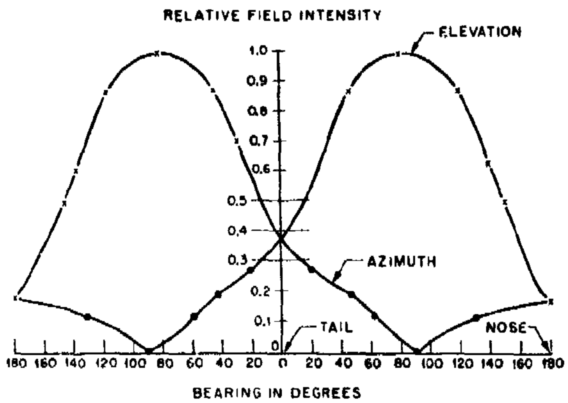


FIGURE 50. Distribution pattern of Control-Roc antenna.

With this arrangement, less than 10 per cent of the maximum signal strength was radiated in a forward (toward the ground) direction. (See Figure 48.) The width of the useful beam in the azimuth plane was 90 degrees to the half-power points; in the elevation plane the width to the half-power points was 125 degrees.

An alternative antenna design was completed which consisted of a slot driven by a folded waveguide (Figure 49). The distribution from this antenna was not materially better than from the tuned dipole, and it had the disadvantage of being extremely critical to carrier frequency.

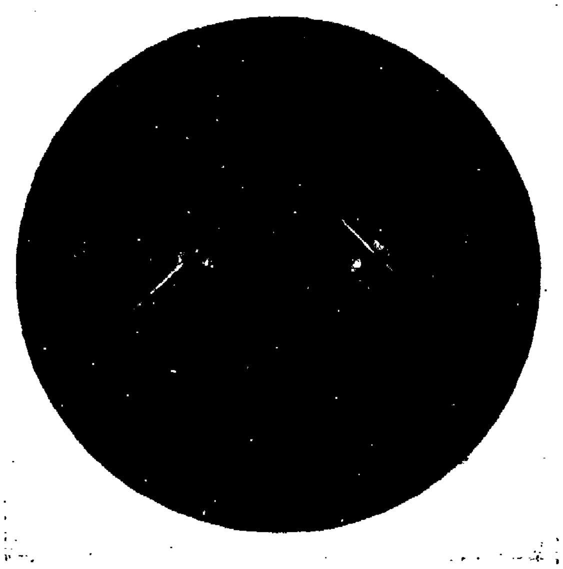


FIGURE 51. Mimo-Plane antenna array mounted on test panel.

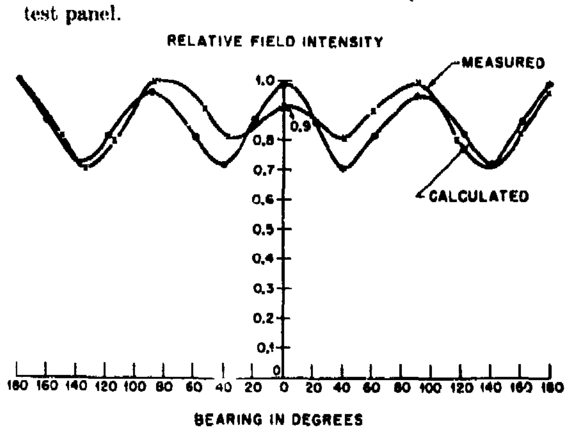


FIGURE 52. Horizontal distribution pattern of Mimo-Plane antenna.

The Control-Roc antenna consisted of the dive brake. Its sensitivity pattern (Figure 50) was not ideal but it was deemed thoroughly satisfactory for tests and probably adequate for initial combat use.

The Mimo-Plane antenna consisted of two quarter-wavelength dipoles (Figure 51) mounted under the skin of the ship. The dipoles were so placed as to straddle the plane of the ship's yaw and roll axes. Their centers were spaced approximately one-half wavelength, and the dipoles were oriented so that their extended axes would intersect at 90 degrees and on the ship's yaw-roll plane. Figure 52 shows the omnidirectional character of this array in the horizontal plane; the distribution in the other planes is shown in Figures 53 and 54.

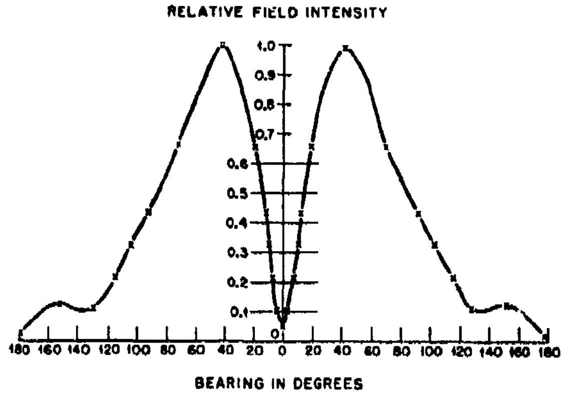


FIGURE 53. Vertical-transverse distribution pattern of Mimo-Plane antenna.

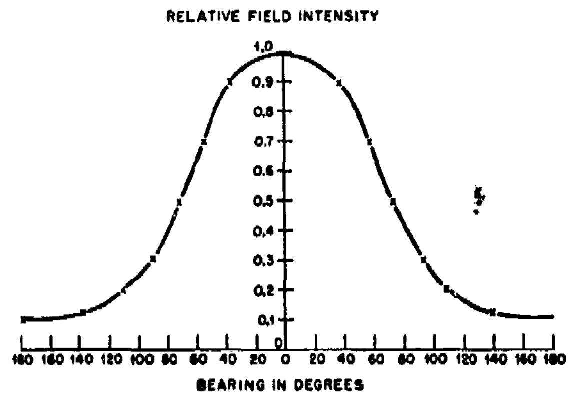


FIGURE 54. Vertical-longitudinal distribution pattern of Mimo-Plane antenna.

The Control-Plane antenna was the standard dipole developed for Razon.

Results of Tests. Ten Roc missiles were dropped with Mimo. The results of the first six drops, which are tabulated below, indicated more promise for this system than any other system of television-guided missile that the Division has encountered.

Drop T-1 Bad picture due to defective pickup tube. Probably spots on photocathode or target.

Drop T-2 Usable picture all the way, somewhat marred by doppler multipath after about 15 seconds of flight. Miss: about 75 ft.

Drop T-3 Usable picture until the last 10 seconds of flight. Very severe multipath developed so an overshoot was corrected near the end of the flight. Miss: about 300 ft.

Drop T-4 Spurious oscillation in transmitter output amplifier; also serious multipath. No guiding was practicable.

Drop T-5 Picture faded because the receiver had been tuned to the carrier image. The receiver was retuned; the balance of the flight—only a few seconds—was marred by multipath. Miss: about 220 ft.

Drop T-6 The target failed to appear in the field of the missile on account of an excessive crab angle in the ship at the instant of release. As the picture of the terrain appeared, it was marred by very serious multipath interference.

Although the target itself (Figure 55), had been scraped clear of desert vegetation and covered with several tons of salt crystals, contrast was, in general, inadequate (Figure 56). The desert floor beyond the target area was extremely deficient in contrast, so that when the target was once lost it was virtually impossible to regain it.

As a result of the foregoing experiments serious efforts were made to improve the contrast of the televised picture and to eliminate the doppler multipath effect. A search for a better Mimo-Roc antenna at this frequency was fruitless. Faster AGC was applied to the receivers in the hope of mitigating the effects

FIGURE 55. Wendover target range for Roc tests.

of doppler multipath interference. A selection of the best Mimo tubes from the stock available was made for the remaining missiles. To improve contrast, the $f/2.0$ lenses were replaced with lenses of $f/4.5$ aper-

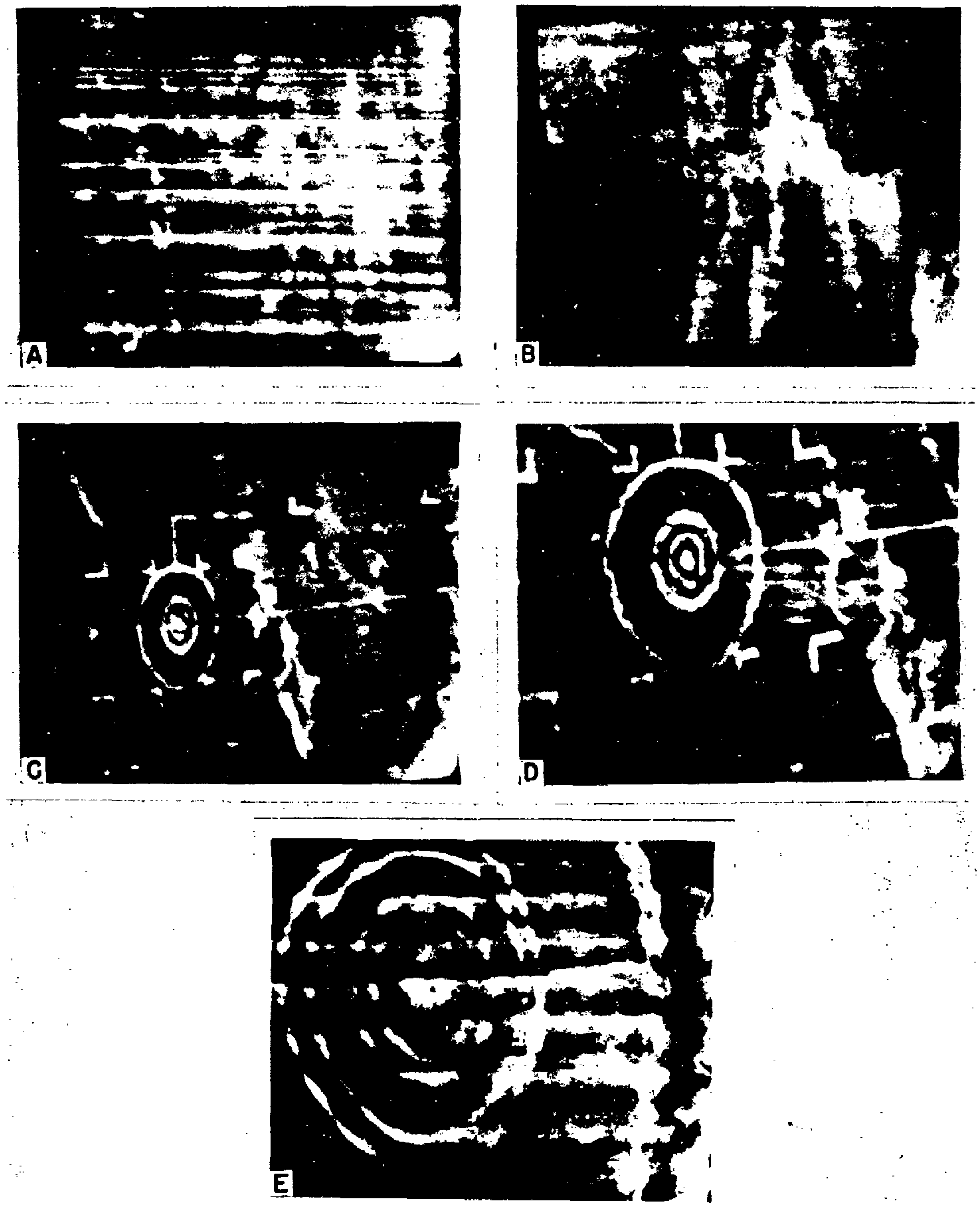


FIGURE 56. Photograph of television screen during drop T-2.

ture; all optical surfaces were treated with fog-repellent coatings.

With the foregoing revisions four more drop tests were made.

Drop T-7 Horizontal synchronism was lost for about 1¼ seconds. Doppler multipath bars appeared for the last half of the flight but their intensity was somewhat relieved by the fast AGC. Miss: about 265 ft.

Drop T-8 Substantially the same as T-4. Miss: about 118 ft.

Drop T-9 Some doppler multipath during the last half of the flight. The missile was controlled from the ground monitor station where the received picture was not marred by multipath interference. Miss: about 140 ft.

Drop T-10 Roll stabilization lost.

Guiding by means of a lead-computing aid (see Chapter 4) was not attempted as the termination of the Division's activities intervened. The work is being carried forward by the AAF. As this report is prepared, word has been received that at least one drop made by the Army has landed well within a 50-ft bull's-eye circle from 15,000 ft.

Chapter 6

RADIO-CONTROL SYSTEMS

6.1 INTRODUCTION

THE RADIO PROBLEM confronting the Division at its formation was threefold: (1) it was necessary to obtain remote-control radio links satisfactory for the control of the missiles during their developmental stages; (2) radio systems adequate for the initial combat phase had to be made available as rapidly as missiles requiring their use were ready for operation; (3) finally, there was a responsibility to maintain a continuing program, seeking to develop systems of steadily increasing security in order that new and less jammable systems would arrive in the theater before the enemy had developed methods of jamming those already in operation.

It would seem that such a problem could hardly be acute. No nation was ever more "remote-control conscious" than the United States; no other people had developed radio communication to anything like an equal degree. It would appear to be necessary simply to procure suitable radio links of already established designs from the sources of proved reliability. Such was the approach by the Division. It proved a gross error.

No mistaken judgment plagued the activities of the Division more than its failure to realize the difficulty of the radio-control problem and to meet it head on. The problems were both organizational and technological. All electronic devices for Army use were the responsibility of the Signal Corps; guided bombs were the responsibility of the Army Air Forces so long as the actual metal container for the explosive was not altered, when the Ordnance Department became an interested party. Without the assistance of the Air Communications Officer to resolve questions of divided responsibility, the whole radio-controlled bomb program within the Division might well have failed.

On the technological side many new problems of unattended operation under conditions of extremes of temperature, humidity, altitude, vibration, and acoustic perturbation had to be solved. Further, in the transmitting equipment, which was by nature airborne, weight was at a premium; the space limitation on the receivers and the aerodynamic limitations on their antennas were extreme.

6.2 RADIO SYSTEMS FOR TEST

6.2.1 Radio Systems for Glide Bombs

In connection with early tests of Robin (see Chapter 1) the National Bureau of Standards secured through Contract NDCrc-141 a small quantity of standard police radio receivers and a transmitter from RCA. These were modified by RCA so that, when a control impulse was transmitted, the gyro bias coils received a fixed value of current to produce a fixed rate of turn or a fixed rate of change of glide path. (See Section 1.6.) Space was adequate within the Robin for a standard receiver, and the wings formed a convenient surface to which a thin ribbon antenna could be cemented without producing any aerodynamic disturbance.

6.2.2 Radio Systems for High-Angle Bombs

For Azon and Razon, however, the situation was entirely different. No space could be made available in the bomb which would accommodate a standard receiver. Development was required, but the usual sources of electronic developmental skill were burdened with other war work of high priority and were hardly to be persuaded to undertake development programs of the speculative character which guided missiles had in their beginnings.

At the outset the Gulf Research and Development Company considered essential a system in which the rudder and/or elevator displacement was proportional to the stick displacement. This later proved erroneous (see Section 2.9 and Chapter 10), but the principle was adhered to throughout the early work. In their search for a commercially available radio, Gulf found two systems. The first had been developed by Bendix Aviation for the AAF target and glide-bomb program; the second was developed by the American Junior Aircraft Company[1] for the control of model airplanes. The Bendix system provided on-off control rather than proportionality. Furthermore, when control was applied in two components, yaw and pitch simultaneously, there was crosstalk between the audio channels. This system was, therefore discarded by Gulf.

The principle of the American Junior Aircraft Company was adopted. Its embodiment was, however, deemed too complicated for satisfactory experimental work on bombs. The transmitter radiated two unmodulated CW signals at 84 mc and 86 mc; one frequency controlled yaw, the other pitch. The CW signals were cyclically keyed so that pulses of each were radiated. The position of the control stick determined the ratio of pulse length to the keying cycle. Equal time-off and time-on indicated a neutral rudder or elevator position.

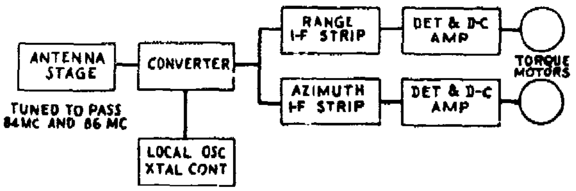


FIGURE 1. Block diagram of American Junior A/C system of radio control.

The receiver was a crystal-controlled superheterodyne (Figure 1). An antenna stage was spot-tuned to the two frequencies. Two i-f strips, detectors, and d-c amplifiers accommodated the azimuth and range channels. The output of each d-c amplifier was a series of pulses of varying length with constant total period. The last stage of the d-c amplifier was driven from cutoff to saturation so that the pulses were of constant amplitude. These pulses were fed to spring-restrained miniature torque motors. The inertia of

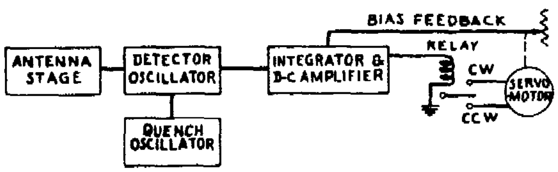


FIGURE 2. Block diagram of Gulf Azon receiver.

the armatures with the compliance of the restraining springs acted as a mechanical integrator, averaging the pulses so that the displacement of the motor was proportional to the fraction of the cycle occupied by the CW pulse. A commutator with sectors on the torque motor governed the servomotors driving the control surfaces.

The American Junior Aircraft Company system was modified by Gulf for the Azon program. The transmitter system was kept intact, with a keying frequency of 40 c. For economy of tubes, power, and space the r-f end of the receiver was changed to a superregenerator with a separate quench oscillator (Figure 2). The Q of the detector-oscillator circuit was kept low enough so that triggering by the quench oscillator was required. For test purposes the broad acceptance of the superregenerative circuit was attractive, as there was but little danger of failure of a test due to transmitter drift or errors of receiver tuning.

The control end of the system was modified by replacing the torque motor by an electronic integrator, followed by a double-throw relay. With the relay energized, the rudder servomotors operated in one direction; with the relay de-energized, the motor reversed. A potentiometer on the servomotor provided a follow-up voltage which biased the final stage to cutoff when the rudder reached a displacement corresponding to the control-stick position. Enough 40-c ripple was allowed to appear in the relay voltage to

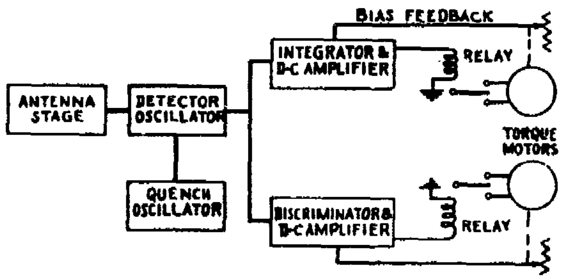


FIGURE 3. Block diagram of Gulf Razon receiver.

cause relay chatter and thus prevent hysteresis in the cores from biasing the relay response.

For Razon control Gulf developed and proposed to use a further modification of this system (Figure 3). The speed of keying under this system was to be varied as well as proportion of time-on to cycle length.[2] Displacement of the control stick in the azimuth sense varied the pulse length as before; displacement in the range sense varied the keying frequency. In the receiver a discriminator stage with a d-c amplifier followed the a-f amplifier, in parallel with the integrator and its d-c amplifier. This stage produced a d-c voltage proportional to the keying frequency. A potentiometer on the elevator motor provided a follow-up voltage to bias the last stage to cutoff as before.

This circuit was built and fully tested in the laboratory at Gulf. It is given here complete (Figure 4) as it has not been elsewhere reported.

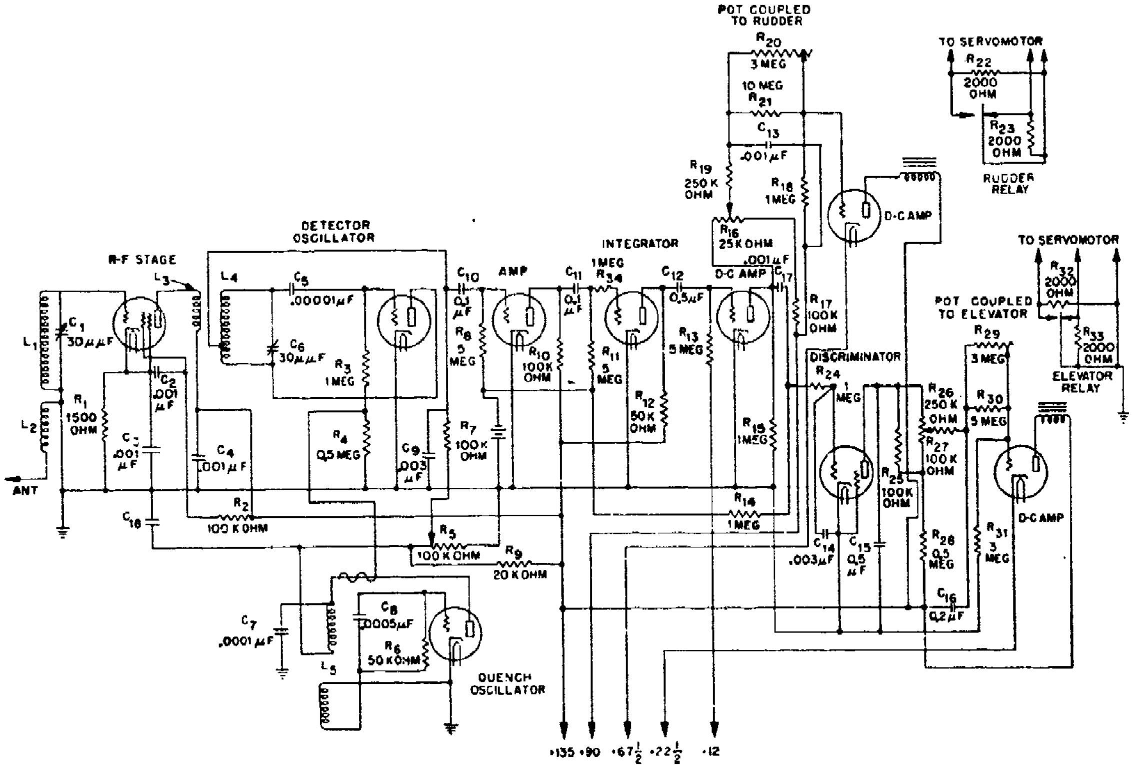


FIGURE 4. Wiring diagram of Gulf Razon receiver.

6.3 RADIO SYSTEMS FOR INITIAL COMBAT USE

6.3.1 Azon Receivers

One of the features which made the Gulf Azon receiver attractive for experimental work spoke strongly against its use in combat. Its broad acceptance made it most undesirable since it precluded the use of closely spaced channels for the simultaneous control of Azons from separate aircraft. It was believed to be subject to microphonic disturbance; in the tests at Muroc on September 10, 1943, the receivers had been packed in sand in the body of the bomb to avoid this difficulty. The superregenerative receiver, while most economical, is notoriously unstable under changes in temperature. Furthermore, the whole system of proportional control which had given rise to the Gulf radio development program had been found to be unnecessary. Even when it was available the controlling bombardier had successfully guided the bomb with rudders full-right, full-left, or neutral.[3] Had proportional control been necessary, a different system would have been required as loss of the control signal with this system results in full-left rudder, which would have produced gross misses.

Under a general consulting-engineering contract (OEMsr-240), MIT made a summary study of the problem and recommended the use of a simple superheterodyne receiver with a crystal-controlled local oscillator and a single tuned-antenna stage. The transmitter recommended was the existing standard RC-186, with provision for selectively modulating the carrier with six audio tones. For Azon one tone was selected for full-right rudder, a second for full-left rudder. Absence of an audio signal was to result in neutral-rudder position. This recommendation was submitted to the Army by the Division at a meeting called by the Air Communications Officer under the auspices of the Joint Chiefs of Staff. The recommendation was accepted without dissent. In spite of such expressed unanimity, the Signal Corps liaison officer on the project, in whom responsibility for the selection rested, insisted on the use of a superregenerative receiver. In the face of such inflexibility the Division was left without option.

A contract (OEMsr-1081) had been negotiated by the Division with Union Switch and Signal Company to engineer Azon for production. This contractor now made a subcontract with General Instrument Company of Elizabeth, New Jersey, to develop a superregenerative receiver[4] which would operate with the RC-186 transmitter in the manner planned for the superheterodyne. This became accepted as the A/N-CRW-2A (Figure 5). In accepting it, the Signal Corps officer found it necessary to waive many applicable portions of Specification No. ARL-102-A. This receiver was produced in some quantity under subsequent Army contracts. A similar receiver, on the whole rather less satisfactory (the A/N-CRW-2), was produced in even greater volume by a different contractor.

6.3.2 Razon Receivers

The unsatisfactory experience with the Azon receiver taught the Division that a radio system satisfactory for initial combat must be available before the Razon would be ready for production. Accordingly, MIT extended their studies under the guidance of the radio specialist in the Division.[5] This more thorough study confirmed their summary recommendations in favor of a crystal-controlled superheterodyne receiver. They further recommended an i-f amplifier operating either below 300 kc or one operating between 10 and 20 mc. The lower frequency held the possibility of resistance coupling, with consequent simplicity and stability; the higher frequency had promise of successful application to supersonic modulation control frequencies or to pulse techniques, each of which offered hope of increased security.

Accordingly, the Division undertook both programs. A contract was made (OEMsr-1195) with Harvey Radio Laboratory of Cambridge, Massachusetts, for the construction, under the close guidance of the MIT consulting engineers, of receivers utilizing a 75-kc i-f amplifier. Under Contract OEMsr-1314, Philco[6] constructed receivers using a 15-mc i-f strip. Each group added special features although, in the main, the receivers were similar. The MIT-Harvey receiver was provided with an AGC actuated from the output of the detector. This type of AGC has the result of widening the acceptance of the receiver. However, if a fifth modulating tone, already available in the standard RC-186 control transmitter, is applied whenever the stick is in neutral, it increases by nearly tenfold the strength of jamming signal required to block the control. The Philco receiver had a plug-in fixed-tuned r-f and local oscillator section, a real saving in storage and issue. Figures 6, 7, 8, and 9 show circuits and photographs of the MIT-Harvey and the Philco receivers respectively.

Figure 10 shows the comparative selectivity of the A/N-CRW-2A, the Philco, and the MIT-Harvey receivers. The last is shown with the audio-actuated AGC and with the more conventional form. For a sensitivity 2,000 times down (i.e., microvolts at antenna to operate relays is 2,000 times value at resonance) the bandwidths are:

			MIT-Harvey Conventional AGC	MIT-Harvey Audio AGC
	A/N-CRW-2A	Philco		
Bandwidth	More than 5 mc	935 kc	450 kc	2.5 mc

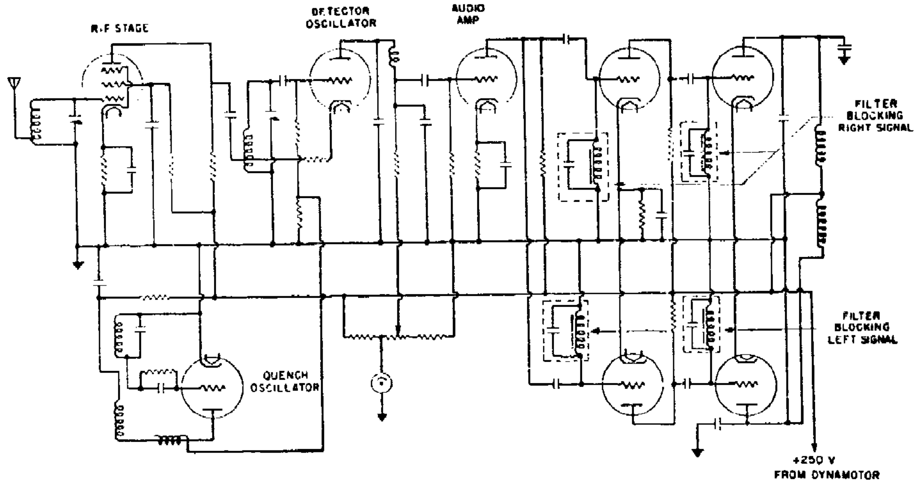


FIGURE 5. Wiring diagram of A/N-CRW-2A.

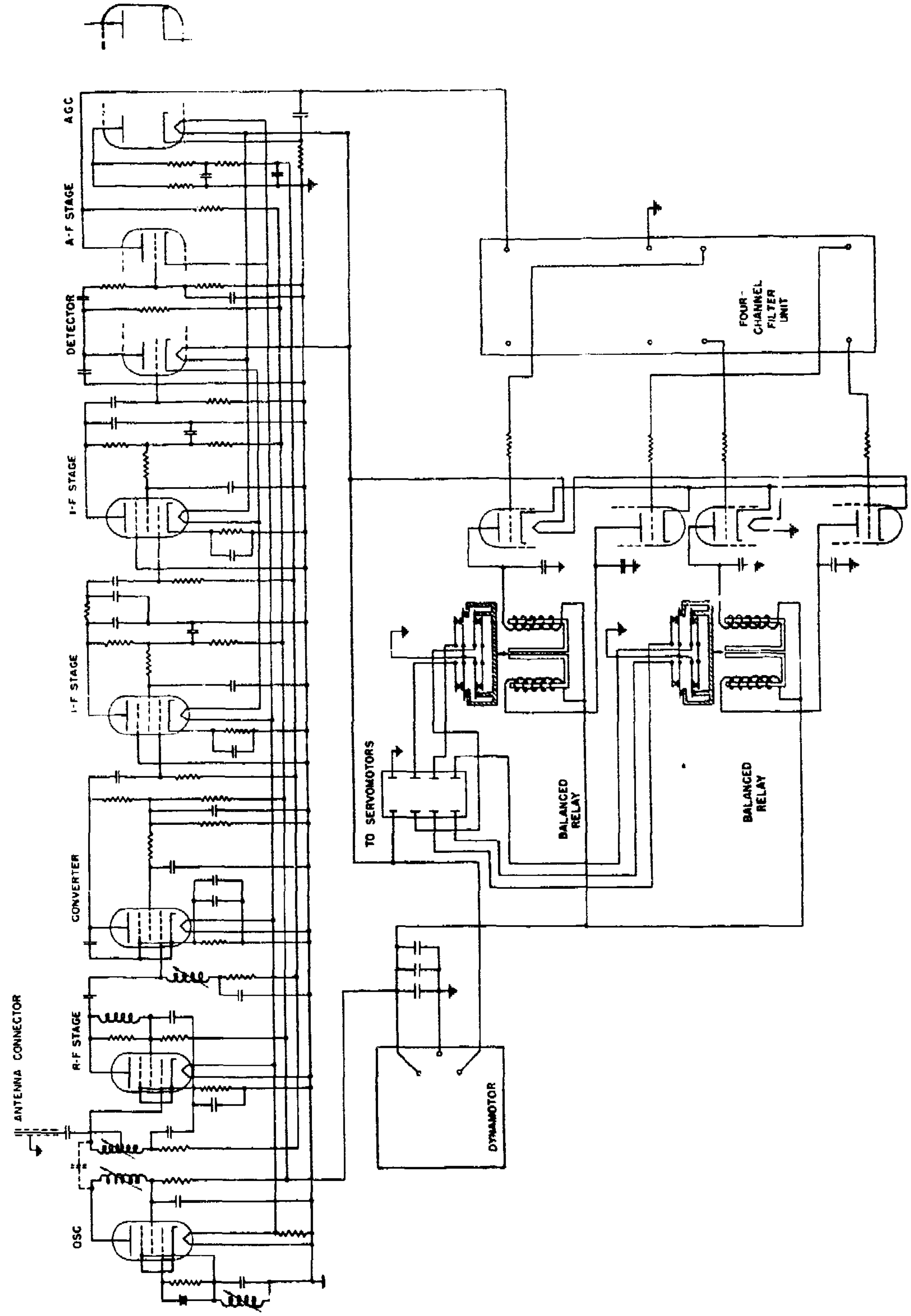


FIGURE 6. MIT-Harvey receiver circuits.

The sensitivities as the battery voltage declines are shown in Figure 11.

The increase in bandwidth of the MIT-Harvey receiver, due to audio AGC, is shown in the preceding paragraph. The antijam tests showed that with a 200-microvolt signal, which is rather below the expected minimum signal strength, from the controlling plane, the enemy would have to transmit to the Razon an 1,800-microvolt CW signal within 200 kc of resonance in order to block the control. This antijamming ratio of approximately 9 remains about constant with change of control-signal strength.

Samples of each of these receivers were sent to the Aircraft Radio Laboratory for test. This organization made a contract with Delco Radio for the development of another Razon receiver. It is substantially the same as the Philco circuit. Crystal control of the local oscillator is retained. The fixed-tuned r-f head and the audio AGC are omitted. It should also be noted that the final stages of this receiver, the A/N-CRW-7, are not biased to cutoff, which makes it extremely sensitive to noise generated by other equipment in the bomb-control assembly.

Some fifty of the MIT-Harvey sets were built and used in Razon and Roc tests while the decision as to the A/N-CRW-7 was pending. After the manufacturing eccentricities present only in the first seven units were eliminated, the sets were wholly satisfactory.

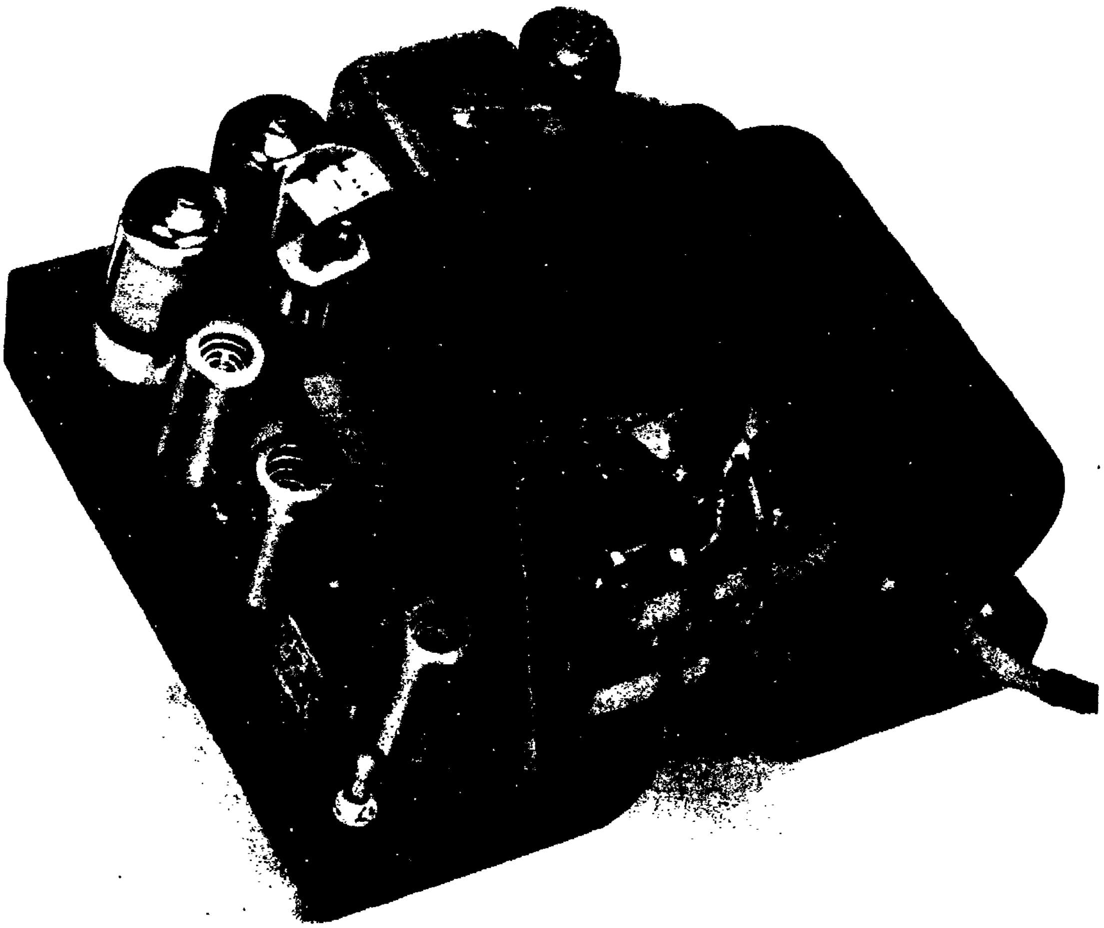


Figure 7. MIT-Harvey receiver.

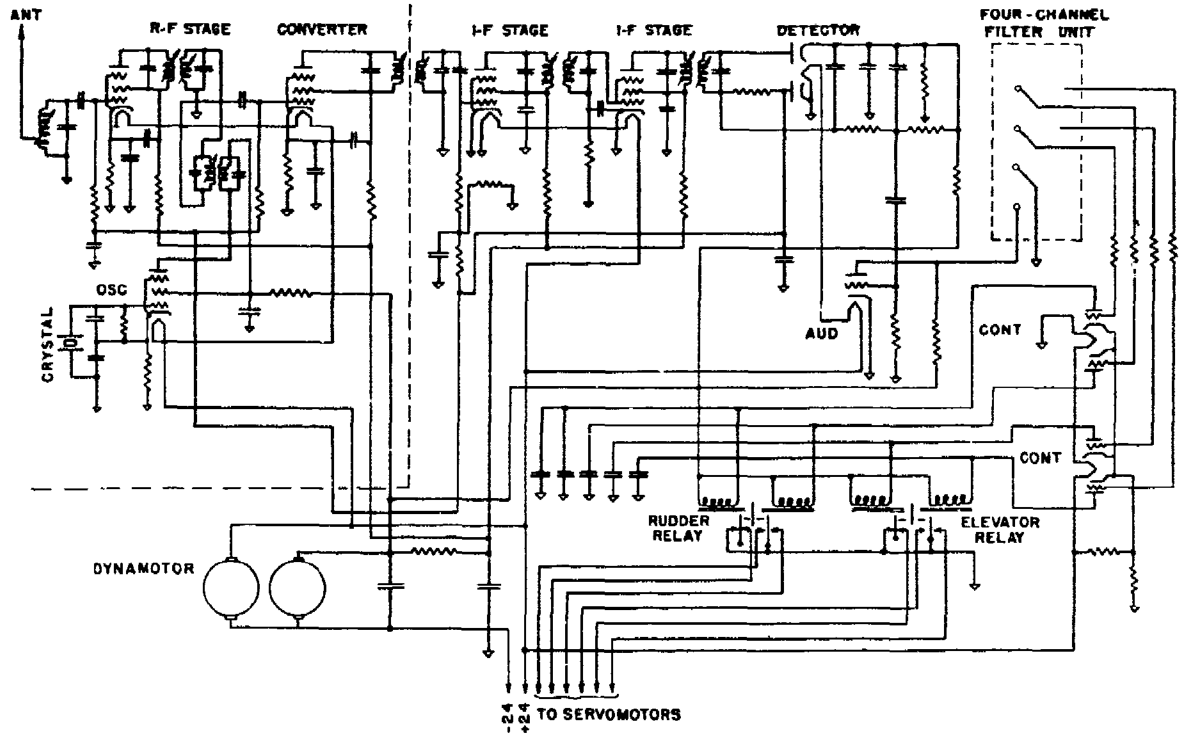


FIGURE 8. Philco receiver circuit.

6.4 SECURE SYSTEMS[a]

Security of a radio-control system for guided missiles can be obtained by two methods. One method is to use secrecy. In the ideal case the enemy would not even know that the missile was under control. This ideal is probably hopeless of realization, but it might be possible to make the system so difficult to analyze that the enemy would have to resort to large blocks of radiated power over a wide range of frequencies. Such a system of jamming would present to the enemy serious logistical problems. The second method is to use a control link in which the receiver antenna is substantially blind to signals not originating at or near the control point and to provide sufficient strength in the control signal to blast through enemy interference.

Soon after its organization the Division canvassed the developmental programs on secure radio-control systems under way in the Services. In view of the acute shortage of research facilities it seemed inadvisable to duplicate any of their projects or to add to their number. Especially was this the case as some of them, notably Rex under development for ARL, were of great promise. The Division, therefore, undertook no new projects in so-called jamproof control systems. From Section D-3, a predecessor unit of NDRC, the Division did, however, inherit one project in secure radio-control systems. It is discussed in Section 6.4.1.

Probably the greatest promise of success for an invulnerable radio-control system lies in the use of coded pulses. If the pulses are made very short, their power levels can be very high. The microwave frequency range is extremely suggestive of possibilities: for example, the continuous focusing of a receiver antenna which would have a narrow field of view on the transmitting antenna. Such a receiver would be substantially blind to an enemy jamming transmitter not collinear with it and its control transmitter.

6.4.1 Hammond Control System[11]

It has been pointed out (Section 6.4), that one way of producing a secure radio link is through secrecy. The contractor's approach to the problem was along this route, producing a radio-control link whose

[a] See also STR of Division 15, NDRC, for a much more complete discussion of jamming and its avoidance.

analysis could be accomplished only with great difficulty.

The system consists of a radio transmitter radiating power at an average carrier frequency of 84 mc. This carrier is "wobbled" at a frequency of 440 c through a band 20 kc wide. Control is applied by the use of two supersonic modulation frequencies, each of which in turn is subject to frequency modulation at five different frequencies, all of which are at the low end of the audio range. The modulating frequencies swing about a mean value of 60 and 80 kc. For a right-turn signal, the 80-kc tone is frequency-modu-

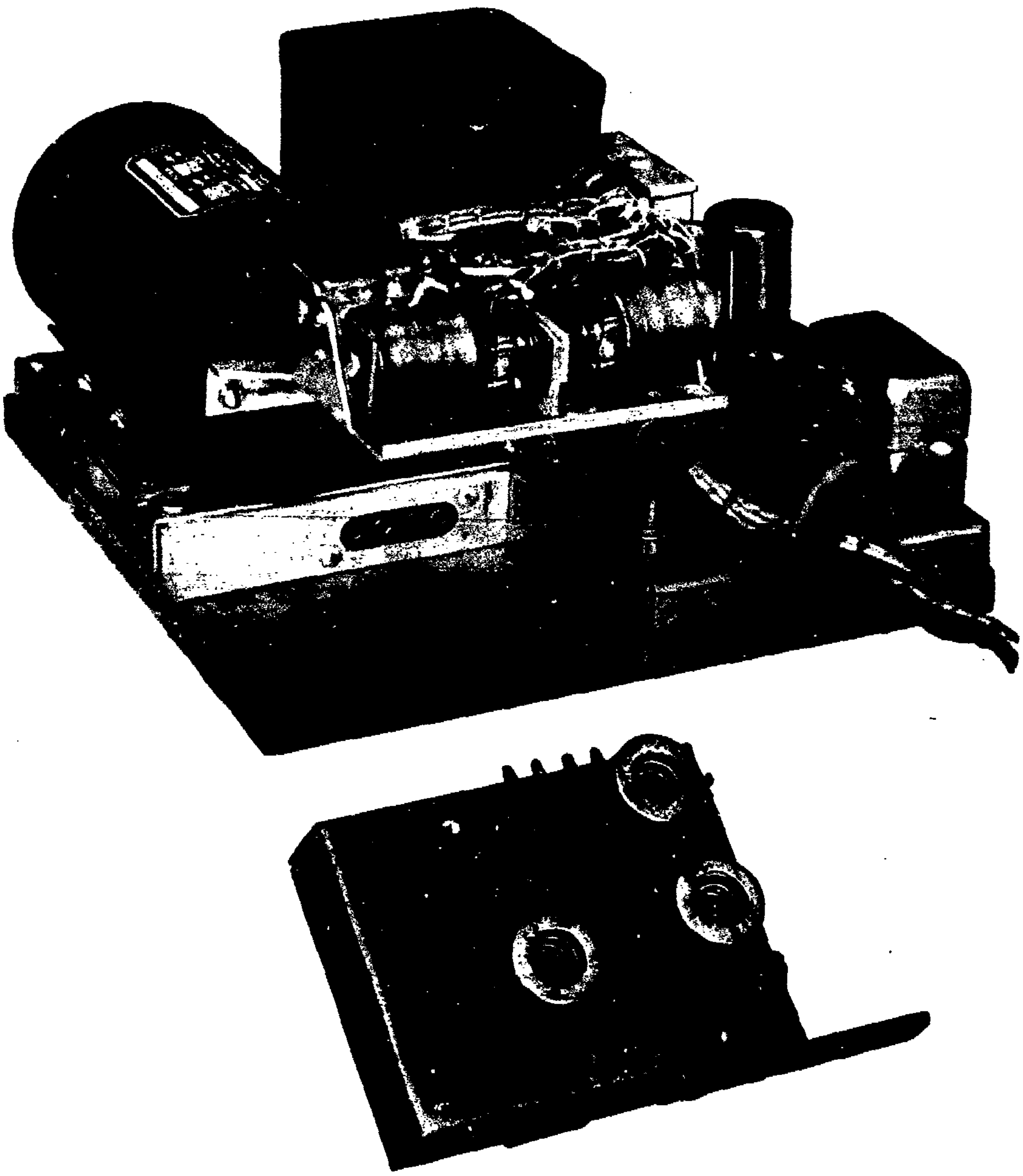


FIGURE 9. Philco receiver.

lated at 140 c; for a left turn, the same carrier is frequency-modulated at 240 c. For an up signal—increase in range—the 60-kc tone is frequency-modulated at 140 c, and for a down signal the 60-kc tone is modulated at 240 kc. When no control is applied, the 80-kc tone is frequency-modulated at 180 c. Thus, the carrier is on continuously, swinging at 440 c around a mean value of 84 mc. It is continuously amplitude-modulated at a control tone with a mean value of 80 kc, and this control tone is in turn frequency-modulated at 140, 180, or 240 c. A second amplitude-modulating control tone of 60 kc is on intermittently and is frequency-modulated at either 140 or 240 c.

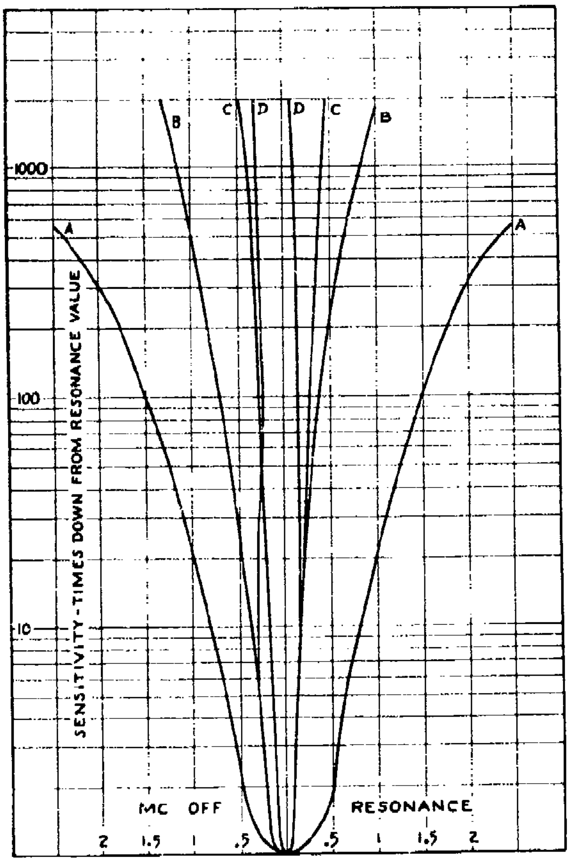


FIGURE 10. Comparative selectivity of *A*, AN/CRW-2A; *B*, MIT-Harvey audio AGC; *C*, Philco; and *D*, MIT-Harvey conventional AGC.

To produce such a complicated energy array required a somewhat complicated transmitter circuit. Even its block diagram is not reproduced here. The decoding of the signal to obtain control operation of the missile is equally complicated. It consists of (1) a superheterodyne receiver, followed by a detector to eliminate the 84-mc carrier; (2) filters to separate the 60-kc control tone from the 80-kc control tone; (3) discriminators to eliminate the low-frequency modulation; and (4) a set of filters to energize the proper relays from the 140-c or 240-c voltages produced. An audio AGC is provided which is actuated by the voltage following the low-frequency discriminators.

The purpose of wobbling the carrier is to make sure that no single jamming note present on the air will beat with the control carrier and produce false

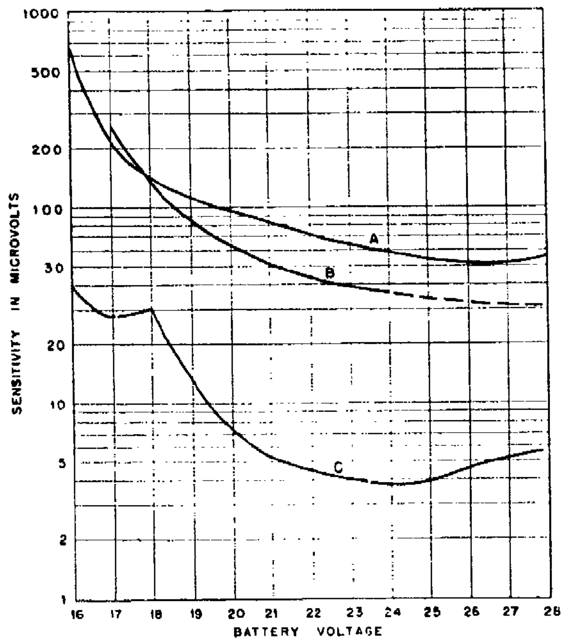


FIGURE 11. Comparative sensitivity of *A*, A/N-CRW-2A; *B*, Philco; and *C*, MIT-Harvey receivers.

operation of the relays. The purpose of the supersonic amplitude-modulating control tones is to increase the difficulty of analysis. The low-frequency modulation provides, among other things, for obtaining more than one control function from a single amplitude-modulating control tone. The purpose of the audio AGC has already been discussed (Section 6.3.2). The other purposes of these circuit elements are explained in the following quotation from the contractor's final report.[11]

a. *Use of Superaudible Modulation.* The prime reason for using superaudible rates of amplitude modulation is because usually types of transmitters do not produce such modulations. If a CW or an ICW signal only is impressed upon the receiver in the wave band of the desired signal, then power representative of the interference will most certainly get through to the detector, but the selective nature of the output system of the detector will reduce the effect of the undesired signal upon subsequent circuits. Only when the transmitter modulations are in the proper frequency range will the effect pass through into the subsequent circuits, and even then only when they are properly otherwise characterized will the later circuits be properly actuated.

b. *Interference Upon Operation by a Standard Transmitter.* There is of course some considerable virtue in a receiver system which cannot be operated by the usual types of transmitters. But the use of such a receiver system does not insure that the control exercised by the proper type of transmitting systems will not be interfered with by a standard transmitter, by causing the final receiver circuits to fail to operate, or to operate in an incorrect manner. Three possible sources of disturbance upon operation by the undesired type of transmission must be recognized and understood.

1. *Beating Effects.* Power which will pass through the receiver and develop output voltages can be produced by the conjoint action of two transmitters. For example, if the wobbler of the radio transmitter of the present equipment, and also the modulation transformer, are not actuated, then the output of the receiver unit will be actuated if the transmitter carrier is heterodyned by any continuous wave transmitter either 60 or 80 kcs. different from the proper 84 mcs. carrier. If now the wobbler is set into operation, then the beat due to the conjoint action of the transmitter and the interference will not be steady, but will be frequency modulated, over a wide range. As a result the root mean square value of the voltage at the radio receiver output terminals will be much less than if a continuous beat note were present, of proper value. The same effects hold if the transmitter is modulated in such a manner that its output is analysable into a plurality of continuous waves. The artificial wobble of the transmitter, in short, is for the purpose of scattering or distributing the beat frequencies due to the conjoint action of transmitter, modulated by signal forming circuit, and the action of continuous wave type interferences. The range of wobble is not desired to be so great as to vary appreciably the ability of the radio receiver to produce the desired output in an efficient manner.

2. *Blocking Effects.* Interfering energy which is impressed upon the detector together with the desired energy can modify the ability of the detector to produce the desired amount of output. The detector sensitivity for the proper signal is a function of the ratio of interference to signal. This is not necessarily a question of overloading, but in the case of linear detection is a natural consequence of the nature of the linear detector report. Unless a "square law" detector is used, which would bring in other undesirable effects, the loss of detector sensitivity as the result of the presence of the interference must be compensated for by use of automatic signal leveling devices subsequent to the detector.

3. *Shocking Effects.* Usually the detector circuit is so connected that the voltage impressed upon the detector input changes the dc current through a filter coil of the selective output system, or changes the dc voltage across a filter condenser. If therefore the detector is energized by a continuous wave signal alone, and this is abruptly changed in strength as by telegraphic keying, then there will be corresponding changes in the energy content of the filter device. If the circuits are too sharp, oscillations may be set up in the filter in the process of changing its energy content, so that voltages of frequencies which the filter would transmit may be produced at the radio receiver output, even though the proper transmitter to produce such voltages in a sustained manner is not operative.

These three effects of beating, blocking and shocking either singly or conjointly limit the ability of the radio receiver circuit to deliver to the signal reproducing circuit a wave form corresponding to the transmitter modulation transformer currents, in the face of excessive interferences.

c. *Volume Control.* When Multiplex transmission is used, as required for the present equipment, the selective channels must be kept at about proper signal level, or else a signal which is sufficiently strong will be able to actuate also the adjacent channel. In general, the lower the degree of selectivity between adjacent channels, the greater is the need for good volume control operation. Proper adjustment of signal level in the selective channels may be made by instantaneously operative volume control devices, such as chopper type limiters, signal amplitude limiters, or by integrating devices such as rectifiers operated by the signal to produce dc which in turn controls the gain of amplifiers prior to or succeeding the signal channel in the receiver chain. The usual Automatic Volume Control systems commonly found in broadcast and communication equipment produce a rectified and integrated dc control voltage in accordance with the amount of total signal impressed upon the detector. This arrangement most definitely should not be used when interference is expected upon the receiver operation, since the gain of the receiver would be diminished even when the true desired signal radio field is constant. Even with reasonable precautions, the amount of operating signal may be decreased by the interference, and very best design may require compensatory gain control of the signal system in accordance with the ratio of interference to signal.

In summary, the radio transmitter-receiver combination must be coordinated so that (a) standard transmitters in common use cannot of themselves cause operative functioning of the final receiver circuits; (b) standard transmitters cannot readily disrupt operation by the proper signal by (1) beating effects, (2) blocking effects, or (3) shocking effects; and (c) standard transmitters cannot readily control the signal level in the final circuits corresponding to the desired signals, through improper arrangement of the volume control system.

The foregoing discussion of invulnerability to jamming is supported at length by mathematical analysis in the contractor's final report. No tests were reported by him, however, as supporting his assumptions and the mathematical analyses developed therefrom. The Division's consulting engineers at MIT (Contract OEMsr-240) made antijamming measurements on the system in the same manner as has already been discussed in connection with the MIT-Harvey receiver. No significant difference was observed in the performance of the two systems.

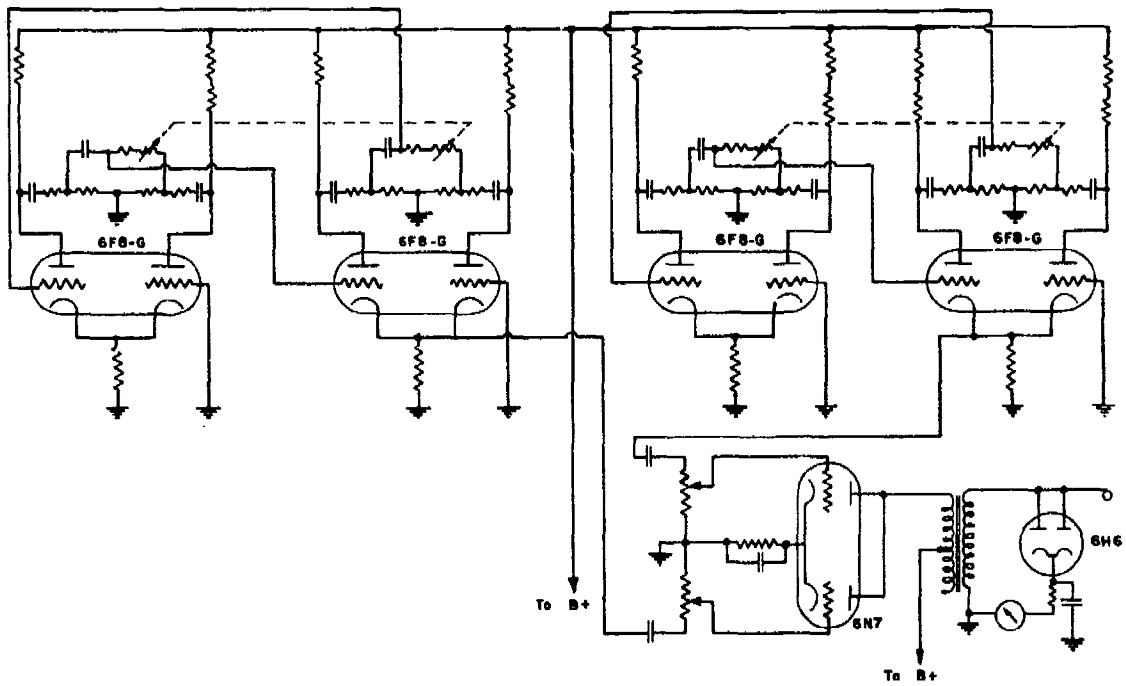


FIGURE 12. Audio-frequency control oscillators of Purdue transmitter.

6.5 EARLY STUDIES IN PROPORTIONAL CONTROL[8]

This chapter on radio-control systems[b] should not close without a brief comment on a research program carried out by Purdue University at the instigation of Section D-3, NDRC. The purpose of this program was to develop a multichannel proportional control link. The scheme developed was to modulate a carrier with one audio tone for each control channel. The frequency of each audio tone was varied in proportion to the control desired. In the receiver sufficiently broad-pass filters separated the channels and drove a discriminator stage for each (Figure 12). The result was a d-c voltage for each channel proportional to the controlling signal.

The audio tones were provided from resistance-capacitance oscillators consisting of two twin triodes in a phase-inverter circuit. One grid of each twin triode was grounded. The other grid was driven from an appropriately tuned phase-shifting circuit across the plates of the second tube. The tubes operated, then, in push-pull output with single-ended input. This type of oscillator gave good stability and waveform, with economy of tubes over conventional oscillator design. The outputs of the oscillators for two channels were combined in a mixer stage driven by cathode followers. The mixed signals amplitude-modulated the carrier in the usual manner.

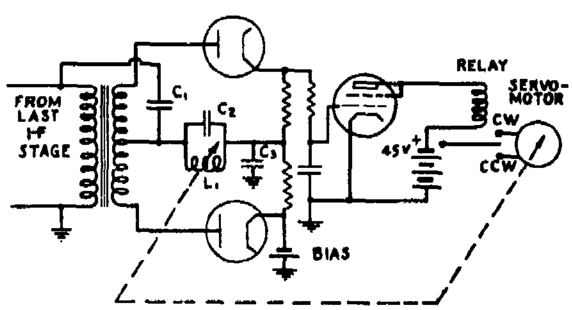


FIGURE 13. Discriminator and motor control of Purdue receiver.

The development of a discriminator for the a-f range presented some new problems. The final design is shown in Figure 13. Twin diode discrimination is used as in conventional r-f practice. In the r-f application, however, the input transformer is tuned so that the voltage across the anodes of the diodes is at 90 degrees with the primary voltage. In the a-f appli-

[b] See Chapter 4 for further discussion of methods of obtaining proportional control.

cation an iron-core transformer is used whose secondary voltage is substantially in phase with the primary voltage. The tuned circuit L_1C_2 is resonant at the frequency corresponding to a zero control signal. It is excited at 90 degrees from the primary through the phase-shifting circuit consisting of C_1, C_3, and the tuned loop. L_1 is made variable, and its value is determined by the servomotor. Thus, if the control-channel frequency is raised, a voltage will pick up the relay RY, energizing the servomotor which readjusts L_1 until balance is restored.

It should be noted that this system is not "fail-safe." The plate current of the d-c pentode stage is adjusted midway between the pickup and drop-out values for the relay. If radio transmission is lost, the servomotor will continue to run to the limit of its travel in whichever direction the relay last happened to be.

Considerable difficulty was experienced with hunting of the servomotor. Although, through an ingenious vernier on L_1, the contractor solved that instability, his success is no indication that hunting would not have appeared if the system had been applied to a missile. Hunting is a servo-system problem. If it is attacked piecemeal, success will result only by chance.

Chapter 7

SERVOMECHANISMS

7.1 INTRODUCTION

Servomechanisms are control devices to impose an output which must vary in time according to a varying input signal. The power for this output must not come from the input but must be supplied locally. The operation of the device depends upon the error signal obtained by comparing the existing output with the existing input and driving the device in the sense to minimize this error signal. Servomechanisms are the mechanical analogue of feedback amplifiers and are subject to similar instabilities. Much of the recent progress in the theory of servomechanisms is due to the recognition of this analogy.

Much progress was made during the war in the development of servo theory and in its application to fire-control problems. Section D-2 of NDRC, its successor Division 7 (Fire Control), and the Applied Mathematics Panel all promoted investigations in this field. Of the several reports written as a result of these activities, the reader is particularly referred to one by MacColl,[1] from which the definition of a servomechanism given above is paraphrased. A homing missile is a particular type of servomechanism. Its direction of flight is controlled by the error signal between its present direction of flight and the direction of the target. This again is a feedback process liable to instabilities. Servomechanisms were developed for the control of the various homing missiles of Division 5. (If the human operator is included, the control systems of Azon, Razon, and Roc are also servo systems.) These have already been discussed; one project, however, deserves special discussion and has been reserved for this chapter.

The Servomechanisms Laboratory of the Massachusetts Institute of Technology had played an important role in the development of servo theory and had been successful in applying it to the design of fire-control equipment. Shortly after Division 5 was organized, the laboratory was persuaded to accept a contract to apply the same principles to the design of a stabilizing and control system for the glide bomb known as Pelican. Before the work was completed, Service interest shifted to Bat, and the design of the control system was altered to fit this missile. A satisfactory control system was developed, and a production design was in progress as the war ended.

Pelican and Bat will soon become obsolete with the advent of powered missiles of long range, but the philosophy of design of the control system and the dynamic methods of testing will, with proper modifications, be applicable to a wide variety of future missiles. Increased speed and cost of future missiles will lend additional importance to the methods of design and of simulative testing. The two reports submitted by the laboratory[2,3] in their entirety are strongly commended to the attention of all guided-missile engineers. The abstracts to be presented here are accordingly brief.

7.2 CONTROL SYSTEM FOR PELICAN (RHB) MISSILE

7.2.1 Principles of Construction

The first report[2] from the Servomechanisms Laboratory at MIT covers the work from May 1, 1943, to March 15, 1945. Because homing control was required, a particular airframe (Figure 1) had been designed by the National Bureau of Standards to give as nearly constant an angle of attack as possible. For this reason the conventional airplane arrangement of rudders, elevators, and ailerons was abandoned in favor of full-span trailing-edge flaps called elevons, which performed the functions of all three types of conventional control surfaces. Differential action of the elevons produced the effect of ailerons in roll control; cooperative action changed the lift of the wing and thus regulated the angle of glide. Turning was accomplished by the horizontal component of lift when the missile was put into a bank by the differential action of the elevons. All this has been described in detail in Chapter 1. It is set forth briefly in the report from the Servomechanisms Laboratory as it governs the design of the servo-control system. Advantages and disadvantages of this type of aerodynamic control are also discussed.

In place of the rate gyros used in the NBS system, free vertical gyros were selected. The first model utilized a vertical gyro manufactured by Minneapolis-Honeywell. It was altered to employ rotatable transformers to indicate gyro angles in pitch and roll. The stators of these rotatable transformers were in turn rotated by trim motors to permit changes in the required angles of glide and of bank. In a second model a Sperry Mark IV bank and climb control unit was used which included rotary air valves to measure the same two angles. The second model used a smaller gyro and required a minimum of electronic equipment; the comparison between gyro position and elevon position was made mechanically through a linkage to the air valves, with differential introduction of trim corrections into this linkage (Figure 2).

In both systems an error of roll position or of glide angle called for elevon action of an amount to set up restoring forces proportional to the magnitude of the error. This was true whether the error was measured from the original preset flight orders or from the altered orders introduced by trim motors responsive to the instructions of the radar receiver. In the pitch control a small permanent-magnet generator, geared to the pitch trim motor, holds the rate of elevon motion proportional to the radar error signal.

After an initial attempt to drive the two elevons independently, a linkage system was developed to control the two elevons from a single motor through four magnetically actuated clutches. The motor was nonreversible, and pairs of clutches connected it in either sense to each of two points in the linkage. Motion at one point in the linkage drove the two elevons in opposing directions, while motion at another point drove them together. This device secured rapid response with high motor efficiency. The relatively short life of the clutches (20 hours) was entirely adequate for the testing and use of the missile.

7.2.2 Flight Test Table

The portion of the report of most continuing significance is a description of a laboratory *flight table* (Figure 3) for the simulative testing of the control system and of its components. Construction of this device consumed considerable time but paid valuable dividends. The table carried the radar receiver and gyro and pointed toward a radar target set up a short distance in front of it. Only those portions of the system sensitive to the motion of the glider had to be on the table. The servomotor itself was set up on a near-by bench, and its output was loaded to represent the elevon wind loads. The position of the elevons in turn controlled the motions of the table. Rate

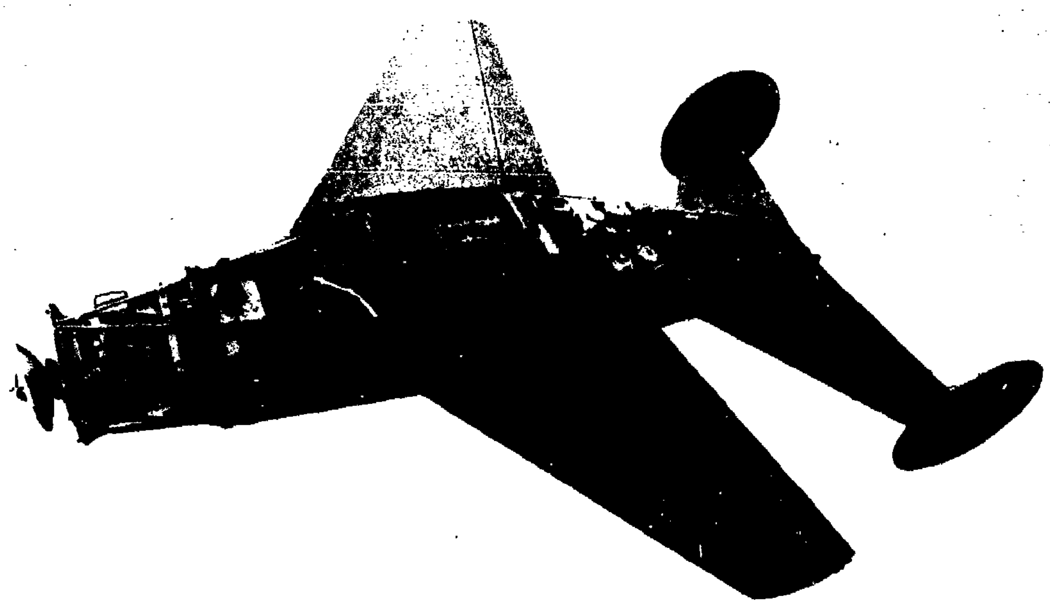


FIGURE 1. Radar-homing glide bomb with MIT stabilizing and servomechanism.

of roll of the table was governed by the differential displacements of the elevons. Roll orientation of the table determined its rate of rotation about a vertical axis. Pitch was simulated by raising and lowering the radar target. The electric, hydraulic, and mechanical components used to accomplish this are described in the report. It is sufficient here to state that the operation of the table approximated the dynamics of the missile flying at large ranges from the target.

Tests using this table gave the quantitative data needed to determine the dynamical characteristics of the overall control system at a fraction of the cost in money and in time that would have been needed to obtain the same data by flight tests. There is the further advantage that in laboratory tests all the variables are under the control of the investigator, whereas in flight tests this is far from true. Some of the flight responses which were studied were (1) the accuracy with which the missile would hold a course; (2) the damping of the missile to suddenly applied roll moments; (3) the nature of response to changes in flight direction. In general the control constants determined from the flight table were found to operate well with the missile in actual flight.

In addition to its use in establishing design parameters for the MIT servomechanism, the table was used to examine other stabilization systems for Pelican. The control system developed at the National Bureau of Standards (see Chapter 1) was also tested on it to find optimum adjustments.

7.2.3 Preliminary Flight Tests

Detailed results are given of a number of flight tests with each of the two systems described. These tests were made against a radar beacon target suspended from a barrage balloon. The tests and the parachute recovery device to preserve apparatus and flight records are summarized in Chapter 1 and Chapter 8. Four units were tested with the Minneapolis-Honeywell gyros and rotatable-transformer pick-offs. The first rolled excessively and tumbled the gyro, then went into a steep dive until the parachute recovery device operated. The second passed about

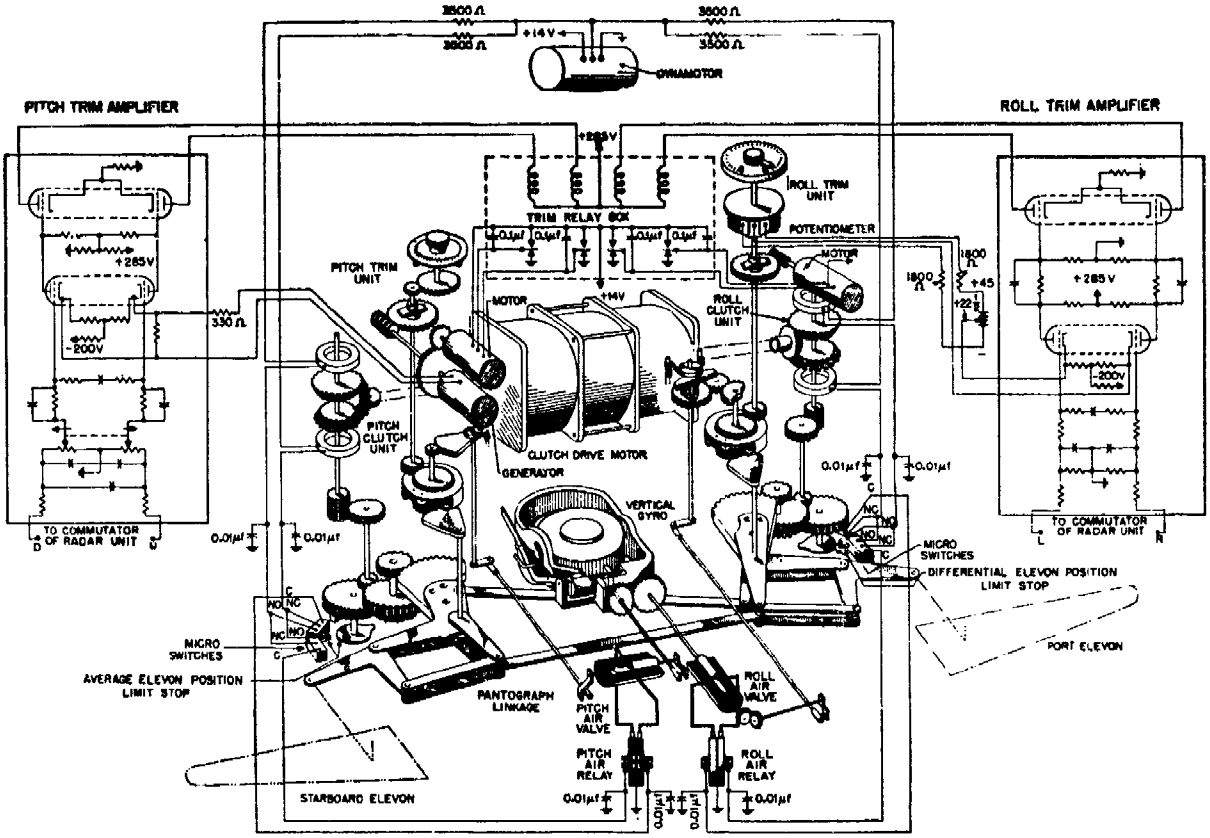


FIGURE 2. Schematic diagram of MIT control system for radar-homing glide bomb.

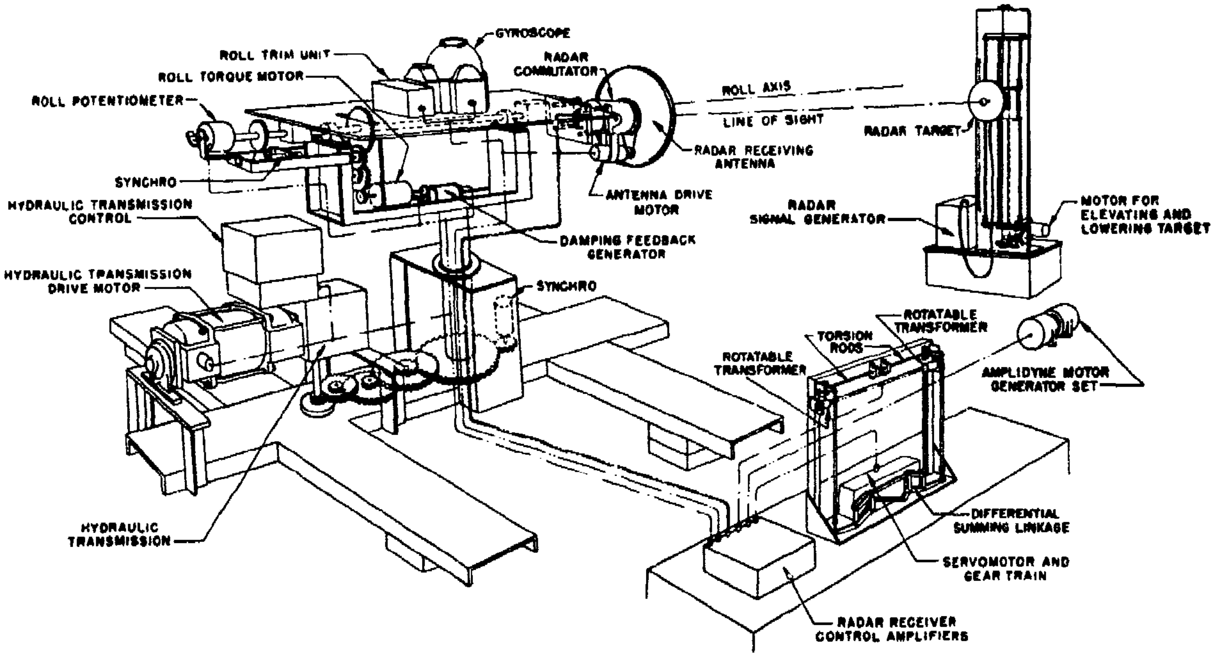


FIGURE 3. Functional diagram of flight-test table.

90 ft to the left of the target and about 90 ft high; a cross wind of approximately 20 mph was blowing from the right. The third test unit flew an oscillating course toward the target but the parachute opened prematurely before reaching the target, and the magnitude of the miss could not be determined. The fourth unit lost its radar signal during an instability early in the flight but later flew a smooth course without radar.

Four units were tested with the Sperry gyro and the pneumatic take-offs. The first test failed because of premature functioning of the recovery parachute. The second unit homed on the beacon and cut the cable of the beacon 18 ft above the target. In the remaining tests the beacon was mounted 12 ft above the ground. The third unit flew well: its nose passed 15 ft to the left of the target and 8 ft above it. The fourth unit passed 18 ft to the right of the beacon and 17 ft above it.

7.3 CONTROL SYSTEM FOR BAT (SRB) MISSILE

As a result of the work described in the contractor's preliminary report,[2] it was decided to develop this type of control for use in Bat. As has been detailed elsewhere, Bat is somewhat larger than Pelican, carries a heavier bomb, and has a send-receive radar rather than the simple receiver used in Pelican. The final report[3] from the Servomechanisms Laboratory is a detailed description of the system developed and of its components. Some of the material contained in the first report is repeated where it is necessary to elaborate it, but the second report should not be read without the first. Some thirty pages of analysis are given which apply to this problem the analytical methods referred to in Section 7.1. The purpose and scope of this analysis is best described by a quotation from the report: "Experience with a variety of control problems has proven that the system analysis must yield much more than an answer as to whether the system is stable or unstable. The analysis must lead to a design with a determinable and satisfactory margin of stability, must determine and control such factors as the natural frequencies of the complete system and its damping characteristics, and must establish the system sensitivity factors." A summary is given of servo theory,[4] so succinct that it is reproduced here.

7.3.1 Dynamical Analysis of System Performance

FREQUENCY RESPONSE OF AN AUTOMATIC CONTROL SYSTEM

"Most automatic control problems can be reduced to a simple block diagram as illustrated by Figure 4.

The problem illustrated by this diagram is that of making an output shaft whose motion is designated by θ_o follow an input shaft whose motion is designated by θ_i. The servomechanism approach to the solution of this problem is to compare the output θ_o with the input θ_i and use the difference between these quantities to so operate the controller and servomotor that the difference between the output and input is made zero or minimized. The difference between the output and the input is termed the 'error' and denoted by ϵ.

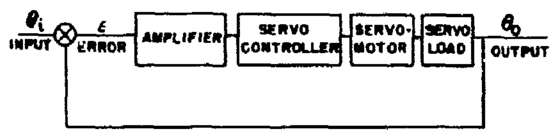


FIGURE 4. Block diagram of automatic control system.

"Two general methods of studying the response of such a system are in use: the first method studies the transient response of the system, and the second method studies the sinusoidal response of the system. In the study of the transient response, the procedure is to displace the input θ_i in accordance with some transient test function and measure or calculate the response of θ_o. A common test function is a step function as illustrated by Figure 5. The output can follow the input in a number of ways, depending upon the

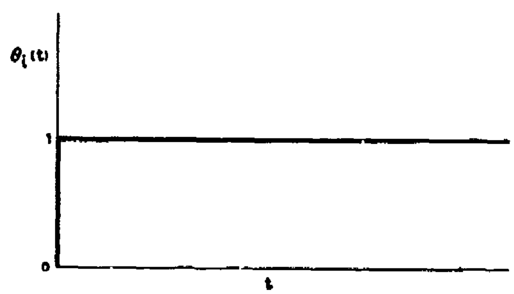


FIGURE 5. Input step displacement.

characteristics of the amplifier-controller-servomotor combination. Certain types of output response to a step input are indicated in Figure 6. If the system parameters are mischosen, the system may be unstable, and output will have a continuing oscillation illustrated by the unstable response. For another selection of parameters the output may approach its required position in a very slow fashion. This response is called overdamped and for many applications is as unsatisfactory as the unstable response. For a variety of applications, the best system response is underdamped, but with a high damping factor, as illustrated by the response curve so marked. The length of time that the output requires to reach a new position is a function of the damping and frequency characteristics of the oscillation. An estimate of the length of time required for a transient to disappear is given by a knowledge of these two factors.

"The transient approach to the problem is satisfactory if the response characteristics as calculated or measured are satisfactory or will be satisfactory with only minor readjustment of system parameters. In general, however, it is very difficult to design or redesign a system from the transient standpoint.

"The second method of approach to the design and analysis problem is to study the response of the system to a sinusoidal input. In this approach θ_i is made

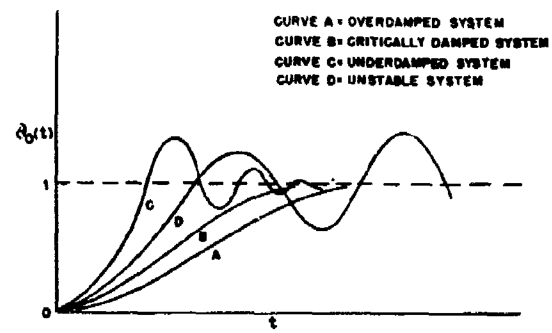


FIGURE 6. Responses of automatic control system to step displacement.

a sinusoidal function of constant magnitude and varying frequency, and the steady-state performance of the output is calculated or measured.

"The response of the system to this type of input is prescribed by determining as a function of frequency, first, the ratio of the amplitudes of the output motion and, second, the relative phase between the output motion and the input motion. Mathematically speaking, if $\theta_i(t)$ is the input and $\theta_o(t)$ is the output of a servomechanism, then, if

$$\theta_i(t) = A \sin \omega t \tag{1}$$

and A is small, it will always be true that

$$\theta_o(t) = B \sin (\omega t + \phi) \tag{2}$$

"In the above equations A is known as the amplitude of the input, B is the amplitude of the output, ω is the angular frequency (equal to $2\pi f$ where f is in c) of motion of $\theta_i(t)$ and $\theta_o(t)$, and ϕ is the relative phase angle between $\theta_i(t)$ and $\theta_o(t)$.

"The amplitude ratio B/A and the phase angle ϕ_2 when determined as functions of angular frequency ω comprise the *frequency-response characteristic* of the system.

"As shown above, the relationship between $\theta_o(t)$ and $\theta_i(t)$ when $\theta_i(t)$ is a sinusoidal function of time is specified by a magnitude B/A and an angle ϕ. These two quantities can be considered as the defining properties of a vector whose amplitude is B/A and whose phase is ϕ. Thus it is frequently stated that a *vector relationship* exists between $\theta_i(t)$ and $\theta_o(t)$ when $\theta_i(t)$ varies sinusoidally with time. This vector relationship is represented symbolically by $(\theta_o/\theta_i)(j\omega)$ in which $j(=\sqrt{-1})$ itself is generally thought of as a vector and emphasizes the vector properties of the ratio. The vector ratio $(\theta_o/\theta_i)(j\omega)$, is characterized by an amplitude $|(\theta_o/\theta_i)(j\omega)|$ and a phase, arc $[(\theta_o/\theta_i)(j\omega)]$.

"The preceding development is briefly summarized as follows:

If in an automatic control system

$$\theta_i(t) = A \sin \omega t \tag{1}$$

then

$$\theta_o(t) = B \sin (\omega t + \phi) \tag{2}$$

By definition, the frequency response is denoted by $(\theta_o/\theta_i)(j\omega)$. The amplitude response is given by

$$\left|\frac{\theta_o}{\theta_i}(j\omega)\right| = \frac{B}{A} \tag{3}$$

and the phase response is represented by

$$\text{arc}\left[\frac{\theta_o}{\theta_i}(j\omega)\right] = \phi \tag{4}$$

"The amplitude and phase response curves of a typical system are illustrated by Figure 7.

"The curves of Figure 7 may be obtained (1) by calculation, if the constants of an actual or proposed design are available, or (2) by measurement, if the servomechanism itself is available. The frequency-response characteristic is measured by moving the input sinusoidally at a fixed amplitude but at various frequencies. At each frequency the amplitude of the output and its phase relation to the input motion is measured. The ratio of the amplitudes, plotted for each frequency, yields the first of the curves of Figure 7. The phase difference between the input and output, plotted for various frequencies, gives the second of the curves of Figure 7. The curves of Figure 7 are readily calculated if the constants of the system and the differential equation relating the output to the input is known. The calculation is effected by replacing the operator p by the frequency operator $j\omega$ and applying conventional vector arithmetic.

"The frequency response of a servomechanism may be closely correlated with its transient response. Important natural frequencies in the transient response are indicated by peaks in the amplitude-response curve. The magnitudes of the peaks of the amplitude response are measures of the relative damping of the natural frequencies of the transient response. The frequency band over which the amplitude response has a substantially constant magnitude is a measure of the speed of response to transients, since a high natural frequency (and, therefore, a high speed of response) is linked with a high resonant frequency in

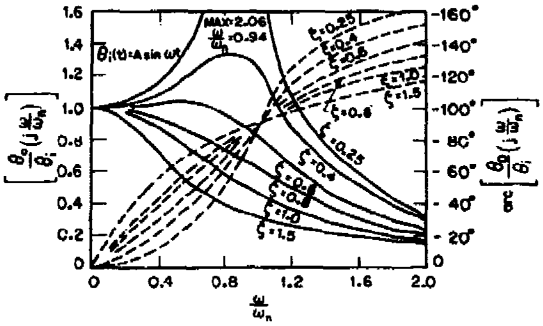


FIGURE 7. Frequency response characteristics.

the amplitude response. When, as indicated above, the frequency-response characteristic is correlated with the transient-response characteristic, the former becomes a powerful means of analysis.

"The correlation between the sinusoidal and transient characteristics is illustrated by comparing the transient and frequency response of a simple system representable by a second-order differential equation.

"If the input $\theta_i(t)$ is a step displacement and the output $\theta_o(t)$ is determined for various values of the damping ratio, the set of transient responses illustrated by Figure 8 results. If $\theta_i(t)$ is made a sinusoidal function,

$$\theta_i(t) = A \sin \omega t \tag{1}$$

and the amplitude response of the output $\theta_o(t)$ is determined, the set of curves of Figure 7 are obtained. Comparison of the transient and frequency responses reveals a number of points of correspondence: (1) the frequency at which the transient response oscillates (the natural frequency) is approximately the same as the frequency at which the amplitude response has a peak (the resonant frequency); (2) as the damping ratio is reduced, the transient response becomes more oscillatory, and the peak in the amplitude response is magnified; (3) when the damping ratio is made larger than unity, the transient response becomes sluggish, and the amplitude response falls off rapidly without a peak.

"It is frequently convenient to combine the information contained in the amplitude-response curve and in the phase-response curve of a system by a single graph. This can be accomplished by remembering that the amplitude ratio and the phase angle are quantities defining a vector which relates the output and input. As the frequency of the input is varied, this vector varies in phase and magnitude, and the amplitude- and phase-response curves present the information on the manner in which these two properties of the vector change with frequency. The same information can be provided in an alternative way by plotting on polar coordinate paper the path followed by the tip of the vector as the frequency varies over the band of interest. If various points of the curve are labeled with the frequency to which they correspond, one curve will supply the information contained in two curves when the amplitude and phase response are plotted separately. This graphical presentation is known as the locus of the frequency-response characteristic. It is illustrated by Figure 9 which was drawn for the same second-order system to which the curves of Figures 7 and 8 apply. The principal advantage of presenting information in this fashion lies in the means it provides for visualizing the frequency response and in the fact that it emphasizes the very important relationship that always exists between the amplitude and phase responses of a system.

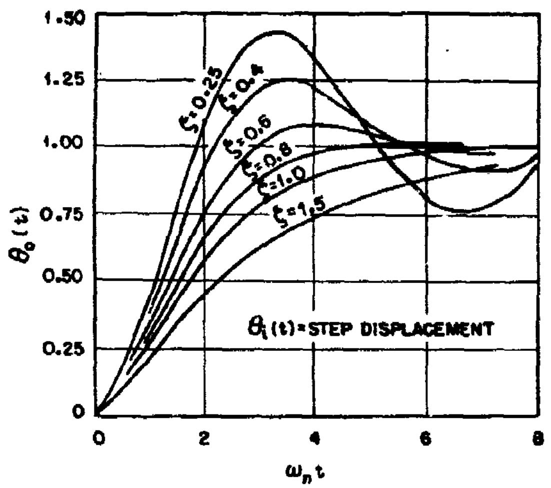


FIGURE 8. Responses of second-order system to step displacement.

Transfer Function of an Automatic Control System

"It is clear from the block diagram of Figure 4 that a single function completely defines the performance of a servomechanism in which the feedback link contains no frequency-dependent elements. The defining function is the relationship between the servo output $\theta_o(t)$, and the error $\epsilon(t)$. If this relation is known in operational, sinusoidal, or time-response form, the performance of the system is completely defined for all conditions that may be imposed upon it. This function, relating the system output of the closed-cycle system to its error, has been termed the *transfer function* of the system. When the sinusoidal or frequency-response form of the transfer function is studied, it becomes a powerful analysis and synthesis tool. The transfer function may be derived from a known frequency-response characteristic of the servo system, it may be measured directly, or, if system constants are known, it may be calculated. The transfer function of the system can be written in the form $(\theta_o/E)(j\omega)$. This function is a vector quantity with an amplitude and a phase characteristic just as the ratio $(\theta_o/\theta_i)(j\omega)$ is a vector quantity.

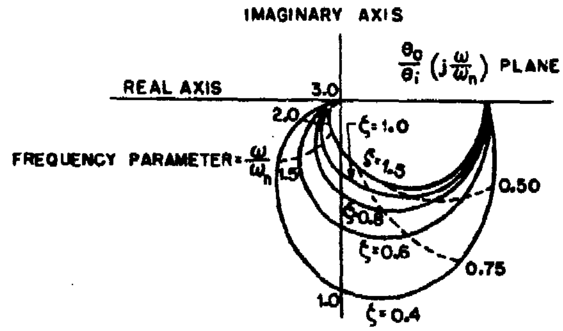


FIGURE 9. Complex plane plot of sinusoidal responses.

"The transfer function of a closed-cycle system is always the product of two parts, one that is invariant with frequency and a second that is frequency dependent. The fact that these two components exist is emphasized by writing the transfer function in the following form:

$$\frac{\theta_o}{E}(j\omega) = KG(j\omega) \qquad (5)$$

"The term K represents that part of the transfer function which is invariant with frequency. This portion is known as the gain or the sensitivity factor and is a function of amplifier gain, etc. The second part of the transfer function is denoted by $G(j\omega)$ and represents the portion of the transfer function which changes with frequency.

"The frequency response of the servomechanism is related to the transfer function by the following vector equation:

$$\frac{\theta_o}{\theta_i}(j\omega) = \frac{KG(j\omega)}{1 + KG(j\omega)} \qquad (6)$$

"The transfer function of a system is calculated by straightforward circuit analysis techniques, or by determining the differential equation relating the output to the error and replacing d/dt by $j\omega$.

The Transfer-Function Locus

"The transfer function can be studied by means of its frequency characteristics just as other functions have been so studied. The amplitude- and phase-response curves of the transfer function can be drawn; these curves completely define the characteristics of the transfer function of the servomechanism and therefore completely define the system itself. Just as the phase- and amplitude-response curves were combined into a single polar plot with frequency as a parameter, so can the frequency- and phase-response curves of the transfer function be combined. This parametric polar plot of the transfer function has been called the transfer-function locus, or simply the transfer locus of the servomechanism. The transfer locus completely defines the characteristics of the servo system. A study of its nature provides a very effective method for the synthesis of servomechanisms intended for particular applications and a useful general guide to the adjustment of servomechanism parameters to secure optimum performance.

"If a parametric frequency plot of the transfer function $KG(j\omega)$ is available, the magnitude and phase of the function $(\theta_o/\theta_i)(j\omega)$ may be found by graphical calculation. The function $(\theta_o/\theta_i)(j\omega)$ has been related to the transfer function by equation (6). A plot of a typical transfer function $KG(j\omega)$ is illustrated by Figure 10. Suppose it is desired to calculate the magnitude and phase of $(\theta_o/\theta_i)(j\omega_c)$ for a particular frequency ω_c with only the transfer locus available. The transfer function at ω_c, $KG(j\omega_c)$, is represented by the vector ***oc*** while the vector ***ac*** represents the term $[1 + KG(j\omega_c)]$, since the point a is located at

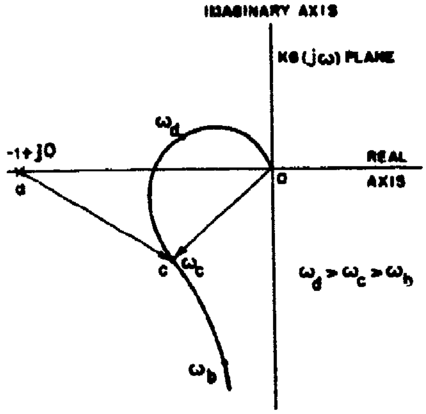


FIGURE 10. Transfer-function locus.

$(-1 + j0)$. Therefore, the magnitude of $(\theta_o/\theta_i)(j\omega_c)$ is given by

$$\left|\frac{\theta_o}{\theta_i}(j\omega_c)\right| = \frac{|KG(j\omega_c)|}{|1 + KG(j\omega_c)|} = \frac{|\boldsymbol{oc}|}{|\boldsymbol{ac}|} \qquad (7)$$

while the phase of $(\theta_o/\theta_i)(j\omega)$ is given by

$$\text{arc}\left[\frac{\theta_o}{\theta_i}(j\omega_c)\right] = \text{arc}\,(oca) \qquad (8)$$

The angle, arc (oca), is negative. Thus the magnitude of $(\theta_o/\theta_i)(j\omega_c)$ is equal to the ratio of the magnitudes of the vectors ***oc*** and ***ac*** and the phase of $(\theta_o/\theta_i)(j\omega_c)$ is equal to the angle between these two vectors.

"Equations (7) and (8) permit ready visualization or calculation of the magnitude and phase of $(\theta_o/\theta_i)(j\omega)$. At small frequencies, such as ω_b (see Figure 10), both vectors ***oc*** and ***ac*** are large and approximately equal, and their ratio is approximately unity. The angle between the two vectors, the phase of $(\theta_o/\theta_i)(j\omega)$, is small at this frequency. As the frequency increases, the angle between the two vectors increases, and their lengths become smaller, so that differences in their lengths cause the ratio $|\boldsymbol{oc}|/|\boldsymbol{ac}|$ to depart from unity. Whether the ratio $|\boldsymbol{oc}|/|\boldsymbol{ac}|$ [the magnitude of $(\theta_o/\theta_i)(j\omega)$] increases or decreases as the frequency increases depends upon the shape of the curve relative to the origin and the point $(-1 + j0)$. A continuation of this reasoning for the remainder of the frequency range permits the general shape of the phase and magnitude of the servo output to be completely determined. If desirable, the phase and magnitude curves can be determined from the transfer locus with accuracy and ease by the use of a protractor and divider to measure the angles and lengths directly from the graph.

"The general nature of the amplitude response may be obtained also by drawing in the complex plane curves of constant $|(\theta_o/\theta_i)(j\omega)|$. These curves are circles and are shown in the upper part of Figure 11. If a servo could have a transfer-function locus that lay along one of these circles, the system amplitude response would be independent of frequency and equal to the value of M for which the circle was drawn. The center and radius of each circle is dependent upon M, and the relation is given in Figure 11. The frequency at which the transfer-function locus crosses one of these circles is the frequency at which the magnitude of $|(\theta_o/\theta_i)(j\omega)|$ is equal to the value of M for which that circle is drawn. If the locus is tangent to a circle it indicates that a maximum or minimum in $|(\theta_o/\theta_i)(j\omega)|$ occurs at that frequency. Thus the amplitude response of the system whose transfer function is plotted in Figure 11 has a peak of 1.5 at a frequency $\omega = 2$, if $k = 1.0$.

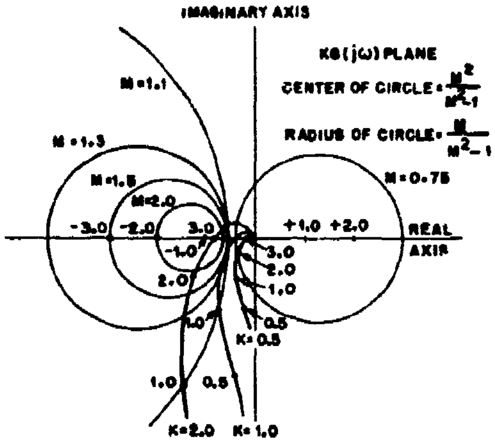


FIGURE 11. Determination of servo sensitivity.

Absolute Stability Criterion

"The primary requirement that almost every servomechanism must satisfy is that of stability. Although a servo system must be more than barely stable to be satisfactory, a stability criterion of one type or another is generally the first test applied to proposed servomechanism design. Several criteria exist; however, the one described here was developed primarily for application to feedback amplifiers.

"It is at once apparent to those familiar with feedback amplifier theory that the transfer locus of a servomechanism is analogous to the Nyquist diagram of a feedback amplifier. The term Nyquist diagram has been given to this type of plot for a feedback amplifier because of a very useful criterion developed by Nyquist for determining the stability of a feedback amplifier. This criterion may be applied equally well to the transfer locus in order to determine from its shape and position whether or not the servomechanism for which it is drawn is stable. To apply the Nyquist stability criterion to servomechanisms the following procedure is employed: (1) the transfer locus $KG(j\omega)$, plotted in polar form, is drawn for all frequencies from zero to infinity; (2) the conjugate of the transfer locus is drawn (the conjugate of a curve is the mirror image of the original curve about the real axis); (3) if the curves so formed enclose the point $(-1 + j0)$, the system is unstable; if the curves do not enclose this point, the system is stable. The application of this criterion is illustrated by Figure 12.

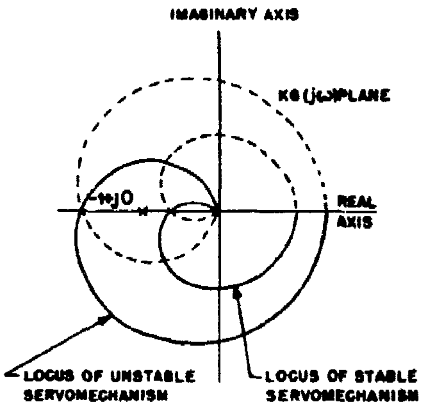


FIGURE 12. Transfer loci of closed form.

"The above criterion applies to curves of closed form; that is, it applies to transfer loci of such character that the loci and their conjugates join at zero and at infinite frequency. Actually the transfer loci of most servomechanisms are of the open form, and some extension is required in order to apply the stability criteria to these forms of transfer loci. The open form of the transfer locus can be changed into the closed form by connecting the curve and its conjugate at the zero frequency point by means of a circle of infinite radius. The connection should always be made in such a way that no phase discontinuity occurs along the path of the curve. This is illustrated by Figure 13, in which are plotted the transfer loci of two common types of servomechanisms, both of which are stable.

Transfer Loci for Various Types of Steady-State Performance

"The performance of a servomechanism under steady-state conditions is always of great importance. If the servomechanism is primarily a positional device, it is desirable that the servomechanism take up various positions without requiring an error to maintain it in that position. Similarly it is frequently necessary for the servomechanism to follow an input of constant velocity, that is, one in which $\theta_i(t) = kt$. In this case it is desirable for the servomechanism to follow various velocities as required without the necessity of a system error to maintain that velocity. Servomechanisms that satisfy the first condition frequently are termed zero-displacement-error servomechanisms, and those that meet the second condition are called zero-velocity-error servomechanisms. It can be readily shown that if the transfer locus of a servomechanism approaches infinity along the negative imaginary axis, the servo will have zero displacement error. Similarly if the transfer locus of a servomechanism approaches infinity along the negative real axis that servo will have zero velocity error. The zero-velocity-error servo will, of course, have zero displacement error also. In Figure 13 is illustrated the transfer loci of a zero-velocity-error system and of a zero-displacement-error system. This concept can be extended to servo systems that will follow a constant input acceleration without steady-state error, and so forth.

Determination of the System Sensitivity

"A very simple procedure exists for determining the system sensitivity K permitted by a prescribed maximum value of $|(\theta_o/\theta_i)(j\omega)|$. This procedure makes use of the fact that variations in the sensitivity K are equivalent to changes in scale of the plot of $KG(j\omega)$. Instead of plotting $KG(j\omega)$, the function $G(j\omega)$ only is plotted. If the scale of this plot of $G(j\omega)$ is correctly altered, then this plot will represent $KG(j\omega)$, and the factor by which the scale must be altered is equal to K. The factor by which the scale of the plot of $G(j\omega)$ must be altered to transform it to a plot of $KG(j\omega)$ is determined by the maximum permissible value of $|(\theta_o/\theta_i)(j\omega)|$. The procedure is as follows:

"It has been shown that if the plot $KG(j\omega)$ is tangent to a circle whose center is $M^2/M^2 - 1$ on the negative real axis, and whose radius is $M/(M^2 - 1)$, that the function $|(\theta_o/\theta_i)(j\omega)|$ corresponding to this $KG(j\omega)$ will have a maximum value of M. Now a circle whose center is at $M^2/M^2 - 1$ on the negative real axis and whose radius is $M/(M^2 - 1)$ will have an intercept on the real axis equal to

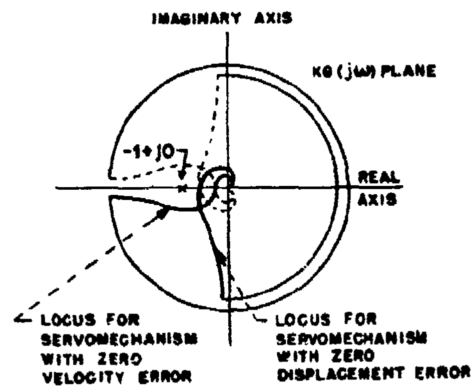


Figure 13. Transfer loci of open form.

$M/(M + 1)$, and the following ratio will be maintained:

$$\frac{\text{Center of circle}}{\text{Intercept on real axis}} = \frac{M}{M - 1} \tag{9}$$

"The scale factor K can be readily found if a circle can be located on the plot of $G(j\omega)$ that is tangent to the locus $G(j\omega)$ and whose center on the negative real axis is $M/(M - 1)$ times its real-axis intercept. The location of such a circle can be found by a cut-and-try process with a pair of dividers and is the work of but a few moments. Suppose such a circle has a center at A, on the $G(j\omega)$ plane. But it has been shown that if the scale were correctly chosen in order that the locus be a plot of $KG(j\omega)$, the center of the circle would be at $M^2/(M^2 - 1)$. Therefore the scale must be changed by the factor $M^2/A(M^2 - 1)$, and the sensitivity K_M is equal to $M^2/A(M^2 - 1)$. The value of K_M is the system sensitivity that will provide a maximum value of $|(\theta_o/\theta_i)(j\omega)|$ equal to M.

"The above procedure of plotting only $G(j\omega)$ and then determining the sensitivity K is easy to use and permits greater freedom in the study of transfer loci since it essentially nondimensionalizes the plots as far as the sensitivity factor is concerned."

7.3.2 Production System

Later chapters of the report[3] cover system description, component description, test equipment, flight tests, and a brief discussion of the production model engineered by the Bell Telephone Laboratories in close liaison with the Servomechanisms Laboratory. The system is essentially that described in the earlier report. It uses the Sperry Mark IV bank and climb control unit with pneumatic take-off of bank and glide angles. Ten units were prepared for flight tests —three against corner reflectors at Warren Grove, N. J., and the remaining seven against a ship target in Pamlico Sound, N. C. In the tests against the ship, comparison was to be made with an equal number of Bats equipped with the system developed at the National Bureau of Standards.

In the Warren Grove tests the first unit hit the ground 60 ft in front of the corner reflector. The second unit flew just over the reflector and landed approximately 70 ft behind. The third unit malfunctioned and dove into the ground immediately after launching. The tests against the ship target were more encouraging. The target ship was 260 ft long and 45 ft wide, and had a wooden lattice built upon the deck to a height of 30 ft above the water line. Six missiles were dropped. There were two direct hits, one 20 ft aft of midships, 2 ft above the water line, the other 45 ft forward of midships exactly on the water line. Three skip hits struck the water 15 to 50 ft short and skipped into some portion of the ship or its superstructure. There was one miss which passed over the bow and hit the water 100 ft beyond. Units with the NBS system had one hit on the ship, two on the top of the lattice, and three misses.

Chapter 8

INSTRUMENTATION

8.1 INTRODUCTION

"ACCURATE AND MINUTE measurement seems to the non-scientific imagination a less lofty and dignified work than looking for something new. But nearly all the grandest discoveries of science have been but the reward of accurate measurement and patient, long-continued labor in the minute sifting of numerical results." These sentences are from an address by William Thomson, Lord Kelvin, on the occasion of his installation as President of the Royal Society of Edinburgh.[1] In a more pungent, if somewhat less elegant, speech Reichsmarschal Goering pointed out the need for scientific and quantitative observation specifically in connection with the development of German guided missiles.[2]

Mature work can go forward neither in the field of scientific research nor in that of engineering development without rigorous quantitative thinking. The requirement of quantitative thinking, however, implies the existence of quantitative data. It is particularly true in the field of guided missiles that observation by trained individuals is wholly inadequate. Different observers differently located will necessarily have different points of view. To each of them the apparent performance of the missile may well be wholly different. The analysis of the performance of the missile made from the reported observation of several witnesses is then a matter of discussion between the witnesses and the chief of the experiment. Always there is a danger that clashes will arise which are resolved on the basis of the skill of the observers in the field of debate rather than on the technical merits of the case. Where the military are involved there is a further complication of rank. In a discussion with juniors it is almost impossible for a senior officer to be in error.

For these reasons it is vital that measuring and recording instruments be provided which will preserve objective and quantitative data as to the performance of the missile during each experiment. Without them the program easily degenerates into Fourth-of-July play. It is significant that the German developmental program on the V-1 missile did not reach material success until Hilda Frisch, the famous glider pilot, volunteered, or was caused to volunteer, to ride a buzz-bomb and take records of its performance during flight. Fraulein Frisch made several flights in buzz-bombs over the Baltic Sea, and the data which she took were of unique value to the scientists and engineers engaged in the development of the weapon.

8.2 GENERAL

8.2.1 The Problem

In order to analyze the performance of a guided missile it is necessary and sufficient to measure its relative motion with respect to the target, and to measure the control applied and the missile's response thereto.

This is a simple statement of an exceedingly complicated problem. The study of the relative motion between the missile and the target involves the position, the velocity, and the acceleration of each. The study of the control involves the determination of what controls should have been given in the particular system of guidance under consideration, what actual control was applied, and, in the case of a discrepancy, the measurement of the performance of each link in the closed loop of the servo system to establish beyond doubt the cause of the malfaction. Furthermore, the complete measurement cannot be made until the response of the missile to the control applied has been determined.

As regards the missile, the problem involves measurements of position, velocity, and acceleration in six degrees of freedom. These can be defined, for example, as location of the center of gravity of the missile in the range, azimuth, and altitude directions, and as rotation of the missile's structure about the axes of roll, yaw, and pitch. As regards surface targets on land or sea, it involves measurement of position, velocity, and acceleration in two degrees of freedom, specifically in the direction of range and of azimuth. For air targets the additional degree of freedom in the direction of altitude is added.

For aerodynamic missiles, that is, missiles which derive their control from the forces exerted by the air mass on aerodynamic surfaces or on the missile's structure, there must also be considered and measured properties of the air mass; wind speed and direction as a function of altitude are vital. Temperature and dew point may also be significant, especially if experiments should be abortive because of icing of control surfaces. With missiles of very high velocity, the relative position of these two properties may interchange, temperature and humidity becoming more important than wind velocity, since the speed of sound in air is inversely proportional to the absolute temperature. With missiles approaching sonic velocity it is probably more important to know the temperature of the medium and, therefore, the velocity of sound and the Mach number of the missile than the ground speed of the air. With reaction-guided missiles, where transverse accelerations are imparted by the reaction of a laterally directed jet, it is possible that the whole problem of air measurement both as to wind velocity and temperature may become insignificant.

8.2.2 Methods Used

In the Division's program all the attacks were made against stationary targets. In general the position of the missile was determined from ground measurement. Observation from the ends of a base line can provide continuous information as to the altitude, range, and azimuth position of the missile during its flight. Such observations were made by phototheodolites, by conventional view cameras when the work was done at night so the shutters could be left open, and by specially constructed slit cameras. The angular position of the missile with respect to its three principal axes was in general recorded by means of missile-borne motion-picture cameras viewing the terrain approached.

In general, the derivatives of the positions of the missile, both spatial and angular, were not measured.

In addition to the determination of the spatial position of the missile from the ground, supplementary measurements were made with bomb-bay motion-picture cameras in connection with the dirigible high-angle bomb project. These instruments provided, perhaps, the most valuable means of obtaining data suitable for rapid analysis. If unaccelerated flight of the aircraft after release of the missile is assumed, they produce a ground projection of the trajectory from the point of view of the bombardier.

Performance of the control system was recorded by means of motion-picture cameras, by chronographic recorders located in the missile, and by radiosonde. The data obtained from these instruments was invaluable. The problem involved in film and record recovery and their subsequent analysis is not, however, to be underestimated. A flight of one of the glide bombs of the Washington Project normally occupies approximately five minutes. With a motion-picture record taken at 16 frames per second, the analysis of 4,800 frames of motion-picture record is involved for every drop. Nor is 16 frames per second too fast a speed for recording such data. Indeed, during transient disturbances due to gusts, fading of the radar signal, or to other causes it is hardly adequate. Radiosonde techniques possess the possible advantage of producing the data in continuously plotted curves, a much more readily analyzed form than the moving picture film. Furthermore, the problem of film recovery, which the Division never completely solved for any of its projects, does not exist with this method. It requires, however, an additional radio link which must be carefully coordinated with other transmission in the vicinity if interference is to be avoided.

8.2.3 Other Possible Methods

The use of two phototheodolites to determine the spatial motion of the missile can give reasonably precise data as to the trajectory of the flight. The addition of a third phototheodolite gives multiple redundancy and increases the precision. Furthermore, it greatly increases the probability of a complete record throughout the flight from two instruments. The problem of coordinating the operation of an aircraft and two or three phototheodolite stations on the ground is acute. Radio communication must be of very high quality—higher than that usually found in portable equipment. Time synchronization is essential, and the development of a routine procedure similar to target tracking in coast artillery practice seems vital. Such a procedure is very difficult to follow where aircraft maneuvers are involved. In experimental work it is desirable that subordinate variables, such as the crab angle of the dropping aircraft, be minimized. The direction of the bomb run is therefore not easily scheduled, especially if the winds aloft are variable. It is probable that radar tracking, using one or more such instruments as the SCR-584, should be invoked either in place of, or as an adjunct to, visual tracking by means of phototheodolites. This technique is particularly attractive since it offers a ready means of obtaining with some precision first and second derivatives of the spatial position of the missile.

Angular motion of the missile is probably better recorded through gyroscopic instruments than from motion-picture records of the terrain. Three gyros can measure the angular position of the missile about each of the three axes. Quantitative take-off has not yet been fully developed, but it would appear that appropriately shaped condenser plates on the inner gimbal frame could be used in a circuit of reasonably high frequency so that the change in capacitance in a bridge circuit with changing relative position of the missile and gimbal frames could be determined. Such a take-off would impose no friction on the gyro.

Rate gyros can measure directly the angular velocity about each of the three axes. Such gyro instruments are already in an advanced state of development.

Measurement of angular acceleration about the three axes poses a different problem. Angular accelerometers are required. An instrument comprising a polar moment of inertia, elastically mounted, would appear to be easily developed. Care must be taken to see that the natural period of such an instrument is well below that of any frequencies likely to be encountered. Strain gauge techniques for proportional takeoff are suggestive.

The experience of the Division indicates that as the velocities of the missiles are increased, the measurement of velocity and acceleration, both linear and angular, will become crucially important.

8.2.4 General Principles

In addition to proving the vital necessity of adequate instrumentation, certain basic principles of instrumental techniques have appeared from the Division program. Derivatives, where required, (and as has already been indicated their importance is likely to increase) should be measured directly. The differentiation of experimental data is subject to error, whether it is done graphically or by a calculating circuit. Physical measurements, particularly in the fields associated with guided missiles, are likely to yield fluctuating results. Their differentiation magnifies these fluctuations, and the resulting derivative may be seriously false. Smoothing of the data can be employed, as in damping of instruments or by smoothing filters in the measuring circuit. Such corrective measures, however, are inherently processes of integration. A careful study of time constants and of frequency of variation is required if specious results are to be avoided.

Where different data are to be compared directly, it is desirable that they be recorded with the same instrumentation. In certain missiles (see Chapter 4) it is significant to measure the angle between the heading of the fuselage of the missile and the tangent to the line of flight. If the line of flight is determined from ground records, either by phototheodolites or otherwise, and the heading of the fuselage is determined, for example, by a missile-borne motion-picture camera, the correlation of these records is tedious and can be ambiguous. The alternative would be a missile-borne instrument which would continuously measure and record the relative direction of the airstream with respect to the axis of roll of the missile. This poses a problem in aerodynamic design. No very suitable angle-of-attack instrument has yet been developed.

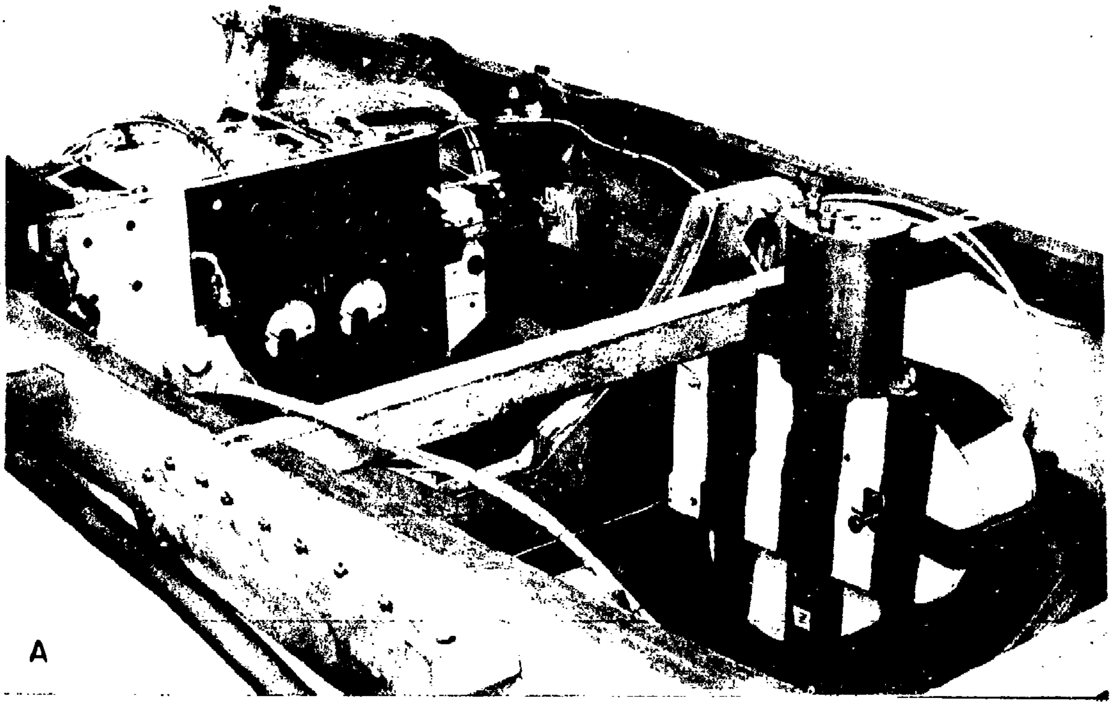
It would appear that radiosonde, particularly with a plotting board which would yield a graphical record of the missile-borne instrumentation is a better approach to the problem than missile-borne motion-picture cameras. Time coordination would appear to be simpler, and the whole problem of film recovery is avoided.

8.3 MISSILE-BORNE INSTRUMENTS

8.3.1 Glide-Bomb Cameras[3,4]

The initial camera installation on the glide bombs of the Washington Project consisted simply of standard 16-mm motion-picture cameras with the spring-motor drive replaced by electric motors powered from the missile's storage batteries. This camera was bore-sighted so that the optical axis would be tangent to the line of flight. Four miniature lights were so placed as to appear in the field of view of the camera but not so as to obstruct the portion of the terrain immediately adjacent to the principal point. These lamps were marked *R*, *L*, *D*, and *G* and were controlled through relays to light when the indication from the radar called for a right or left turn, dive, or an extension of glide.

This somewhat qualitative record was soon improved by providing miniature instruments which indicated the output of the radar in milliamperes from the differential amplifier which biased the gyro coil (see Sections 1.6 and 1.7). An attempt was made to establish a standardized instrumentation scheme, and the Division made a contract with Eastman Kodak Company to develop a recoverable motion-picture camera which would photograph the field of view along the line of flight together with the radar output meter and a mechanical indicator of the elevon position. The very large number of variables



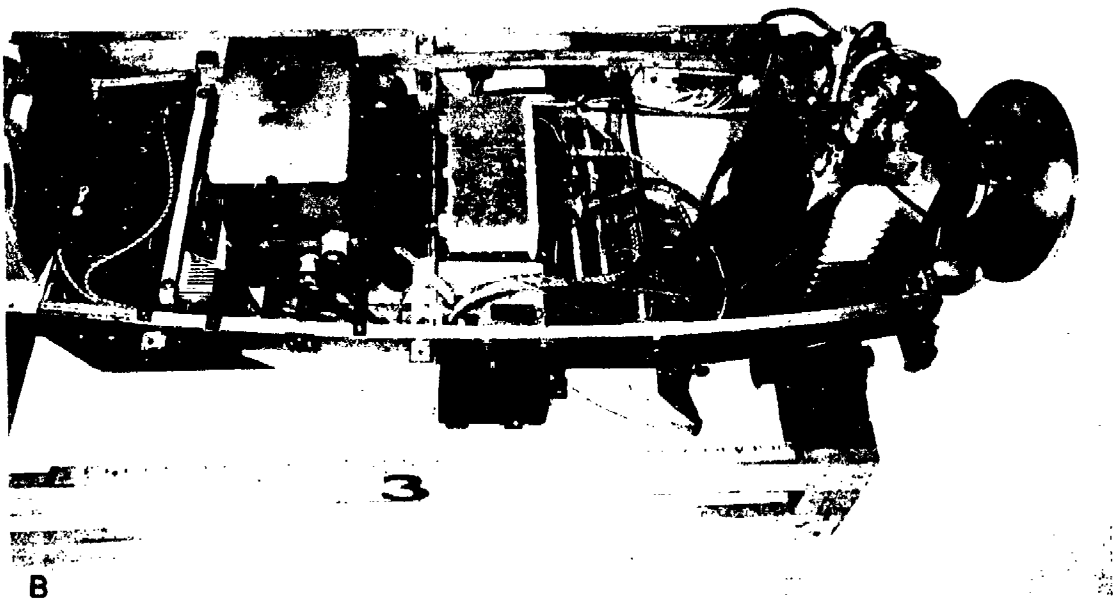


FIGURE 1. Camera installation in Pelican. (A) Internal camera, (B) external camera.

capable of measurement, however, precluded the standardization of a single instrumentation scheme. Furthermore, GSAP (gunsight aiming point) cameras were more readily available from the Services than new cameras of the type developed under the contract.

The method finally used on most of the flights placed two GSAP cameras within the fuselage of the missile (Figure 1). One camera photographed the field of view along the line of flight through a train of mirrors penetrating the fuselage skin. The other camera photographed an instrument panel containing the elevon position indicators and instruments appropriate to measure the parameters of major interest. The film drive mechanisms of the cameras were mechanically connected to assure synchronism, and a cueing light in the field of the camera which viewed the terrain in series with a similar light of the instrument panel provided means of tying the film records together. Steel casing of ¼-in. plate lined with sponge rubber sufficed to protect the cameras from damage in crash landings.

The data obtained from the internal camera (that recording the instrument board) was of predominant importance. The data from the external camera (that recording the terrain along the line of flight) was of qualitative value only. GSAP cameras are not provided with fiducial marks which record sharply at the focal plane. The somewhat blurred outline of the frame has to be used. Since the data required from this instrument, however, comprised only the bearing of the target with respect to the line of flight, inaccuracies remote from the principal point of the frame were not important.

8.4 NOSE CAMERAS FOR HIGH-ANGLE DIRIGIBLE BOMBS[5]

The early high-angle dirigible bombs were made approximately the same size as a standard 1,000-lb GP bomb, but were fabricated of sheet metal and loaded with lead. The purpose of this construction was to provide room for instrumentation and later (see Chapter 2) to provide room for television. The instrumentation consisted of a standard 16-mm motion-picture camera. By means of partially silvered mirrors the image of the sweep second-hand of a stop watch was projected onto a ring immediately surrounding the central field of view. Small sectors at the top and bottom of the frame carried records of the position of the aerodynamic surfaces.

This method of instrumentation was followed throughout the dirigible high-angle bomb program, including Felix. In the early work the cameras were recovered by parachutes ejected by squibs fired by

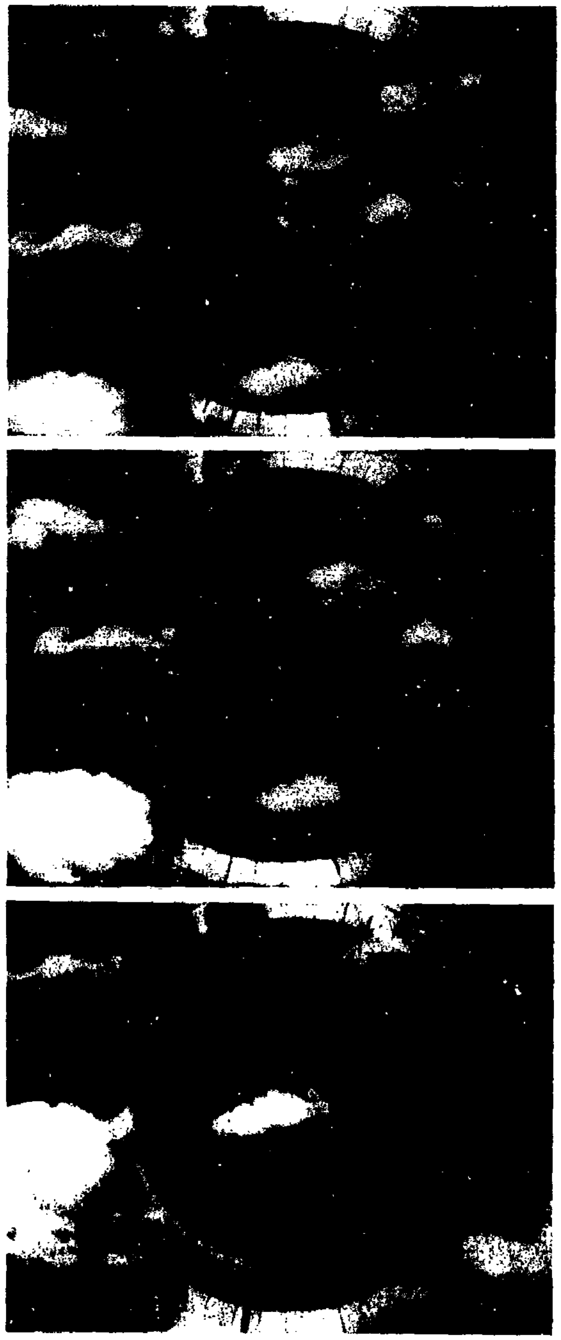


FIGURE 2. Sample frames from Gulf nose camera.

barometric switches a few seconds before impact. Parachutes proved unreliable; in any event, the crucial information is obtained in the last few hundred feet of the flight.

Camera cases were built of welded ¾-in. cold-rolled plate to protect the film against destruction at impact.

The steel camera casing was not adequate to protect the camera, nor indeed was it expected to be. The impact velocity of a dirigible high-angle bomb dropped from 15,000 ft is in excess of 800 ft per second. Even in moderately soft ground decelerations of several thousand g can be expected. Much of the film

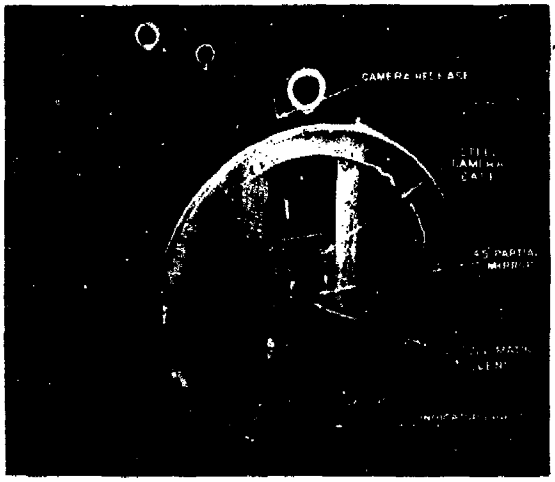


FIGURE 3. Nose camera assembly for high-angle dirigible bomb.

was recovered (Figure 2) but almost never in one piece. The data were available, but too much credit can hardly be given to the contractor's personnel for patience and perseverance in transcribing and analyzing 16-mm motion-picture film in fragments.

In the Roc program a similar problem confronted the investigators. For Roc-1 the cameras were mounted externally behind the dive brakes on the empennage. Their function was to photograph the field of view, consisting of a light target (see Chapter 4). In addition, a telltale light between the wings indicated the operation of the rate gyro which limited the rate of roll of the missile. In this position, the cameras (Figure 3) were somewhat protected by the empennage structure of the missile; nevertheless, much film was lost.

To correct this difficulty this contractor designed an armored magazine aimed to protect the film (Figure 4). Initial tests with this type of camera showed that the film was protected within the cassette from tearing or breaking. The camera was dashed to pieces on impact, and the portion of the film in the shutter mechanism unwound and exposed much of the film contained in the cassette. A spring-loaded knife was mounted at the opening of the armored magazine. The shock of impact tripped the knife, shearing off the portion of the film which had been exposed and wound within the armored casing. The

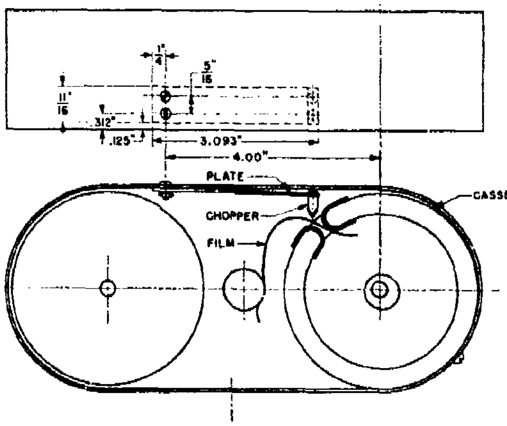


FIGURE 4. Cassette with shearing knife for Roc missile-borne motion-picture camera.

knife also helped to close the slot and prevent light from fogging the records.

8.5 GROUND INSTRUMENTATION

8.5.1 Phototheodolites[6]

Phototheodolites were used in connection with the high-angle dirigible bomb developmental work at Eglin Field. This use, however, was not successful because of the difficulty of coordinating the activities of the airship crew with the phototheodolite operators.

In connection with the Roc project, however, they proved very valuable. The instruments are complicated and need to be carefully maintained. Well maintained, and in the hands of competent operators, they can yield accurate data for missiles which are visible and whose speeds permit manual tracking. With two phototheodolites located at the end of a reasonably long base line, say 35,000 ft, the precision of location of any point on the trajectory is probably of the order of 50 ft.

The use of three instruments giving three pairs of data would reduce the error by the square root of 3. A further advantage, however, would obtain. With two instruments, failure to track by one ruins the trajectory from that point onward. With three instruments, the probability of a failure which would frustrate the reconstruction of the trajectory is reduced to ¼. Care must be taken to insure that the bombing run and the flight path of the missile do not require the operator to look into the sun. Furthermore, a path of the missile over the zenith of any observer is almost impossible to track.

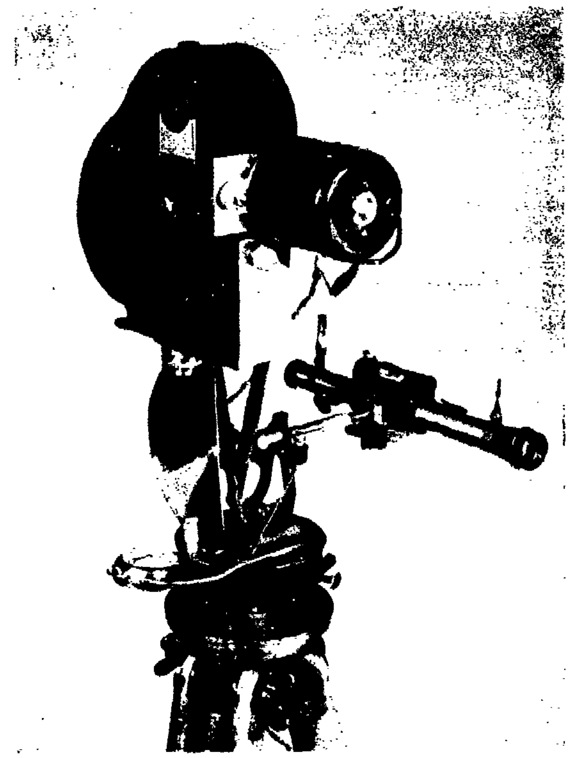


FIGURE 5. Washington cinema recording theodolite.

The data obtained from the phototheodolite consists of 35-mm motion-picture film with the image on the missile photographed against a fiducial scale. Superposed on the same frame are the readings of the azimuth and elevation scale of the instrument. The record on the film thus consists of the bearing of the telescope in azimuth and in elevation with the error due to faulty tracking preserved. A time interval circuit periodically photographs a serial number on the frame of all instruments, synchronizing them at that point.

The data are thus presented in a form suitable for analytical, rather than for graphical, analysis. It appears that a punched-card or punched-tape computing machine technique would be valuable with the instrument.

A simplified method of reducing the data was developed by the contractor.[7] This method, easier to apply than the standard method of the technical manual, gives somewhat improved accuracy.

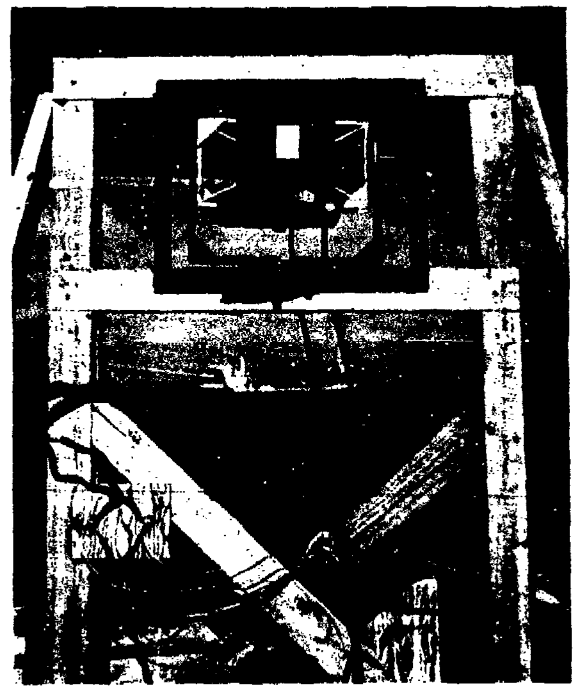


FIGURE 6. Unattended K-24 camera station.

8.5.3 Open Cameras

Where experimental flights are made at night and the missile carries a flare, qualitative data which may have some quantitative significance can be obtained by ordinary view cameras located in the plane of the target and the bomb run and on its flank. Indeed if the cameras are provided with fiducial scales, good quantitative data may be obtained with them, using the technique well known to astronomers.

Such quantitative refinement was not employed by the Division's contractors. The use of open cameras, however, furnishes a rapid means of getting an overall assessment of the trajectory. It is particularly valuable with homing missiles as it discloses to a first order of approximation whether the control is oscillatory, damped, or unstable. Figures 12 and 13 of Chapter 4 present data of this type.

8.5.3 Synchronized Ground Cameras[3]

Recording the motion of an object by simultaneous tracking from two base-end stations can be precise only if the instruments are carefully maintained. The optical axis must be carefully aligned with the azimuth and elevation scales, and these must be free from backlash. Section 8.5.1 describes the use of instruments carefully designed to avoid these errors.

In the early work of the Washington Project special theodolites were constructed, designed so that the azimuth and elevation scales could be photographed from a single point of view. A stop watch was placed near the instrument scales and photographed with them. At an oral signal the motor-driven cameras and stop watches were started, tracking by both base-end operators having been established (Figure 5).

This method assumes that tracking is perfect, since no photograph of the missile is obtained. Analysis of the records, as in the phototheodolite method, leads to redundance in the apparent altitude of the missile. Without means of correcting for errors in tracking, discrepancies of several hundred feet in missile elevation were not uncommon.

To eliminate these errors a photogrammetric method was evolved. Two AAF K-24 cameras were mounted at base-end stations. These cameras have motor-driven film transport mechanisms and an electrically tripped shutter. The minimum cycling time is 0.3 second. The pictures are 5 in. by 5 in., and the magazine carries about 120 exposures. Lenses of 5- to 12-in. focal length were used. The shutters and transport controls were wired in series so that strict synchronism was assured. An intervalometer, tuning-

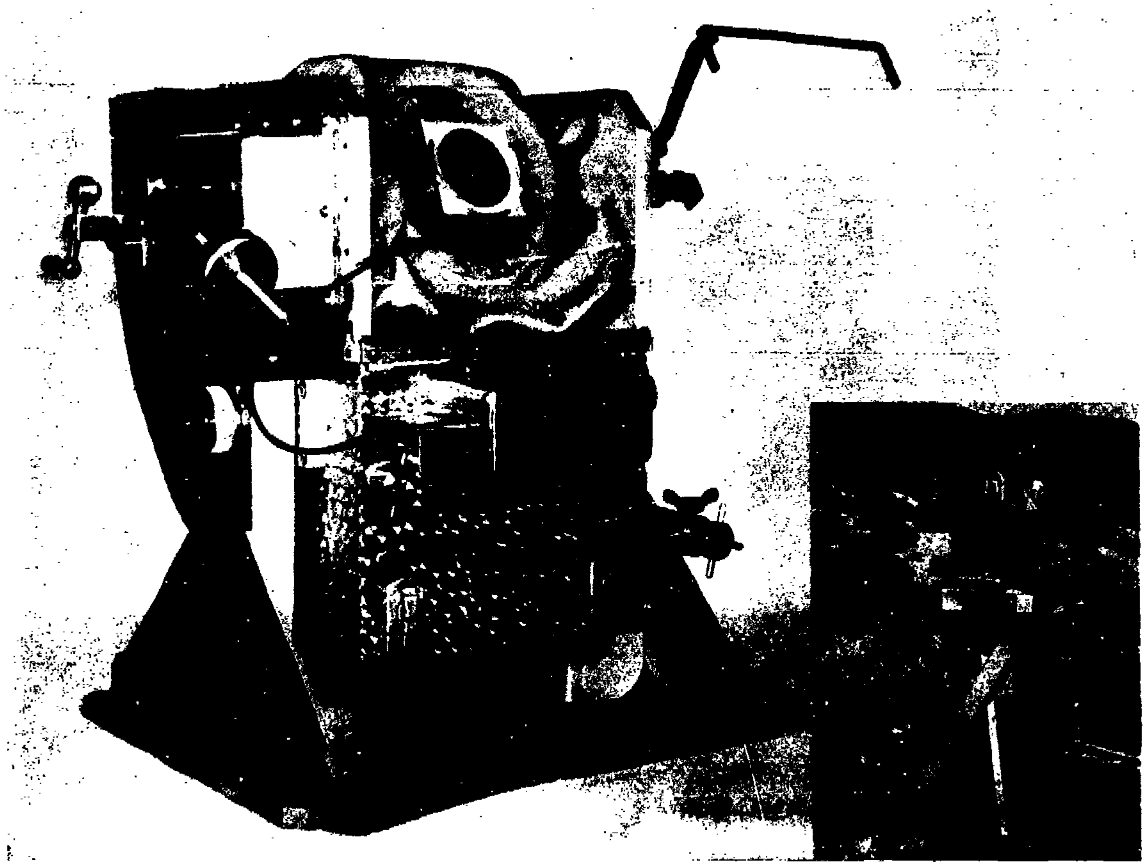


FIGURE 7. Bomb-trajectory camera.

fork controlled, produced the impulses to trip the shutters.

These cameras were left fixed during a trajectory determination (Figure 6). Thus the analysis became a photogrammetric process. The K-24 camera is provided with fiducial marks which produce an accurate coordinate system on the film. A transparent overlay of 0.005-in. cellulose sheet was laid successively over

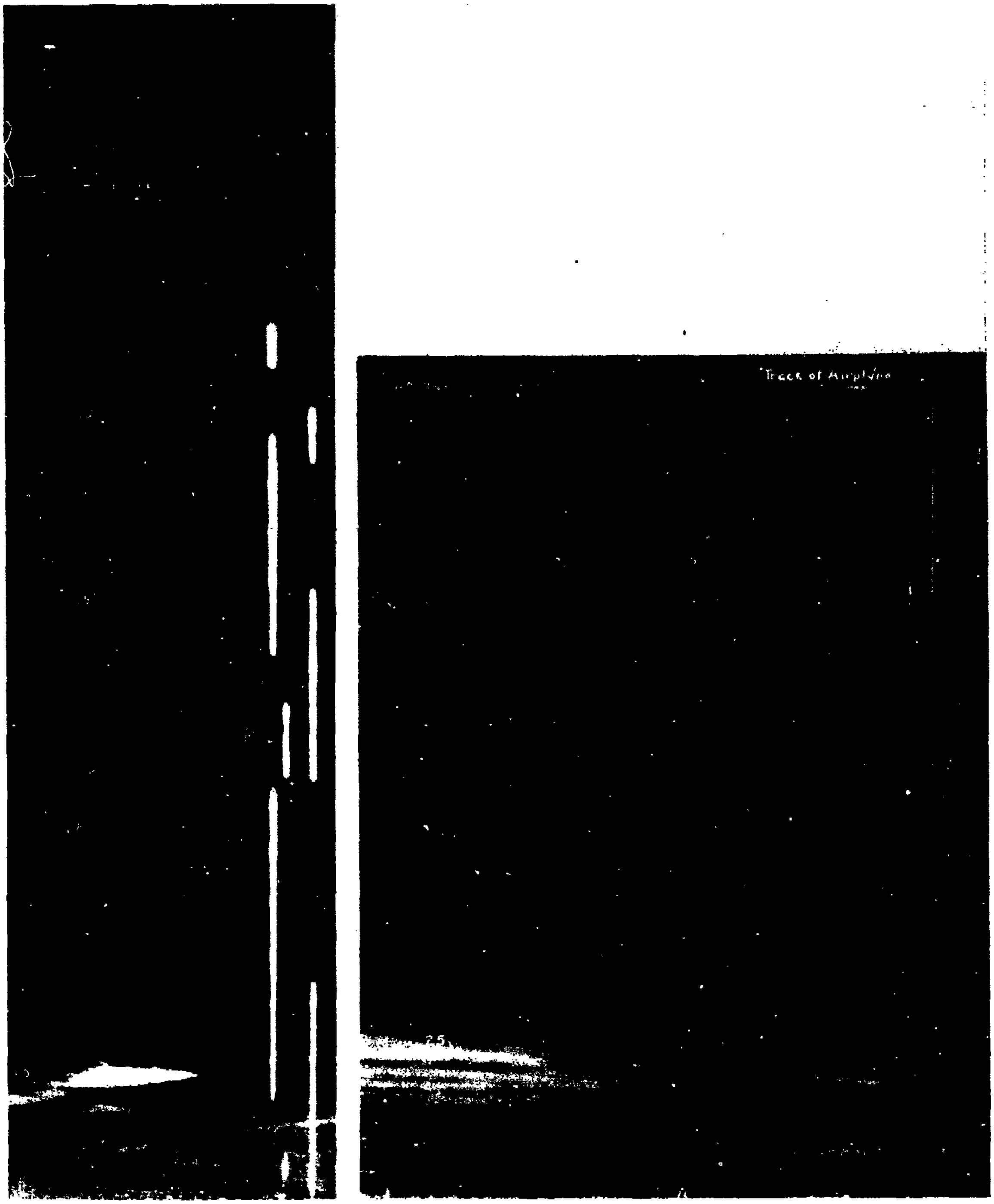


FIGURE 8. Frontal (right) and profile (left) traces of typical Razon drop made with bomb-trajectory camera.

each exposure and the position of the missile pricked on it. With the aid of a watchmaker's glass a precision of approximately 0.003 in. could be obtained, which resulted in an overall precision of about 10 ft in the elevation of the missile.

8.5.4 Slit Cameras[8]

The phototheodolite technique described in Section 8.5 poses problems in coordination. In order to obtain trajectory information more rapidly a special trajectory camera was developed by Gulf (Figure 7). This instrument is panoramic in principle. The camera is fixed during a trajectory, and successive exposures are made on a single film. In order to avoid overexposure a moving mask successively uncovers those zones of the film where the image of the missile will appear. The film is held in a cylindrical frame concentric with the axis of tracking. A chronometer momentarily closes the shutter, giving a time record as well as the spatial geometry of the trajectory. In addition, the instrument having been developed for Azon and Razon, pilot lights controlled from a radio receiver, recorded the instructions given the missile. Figure 8 shows typical frontal and profile traces of a Razon drop.

Chapter 9

MISCELLANEOUS CONTROL SYSTEMS

9.1 INTRODUCTION

In addition to the four integrated systems of guided missiles discussed in Part I of this report, the Division undertook the development of a small number of separate control devices. All but two of these control devices were calculated to produce homing flight of the missile for test purposes only. There were two reasons for adopting this course of action: (1) homing devices suitable for combat application were in general complicated and difficult of procurement; (2) as an interim measure during the development of the missile, it was essential that a homing device so simple in concept that its reliability was certain could be available to test fundamental homing qualities of the missile and other elements of the servo system.

There was also the possibility that a control device might appear in a laboratory not connected with the development of missiles. It was conceivable that a profitable development could be undertaken under these circumstances. The Division undertook two programs in this category: the organic homing system and the to-and-fro scanner. Neither of these devices reached a successful degree of development, although there is some evidence that had it been possible to achieve closer integration between the group engaged in the development of control devices and those working on the other portion of the servo system, each of them might have been carried at least to successful test, if not to actual combat application.

Until a system of analysis appears which will indicate clearly and reliably the interrelationship between all the elements which comprise such a guided-missile system, separate development of components followed by their assembly can only be regarded as most hazardous.

9.2 HIGH-ANGLE PHOTOELECTRIC HOMING BOMB[1]

9.2.1 General

As has been discussed in Chapter 3, the Felix bomb under development by the Massachusetts Institute of Technology was conceived as a high-angle bomb having the minimum departure from the standard geometry of the 1,000-lb GP bomb. Chapter 2 discussed the cooperative investigation made by MIT and the Gulf Research and Development Company in the evolution of a dirigible high-angle bomb. This cooperation was continued in the development of Felix. Gulf concentrated on the development of a high-angle bomb demonstrably capable of homing, MIT on the sensory or target-seeking device. For preliminary work it was impossible and indeed undesirable to use thermosensitive elements to detect the target. For the experimental purposes of proving the capability of the missile to home satisfactorily, a photoelectric target seeker seemed much more desirable. Photoelectric cells of high sensitivity were plentifully available. By performing tests at night, a very high degree of contrast between the target and the background surrounding it could be assured.

The experimental bomb was constructed of sheet metal, like the early Azon and Razon bombs, and was provided with a cylindrical shroud substantially at the center of gravity to increase its maneuverability (Figure 1). The empennage was made octagonal as a result of the work done in the wind tunnel at MIT in connection with roll torques and cruciform structures with simultaneous yaw and pitch. (See Chapter 2.)

The missile was stabilized in roll in the same manner as the Azon and Razon. Absolute roll stability in a homing missile of symmetrical structure is probably unnecessary. In fact, it will be shown in Sections 9.3 and 9.4 that Roc was made to home successfully without being so stabilized. All that is necessary is to limit the rate of roll in such a manner that the sensory device which detects the target can cause appropriate operation of the control surfaces to produce a lift in the direction to correct the error. This means that the scanning period, with the accompanying lag in computing circuits and operation of servo link, must be short enough to permit only a negligible change in the attitude of the missile about its roll axis. In this project, however, the determination of a suitable limit for rate of roll seemed undesirable since absolute control of roll had already been established by the contractors in connection with the Azon and Razon projects.

Missiles with fixed wings, such as the lift shroud provided for the photoelectric target-seeking bomb, or with bomb casing itself acting as a wing, fly with an appreciable and varying angle of attack. A scanning device rigidly mounted in such a structure will have a field of view centered around some rigid axis in the missile, which in general is not along the line of flight; that is, a homing device simply will not look where it is going. For this reason, a portion of the optical system of the photoelectric scanner was mounted on a wind-vane-actuated support, so that the axis of scan was always parallel to the axis of flight. Potentiometers mounted on the control surfaces provided a feedback to cutoff so that the position of the rudder and elevators satisfied the equation

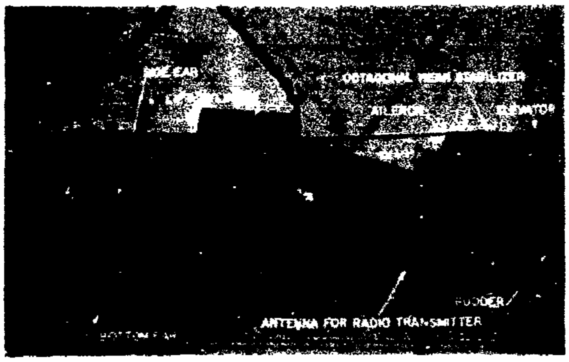


FIGURE 1. Photoelectric target-seeking bomb.

$$\delta = -k_1\theta \tag{1}$$

where δ is the rudder or elevator displacement and θ is the course error in the corresponding sense.

9.2.2 Dynamics of Flight

Figure 2 represents a portion of the trajectory of a homing missile. At the instant under consideration the missile has a velocity along the vector **V** to produce an expected miss h. The homing device, which is assumed to look along the velocity vector, measures the course error θ. Under the system of control selected for the photoelectric target-seeking bomb, the servomechanism causes the rudders to deflect proportionally to θ.

For small values of θ, such that $\tan\theta$ is negligibly different from θ, the lift L is proportional to the angle of yaw ψ, which in turn is proportional to the rudder displacement δ.

$$L = c_1\psi \tag{2}$$
$$\psi = c_2\delta \tag{3}$$
$$\delta = k_1\theta \tag{4}$$
$$\begin{aligned} L &= c_1c_2k_1\theta \\ &= -k\theta \end{aligned} \tag{5}$$

Gravity being neglected, the lift is balanced by two accelerations, centripetal and yawing, so that

$$-k\theta = k_3\dot{\theta} + k_4\ddot{\psi} \tag{6}$$

Under the assumption of linearity between ψ and θ this reduces to

$$k_5\ddot{\theta} + k_3\dot{\theta} + k\theta = 0$$

$$\theta = \theta_0\epsilon^{-k_3t/k_5}\sin\left(\left(\sqrt{\frac{k}{k_5} - \frac{k_3}{4k_5^2}}\right)t + \beta\right) \tag{7}$$

the well-known damped oscillation.

The validity of equation (6) is dependent on the assumption of linearity expressed in equations (1) to (5) and also upon the assumption of secularity of such parameters as the range R and the velocity. Furthermore, there must be no time lags in the system of control. Actually such time lags always exist so that the real control equation is

$$\delta = -k\theta f(t) \tag{8}$$

The presence of lag introduces negative damping. As the missile comes on course, the rudders should be in neutral under the control regime selected. If they lag, however, then an aerodynamic moment appears which causes an overshoot. Energy is fed into the system in an amount equal to the summation of the overshoot multiplied by the moment producing it. Only one thing appears to balance this source of energy, namely the aerodynamic damping of the missile. Transient wind-tunnel studies are needed for its determination.

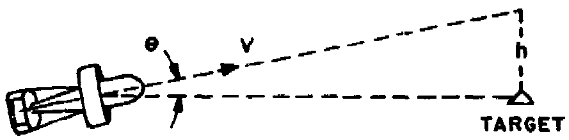


FIGURE 2. Projection of homing trajectory.

9.2.3 Photoelectric Homing Device

SCANNING SYSTEM

The preceding section showed the necessity of proportional control. The optical system, including the method of scan, was designed to attain it. An objective lens focused the target image on a scanning disk. The scanning disk was provided with slits mutually at right angles which periodically swept the field of view in an approximately horizontal and vertical direction. The target, therefore, appeared as a single flash of light through the slit which ultimately determined its vertical or its horizontal position within the field of view. A triple condensing lens focused the spot of light on the cathode of the photocell irrespective of the position of the spot within the frame.

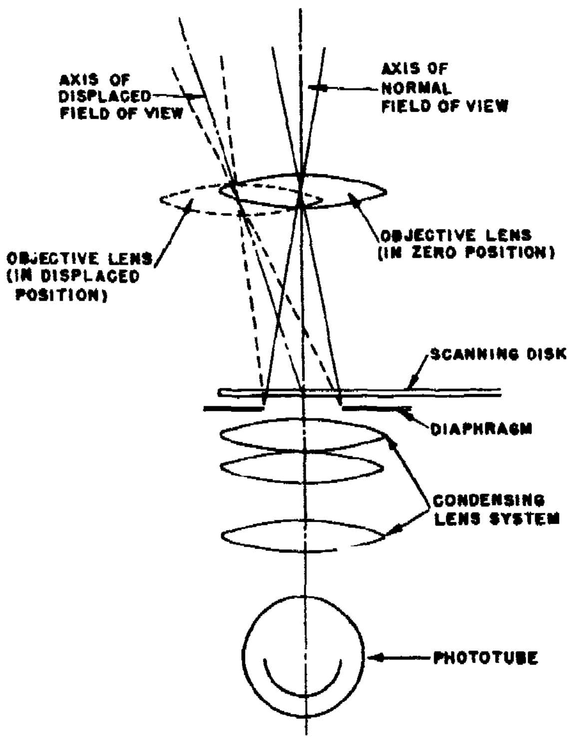


FIGURE 3. Optical system of scanning unit.

Figure 3 shows the limit of displacement of the objective lens in one direction due to the operation of the wind vane. The wind vane controlled a racking system similar to the rising and falling front of a view camera. Racking in the pitch direction was accomplished by two wind vanes connected to the rack mechanism through a differential which averaged the direction of the wind stream on each side of the bomb. Racking in the yaw direction was accomplished by a single wind vane well below the body of the bomb to avoid turbulence. The differential construction was impossible in the yaw direction because the presence of a wind vane on top of the bomb would have interfered with hanging the bomb from the usual shackle.

The slits of the scanning disk swept the image area alternately up and down and then left and right. The scanned image of a point source produced a pulse output of the phototube. This pulse was amplified and fed into the grid of a thyratron (Figure 4). The plate circuit of the thyratron was closed by a commutator at the beginning of the scanning cycle, thus setting the tube up to conduct at the instant a pulse was received. The tube remained non-conducting until the pulse on the grid triggered it, at which time it remained conducting until the commutator broke the plate circuit at the end of the scanning cycle.

A voltage thus appeared across the plate resistor of the thyratron as a square wave, the length of which measured the position of the point of light in the field of view. This square wave was filtered and amplified to operate relays controlling the rudder and elevator servomotors. The final stage of the control amplifier was biased by a voltage fed back from potentiometers driven by the servomotors operating the control surfaces. Thus, any given length of pulse would establish a voltage level in the control amplifier. This voltage would be extinguished by the bias voltage from the control surfaces, and proportionality was obtained.

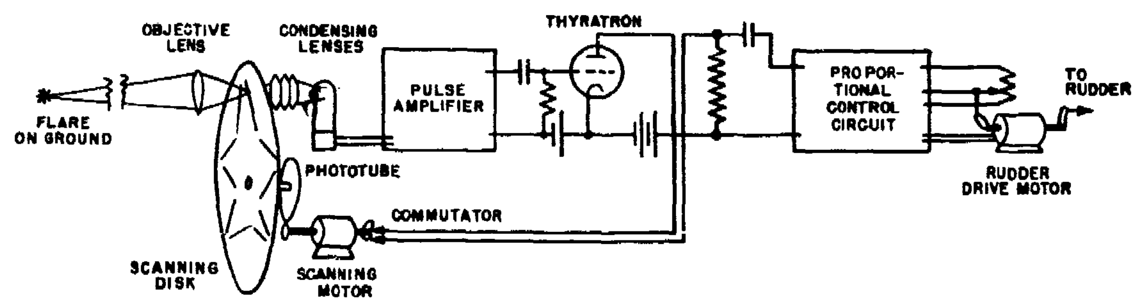


FIGURE 4. Schematic diagram of scanning system

PHOTOTUBE AND AMPLIFIER

The phototube selected was a CE-1-AA with a sensitivity of approximately 300 microamperes per lumen. The pulse output of this tube was amplified through two pentode and three triode stages. The pulse amplifier was resistance coupled, with time constants of the coupling circuits selected to give negligible phase distortion in terms of the scanning frequency (approximately 40 c). A single photocell scanned both up-down and right-left directions, the output of the pulse amplifier firing a type 2050 thyratron. Alternate pulses from the thyratron were switched by the commutator to the left-right and up-down channel so that the actual scanning frequency is approximately 20 c.

With the target directly on course, the pulse will appear in the center of the scanned field, and the rudders and elevators will assume the position required to maintain that course. The correct heading depends upon the continuous reception of a light signal from the target. Failure of the signal due to the extinguishing of the target flare or the failure of the phototube would cause the rudders and elevators to go to their extreme position, say left and down.

In the first few seconds of flight until the bomb has nosed over on its parabolic trajectory, the target is not in the field of view. An auxiliary relay was provided to hold the rudders and elevators in the neutral position until the target first appeared in the field of view. It then closed and sealed itself in, making the servomotors operative. This system can hardly be considered "fail safe." The relay which centers the rudder and elevator should not seal in but should be allowed to return to the centering position after a reasonable time delay following the loss of a target signal.

For the purposes for which this homing device was intended, this was not an important feature. It should, however, be incorporated in any combat application of a homing device. Loss of signal should not result in gross errors, that is, errors greater than would have been attained had there been no attempt at automatic homing.

9.2.4 Radiosonde

Azon and Razon were checked during the early experimental phases of their development by means of motion-picture cameras located in the nose, photographing the terrain toward which the bomb was falling. With the photoelectric target-seeking bomb, all operations were planned to take place at night, and such photographic techniques were impracticable. Accordingly, a simple radio transmitter was installed in the bomb to transmit to a ground station the output pulse, the length of which measured the position of the target with respect to the line of flight. The received pulse was applied to the vertical deflection circuit of an oscilloscope through an electronic switching circuit which produced reversal of alternate square-wave pulses. Thus the length of positive pulses on the oscilloscope screen measured the bearing of the target in one coordinate (e.g., azimuth), and the length of the negative pulse measured the bearing in the orthogonal direction. These measurements were recorded by means of 16-mm moving-pictures (Figure 5).

9.2.5 Dropping Test

Five missiles were dropped at Eglin Field in December 1943. Of these five missiles, one failed; the remainder made scores of 116 ft, 89 ft, 94 ft, 243 ft, and 47 ft.

The target consisted of a 1,000,000-candlepower pyrotechnic flare. At an altitude of 4,000 ft, the resulting intensity of the photoelectric target-seeker was approximately 34 times the threshold of operation. In addition to the radiosonde system just mentioned, records were taken with bomb-bay cameras giving the ground projection of the bomb from the point of view of the aircraft. Slit cameras approximately 6 miles on the flank of the trajectory recorded its profile (Figure 6).

Frame-by-frame analysis of the records from the radiosonde apparatus gave a continuous plot of the apparent bearing of the target along the line of flight (Figure 7). A similar analysis of the bomb-bay camera gave the approximate ground projection of the trajectory (Figure 8).

Section 9.2.3 showed that a control system, in order to produce nonoscillating flight, must develop lift forces which are proportional to the time derivative of error in heading, as well as to the error itself. The records, just given for bomb No. 83, which are typical of the four successful missiles, failed to show any signs of such oscillation. The yawing and pitching of such a missile as this to produce lift forces in the azimuth and range direction must be accompanied with sufficient aerodynamic damping to absorb enough energy to make the system nonoscillatory.

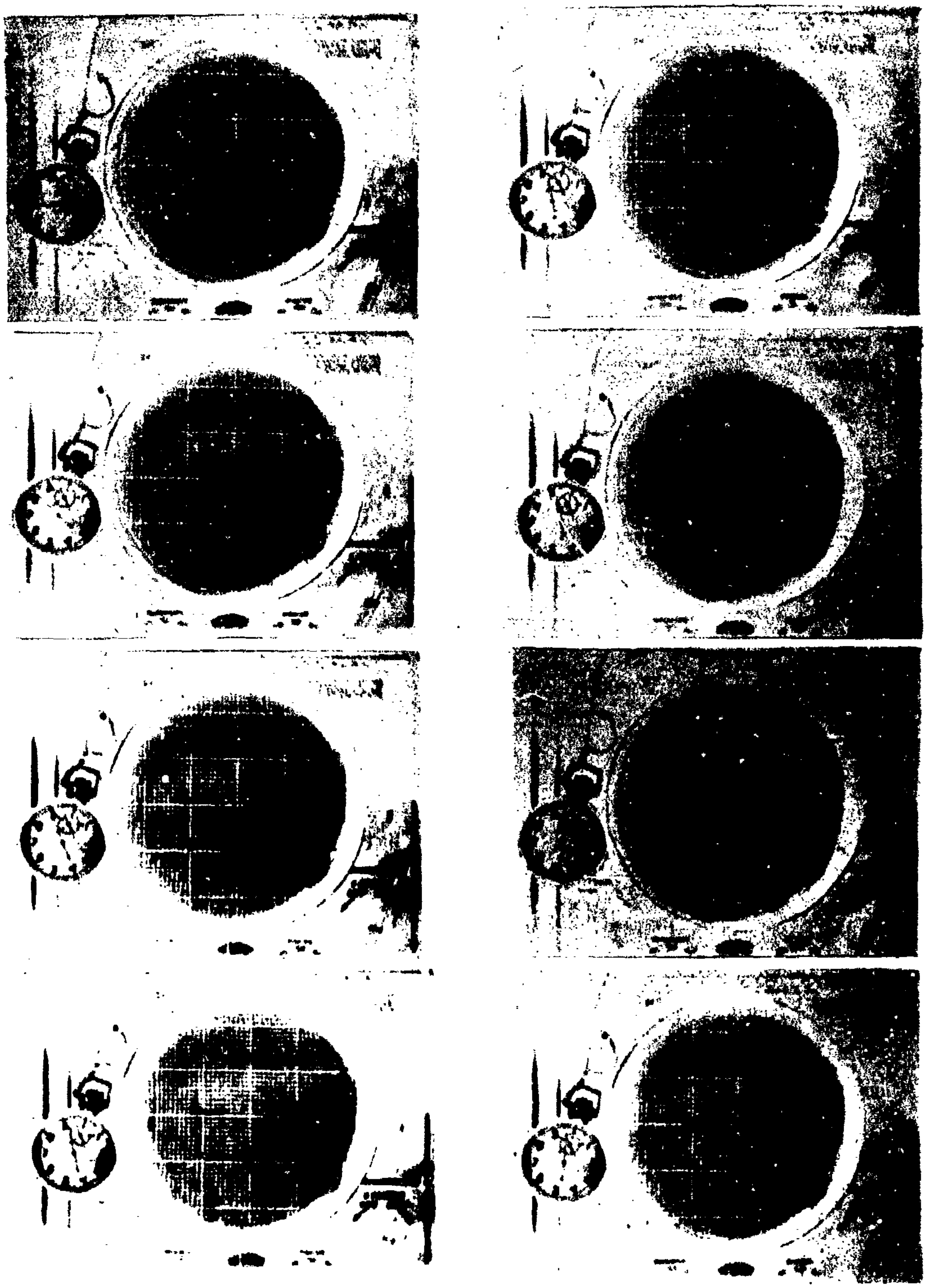


FIGURE [illegible]. Successive frames from radiosonde oscilloscope record.

9.3 QUADRANT PHOTOCELL TARGET SEEKER[2]

As has been stated in Chapter 4, the missile Roc was originally intended for use with radar target seeking. The extreme scarcity of radar target-seeking equipment made it wholly undesirable to use this means of intelligence during the developmental stages of the missile itself. As a portion of their contract for the development of the missile, the Douglas Aircraft Company undertook the development of a photoelectric target-seeking device to prove the homing property of the missile.

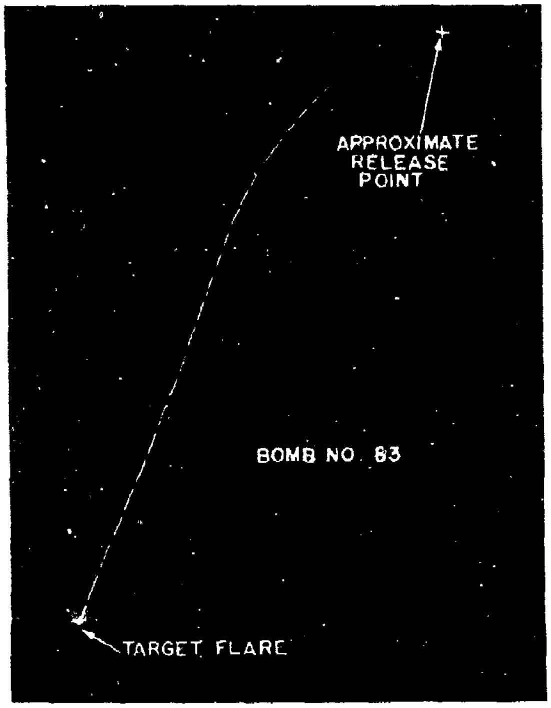


FIGURE 6. Trajectory of photoelectric target-seeking bomb.

The scanning system consists of a cloverleaf photocell having four cathodes, each occupying approximately one quadrant sector of a disk $1\frac{1}{2}$ in. in diameter (Figure 9). This photocell is located in the focal plane of a scanning lens which is mounted eccentrically with respect to the four cathodes. The eccentric lens with its housing is rotated at 1,800 rpm concentrically with the photocell axis.

With this scanning system a target flare describes a circle as the objective lens rotates around the center of the quadrant-cathode array. If the target is dead ahead, the circle will lie for an equal time interval in each of the quadrants. If the target is off course, the duration of its excursion within one of the quadrant sectors will be greater than its excursion on the diagonally opposite one. The time difference between the length of excursion in diametrically opposite cathodes is a measure of the error in heading.

A two-channel preamplifier accepts the output of two diagonally opposite cathodes, amplifies them to a suitable level, and in a saturated stage clips them. The result is a pair of pulses of equal amplitude but differing in length. These pulses are then subtracted and the output filtered and integrated. For each of

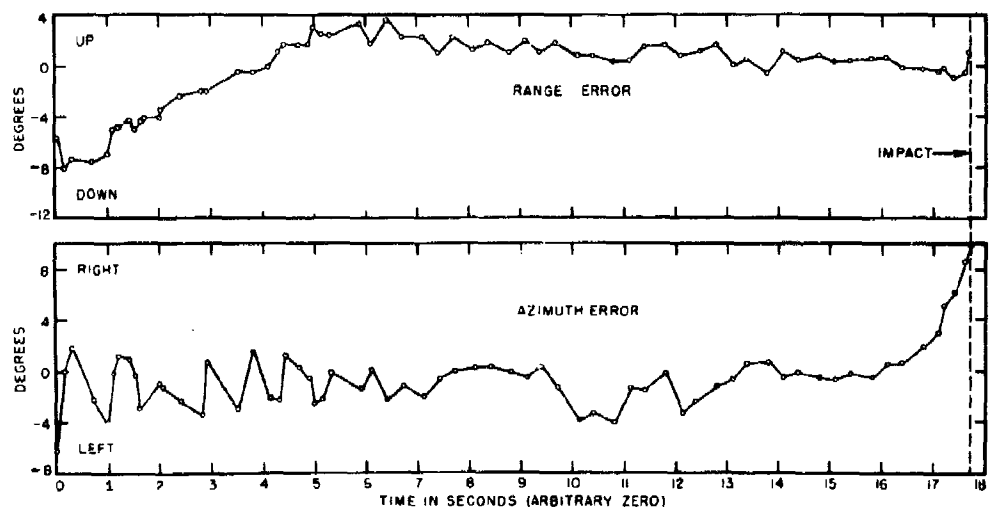


FIGURE 7. Error in heading of photoelectric target-seeking bomb No. 83.

the two channels, right-left or up-down, there then appears a d-c voltage which is a function of error in heading. For small errors in heading, the relationship is nearly linear, so that the output of the photocell amplifier for small errors in heading can be considered to be: $e = K\theta$, where e is the output of the amplifier, K is a factor of proportionality, and θ is the angular error in heading. This voltage is then fed to a differentiating-mixing circuit which develops a voltage for driving the flap motor at a speed proportional to the course error and to its first time derivative. (See Chapter 4.)

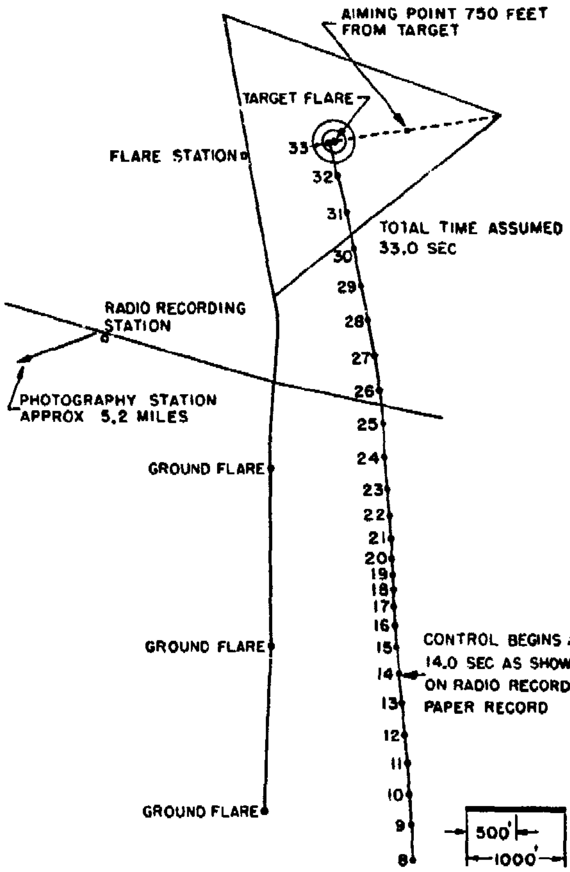


FIGURE 8. Projected path of Gulf photoelectric target-seeking bomb No. 83.

The missile is a four-winged device with individual servomotors driving full-span flaps on each of the wings. Consequently, each of the two channels has two outputs, and each of the opposite wings is controlled from one of the amplifier channels. The up-down channel (Figure 10) is biased by a feedback voltage from potentiometers mounted on the wing flaps; if the displacement of one flap advances ahead of that of its mate, a voltage is injected into the control amplifier to extinguish this differential, thus maintaining control surfaces of this pair of wings in phase.

No attempt is made to keep the control surfaces on the other pair of wings in step. In fact, a rate gyroscope is provided on this channel to bias the speed of the wing motors to correct excessive rate of rotation. To repeat, no attempt is made to maintain an absolute roll of stabilization. Designation of the channel, therefore, as "up-down" or "right-left" is for convenience only and has no physical significance. As the missile rolls during its flight, the different pairs of wings successively perform the function of providing lift in the range and in the azimuth directions. It was well understood that such a target seeker was somewhat qualitative in its response. Figure 11 shows that the output of the photocell preamplifier depends not only on the error in heading but also on the bearing. Further, it shows that the right and

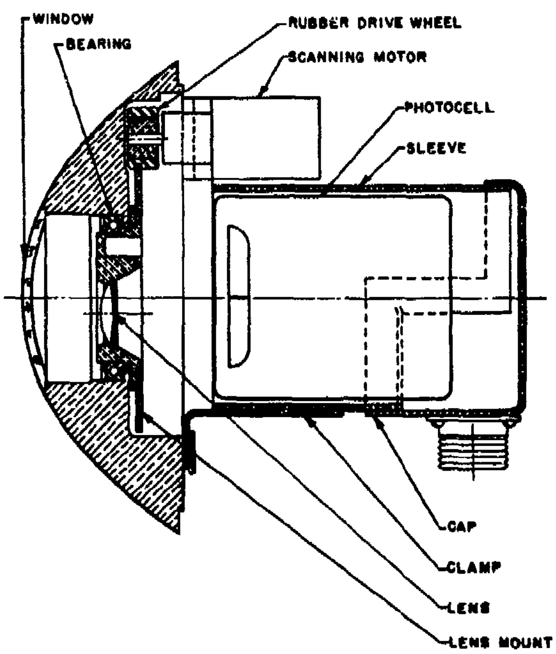


FIGURE 9. Section of quadrant photocell target seeker.

down, or better, the x and y components, or the error in heading were not pure orthogonal components; that is, the voltage resulting from an error in heading of 5 degrees in azimuth varies with varying errors in heading in the range sense. These vagaries, however, were considered as not seriously affecting the significance of the experiments in proving the homing characteristics of the missile.

Other difficulties with the system were, however, serious. The initial quadrant photocell was a CE-47 which the Army Air Forces had made available for this project. Serious variations appeared in the sensitivity of the various quadrants, even within a single tube. In many cases these variations were beyond the capability of the preamplifier to limit and clip. Furthermore, the glass work of the envelope was seriously defective, the end of the envelope being so irregular that the path of the rotating circle of the target image was seriously distorted. This tube was finally replaced by a much better quadrant tube especially developed by the Farnsworth Radio and Television Corporation through the cooperation of Section 16.4, NDRC. The four cathodes of this tube were mounted in an envelope having an end of optical glass optically polished. Greatly increased sensitivity was obtained by photomultiplication. Each cathode quadrant had its individual assembly of multiplier cups and collector anodes so that the whole tube comprised four six-stage photomultipliers.

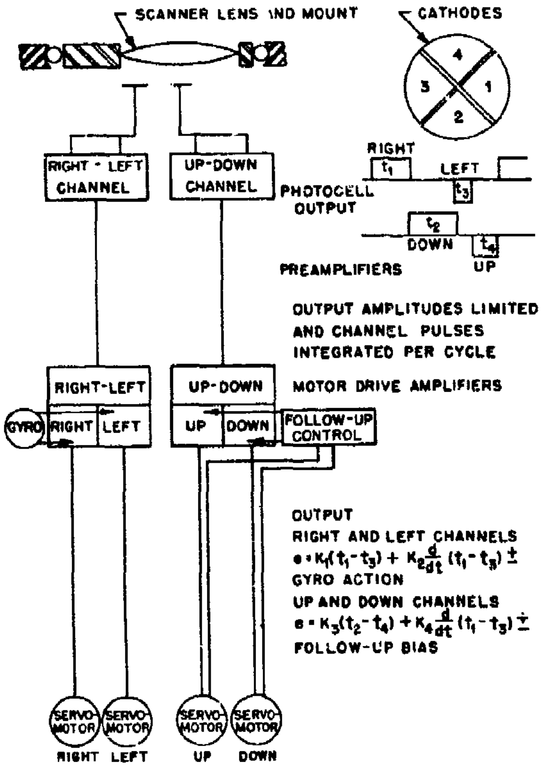


FIGURE 10. Block diagram of quadrant photocell target seeker and control circuit.

The basic scheme of operation of the preamplifier involves the measurement of the length of the voltage pulse arising from the time that the target image is on a particular quadrant. This requires that the sides of the voltage pulse shall not deviate materially from the perpendicular. The physical circuit cannot tolerate even finite discontinuities. It is impossible for a voltage to rise instantly across a condenser without the expenditure of energy at an infinite rate. An engineering compromise is effected by designing circuits which would tolerate reasonably rapid voltage rises, and by incorporating into the power supply to the dynodes current-limiting resistors to provide within the photomultiplier itself a measure of AGC, so that the clipping action required from the preamplifier would not be excessive. Thus spurious lengthening of the pulse due to clipping farther and farther down on a trapezoidal wave was eliminated.

Test results with this homing device have been discussed at some length in Chapter 4. In summary it can be said that the quadrant photocell target seeker gave good qualitative proof of the homing characteristics of Roc and a measure of quantitative support for the particular control regime selected.

9.4 WIDE-ANGLE PHOTOELECTRIC SCANNER[3]

9.4.1 General

The photoelectric target seeker just described had certain inherent limitations. The corrective signal in azimuth depended not only on the azimuth error but also on the error in range. Furthermore, as has been already mentioned (see Section 9.3), difficulties in procuring suitable quadrant photocells made the outcome of the project rather doubtful. To overcome both of these difficulties, the Division made a contract, OEMsr-1182, with the Fairchild Camera and Instrument Corporation to develop a wide-angle photoelectric scanner which would develop a signal suitable to control Roc through the servo link designed for it.

Specifically, this requirement is for an output voltage from the scanner such that when

$$0 \le \theta \le 10 \text{ degrees}$$
$$e = k_1\theta$$

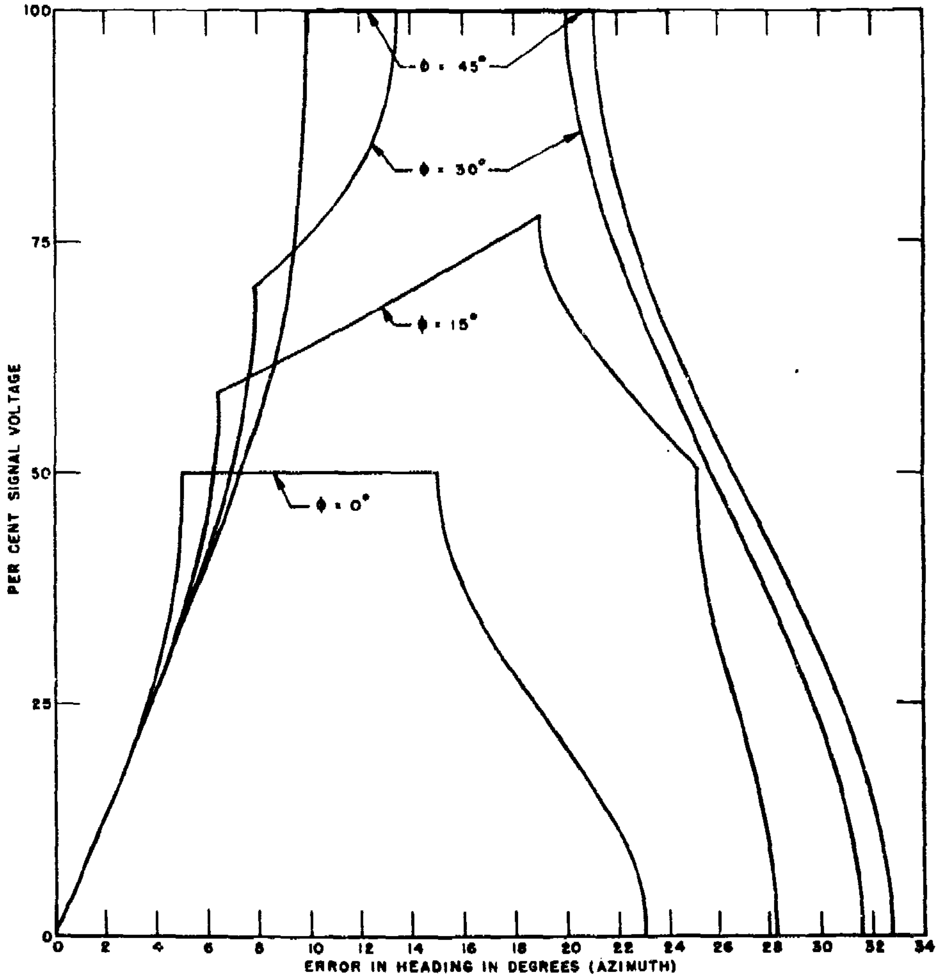


FIGURE 11. Output of quadrant photocell preamplifier. Parameter ϕ is measure of direction of total error.

$$\phi = \tan^{-1}\frac{\text{degrees range error}}{\text{degrees azimuth error}}$$

and when

$$10 \text{ degrees} \leq \theta \leq 40 \text{ degrees}$$
$$e = E$$

The general approach was to scan the landscape so that a luminescent target such as a pyrotechnic flare would produce a spot of light on the cathode of a single photomultiplier tube. The optical system was arranged so that the length of the pulse produced by the image of the target would be proportional to the error in heading for small angles and constant for larger errors. A cardioid aperture in the focal plane of a simple lens, if rotated at a constant speed, produced a pulse of light the length of which was proportional to the error in heading of the missile with respect to a luminescent target. Such a system, however, required good optics; the resolution had to be such that the size of the image of the target was small in comparison with the width of the cardioid slit at the smallest error angle which it was desired to measure. Without resorting to elaborately corrected lenses, it was found impossible to attain so small a circle of confusion. For errors of the order of 1 to 2 degrees off course, the diameter of the target image was greater than the width of the cardioid aperture.

The general system was reversed, therefore, and an aperture similar in shape to half a keyhole was made, such that the light from the target excited the photomultiplier cathode for a period varying proportionately from $\frac{3}{8}$ of a scanning cycle with zero error in heading to $\frac{1}{24}$ of a scanning cycle for a 10-degree error. For errors in excess of 10 degrees, the excitation period was constant at $^1/_{24}$ of the scanning cycle.

The output of the scanning cycle was then made proportional to the dark time of the phototube. A commutator driven synchronously with the scanner analyzed the output voltage into orthogonal components and distributed them to the up, down, right, and left channels of the motor-control amplifier. The Roc missile is essentially a Cartesian structure. Corrective instruction to the control apparatus has to be given in terms of right, left, up, or down, or better, since the missile is not absolutely stabilized in roll, in terms of $\pm x$ or $\pm y$. The commutator, therefore, must not only distribute the output of the scanner amplifier to the appropriate quadrant corresponding to the wing system on the missile, but must also resolve the output in accordance with the sine and cosine of the instantaneous roll attitude of the missile.

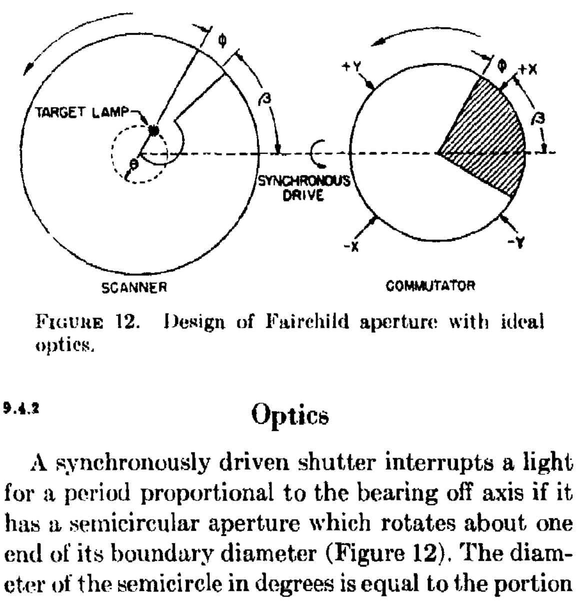


FIGURE 12. Design of Fairchild aperture with ideal optics.

9.4.2 Optics

A synchronously driven shutter interrupts a light for a period proportional to the bearing off axis if it has a semicircular aperture which rotates about one end of its boundary diameter (Figure 12). The diameter of the semicircle in degrees is equal to the portion of the field of view in which proportionality is desired. A sector from the outer edge of the semicircle to the edge of the field of view gives constant dark time for errors in heading greater than the semicircle diameter. The scanning aperture thus has the shape of half a keyhole. For the signal to be of the character desired, the aperture (Figure 13) must be located in the focal plane of the lens and must rotate about the optical axis. Then, if the target is dead ahead, the image of the target will lie at the principal focus of the lens, which is the center of rotation, and no pulse will be transmitted through the aperture to the photocell. Such a system, however, has a limited field of view; 35 degrees is approximately the limit of total angle attainable with a system of uncorrected lenses without experiencing serious aberration, with consequent increase in the size of the circle of confusion.

In order to increase the angle of the field of view, a wedge prism was mounted in front of the objective

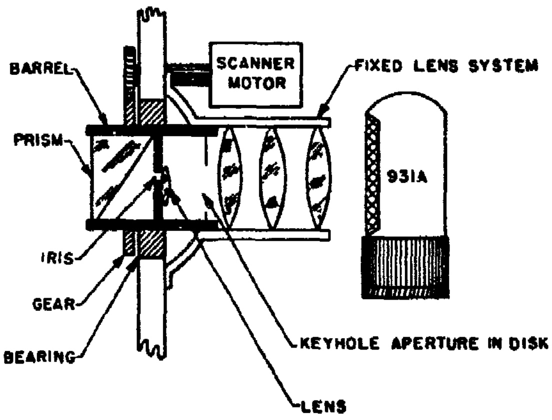


FIGURE 13. Lens and prism system of wide-angle photoelectric scanner.

lens. The angle of the prism was such as to bend the optical axis of the system so that the boundary generatrix of the cone of scan was parallel to the axis of the objective lens. The whole optical system, then, prism, objective lens, and iris diaphragm, was rotated about the optical axis of the objective lens. This gave the optical system a squint so that at one instant it viewed the terrain from dead ahead to 40 degrees to one side. One-half scanning cycle later it viewed the terrain from dead ahead to 40 degrees in the reverse sense. A second effect of the prism was to move the principal focus of the entire optical system to a point

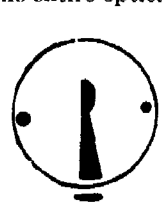


FIGURE 14. Actual shape of keyhole scanning aperture.

on the edge of the field of view in the focal plane at the end of a radius perpendicular to the dihedral of the prism. As the optical system was rotated by the scanning motor, a point dead ahead would be continuously focused on the outer end of this radius. All other points in the field of view would describe concentric circles around this point. The radius of these concentric circles was proportional to the error in heading. The total effect of the prism, then, was to increase the field of view and, by shifting the principal focus of the optical system from a fixed point at the center of the focal plane to a synchronously revolving point on its boundary, to require that the aperture (Figure 14) be reconstructed so as to cover substantially the entire diameter of the focal plane. Some distortion resulted from the use of the prism, and the aperture no longer consisted of a semicircle terminating in a wedge sector.

The technique of producing the aperture is worthy of note. A shape simulating the ideal aperture (see Figure 12) to scale was cut out of black cardboard and mounted on a white screen. This shape was then floodlighted and photographed on a sheet of Kodalith film mounted in the focal plane of the scanner with which the aperture was to be used. This technique automatically compensated for the aberrations in the optical system. After the film was developed, retouch artists made the negative opaque, to give sharp boundaries to the aperture. The iris diaphragm is located at a focus conjugate with the cathode of the photomultiplier.

9.4.3 Preamplifier

The phototube was a type 931-A ten-stage photomultiplier. With 1,000 v between the cathode and the ninth dynode, threshold sensitivity was approximately ⅓ microlumen, 0.001-footcandle intensity at the scanner. This threshold sensitivity is equivalent to a signal-to-noise ratio of about 2.

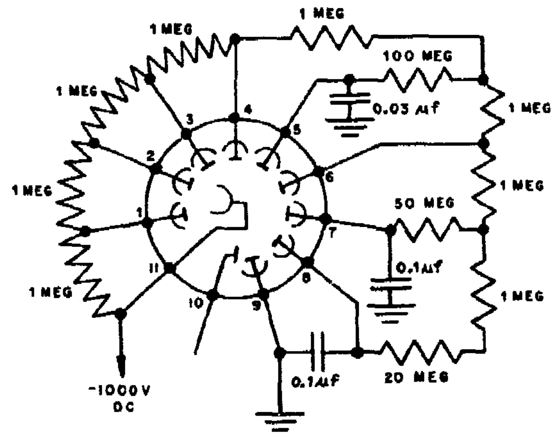


FIGURE 15. AGC arrangement in phototube connections.

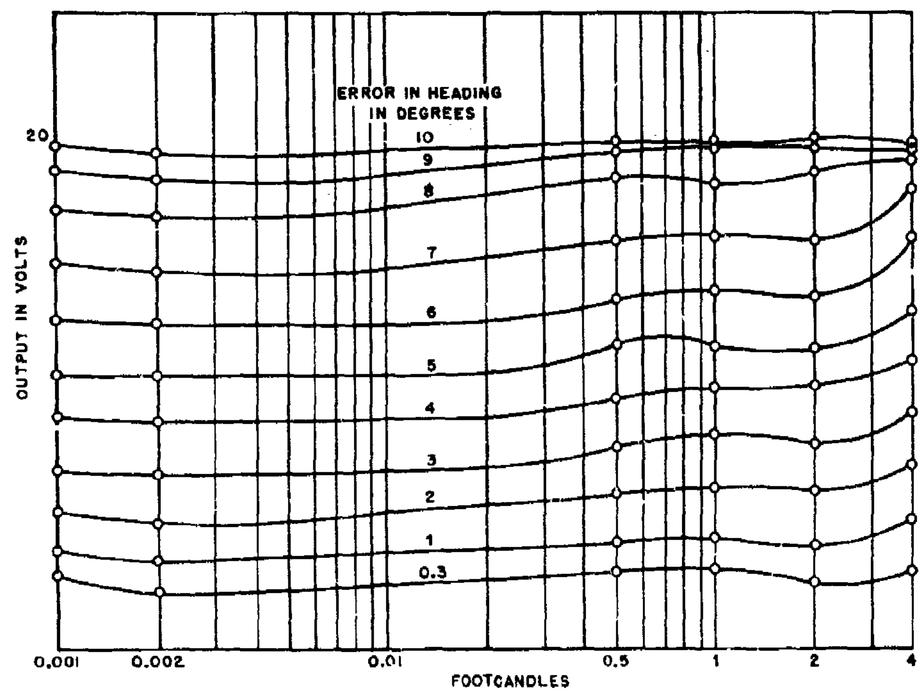


FIGURE 16. AGC characteristics of wide-angle scanner preamplifier. Response approximately proportional at 8 footcandles.

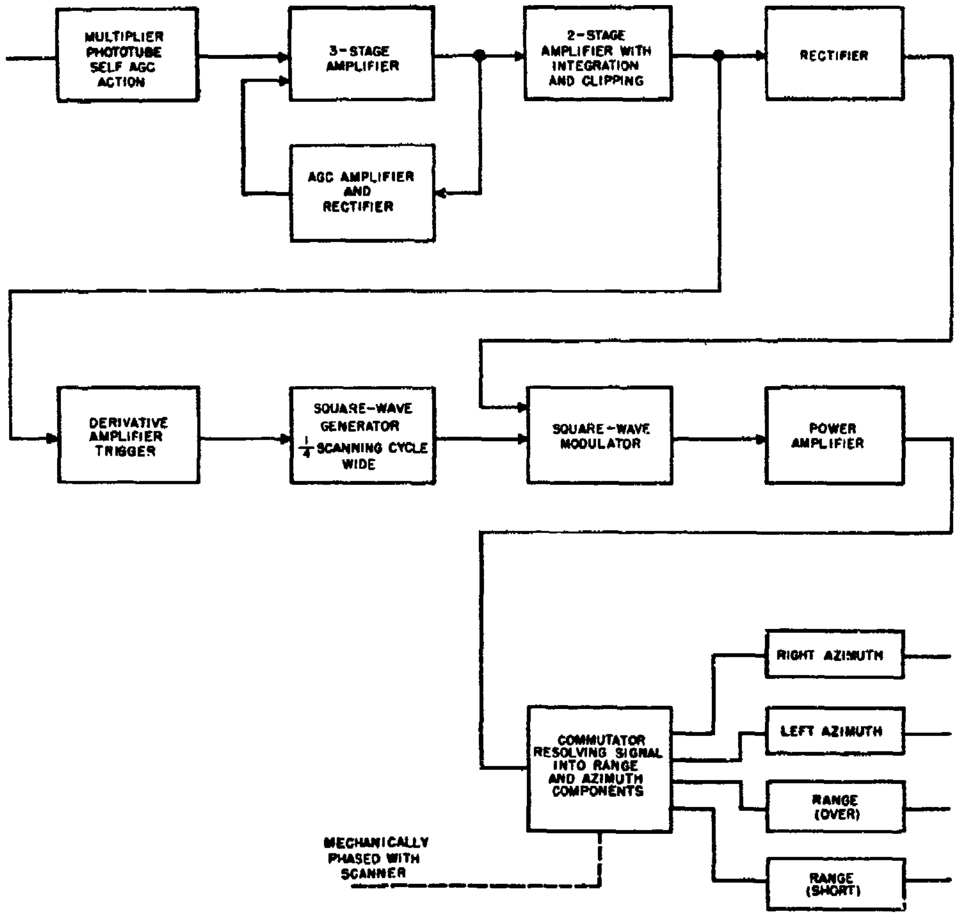


FIGURE 17. Block diagram of wide-angle scanner circuit.

The illumination intensity undergoes enormous gain during a missile flight. In a drop from 10,000 ft (14,000-ft slant range) it rises from 0.005 footcandle at release to 4 footcandles at the beginning of the last second before impact, some 58 db rise in power level. It was therefore necessary that the preamplifier supplied by the phototube have as much AGC as was practicable (Figure 15). In addition it was necessary to limit the current from the dynodes at stages 5 and 7. The overall effect of the AGC amplifier and the photomultiplier power-supply network was to give substantially flat voltage from 0.001 footcandle to 4.0 footcandles.

After they were amplified, the pulses were clipped to a fixed amplitude and then integrated to produce a triangular pulse, the amplitude of which was proportional to the excitation time of the phototube (Figure 17). The output of the integrator was fed to a differentiating amplifier, which produced a very high pulse at the trailing edge of the triangular wave. This pulse was used to trigger a square-wave generator. The amplitude of the triangular pulse, passed through a rectifier, was applied to the square-wave modulator.

The square wave produced by the generator was essentially a gate exactly ¼ of the scanning cycle wide. The output of the square-wave modulator, therefore, was a pulse 90 degrees in width and having an amplitude proportional to the error in heading for small errors and constant for larger errors. This wave was suitably amplified and commutated. The commutator was phased mechanically with the scanner and the wing structure of the missile. A ladder filter in the output of the commutator provided smoothing so that the final output was substantially a d-c voltage.

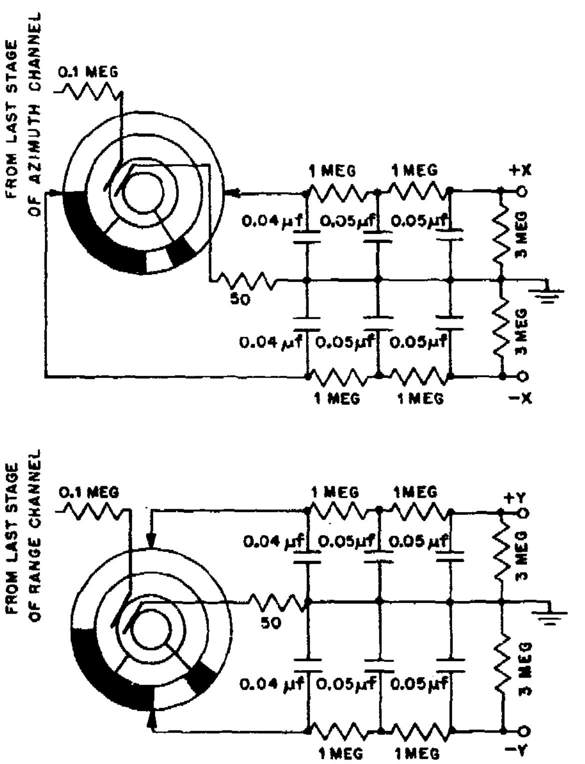


FIGURE 18. Commutation system and ladder filter for wide-angle scanner.

In order to change the polar coordinate characteristics of information developed by the scanner to the Cartesian information required by the wing structure of the missile, the first element of the ladder filter (Figure 18) consists of a series resistor and a condenser, the constants of which are so selected that the charging rate of the network closely approximates a sine function. Without these stages, the common 0.1-megohm resistor and the 0.04-µf condenser, the x and y components of scanner output would be proportional to the instantaneous phase in roll of the missile rather than to the sine and cosine of this phase. Figure 19 shows the degree of approximation to the appropriate sine and cosine function obtained by the exponential function expressing the charge of the initial condenser in the output filter of the scanner system. Figure 20 shows the output of the preamplifier and wide-angle scanner combined.

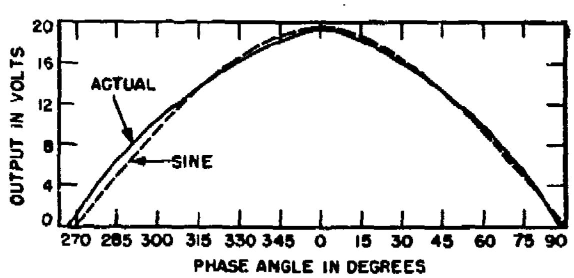


FIGURE 19. Approximation of sine function by condenser-resistor combination.

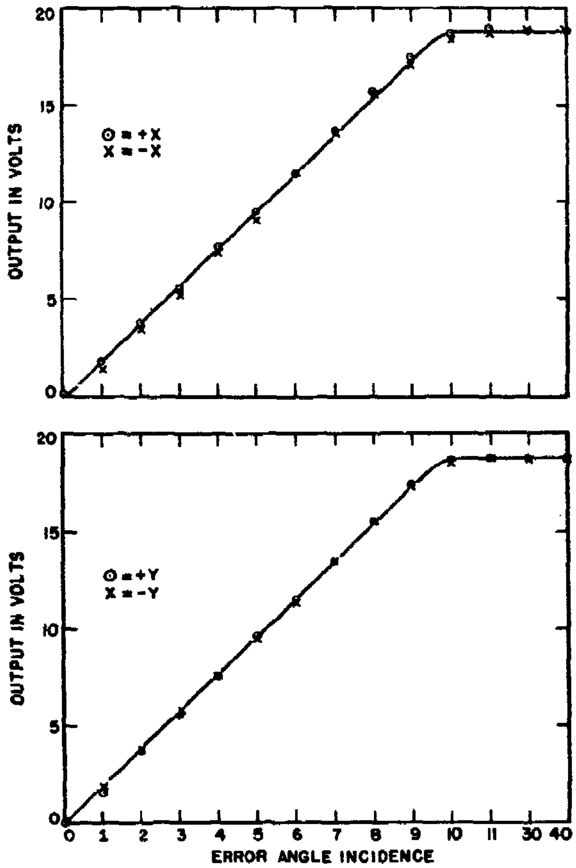


FIGURE 20. Output of preamplifier and wide-angle scanner.

9.4.4 Test Results

Six scanning devices were constructed in accordance with the principle above described. Three were tested with Roc missiles during the early summer of 1944; the remainder, unexpended, have been turned over to the Air Technical Service Command.

Considerable difficulty was experienced, due to erratic operation of the control surfaces when operated by the output of this device. As has already been stated, the control system for Roc (see Chapter 4) was built about a regime of control such that the rate of change of wing incidence angle was proportional to the error in heading and to its first time derivative. The error in heading was measured by the output of the amplifier associated with the wide-angle scanner. This output was then passed to a differentiating-mixing circuit for each of the two channels, right-left, or up-down, or preferably, $+x - x$, $+y - y$. The output of the mixing circuit produced a voltage proportional to the input voltage and to its first time derivative. The factors of proportionality were such that the derivative component in the output was about five times the component due to input voltage. Thus the whole control system following the preamplifier was extremely sensitive to irregularities and fluctuations in the output voltage of the preamplifier.

Fluctuations can result from several causes. Those due to variation in light intensity can be eliminated by an appropriate AGC system; this was done. Those due to noise originating within the preamplifier circuit and to interference from other radiating circuits in the missile are overcome with more difficulty. Circuits with high grid impedances are much more subject to both of these types of fluctuation than are circuits with moderate grid impedances. The preamplifier associated with the wide-angle scanner consisted of a triode stage, a pentode stage, and two triode stages. The grid impedances respectively were 10 megohms, 5 megohms, 10 megohms, and 5 megohms. Even beyond this point, grid resistors of higher value than 3 megohms were the rule.

After the input circuit to the preamplifier is carefully shielded and suppression filters are applied to the noise-generating equipment on the missile—gyro motors, wing-flap motors, and scanning motor—the output of the preamplifier associated with the wide-angle scanner for various errors in heading up to 10 degrees is as shown in *A* of Figure 21. *B* shows the results of differentiating the output for 1 degree, 5 degrees, and 10 degrees. The corresponding armature voltage is shown in *C*, and the flap displacement vs time resulting from the overall control system is shown in *D*. Three missiles were dropped with this control system. One of the three failed to operate for causes which could not be determined. The two remaining missiles scored errors of 142 ft and 372 ft, correcting aiming errors of 2,400 ft and 900 ft respectively.

Three drops constitute a wholly inadequate sample on which to base mature conclusions concerning a device of this nature. The project was relinquished in favor of other developments in connection with Roc. So far as photoelectric target seeking itself is concerned, this development seems an adequate solution to the problem of providing quantitative response over a wide field of view. With some further engineering, directed, perhaps, toward simplification of the preamplifier, there appears to be no reason why it would not furnish adequate means of testing homing missiles.

9.5 ROLL STABILIZATION WITHOUT A FREE GYRO[4]

In Section 2.4 the problems of roll stabilization were discussed in detail. Early in 1943 the Division was seriously concerned over the threat to the Razon program due to failure of the roll-stabilization system then in use, and also wished to make a stabilizer available for Roc should it be needed. Electro-Mechanical Research, Inc., who had worked upon the problem, was asked to perfect its device. Eventually Gulf and Douglas solved the problem for their specific missiles, but in the meantime some work had been done on the alternative device.

Lacking a free gyro, this system reduced roll to a minimum value rather than eliminated it. This was in accordance with the thought (Section 2.4.1) that in cylindrical coordinates or for a homing system (Chapter 4) a slow roll is inconsequential.

9.5.1 Theory of Operation

The EMR device used conventional ailerons for control, the only unique feature being the method by which hunting was minimized. By means of a condenser memory circuit, the position of the ailerons was reversed whenever the angular velocity was reduced to an arbitrary fraction, for example, ½ of its original value. In the absence of time lags in the system, rolling should be reduced to zero in less than three cycles. In an actual mechanism, sustained oscillation will occur, the amplitude of which varies with the cube of the total time delay, with the size of the flaps, and inversely with the run-out time of the flaps.

Ideal Case—No Time Delay

Case 1. *No initial acceleration.* In this case control starts when the bomb has an angular velocity $\dot{\phi}$ but no initial accelerating torque. At $t = 0$ a motor starts to move the control flaps so that the restoring torque is directly proportional to the time. If aerodynamic friction is neglected, the total angular acceleration will be expressed by

$$I\ddot{\phi} = -kt \tag{9}$$

in which I is the moment of inertia about the roll axis. By integrating equation (9)

$$\dot{\phi} = -\frac{I}{2k} + \dot{\phi}_0 \tag{10}$$

and, eliminating t between equations (9) and (10)

$$\dot{\phi} = -\frac{I}{2k}(\ddot{\phi})^2 + \dot{\phi}_0 \tag{11}$$

which gives the relation between the velocity and the acceleration.

Control starts at A, and $\ddot{\phi}$ decreases until $\dot{\phi} = \dot{\phi}_0/2$ at point B (Figure 22). The direction of motion of the control flaps is then reversed, and the correcting torque decreases in proportion to the time. At O, $\dot{\phi}$ and $\ddot{\phi}$ reach zero simultaneously, and there is no overshoot.

If the ailerons were not reversed at some arbitrary value of roll velocity shown here as $\dot{\phi}_0/2$, the missile would continue to return to a stationary condition in the roll sense but would have a considerable displacement of the ailerons resulting in a large roll acceleration, as indicated in the extension of AB to U in Figure 22. While there is no fundamental method in mechanics to store acceleration, the structure of a missile with ailerons does exactly that because of the time required to move the control surfaces. Thus, while it would appear that a system sensitive only

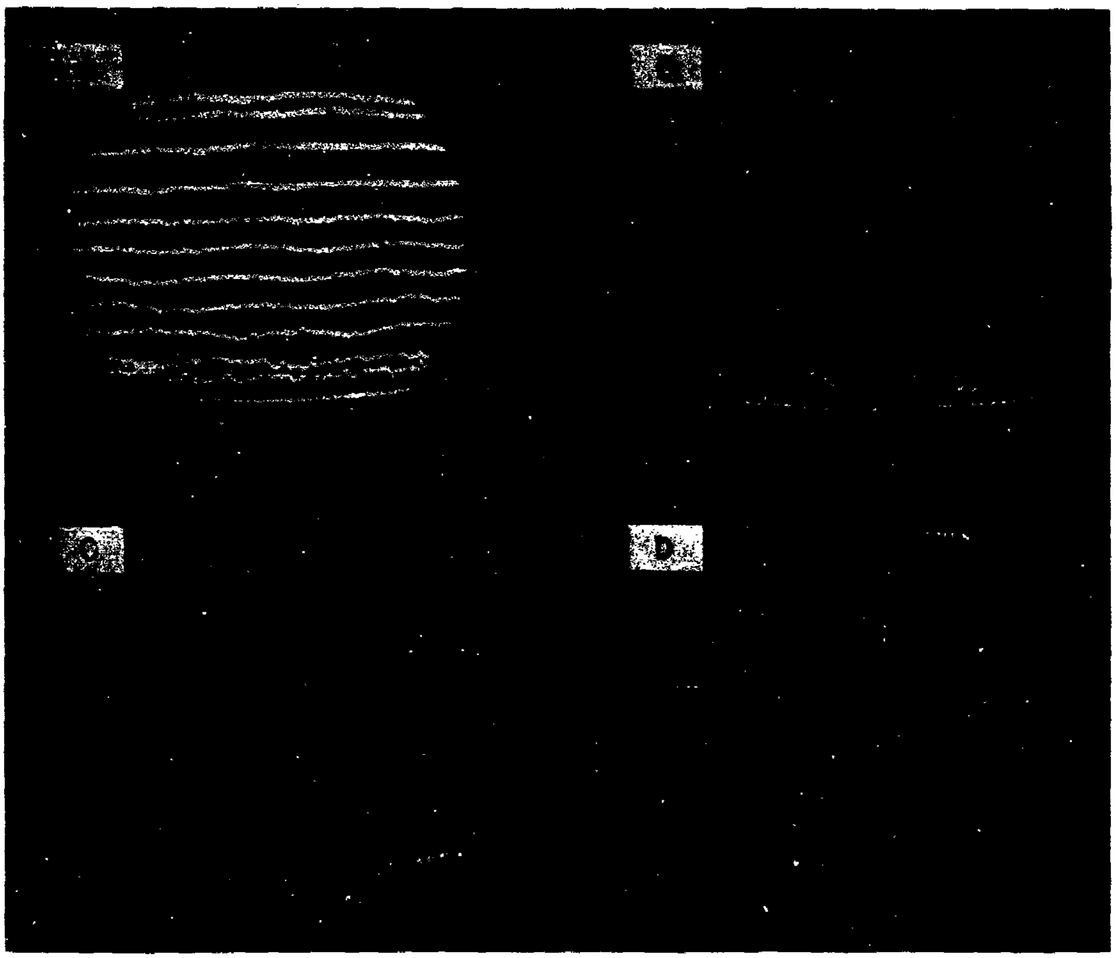


FIGURE 21. Fluctuation in output of wide-angle scanner and its effect on flap motion.

to velocity is fundamentally not oscillatory, oscillations creep in by virtue of this apparent storage of acceleration.

With reversal of the ailerons at the appropriate time, the roll velocity will reach zero at the instant

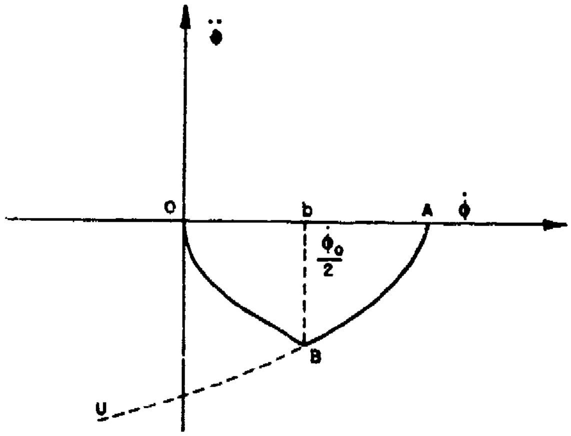


FIGURE 22. Relationship between roll velocity and acceleration for nonoscillatory stabilization. No initial acceleration.

when the acceleration is also zero, and no further angular motion will take place.

Case 2. *Initial acceleration not zero.* To eliminate one of the unreal assumptions, assume that asymmetry in the bomb construction introduces a roll

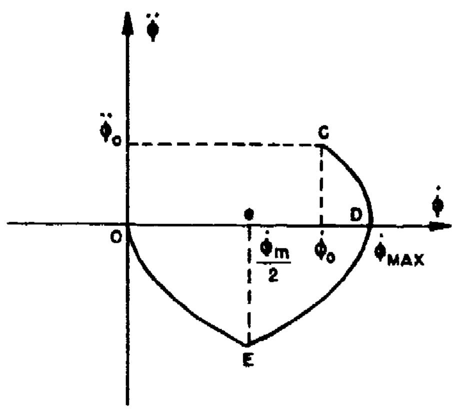


FIGURE 23. Nonoscillatory roll stabilization with initial roll acceleration.

torque. This adds the constant term $\ddot{\varphi}_0$ to equation (9). Graphically it is expressed directly by changing the starting point of the $\dot{\phi}$ vs $\ddot{\phi}$ graph as in Figure 23. If both $\dot{\phi}_0$ and $\ddot{\phi}_0$ are positive, the curve will start at a point such as C in Figure 23. The control surfaces reduce the total roll torque, and therefore the acceleration, to zero at D. At this point conditions are the same as at A in Figure 22 and the curve subsequently traced, DEO in Figure 23, will be similar to ABO in Figure 22.

If, instead, $\dot{\phi}_0$ and $\ddot{\varphi}_0$ are opposite in sign, the course of events will be as indicated in Figure 24, starting

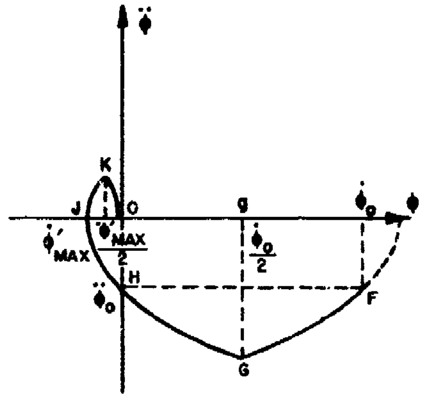


FIGURE 24. Nonoscillatory roll stabilization with initial roll velocity and acceleration of opposite sign.

at F. Here two reversals of the ailerons, each at the instant when the angular velocity has been reduced to half its most recent maximum value, are necessary to stop rotation at an instant of zero acceleration.

Case 3. *Initial velocity high.* If the initial roll velocity, $\dot{\phi}_0$, is very high there may be oscillation. This

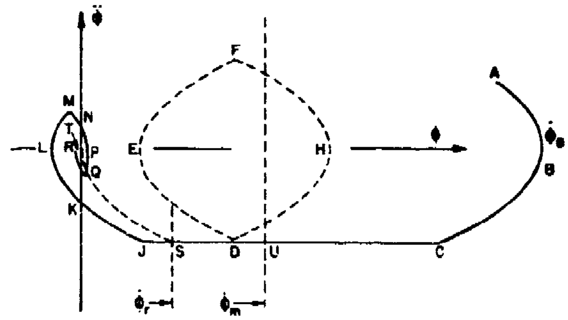


FIGURE 25. Oscillatory stabilization produced by excessive initial angular roll velocity.

oscillation derives from the memory circuit and can continue only if memory is permanent—that is, if direction of the aileron motion always reverses when $\dot{\phi} = k\dot{\phi}_{max}$. Consider a missile with initial conditions represented by A in Figure 25.

The roll velocity will increase until the aileron excursion has developed sufficient torque to kill the initial roll acceleration. From this point B, the velocity will decrease with increasing (negative) acceleration until the limit of aileron travel is reached at C. From C the velocity will decrease under constant acceleration until the critical velocity, say $\frac{1}{2}\dot{\phi}_{max}$, is reached at D. Here the direction of aileron travel reverses, and the velocity and deceleration decrease along the locus DEF. At F, on the same ordinate as D, reversal again takes place, and stable oscillation is set up about a mean value of roll velocity $k\dot{\phi}_{max}$.

Memory is established by charge on a condenser. Since the time constant cannot be infinite, the voltage on the condenser and, therefore, the critical value of velocity at which the ailerons reverse their direction gradually decay toward zero. The locus $DEFH$, therefore, drifts slowly toward the origin.

When a point J is reached such that the next swing will result in a reversal of velocity, damping will set in, since memory is erased with each crossing of the axis of roll acceleration.

Case 4. *Measured angular velocity limited.* If, instead of always reversing the ailerons at the maximum value of $\dot{\phi}$, a limit $\dot{\phi}_m$ is set to the angular velocity that can be registered linearly by the control circuits, any increases in velocities higher than $\dot{\phi}_m$ will be disregarded; that is, a voltage used to operate the control would be proportional to $\dot{\phi}$ in the range from $-\dot{\phi}_m$ to $+\dot{\phi}_m$, and constant for values of $\dot{\phi}$ outside these limits. Then, in Figure 25, the actuating voltage would be constant from A to U. There the control would operate as before, the flaps would reverse at J, where the velocity is half that at U, and the bomb would come to rest as indicated.

Evaluation of $\dot{\phi}_m$. From Figure 25 we can obtain information for design. If we define $\dot{\phi}_r$ as that value of $\dot{\phi}$ at which the flaps must be reversed to stop the roll without oscillation (SQT), the value of $\dot{\phi}_r$, and hence $\dot{\phi}_m (= 2\dot{\phi}_r)$ will be uniquely determined by the line CJ. This in turn is determined by T_m, the torque generated when the flaps are in their position of maximum deflection.

If I is the moment of inertia about the longitudinal axis, λ the coefficient of aerodynamic friction, and τ the run-out time of the flaps, it can be shown that

$$\dot{\phi}_r = \frac{T_m I \epsilon^{\frac{\lambda\tau}{I}}}{\lambda^2\tau} - \frac{1}{\lambda}\left(\frac{T_m I}{\lambda\tau} + T_m\right) \qquad (12)$$

If in turn $\lambda\tau/I$ is small, this reduces to

$$\dot{\phi}_r = \frac{T_m\lambda}{2I} \qquad (13)$$

In this expression all parameters are determined by the construction of the missile, which permits the evaluation of $\dot{\phi}_r$.

Preferred Arrangement of Control System. It is implicit in the foregoing that $\dot{\phi}_r$ should be made small enough so that the locus will reach the axis of $\ddot{\phi}_0$ on the first reversal of the ailerons. $\dot{\phi}_m$ need not exceed $2\dot{\phi}_r$.

When the value for $\dot{\phi}_m$ has been chosen in this way the controlling voltage is made proportional to $\dot{\phi}$ for absolute velocities smaller than $\dot{\phi}_m$, but the rate gyro is blocked so that higher values of $\dot{\phi}$ cannot be registered. In this way sensitive control is provided for low velocities, and at the same time a means is available to handle high velocities in the manner indicated in Figure 25.

9.5.2 Effect of Time Lags

Unavoidable time delays in operation of relays and aileron mechanisms must introduce residual oscillation in any actual device. Assume for example that the representative point is traveling from F to A along the locus of Figure 26. Instead of reversing instantaneously at A, where $\dot{\phi} = \frac{1}{2}\dot{\phi}_m$, and proceeding to O along the dotted path, the mechanism suffers a time lag and does not reverse until some point B has been reached. The path BCE will be followed, reversal being called for at D and actually accomplished at E. It is evident that sustained oscillation must occur.

If τ_o is the total time delay in seconds, P the period of the residual oscillation, and ϕ_m its amplitude, it can be shown that

$$P = \frac{4\sqrt{2}\tau_o}{\sqrt{2}-1} = 13.7\tau_o \text{ seconds} \qquad (14)$$

$$\phi_m = \frac{4\sqrt{2}T_m\tau_o^3}{3(\sqrt{2}-1)^2\tau I} = \frac{26.6T_m\tau_o^3}{\tau} \text{ radians}^a \qquad (15)$$

[a] See *Experimental Investigations in Connection with High-Angle Dirigible Bombs—The AZON Bomb*, Gulf Research and Development Co., October 15, 1943. OSRD No. 3086, in which the author finds that the amplitude of oscillation is:

$$\phi_{max} = \frac{(\tau)^2(2k-\tau)^2T_m}{8(k-\tau)^2I}$$

where k is a constant relating the coupling between the rate gyro and the free gyro which were used in the stabilizing of Azon. In equation (15), reducing τ to a very small value causes ϕ_{max} to increase. In the Gulf equation, making τ equal to zero reduces the amplitude of oscillation to zero.

Actually the Azon ailerons were powered by solenoids and the action was made very rapid ($\tau = 0.1$ second). The observed oscillation during drops (see Chapter 2) was very small.

It is evident that (1) τ_o should be minimized; (2) decreasing T_m and increasing τ improve performance as far as oscillation is concerned.

9.5.3 Control Circuits

Figure 27 shows the essential storage circuit which causes reversal of the ailerons when ϕ is reduced to any desired fraction of ϕ_m.

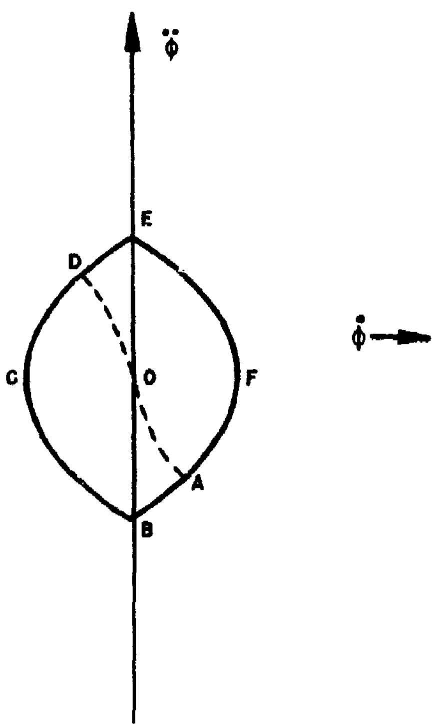


FIGURE 26. Oscillation caused by time delay in mechanism.

Potentiometer 1 is driven by the rate gyros. A positive voltage charges condenser 4 but is blocked from condenser 10 by diode 11. A negative voltage charges condenser 10 but not 4. The polarity is referred to terminal 8, at the midpoint of the potentiometer. If ϕ increases positively, the charge on 4 builds up to a value E_m, corresponding to ϕ_m. Then as ϕ decreases, the time constants of the circuit are sufficiently long (of the order of 20 seconds) so that the charge on 4 remains constant until ϕ reaches zero. A relay (not shown) then short-circuits the condenser. Similarly a negative swing of ϕ will impress a voltage on 10 representative of $-\phi_m$.

The voltage E_2 across terminals 7 and 8 can be computed to be

$$\begin{aligned} E_2 &= \frac{E - KE_m}{2 + K} \\ &= E - HE_m \end{aligned} \tag{16}$$

If $K = 2$, $H = \frac{1}{2}$; if $K = 1$, $H = \frac{1}{3}$. When E drops below HE_m, the polarity of E_2 reverses. This, through amplifiers, a polarized relay, and magnetic clutches, is made to operate the ailerons,

where K = proportionality constant in resistors 6 and 9 of Figure 27,

$$H = \frac{\dot{\phi}_m}{\dot{\phi}_r},$$

E = voltage across potentiometer 1.

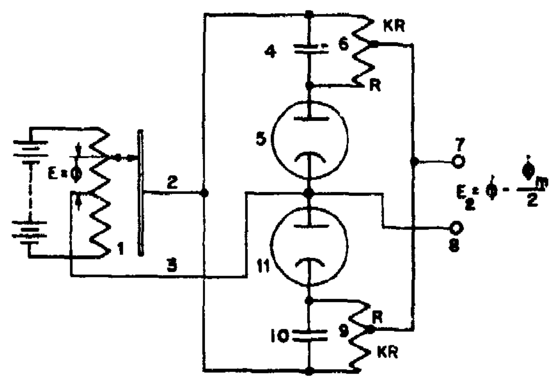


FIGURE 27. Storage circuit for reversal of ailerons.

9.5.4 Experimental Results

Using a model bomb in which the control apparatus was mounted, wind-tunnel tests at low wind velocities were made. Direct measurements were made of T_m, τ, and the time for various amounts of rotation. The period of oscillation of the actual device as built was measured and found to be 1.37 seconds. The amplitude as measured and computed agreed well at about 16 degrees.

Faulty adjustment of the potentiometers, so that reversal occurs at values of ϕ greater than $\phi_m/2$, can be shown to induce sustained oscillation accompanied by drift. This was confirmed by test.

By the time this work was completed it was evident that the bomb was operable. Nevertheless, stabilization of the Gulf bomb had by then been accomplished by other means and there was no further demand for this device.

The following comments are pertinent.

1. If the reversal of the ailerons occurs too soon, because of improper functioning of the storage circuit, roll oscillation superposed on a drift of roll orientation must ensue.

2. Functioning of the storage circuit is contingent upon discharge of the memory condensers every time the angular velocity becomes zero. This is accomplished by a circuit containing two d-c amplifiers and a relay. Sensitivity is a function of the adjustment of these amplifiers.

3. The whole device is operable when properly adjusted, but has many more parts, more adjustments, and hence more chance of malfunctioning than parallel devices developed at Gulf and at Douglas.

4. In retrospect it is difficult to see what major advantage is obtained by this rather elaborate circuit over the very simple devices developed for the same purpose by MIT (see Chapter 2) and Douglas (see Chapter 4). This conclusion could not, of course, have been reached *a priori*. The contribution of this contractor to the analysis of roll-stability problems was valuable and encouraged the Division to continue the experimental work necessary to embody the principles of his analysis in a working system.

9.6 THE TO-AND-FRO SCANNER

Section 4.2.4 described how Roc was built so that the rate of change of transverse lift was proportional to the error heading and to its first derivative. All the early Gulf bombs (Section 2.2.7) also used proportional control until (Section 2.7.3) it was discovered that, for Azon at least, it was not needed. In an attempt to supplement the Roc and Felix projects by developing an infrared scanning device capable of giving quantitative measurement of error angle (rather than quadrant indication alone), Electro-Mechanical Research, Inc., was directed to continue portions of the work they had started independently on a heat-homing bomb similar morphologically to Roc.

Under the EMR contract, a roll-stabilizer was developed which needed no free gyro (Section 9.5), bolometers were improved (Section 9.6.2), six successively refined scanning devices using to-and-fro scanning were built, and contributions were made to the theory of bolometer response to modulated heat energy. No way was found by this contractor, however, to achieve proportional control.

9.6.1 Horizon Difficulties

A heat-homing device using a conical scan, such as Felix and Dove Eye (Chapter 3), cannot be allowed to see the horizon. Since such a device operates on the largest thermal discontinuity within its view, it tends to attempt the maneuver of homing on the horizon. On the other hand, if the area scanned can be kept wide horizontally but narrow vertically, it is possible to prevent the scanning element from seeing the horizon even if the angle of flight is fairly flat, say 11 degrees. The only method of obtaining a scanning pattern of this shape utilizes a to-and-fro scanner.

9.6.2 S-3 Scanner[5]

The first laboratory model of such a scanner was equipped with lights to indicate right or left target bearing, and operating relays in lieu of bomb controls. An 8-in. parabolic mirror (focal length 6 in.) reflected the target image upon a bolometer strip. The optical system, including the thermal receptor, was oscillated at 12 c about a vertical axis through the apex of the mirror. A narrow-band amplifier, tuned to the scanning frequency, amplified the bolometer output.

Theory of Operation[6]

Consider a parabolic mirror which oscillates in a to-and-fro manner so that it scans a field of view containing a thermal target. If an ideal bolometer, i.e., one having a very small mass and specific heat, is located at the focus of such a mirror, its resistance will rise sharply each time the image of the target

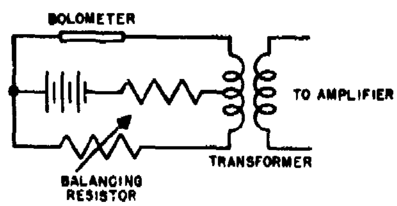


Figure 28. Typical bolometer input circuit.

falls upon it. If the bolometer is connected in a bridge circuit such as that in Figure 28, the rise in resistance will be accompanied by a voltage pulse at the secondary of the transformer.

In general there will be two voltage pulses per cycle of scan. If the target is dead ahead, the pulses will be evenly spaced at double the scanning frequency. At some error angle θ, the pulses will be spaced at intervals of $\pi \pm 2\theta$, where 2π is the period of the scanning cycle (Figure 29). In the special case where the target is at the edge of the field of view,

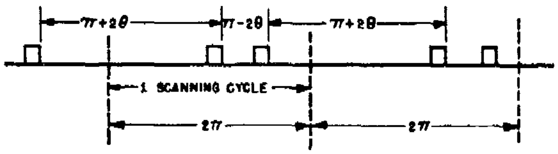


FIGURE 29. Pulses due to thermal target.

$\theta = \pi/2$ and $\pi - 2\theta$ becomes zero, so that the two pulses coalesce.

Now let the secondary of the transformer in Figure 28 supply an amplifier tuned to the scanning frequency, the frequency at which the mirror oscillates, but with sufficient band-pass to prevent material phase shift. The output of this amplifier will consist principally of the fundamental components of the Fourier expansion of the pulses at scanning frequency. Each fundamental component will be in phase with its pulse.

If a rotating vector so represents the position of the axis of the mirror during a scanning cycle, the diagram of Figure 30 reproduces in a polar plot events during the scanning cycle in Figure 29. At time 0 the

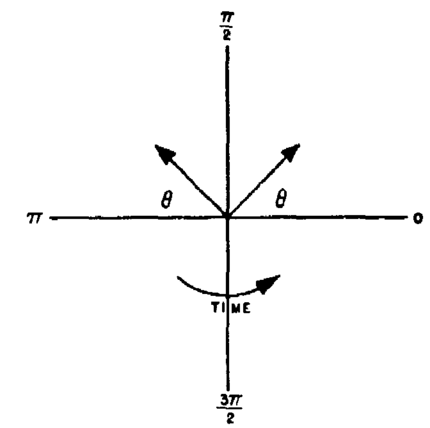


FIGURE 30. Vector representation of fundamental component of pulses from target.

scanning system is looking dead ahead. At some later instant, after the system has swept through the error angle θ, the receptor will pick up the thermal target and produce a voltage pulse whose fundamental component is in phase with the pulse at V_1. At time $\pi/2$ the system is in an extreme position and starts back. When it is short of the mid-position π by the error angle θ, it will again pick up the target, producing a second pulse with a fundamental frequency component V_1. The sum of these two sine waves at scanning frequency is

$$E = 2V_1 \sin \frac{\pi\theta}{2\theta_{max}} \qquad (17)$$

The magnitude of the voltage produced as a function of error angle can now be plotted from equation (17). It must be emphasized, however, that this plot (Figure 31) does not represent the instantaneous output of the amplifier as the scanning mirror makes a swing through half a scanning cycle. Rather it is a steady-state plot of the *magnitude* of a sinusoidal voltage which varies with error angle.

As the voltage passes through zero, corresponding to zero error, there is a phase reversal. With a left error the crest of the voltage occurs when the system

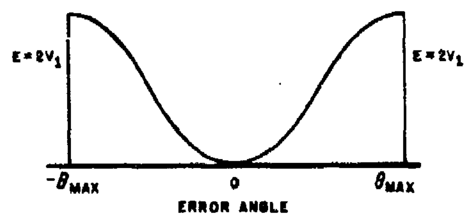


FIGURE 31. Output of S-3 scanner preamplifier.

is at its extreme of left travel, that is, at time $-\pi/2$; with a right error the voltage is at a maximum when the system is at its extreme right travel, that is at time $\pi/2$.

Sense of direction is readily obtained if a synchronous voltage is added to the output of the preamplifier at a phase to support the output when the error is in one sense and to suppress it if the error is in the reverse sense. Equation (17) represents the maximum value of the fundamental component of the output. Its instantaneous value is

$$e_1 = 2V_1 \sin \frac{\pi\theta}{2\theta_{max}} \sin\left(\omega t \pm \frac{\pi}{2}\right) \qquad (18)$$

The double sign for the phase angle indicates the phase reversal which takes place as θ, measured from the scanning axis, changes sign. The added voltage can be written as:

$$e_2 = E \sin\left(\omega t + \frac{\pi}{2}\right) \qquad (19)$$

In this case the sign of the phase angle is arbitrary but not ambiguous. The sum of these two voltages as a function of θ is plotted in Figure 32. It is seen to have the form

$$E + 2V_1 \sin \frac{\pi\theta}{2\theta_{\max}} \tag{20}$$

The curves of Figures 31 and 32 are plotted as pure single-frequency functions since all the development of the theory has been concerned with the fundamental component of the detected pulse. The addition of harmonics distorts the shape of the curve but

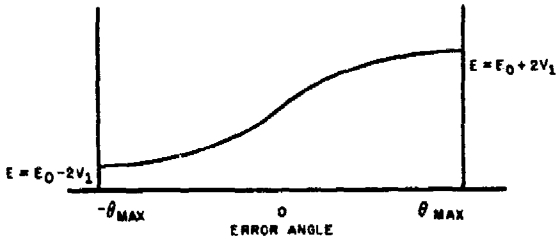


FIGURE 32. Combined output of preamplifier and synchronous local voltage.

does not introduce modes unless the harmonics are high compared to the fundamental (Figure 33).

The local voltage was produced by a synchronous generator driven from the same motor which oscillated the scanning mirror (Figure 34). The combined outputs of the preamplifier and the generator were amplified in a narrow-pass pentode stage and supplied to a two-channel rectifier and amplifier, which operated the control relays.

The Bolometer

The Division had three contractors working on bolometer development. Felix used nickel strips, Dove Eye used thermistors, and the EMR to-and-fro scanner used metallic gold evaporated upon thin films of cellulose nitrate. Each of these bolometers had its own characteristics, but all had a useful sensitivity of the same order of magnitude, 2.0×10^{-8} watt per sq cm. Some experimental models, both of Felix and of Dove Eye, used film-type bolometers.

Early EMR bolometers consisted of a thin strip of gold evaporated upon a cellulose nitrate film (0.1

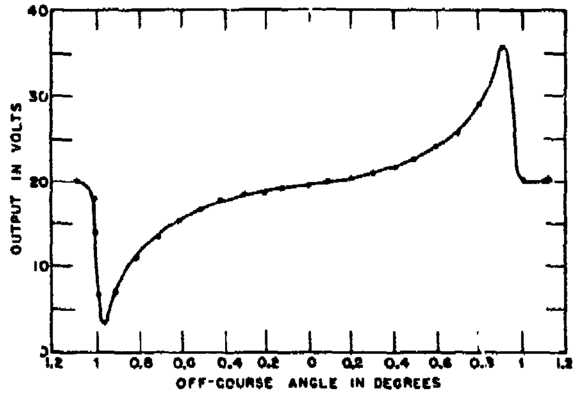


FIGURE 33. Typical signal from S-3 scanner as function of error angle.

micron thick) with zinc black (later replaced by gold black) evaporated in turn upon that. Sodium chloride windows, ground flat and sealed with beeswax, allowed transmission of infrared energy to the bolometer. After a short time the seal usually leaked and the vacuum was destroyed.

As development proceeded, glass cases were replaced by successively smaller metal cases, various protective coatings for the salt windows proved none

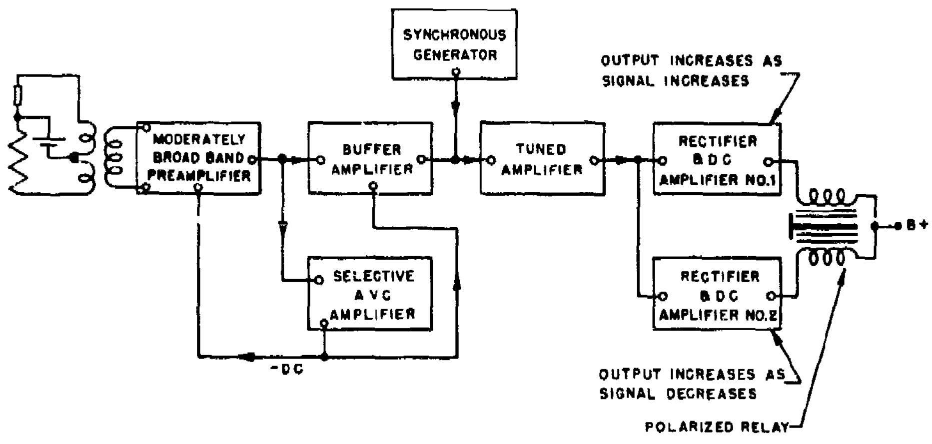


FIGURE 34. Block diagram of scanner.

too good and silver chloride windows were substituted, and finally gold blackening in the presence of traces of tellurium was shown to give the most satisfactory performance.

A lengthy study of desirable characteristics of bolometers[7] showed that a metal plate about 0.006 in. behind the film should give greater sensitivity in nitrogen (100-mm pressure) than under a vacuum; this was confirmed. Of the metals tried gold proved best.

Sensitivities measured were of the order of 1 v per watt per sq cm at the grid of the first tube, in terms of the total energy field at the bolometer. It is pertinent at this point to mention that MIT, Polaroid, and EMR all measured sensitivities of bolometers by slightly different methods and obtained results which agreed within about 10 per cent. Polaroid has shown that, because of variation in the absorption coefficient of the blackening resulting in spectral distribution of the incident energy, this much difference is to be expected. For a given total quantity of energy incident upon the bolometer, the amount absorbed (and hence effective) from a short-time high-temperature pulse will differ from that from a longer low-temperature pulse. Therefore, the measured sensitivities will differ in the two cases. No general law has been adduced, and the only remedy is to specify experimental conditions exactly. Polaroid has also shown that the time constant of the entire system is an important variable factor in the measurement of sensitivity.

Results

When tested at MIT the scanner was set up looking vertically downward at a tank of water 430 cm (14 ft, 2 in.) below. The blackened end of a brass cylinder, 15 sq cm in area, was the target. A difference of 1.5 C to 2 C between target and surroundings, corresponding to a signal intensity of 0.02 microwatt per sq cm, operated the signal lights in correct order as the target moved across the field.

Taken outdoors and fitted with a magnesium oxide filter to eliminate visible light, the device was tested on ships in Boston Harbor. Correct indication was obtained from a destroyer at 3,100 yd but not at 4,500 yd.

Operation was seriously hampered by the necessity for frequent readjustment of the level of the local signal. This was caused by background irregularities, which of course served as false targets.

9.6.3 Conclusions

The device as built was much too large and cumbersome; it possessed moderate sensitivity; it was operable only when adjusted frequently to eliminate the effect of variation of background noise. It was therefore not suitable as a military device.

9.6.4 S-4 and S-5 Scanners

The S-4 was essentially the same type as the S-3 except that the frequency and amplitude of the scan were adjustable. Amplitude was variable from 0 C to ±8 C, frequency from 3 to 12 c. Work with the S-3 had indicated that there might be advantages to using higher harmonics of the fundamental scanning frequency, so two amplifiers were used simultaneously in series with the bolometer, one tuned to 12 c and the other to 24 c.

The S-5 scanner was designed for compactness. A spherical mirror with a diameter of 3⅝ in. and a focal length of 2.25 in. collected the incoming energy. The bolometer was mounted in a hole in the center of this mirror. Energy collected by the spherical mirror was reflected by it upon a plane mirror 1¼ in. in diameter, which in turn reflected it upon the bolometer. The flat mirror was oscillated about a vertical axis. The advantages of this type of construction were (1) small power consumption and (2) compactness. Its main fault was that it was useful only for narrow scanning angles. When the scanning angle was such that the field of the flat mirror passed the edge of the curved mirror, energy from a uniform background would be modulated at the scanning frequency, giving a spurious signal. This limitation removed the S-5 from serious consideration.

9.6.5 Harmonic Scanning

From this point on the discussion will deal largely with operation based upon use of the second harmonic of the scanning frequency. It is necessary, therefore, to see what is to be gained therefrom, and at what cost.

If the scanner consists of a bolometer and a fixed mirror, the plot of output vs azimuth angle will be qualitatively as shown in Figure 35A.[8]

Now if an oscillating mirror is used, and the bolometer output is fed to a sharply tuned amplifier responsive only to the mirror frequency, the plot of output vs angle will be as in Figure 35B. The exact shape depends upon the design factors, but it will always be of the general shape shown.

If the amplifier is tuned to the second harmonic, twice the mirror frequency, the response curve will be as shown in Figure 35C. This curve will obtain if the scanning angle and the bolometer strip are both narrow. For larger angles, the relative heights of the center peaks and the outer peaks will change.

Figures 35D and 35E show the patterns obtained with the third and fourth harmonics respectively. It is evident that the number of peaks is $n + 1$, if n is the order of the harmonic used, and the number of interior minima is equal to n.

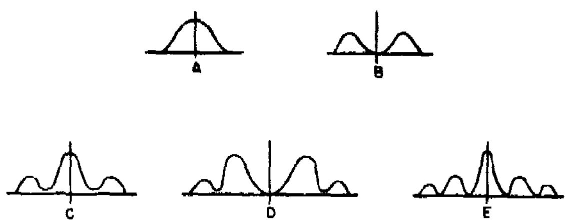


FIGURE 35. Output of tuned amplifier with error angle: (A) fixed mirror, (B) amplifier tuned to scanning frequency, (C) amplifier tuned to two times scanning frequency, (D) amplifier tuned to three times scanning frequency, (E) amplifier tuned to four times scanning frequency.

Fundamental Response

This results from the general analysis described in Section 9.6.2. Two pulses per cycle are produced by the bolometer. The amount of the voltage output depends upon the position of the target with reference to the swing. With the target at either end of the scanning arc, the fundamental-frequency outputs add up to a maximum. As the target nears the center, the vectors representing the two pulses rotate in opposite direction, reaching direct opposition with the target on course. The two pulses being equal and 180 degrees out of phase, a minimum voltage output is obtained.

Higher Harmonics

Each series of pulses will also generate harmonic components of voltage in the output, and each pair of such components of a given frequency can be represented by a pair of vectors, as shown above. With the target at the extreme right of the swing, a maximum is obtained as before. As the target moves to the left, however, the phase shifts will be proportional to the order of the harmonics. For the second harmonic the two pulses will be 180 degrees out of phase, producing a minimum at two points along the scanning cycle. Similar analysis applies to higher harmonics.

When the individual energy pulses are short (narrow image, narrow bolometer, wide scanning angle), the amplitudes of the fundamental and of the lower harmonics are approximately equal. This is based upon the following reasoning.

In the case of rapidly interrupted energy of rectangular waveform, the amplitude of the nth harmonic of the output voltage is

$$E_n = \frac{2E}{n\pi\sqrt{1+U_n^2}} \sin\left(\frac{n\omega\Delta t}{2}\right) \tag{21}$$

where E = voltage when ample time is allowed;
E_n = voltage of nth harmonic;
n = order of harmonic;
$\omega/2\pi$ = frequency of pulse;
Δt = duration of pulse.

U_n is analogous to the ratio of reactance to resistance in an electric circuit containing inductance and resistance in series. In the simple case of a bolometer which loses heat only by radiation

$$U_n = \frac{n\omega H}{4\sigma T_1^3} \tag{22}$$

In this σ = effective radiation constant of the strip;
H = total thermal capacity of the strip;
T_1 = absolute temperature of the strip.

Since U_n is directly proportional to the frequency of interruption of the received energy, equation (21) indicates that the response should be proportional to $1/\sqrt{1 + k^2f^2}$. This is substantially true experimentally.

Other things being equal, equation (21) shows that the amplitude of the nth harmonic of the bolometer output is proportional to $1/n \sin (n\omega\Delta t/2)$. For small values of the quantity in parentheses, this reduces to $\omega\Delta t/2$, and the amplitudes of the lower harmonics are equal.

The above has been predicated upon a rectangular pulse. Theory and experiment agree that the value of the peak amplitude will be less if the pulse is a half sine wave instead of rectangular, but the relationship among the harmonics is undisturbed.

So far we have deduced that the target signal should be approximately the same amplitude whether the amplifier is tuned to the fundamental or to one of the lower-order harmonics. Similar analysis shows that slow changes in the intensity of a uniform background, or a uniform gradient across the background, should introduce greater background noise into the fundamental than into each successive harmonic. This was also verified experimentally.

Choice of Second Harmonic

If the fundamental or the third harmonic is used, distinction between right and left indication is by phase determination, as has been seen in the S-3. With the third harmonic, however, peaks 1 and 4 (Figure 35D) have the same phase as peaks 3 and 2 respectively, and if the target is at the extreme of the field of view, the resulting voltage will be of the wrong phase and the control reversed in sense. This limits the use of the third harmonic to targets near the center of the field—obviously impossible to guarantee in a military application.

Using the second harmonic—which has been seen to give a better signal-to-noise ratio than the fundamental—the response curve (Figure 35C) is symmetrical, and the phase of the voltage cannot be used for control. In the case of the bomb control, this led to the design of the S-8 scanner, in which two halves of the mirror oscillated independently, and right-left indication was derived from this fact. Before that was built, however, much experimental evidence verifying these theoretical considerations was acquired in work on scanners S-4, S-6, and S-7.

Laboratory Results

In the laboratory, with a target showing a uniform gradient across the field of view, the second-harmonic noise for a scanning angle of 3 degrees was shown to be from $1/4$ to $1/10$ the fundamental-frequency noise.

In the field, at an observation station overlooking Galveston Bay, results were similar. Recording the output voltages of the two amplifiers simultaneously by means of recording voltmeters, curves similar to Figure 36 were obtained. These typical runs show that differentiation between the target and the background noise is very much better with 24 c than with 12 c (the fundamental).

9.6.6 S-6 Scanner

For use in a target survey to be made by a Navy Bureau of Ordnance plane, a scanner was built to operate on both 12 and 24 c, as before, without right-left indication. Essentially it was very similar to the S-4 except that it was built for mounting in the plane and therefore was not geared to the recording voltmeters.

At the wide scanning angle of 14 degrees, the advantages of second-harmonic tuning were not very great, and results in general were none too satisfactory. Among the reasons were:

1. The scanner was being compared by the Navy with instruments having much smaller fields of view. They necessarily showed less background noise (and consequently higher signal-to-noise ratio).

2. It was a laboratory device operated by field personnel. Such a combination frequently leads to a feeling by the operators that the apparatus is unreliable, by the development personnel that it is incompetently used.

3. Sensitivity (again a function of the scanning angle) was too low, so that at desired ranges unreliable target indication was observed.

It is important that liaison on this project was not adequate to keep either the Division or the contractor fully advised as to the success or failure of the scanner in the field. As has been repeatedly pointed out, only by continuous correlation of all the data taken by all agencies associated with a project can successful work be done.

9.6.7 S-7 Scanner

While the S-6 was on loan to the Navy, a similar scanner was built for laboratory and field use.

Construction

This is shown in Figures 37 and 38.

The new features were provision (1) for adjustment of the scanning angle (from 0 to ± 1.75 degrees) by the larger knob seen at the back of the case, and (2) for focusing the bolometer during operation.

The reduction in size from the S-3 is evident. The desirable reduction in electrical complexity is also apparent. Target indication was accomplished by lights operated by a relay connected to the output of the 6C8 tube seen at the right.

When the scanner is pointed directly at the target, the phase of the output voltage of the amplifier can be adjusted (by the phase-shifting network at the top left) so that one element of the 24-c synchronous rectifier produces a maximum positive potential. The other element of the rectifier is permanently 180 degrees out of phase with the first; it therefore develops

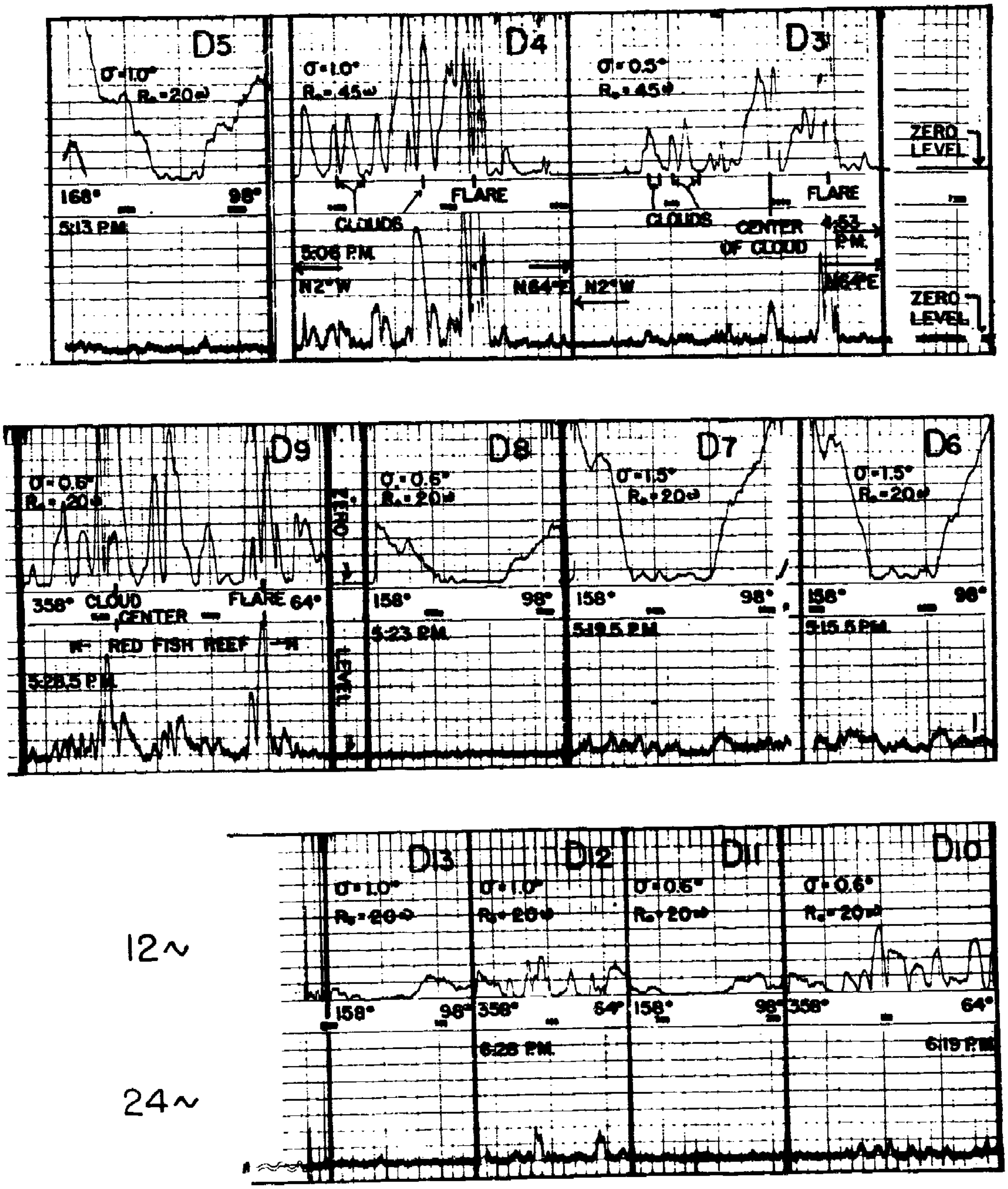


Figure 36. Test results with to-and-fro scanner.

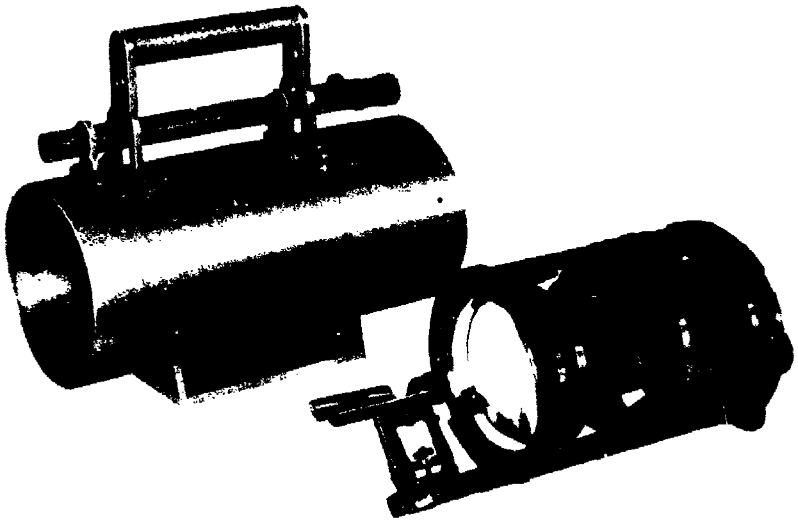
a negative output potential, and the two sections of the 6C8 twin triode are acted upon oppositely by the voltages from the two rectifiers. If each plate is connected in series with one winding of a differential relay, the armature will be drawn to one side.

Now if the scanner is turned so as to bring one of the side peaks of the response pattern into play, the phase of the amplifier output will be reversed. This reverses the polarity of the d-c potential upon the 6C8 grids and reverses the relay. Signal lamps connected to the relay can then show whether the target is in the center or a side lobe.

Results

Field runs (Figures 39 and 40) showed the typical two-peak pattern for the 12-c log and three peaks for the 24-c, together with lowered background noise for the latter.

The major conclusions from the experience with scanners S-3 through S-7 were that second harmonic tuning gave a greatly improved performance, that the scanning angle must be at a minimum, and that with proper adjustment a signal strength below 1 microwatt per sq cm at the mirror was adequate for reliable operation. The first two conclusions, inconsistent with the principles of the S-3 (which involved wide-angle scanning and phase discrimination for right-left indication), forced design changes in S-8.



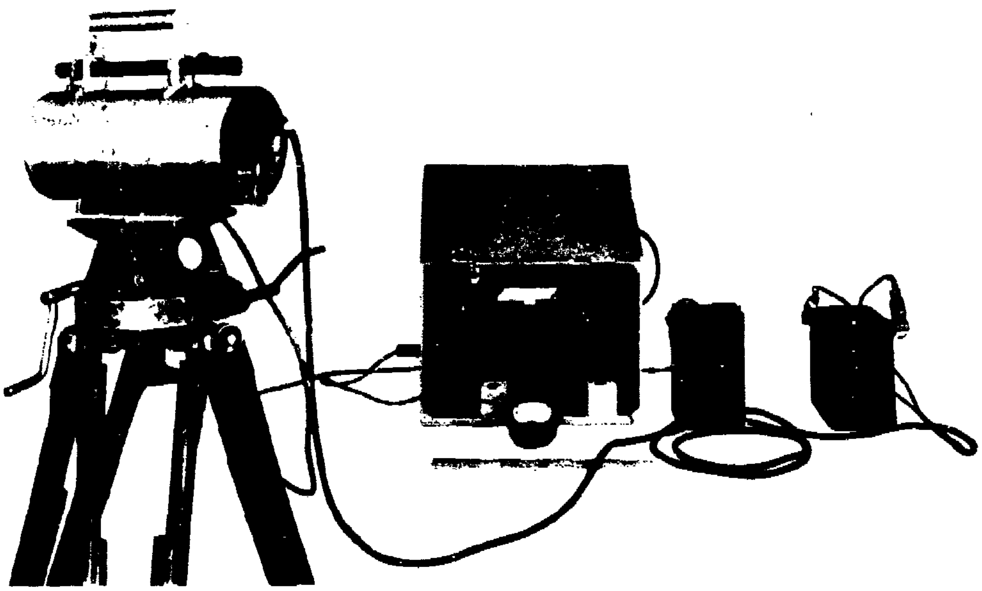


FIGURE 37. Scanner head (top) and complete S-7 scanner (bottom).

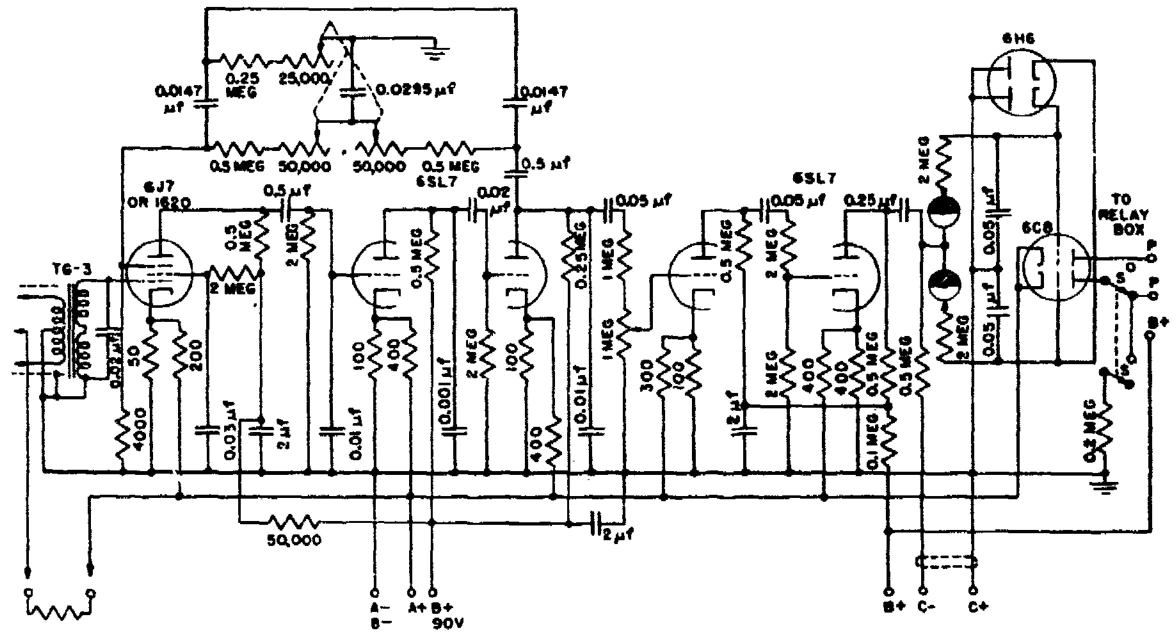


FIGURE 38. Wiring diagram of amplifier of S-7 scanner.

9.6.8 S-8 Scanner

The foregoing portions of this section report the development of a principle for scanning which might be applicable to a missile. None of the scanners so far discussed was contemplated for such application. The S-8 scanner was an attempt to show the applicability of the principles discovered in development of the earlier models to the guidance of a glide bomb in azimuth. Control in the range sense was to be considered later. After the termination of the project by the Division, the contractor completed this latter phase of the investigation under contract with the Air Technical Service Command.

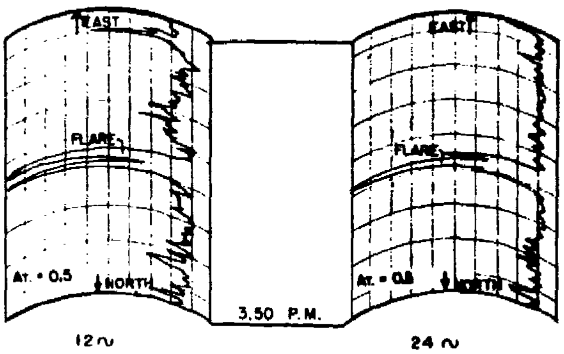


FIGURE 39. Field results with S-7 scanner (run from east toward north).

CONSTRUCTION

Figure 41 shows views of the scanner as assembled and with the case removed. The first novel feature is the split mirror. The same type of spherical mirror is used as in previous models, but it is cut along a horizontal diameter so that the two halves are, in effect, separate mirrors which can look in different directions. The two halves are oscillated at the same frequency, but both the angle between their axes and the relative phase of the motion are continuously ad-

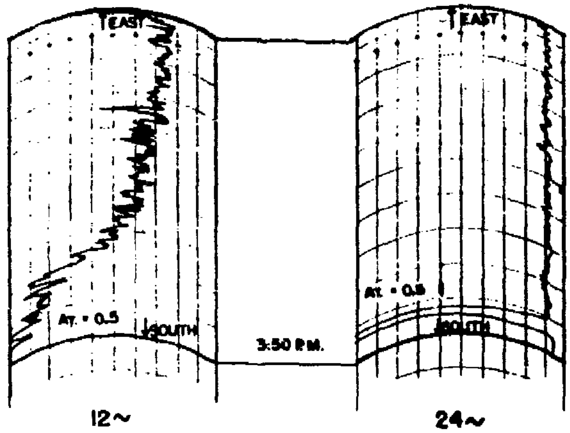


FIGURE 40. Field results with S-7 scanner (run from east toward south).

justable by knobs. This latter makes it possible to distinguish between the signals derived from the two halves by using phase-se ting circuits.

Secondly, the scanner is mounted on a motor-driven turntable to permit automatic tracking of the target.

Thirdly, driven by the scanning motor are two 2-element 24-c synchronous rectifiers whose functioning is described below.

Amplifier Circuits

The amplifier circuit (Figure 42) consists of four parts: a tuned preamplifier, a volume limiter, the rectifier and d-c output circuits, and a vacuum-tube voltmeter incorporated for experimental convenience.

It will be noted that the wide-band amplifier of the S-3 has been eliminated. Instead, the phase-shifting network at the upper left adjusts for any phase shift through the tuned amplifier.

Following the phase shifter comes a three-stage limiter. This simple circuit will handle a very wide range of input voltage with practically no change in output level.

Voltage from the last limiter tube is supplied to the four rectifier elements. The two upper rectifier elements deliver output voltage of opposite polarity. The two lower elements are also 180 degrees out of phase with each other, but are in quadrature with the lower elements.

Synchronous Rectifiers

These rectifiers serve two functions: first, they provide a means for distinguishing between the signals received from the two halves of the mirror, and second, they enable all three lobes of the response pattern of one mirror to operate the relay in the same way. Since the signal from the center lobe is out of phase with that from either of the outer lobes, two rectifiers 180 degrees apart must be associated with each mirror. One element develops a positive potential for closing the relay when the target is in the central lobe of the pattern, while the other develops the

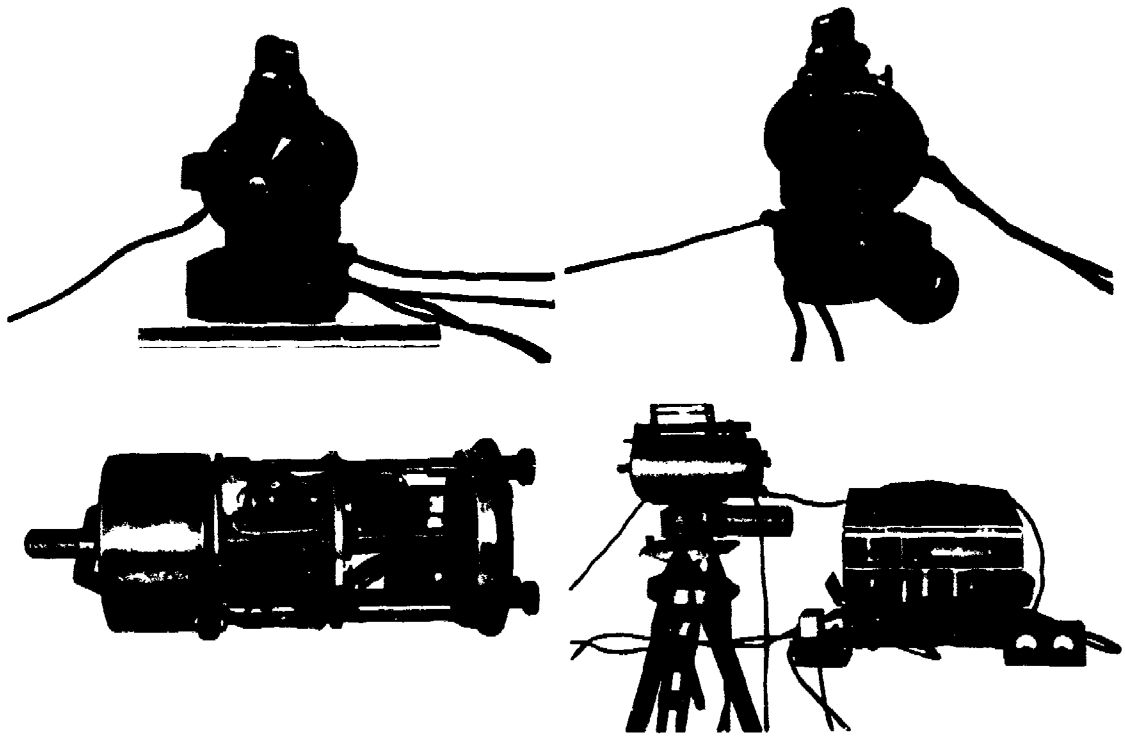


Figure 41. S-8 scanner.

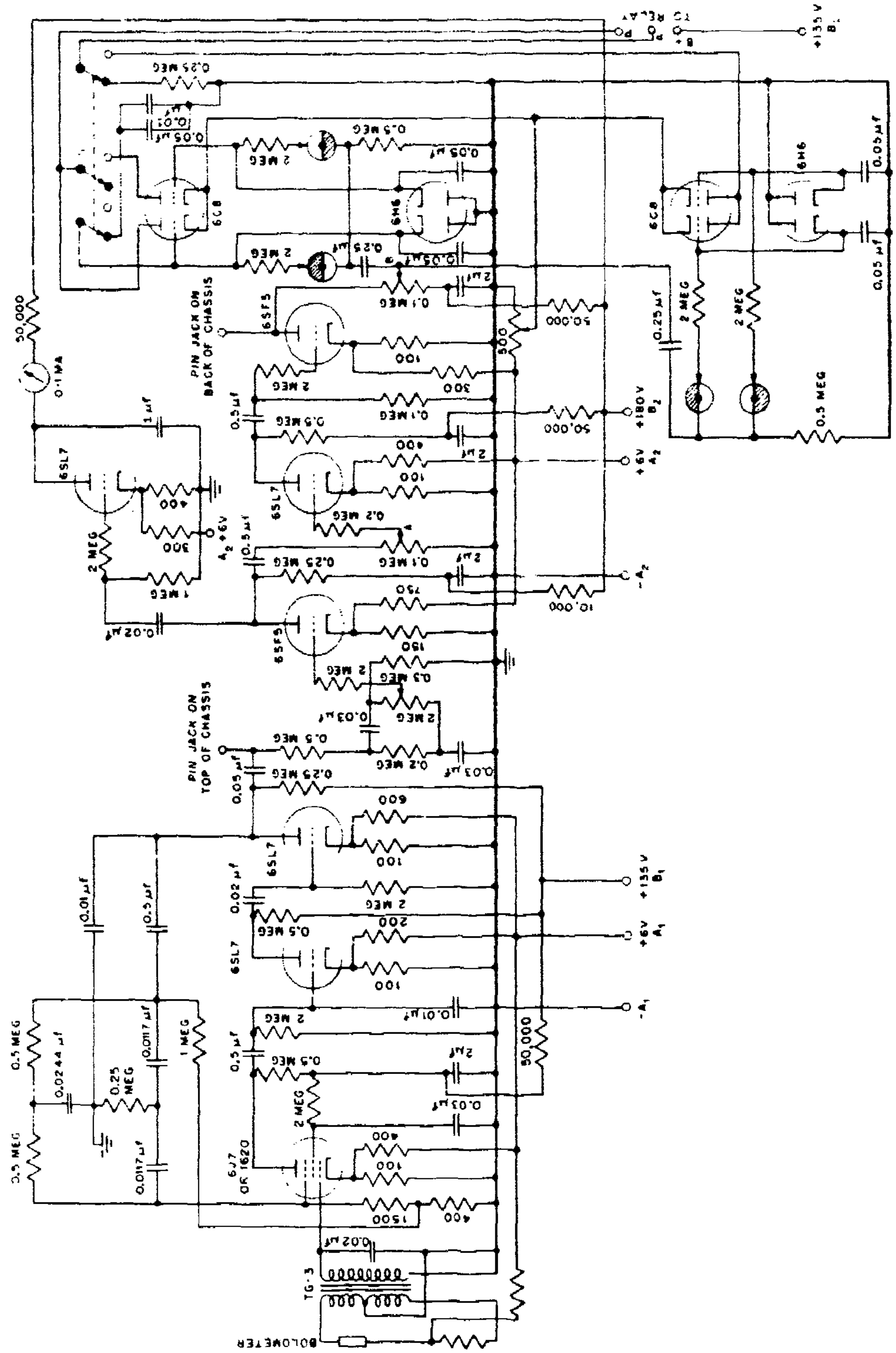


FIGURE 42. Wiring diagram of S-8 scanner.

necessary positive potential when the target lies within either of the outer lobes.

The magnitude of the output of a synchronous rectifier is dependent upon the phase of the impressed a-c potential with respect to the rectifier. When the phase difference is 90 degrees, the output is zero. The two pairs of rectifiers shown in Figure 42 are in quadrature with each other. The two halves of the mirror are 45 degrees out of phase, which puts the second-harmonic signals from the two mirrors also in quadrature. Therefore, the upper pair of rectifiers will respond only to signals from the right-hand mirror (one looking to the right) and the lower pair only to signals from the left-hand mirror.

The differential relay shown operates two indicating lights and also two single relays for operating the turntable motor.

Results

In the laboratory, while the amount of hunting depended upon the strength of the target, it was of the order of ±1 to 2 degrees. The minimum radiation field strength to operate the steering mechanism under favorable conditions was 0.01 microwatt per sq cm at the mirror. This was when the scanning angle was ±1 degree and the angle between the two mirrors was 4 degrees, giving a total field of view of the bolometer of between 7 and 8 degrees.

Outdoors, operation was irregular, some of the few possible targets observed being tracked reliably, others not. One successful run involved tracking a black barge and tug to a range of 2,850 yd. At 2,700 yd the Farrand Heat Meter recorded a field strength of 0.11 microwatt per sq cm. On another run, a freighter was tracked at about 7,000 yd when its field strength was 0.03 microwatt per sq cm.

Conclusions

The S-8 showed much more satisfactory sensitivity than its predecessors. The signal-to-noise ratio is a function of the scanning angle, since the greater the angle the greater must necessarily be the probability of picking up background irregularity. Two mirrors at an angle with each other, each oscillated independently, will cover an effective area slightly larger than the sum of the angles measured (because of the length of the bolometer strip) with only a small scanning angle. The S-8 provided a reliable means of steering, the first in the series so equipped.

Its sensitivity was of the order of magnitude observed for Dove Eye and for Felix—in other words, it should have been capable of operating bomb controls at usable distances.

It had fewer tubes than its predecessors, and far less complexity than Dove Eye, but some of the adjustments, for example the phase-shifting network, were critical.

9.7 PROJECT BEETLE[9]

The difficulties enumerated above in connection with the quadrant photocell target seeker and with the wide-angle photoelectric scanner led the Division contractor, Bendix Aviation Ltd., to suggest the use of CW radio target seeking. In the centimeter range, this could have been the Moth technique (see Chapter 1) and would have been parallel with the testing technique used in the early phases of the radar-homing glide-bomb program. The technique envisaged by the contractors, however, involved less complicated techniques than those of centimeter radar. The frequency proposed was in the neighborhood of 200 mc and the corresponding techniques were parallel with those well established for radio goniometry. The Division supported this suggestion of its contractor and extended the contract (OEMsr-1002) to include the development of radio-homing devices for experimental purposes.

9.7.1 Design of System

The system proposed by Bendix consisted of four antennas symmetrically and orthogonally arranged about the roll axis of the missile near its nose. Each antenna was successively connected through a commutator to a fixed-tuned receiver. The signals from diagonally opposite antennas, suitably rectified and compared, gave an error signal proportional to the error in heading.

The four antennas consisted of quarter-wavelength spikes radiating from a tapered nose on the forebody of the missile. A superregenerative detector was capacitively coupled to each of the antenna spikes in rotation through a motor-driven commutator. A synchronously driven commutator at the output of the detector and amplifier distributed the rectified and amplified output to a smoothing filter, so that a smooth d-c voltage appeared across the output terminals of the filter. (See Figure 43.)

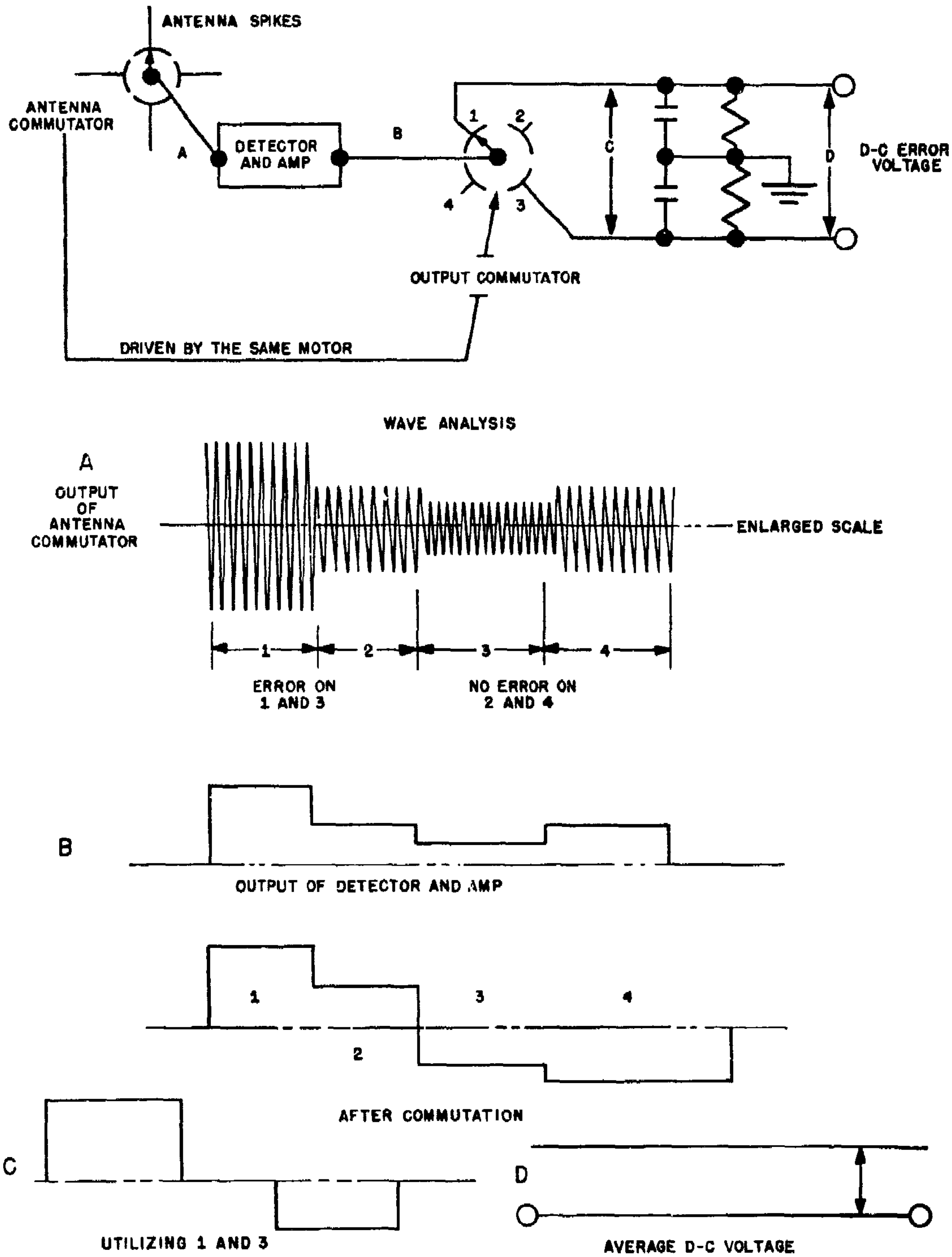


FIGURE 43. Block diagram of Bendix Beetle system.

With the missile directly on course, the signal intensities at each of two diametrically opposite antenna spikes would be equal. With an error in course heading, the differential in signal strength at two diagonally opposite antenna spikes, shown in Figure 43A, would be measured by the receiver, the output of which during a cycle of commutation would be as shown in Figure 43B. Figure 43B shows the result of commutation and the appearance at the output of the filter of a smooth d-c voltage at the filter output terminals, proportional to the difference in received signals at the antenna.

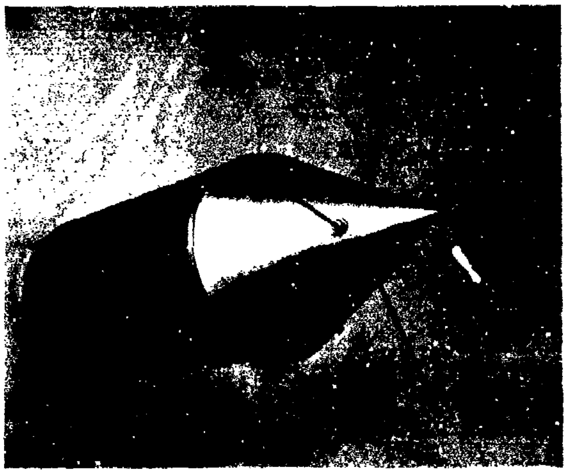


FIGURE 44. Beetle CW radio target seeker.

9.7.2 Tests with Beetle

An experimental model (Figure 44) of this homing device was constructed, and was tested on the ground at Rosamond Dry Lake. The ground test showed reasonable promise for this system of control in the azimuth sense, although signals with azimuth errors in one direction were not precisely symmetrical with those in the reverse direction (Figure 45).

The ground tests were followed by airborne passage tests to give an indication of its probable effectiveness in the range direction. Reflections from the ground gave erratic signals in the region adjacent to zero error heading. Since precise quantitative results are required in this region for accurate homing flight, this failure was considered sufficiently serious to justify shelving the project. It is probable that a more elaborate transmitting antenna structure than the one shown in Figure 46, with a suitable reflector behind the radiating element might have eliminated this difficulty. The appearance of satisfactory quadrant photocells from Farnsworth Radio and Television Corporation, however, eliminated the pressing need for this type of target seeker and the project was dropped.

9.8 ORGANIC TARGET SEEKING[10,11,12]

9.8.1 General

The simplest method of obtaining target discrimination is through its recognition by intelligence. The Japanese suicide missiles employed exactly this technique, using human organisms to guide the missiles into impact. While this technique was extremely effective and imposed serious losses on our naval units, many misses were scored, and it was obvious after the program had been in operation for some months that the problem of steering an aircraft into a small target at combat speed is not a simple one.

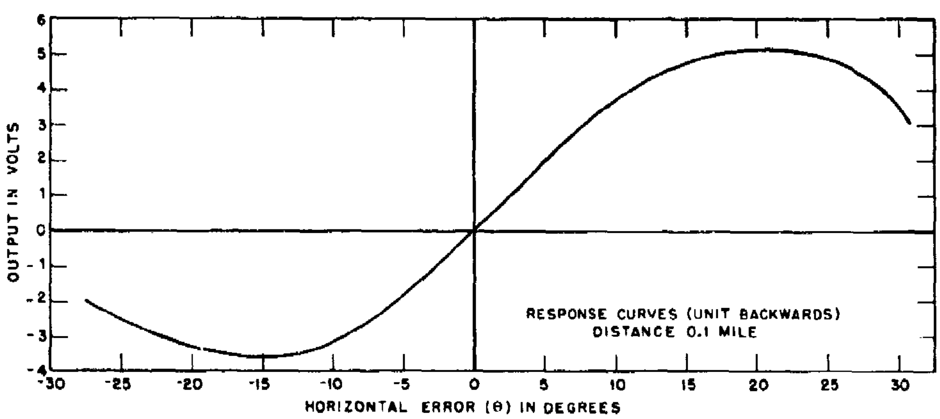


FIGURE 45. Error of signal from CW radio target seeker.

Economy as well as considerations of humanity suggests the use of lower organisms to perform the functions of the Japanese suicide pilots. The use of trained house cats to steer a homing torpedo was suggested in World War I. In this program the suggestion was to use any easily available and readily trained animal organism. The contractor, General Mills, Inc., retained a psychologist in the field of organic behavior who made a broad preliminary study before submitting his proposal to NDRC. In his preliminary investigation the contractor concluded that the common pigeon or dove, *columba livia*, is a satisfactory organism for rapid and easy training and that the supply is considerably in excess of what would be required for military operations. Following the contractor's initial survey, the Division made preliminary studies on the assumption that a satisfactory servo link could be developed to couple the response of the pigeon with the control surfaces of the missile. These studies justified a small contract (OEMsr-1068) for further developmental work.

The advice of the Applied Psychology Panel of NDRC was solicited and their approval of the standing of the psychologist was obtained.

9.8.2 Training of Pigeons

The training program is divided into three phases. In the basic phase, the birds are taught to peck at a distinctive object, not necessarily related to any military target. During this period, birds with apparently low intelligence levels and temperamental birds are weeded out. The basic training course consists of feeding the birds through a metal plate provided with a hole of distinctive shape. The entire plate is covered with a translucent membrane such as vellum paper, and the whole assembly illuminated from the rear. The birds learn to peck at the illuminated spot and recover grain located behind it. Additional feeding is restricted during this period to a level at which the birds lose weight. Their weight is plotted, and those birds which lose weight without developing a conditioned reflex to peck at an illuminated spot on a sheet of paper are culled out.

The selected birds are then given a more advanced training in which they learn not only to peck at a distinctive object but to peck more accurately and at a higher frequency. Accuracy is taught by reducing the size of the target which will result in delivery of food to reinforce the conditioned reflex. Higher frequency is taught by introducing into the training system a counting relay system which will deliver food only if a predetermined number of pecking impulses have been made against the processed plate within a predetermined interval. Initially, a single peck will deliver a few grains. At a more advanced stage, several pecks, for example five delivered within ten seconds, will result in the delivery of food. In the final stages of this phase of training, thirty pecks must be made in ten seconds in order for the conditioned reflex to be reinforced.

This method of training builds up what is known as a reserve of impulses. If the bird is placed in the environment in which he has been conditioned to expect food by pecking, he will proceed to peck and will continue to peck although no food appears. It is this property which made the organism attractive for combat use. A complicated mechanism in the bomb to assure that the bird would be fed during the combat flight proved unnecessary. Once this reserve has been exhausted, however, there is doubt whether it can be restored. That is, if the bird's faith is broken that pecking in the approved manner will produce food, he cannot be so trained as to restore that faith. Care must be taken, therefore, during the training program to see that at no stage are the birds subjected to a requirement which will extinguish the reserve of impulses.

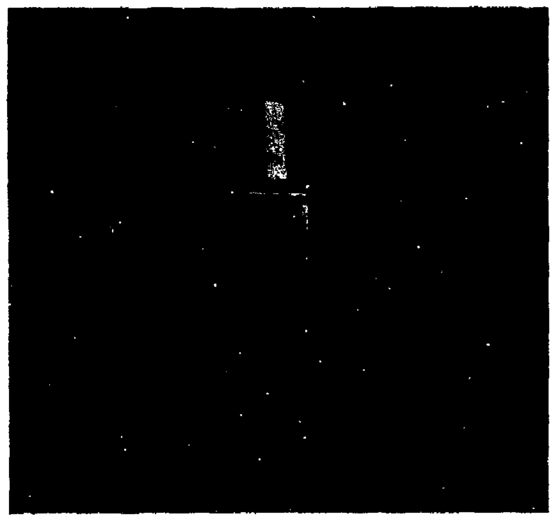


FIGURE 46. Radio transmitter, including batteries.

After the pigeons have been trained to peck at distinctive objects, the final phase in the program is to train them to identify and to peck at a specific, dis-

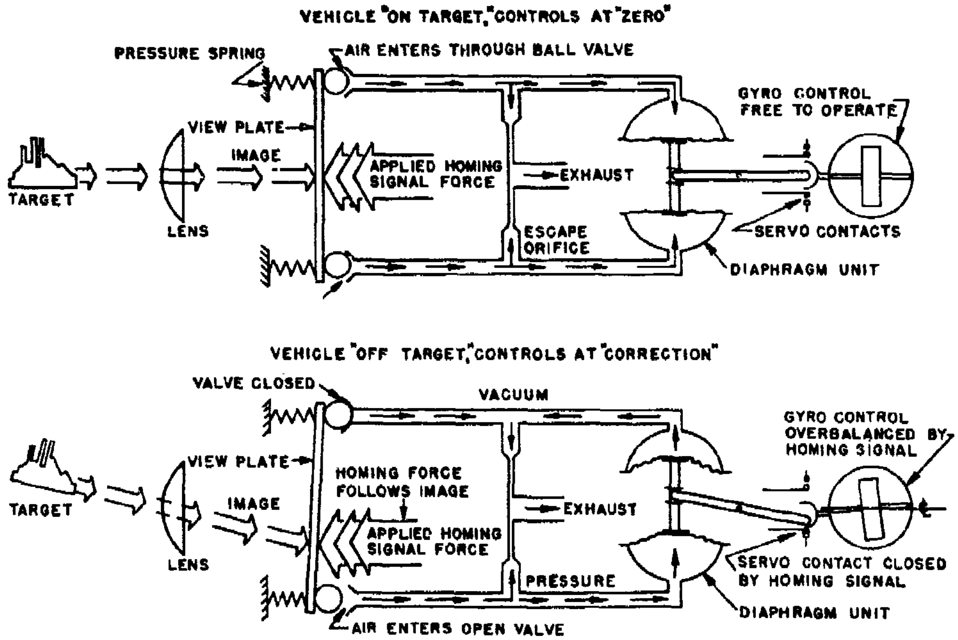


FIGURE 47. Diagram of pneumatic servo for pigeon-controlled bomb.

crete object. Considerable work was done by the contractors from aerial photographs of ships at sea. Well-trained birds, approximately the top 50 per cent of the class, would invariably, at the close of the training program, peck at the largest boat in a convoy irrespective of its position in the array. Other birds were trained on aerial photographs of cities, and were trained to select a particular building or street intersection and would attack the image of this spot, irrespective of the orientation of the photograph as presented to them.

The basic training course, involving culling out unsatisfactory birds and training the remainder to peck at a satisfactory frequency at any distinctive object, occupied approximately six weeks. Having completed this course, the birds require approximately 48 hours briefing on a specific target.

9.8.3 Servo Links

This method of target seeking was intended for use with the glide bomb. The reason for selecting the glide bomb was that it flies with very little change in angle of attack. Therefore, the problem of the bird was much simplified. If he could keep the glide bomb pointed at the target, the probabilities of a hit were high.

The scanning system consisted of a camera obscura enclosing the bird. A simple convex lens projected the image of the target field onto a sheet of ground lucite in front of the bird. The focal length and angle of the lens were selected to give a reasonably large field of view so that for any expected launching error the target would lie somewhere within it.

The lucite screen which presented to the pigeon the field of view with the target on it was mounted on a double gimbal system. With an error in heading which would make the target appear up and to the right, the pecking of the pigeon would affect the gimbal-mounted screen to give corrective impulses downward and to the left. A pneumatic control system (Figure 47) was developed to connect the deflection of the screen with the gyro pilot (see Section 1.6) of the glide bomb. There was considerable doubt as to whether this system of control was adequately quantitative to control a glide bomb without serious hunting. The fundamental problem in the servo system was to obtain an error signal proportional to the error in heading. The initial link in the chain which developed the signal produced an impulsive force of random magnitude which was exerted at a distance from the center of the platen proportional to the error in heading.

The contractors built a flight test table which was controlled so as to point at a moving target under the guidance of a conditioned bird. Hunting with this flight test table was not unduly serious, the bird being able without great difficulty to keep the target within 2 or 3 degrees of the center of the screen. There was considerable doubt, however, as to whether the parameters of the flight test table closely matched those of a glide bomb in flight.

The program was given up because the mechanical engineering problem of developing an appropriate servo link seemed too difficult in view of the available personnel for solving such problems and the high promise of success with Pelican and Bat. The Division is not prepared to recommend whether further study along these lines should be made. Certainly, however, should the suggestion be made in the future, it should be examined on its merit. The program of conditioning organisms is far from a difficult one to solve. The problem of devising a stable nonoscillatory servo system is difficult. Whether it is more difficult to solve than some of the servo systems developed during this war for fire control and for other purposes is debatable. The frequency of the response of the bird was dependably three per second. This is admittedly marginal for a rapidly moving missile.

The experience of the Division, so far as it is conclusive, would point to the general observation that an organic system of control should not be rejected simply because it is organic. Investigators in the physical sciences are inclined to discount unduly the findings of their colleagues in the field of psychological behavior. Such an attitude is far from scientific, and there is implicit in the success of the Japanese program with organic homing systems the suggestion that further study in this field might well be profitable.

Chapter 10

SIMULATION AND TRAINING AIDS

10.1 INTRODUCTION

Francis Bacon is quoted as having cited as the greatest need of mankind "a machine to aid the mind in thinking as a tool aids the hand in working." Mathematics is such a machine. Without its aid quantitative thought becomes almost impossible; in the field of science and technology, general thinking not reduced to quantitative evaluation is at a very low level indeed. In many cases, however, ordinary mathematics breaks down in the solution of problems in research and development. In the field of manual activity, hand tools become inadequate where the scope of effort to be expended exceeds what can economically be supplied by the energy of workers. Where hand tools are inadequate, machine tools supplement or replace the energy available from the operatives.

In research and development, problems similarly arise where the scope of mathematics, as ordinarily conceived, is inadequate for the solution of the problem. Sometimes this inadequacy finds its expression in a loss of economy. Thus, when many repetitive operations are to be performed, the computing and tabulating machines of Hollerith and his successors perform analytical processes more rapidly and with more accuracy than they could be accomplished through the effort of many workers.

Problems in mechanics find their most succinct statements in the differential equation. A numerical solution, however, is possible only if the function involved in the differential equation can be integrated. The solution can be obtained only with considerable difficulty if the coefficients of the derivatives are not linear. These are various limitations in the application of mathematics to engineering problems, so that the ruse is frequently adopted of considering the relationship between the elements of a problem as being linear in the region in which a solution is sought. Such simplification, necessary though it is to permit application of conventional mathematics, is frequently unjustifiable. The naval architect's curve expressing the relationship between driving horsepower and the ratio of the square root of the length to the speed of a hull is a well-known example. This curve commonly has a sharp break in the region adjacent to the value of unity for the speed-length ratio, and it is precisely in this region that the interest of the naval architect is most acute.

The product integraph[1] and its successor, the differential analyzer,[2] were developed at MIT to meet exactly this need. With these powerful tools differential equations can be solved, if their order is not excessive, provided only that the coefficients of the derivatives in the equation can be presented graphically. Thus, not only is the limitation of linearity avoided, but a further extension of power is made in that it is unnecessary to express the derivative coefficient in algebraic language. Empirical data from the wind tunnel or from the model towing basin can be used directly without recourse to an approximate algebraic fit of the experimental data.

These aids to analysis are simulative in nature. They consist of electrical and mechanical circuits which can be so adjusted that their performance exactly solves the differential equation under consideration. They have been classified as *replica computers* in contrast with counting computers of the Hollerith type.

Other types of simulative computers are also well known. C. A. Nickle[3] constructed in 1924 a transient analyzer which explored the transient behavior of electrical and mechanical systems by recording oscillographically the performance of a dynamically similar electrical system. In general, Nickle's analyzer was limited to linear systems, although he recognized that the introduction into the simulative circuit of electronic elements gave a possibility of exploring systems with nonlinear characteristics.

10.2 GENERAL

In the analysis of guided-missile performance, simulation has been a powerful tool of the Division's contractors. Its aid has been invoked to accomplish three aims. As an analytical tool, simulators have been built by the Division's contractors to solve performance equations of missile systems and to adjust the parameters of design so that the probability of successful flight test with the missile would be at a maximum. This is not to say that simulative studies can replace flight tests; rather, they serve as a valuable preliminary supplement to flight tests so that valuable effort and irreplaceable time are not expended unnecessarily. This is one of the most valuable functions which simulative analysis can perform. In general, a simulative test can be performed in minutes or, at most, hours, whereas flight tests with the missile occupy days and, if the time of preparation and analysis of the test is included, weeks.

A second function of simulative analysis by the Division was the determination of the optimum combat use of the missile and the exploration of tactics which could be employed by the bombardment aircraft using them. The economy of such a method where the dynamic similitude is authentic is obvious.

The third application of simulation by the Division was in the development of training devices intended to go in the field with the combat crew, continually to supplement their training and combat experience. Such a device could also perform an extremely useful function in basic training by giving the bombardier his first experience with the peculiarities of the new weapon.

Each of these three functions permits a different standard of construction. For the analytical device, to be used only by trained laboratory personnel, devices may be crude, yet extremely valuable. Accessibility of components and adaptability to variations of parameters add to the power of the simulator in such cases and are more readily achieved when the design is fluid than when it is frozen. To investigate possible tactics, the engineering must be sufficiently refined to convince the operating personnel of the authenticity of the simulation. The construction must be good enough to allow the average technician to keep it in operating condition. Lastly, the training device must be light, portable, and well engineered to operate correctly and reliably under adverse conditions.

10.3 GULF PHOTOELECTRIC BOMB[4]

In the experiments leading to Azon, Razon, and Felix, the question arose as to the practicability of any homing mechanism; whether a target seeker attached to a wingless bomb could ever supply sufficient stable control, utilizing the limited available amount of lift, to bring the bomb to the target. As pointed out in Section 9.2.1, the answer to the general problem was sought by using the simplest, most foolproof target seeker available, one utilizing a photoelectric cell.

The general principle of operation of the Gulf bomb, that the bomb body supplies most of the lift, left some problems to be settled in the design of the mechanism. Preliminary experiments with the test table, for example, showed that oscillations of dangerous amplitude could be set up if the target seeker were rigidly aligned with the axis of the bomb and on-off control used. This effect was due to the spring-like reaction between rudder deflection and yaw angle. After a sudden reversal of rudder setting, it took some time for the bomb body to assume a trim angle of attack. During this time it was oscillating, and the target seeker was therefore yielding alternating error signals. Later investigations dealt with the type of control that the preliminary analysis had shown to be most suitable—the target seeker directed by "ears" to point in the instantaneous direction of travel, and with proportional control. As the coupling ratio of ears to rudders, range of proportional control, and spring and damping constants were varied, the stability of the bomb in yaw and pitch was observed.

10.3.1 The Test Table

This table (Figure 1) was built for the purpose of simulating angular motions of target-seeking bombs in yaw and course. One of the photoelectric target-seeking units identical with those in the six bombs was mounted on the top platform, which rotated in accordance with the motion of the bomb axis. The lens was coupled as shown (*lens coupling linkage*) directly with the large spur gear. The latter, driven by the course motor, rotated according to the variation of the bomb in course, right or left. The three light beam projectors shown in the photograph were used to show, respectively, rudder motion, yaw motion, and course motion of the bomb.

A few liberties had to be taken to reduce the number of factors to be simulated. The parameters necessary to account for the effect of gravity and for variation of aerodynamic behavior with bomb velocity were maintained constant. The yaw displacement was spring-coupled with the rudder deflection to simulate the aerodynamic coupling between rudder and yaw in flight. Similarly, as shown, the yaw motion was subjected to viscous damping by means of a paddle wheel moving in oil.

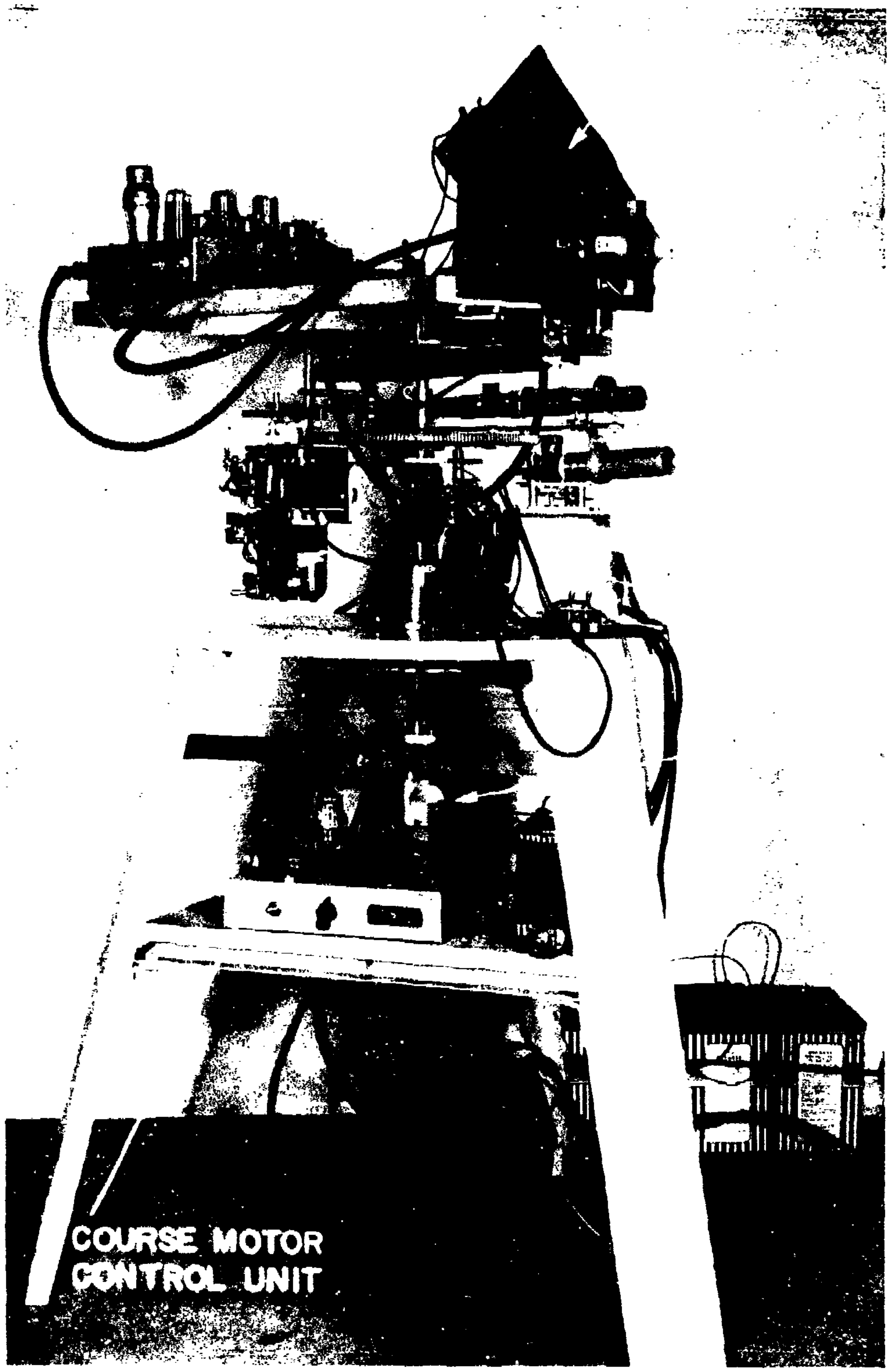


FIGURE 1. Gulf target-seeking test table.

In the vector diagram shown in Figure 2,

ψ = course error angle;
α = angle of attack;
ϕ = angle of bomb above line of sight;
ϵ = target bearing;

then

$$\epsilon = \phi - \alpha - \psi.$$

The equations the simulator solves are derived as follows:

$$I\ddot{\alpha} + \mu\dot{\alpha} + k_1\alpha = k_2\delta \quad (1)$$

In the above

I = moment of inertia
μ = aerodynamic damping coefficient
k_1 = spring coupling coefficient representing the stabilizing moment
δ = rudder angle

$$k_2 = \frac{k_1\alpha_{\text{trim}}}{\delta}$$

$$\delta = k_3\epsilon \text{ when } -5 \leq \epsilon \leq +5 \quad (2)$$

or

$$\delta = -20 \text{ degrees when } \epsilon < -5$$

and

$$\delta = 20 \text{ degrees when } \epsilon > 5$$

and $\alpha - \phi = k_4\alpha$,

when $$k_4 = \frac{\text{Per cent coupling} - 100}{100} \quad (3)$$

By substituting in equation (1), within the range of proportional control,

$$I\ddot{\alpha} + \mu\dot{\alpha} + k_1\alpha = k_2k_3\epsilon \quad (4)$$

or beyond that:

$$I\ddot{\alpha} + \mu\dot{\alpha} + k_1\alpha = k_2 \cdot 20 \quad (4a)$$

$$\psi = k_5\alpha \quad (5)$$

Equations (4) and (4a) were solved by the simulator. Equation (3) was set up by adjusting the coupling between the lens and the course gear. μ, k_1 and k_1/k_2 were varied by adjusting the stiffness of the spring and the viscosity of the damping oil.

10.3.2 Results

The yaw stability was found to be sensitive to the value of the percentage of coupling between the lens and the course. (100 per cent coupling is defined as the case in which the motion of the lens exactly compensates for the change in the field of view caused by yaw motion.) Very small decrease below 100 per cent coupling was found to result in yaw oscillation, whereas overcoupling gave stability, but at the penalty of decreasing the range of error angles for which the rudder displacement can be kept proportional to the target displacement. In turn, this proportionality was necessary to prevent hunting (see Section 9.2.2). The curves in Figures 3 and 4 show the effect of varying the coupling ratio.

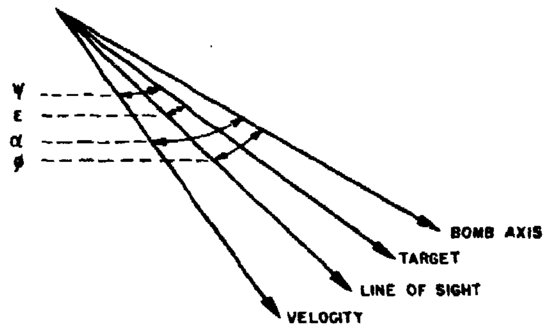


FIGURE 2. Vector diagram of homing bomb.

As it affected the design of the bomb, this observation meant that it was essential for stability that the lens (which was directed by ears projecting into the wind stream) move exactly the amount to compensate for pitch and yaw motion of the bomb. This was accomplished by adjustment of the linkage between the ears and the lens.

This test table had its faults: it did not yield its own record except as the observer watched the lights move, its damping was partly frictional and only partly proportional to velocity, and there were indications that the coupling between the lens and the course indicator was not free from backlash. But with all its approximations, it gave evidence which was used in adjusting the actual bomb for field tests. In turn, five out of six bombs so tuned made good scores on the target, a record unique in the Division's experience. As a by-product, this table served as the basis for the design of the Felix simulator.

10.4 THE GOLD BUG[5]

Early work on the test table described above showed the general feasibility of the method of control adopted for Felix, the MIT heat-homing bomb. Because of the bulk of the apparatus, the direction of view of Felix could not be shifted readily by means of ears; instead, the scanning element was coupled mechanically with the rudders and elevators. By using the known value of the trim angle of attack

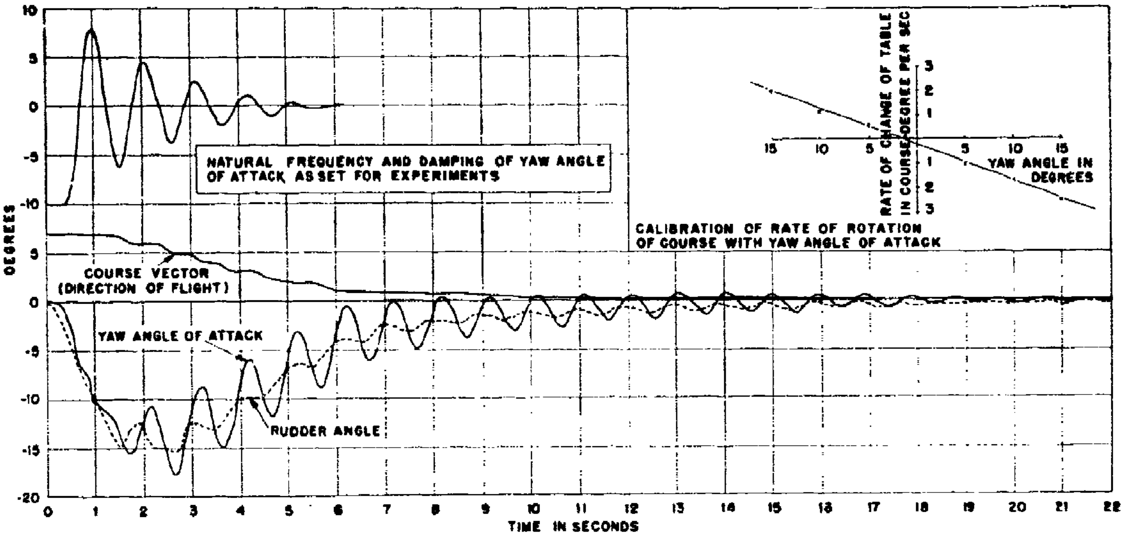


FIGURE 3. Response of test table simulating target-seeking bomb; 100 per cent ear-to-lens coupling, ±5-degree range of proportional response.

produced by a given rudder setting, and hence the direction of flight with respect to the bomb axis, it was possible to couple the rudders and target-seeking eye in such a manner that the latter was always directed along the line of motion at equilibrium. To the extent that equilibrium was reached without oscillation this represented the ideal case, in which it was learned that the method was basically sound. To insert the oscillation about the trim position, computation was resorted to.

Eglin Field tests of Felix showed that the general principles seemed sound but that details needed correction. It was realized that manual computation of the effects of altering each of the variables was impossible, and MIT built a simulator using the Gulf model design as a basis but capable of giving more information. The main improvement was the addition of recording pencils to draw curves showing the oscillations of the various vectors.

With the same terminology as in Section 10.3.1, the equations to which the Gold Bug conformed follow.

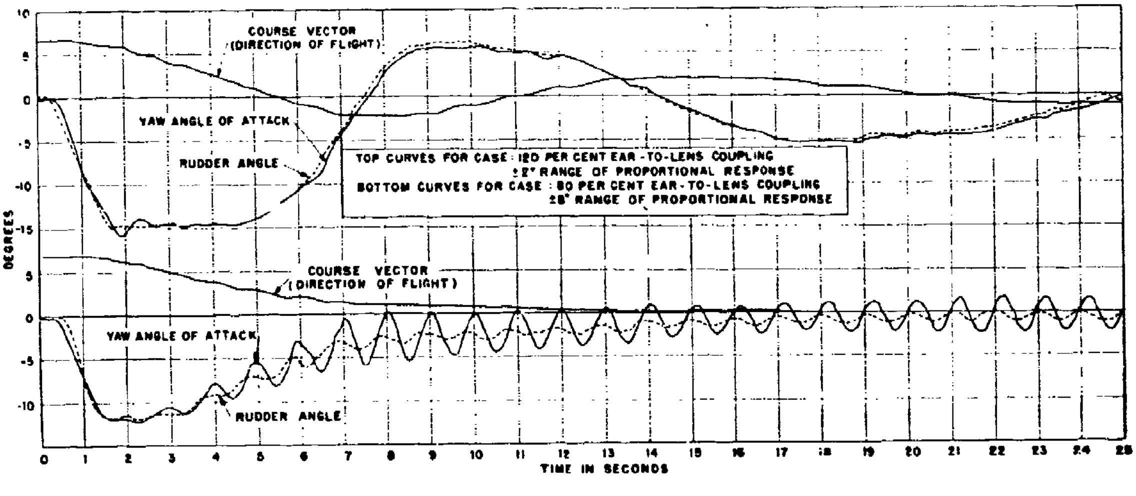


FIGURE 4. Response of test table simulating target-seeking bomb; cases illustrating under- and over-coupling.

Coupling:

$$\phi = k_F\delta \tag{6}$$

k_F = coefficient of coupling (controlled)

Bomb body:

$$I(\ddot{\gamma} + \ddot{\psi} + \ddot{\alpha}) + R\dot{\alpha} + k(\alpha - \delta) = 0 \tag{7}$$

γ = angle between vertical and line to target

Velocity vector:

$$\dot{\gamma} + \dot{\psi} = k_L\alpha \tag{8}$$

k_L = lift factor

Rudder:

δ = zigzag, with reversals shortly after target crosses line of sight

Angle of attack:

$$I\ddot{\alpha} + R\dot{\alpha} + k\alpha = k\delta \tag{9}$$

$R = Ik_L + R'$

k = spring coupling coefficient

R' = aerodynamic damping

It will be noted from the schematic diagram (Figure 5) that gravity is inserted as a factor, and that seven variables are recorded.

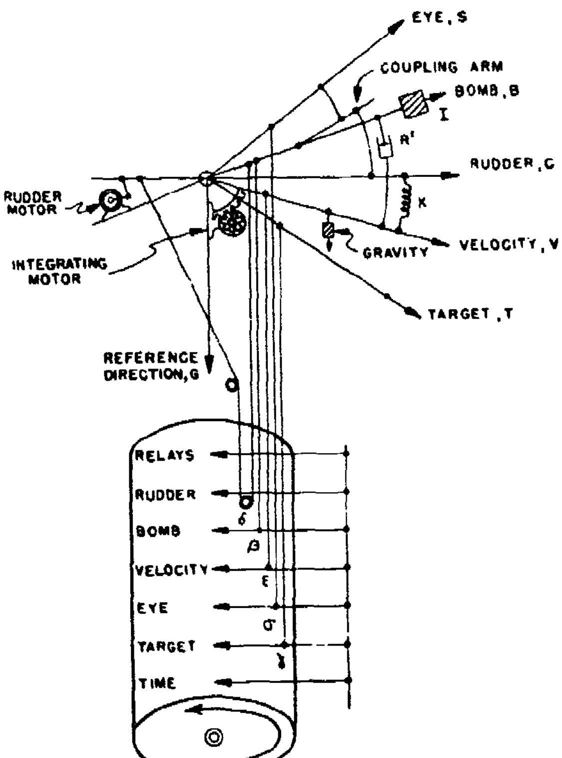


FIGURE 5. Schematic diagram of Gold Bug.

10.4.1 Construction

The photograph (Figure 6) shows the construction. The recording drum and attached pencils with their piano-wire drives are easily recognized. Heavy cylindrical weights supply the inertia. The scanner is near the top center of the picture, and the target is under the wooden housing to the right.

Figure 7, taken from the opposite side, pictures the inertia weights, the coupling springs, the five arms which drive the recording pencils, and the differential which operates the course arm.

Reference to Figure 7 reveals how little engineering refinement is required to build a simulative mechanism of great analytical power. In spite of its crude appearance, it was thoroughly adequate to give quantitative answers which determined the optimum coupling ratio between the control surfaces and the scanning system, and to evaluate the permissible overall time lag within the precision with which the fundamental characteristics of the missile could be determined.

10.4.2 Results

Representative curves as drawn by this device are shown in Figure 8. It will be seen that as the target was moved manually, the elevators and bomb body oscillated about an average position, following the target motion, and the velocity vector swung around smoothly.

It is safe to say that not until this machine was put into operation was it possible to settle design factors upon a basis better than an inspired guess.

10.5 THE PELICAN SIMULATOR[6]

In the two simulators described above, the computations were carried out mechanically. The investigators on the Pelican project found it profitable to combine electrical and mechanical computation in their study of longitudinal (pitch) stability. The controlling equations have been derived in Section 1.4.

10.5.1 Construction

The circular table (Figure 9) was free to rotate about a vertical axis. Angular motion was damped by a direct-connected oil-filled cylinder with close clearances, so that the damping was directly proportional to angular velocity.

Geared to the table were two synchros.[a] The first, the table synchro, produced a voltage proportional to the angular displacement of the table from the neutral position. The second, the torque synchro, applied a driving torque of a magnitude and direction determined by the gyro mounted on the table, the servo link under test, and the computing circuit (Figure 10). The third synchro shown in this figure was mounted on the output of the servo link so that its voltage was proportional to servo output velocity. The torque applied to the table then becomes:

$$L = KE_g \tag{10}$$

where E_g is the voltage between the two grids of V3. Now if

I = moment of inertia of the table system
μ = damping coefficient of the table system,

then the motion of the table will be exactly identical to the pitching action of the glide bomb when controlled by the same gyro and servo link, provided the following relationships between the glide-bomb characteristics and the circuit parameters are maintained.

$$\begin{aligned}
&\text{I} && \frac{\mu}{I} = -Mq - M\dot{\alpha} \\
&\text{II} && \frac{1}{R_9C_7} = \frac{1}{R_8C_6} = a \\
&\text{III} && \frac{KC_1}{I} = -M\alpha + aM\dot{\alpha} \\
&\text{IV} && \frac{KC_2}{IR_8C_6} = b(-M\alpha + aM\dot{\alpha}) \\
&\text{V} && \frac{C_3}{I} = Mg - bM\dot{\alpha} \\
&\text{VI} && \frac{C_4}{I} = Mj
\end{aligned} \tag{11}$$

[a] Synchro is a word coined by the Navy to indicate a dynamo-electric machine having a single-phase rotor and three-phase stator. Specifically, Bendix Co. Autosyns were used.

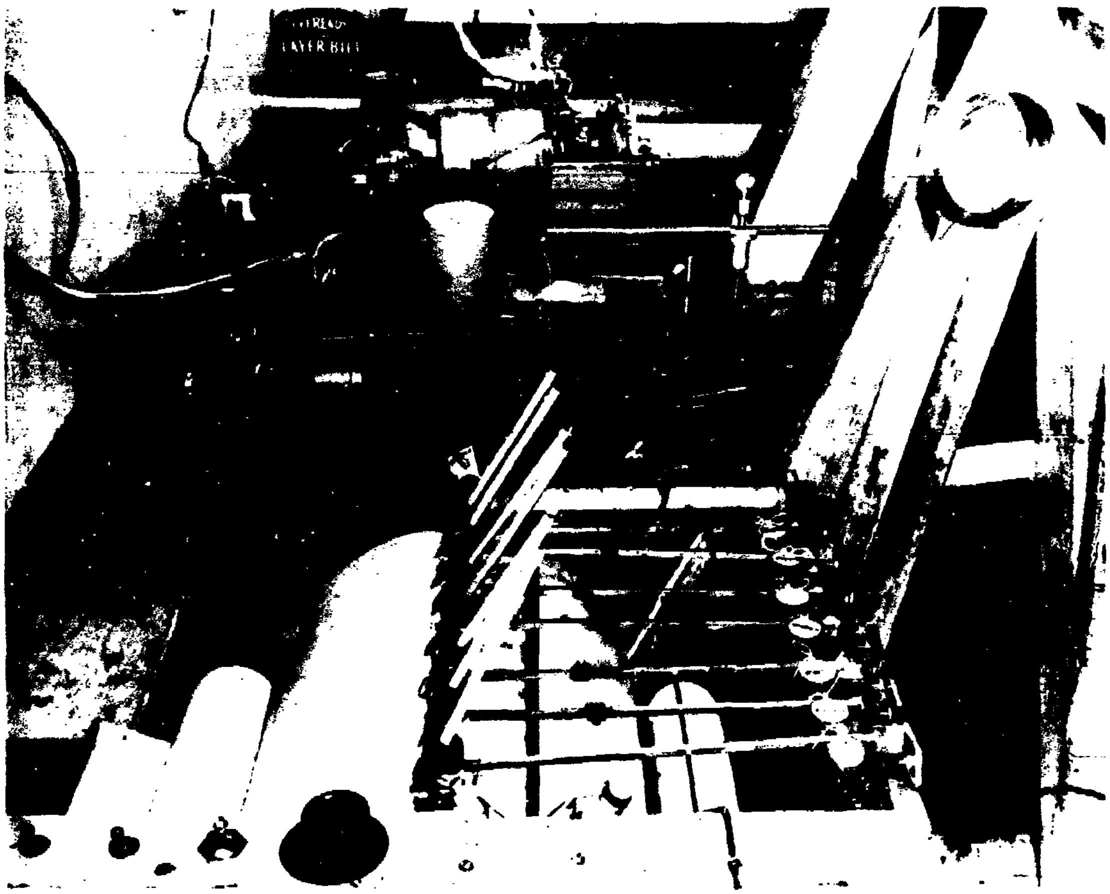


FIGURE 6. Gold Bug calculating machine, front view.

In the above, M = angular acceleration in pitch

$$M\alpha = \frac{\partial M}{\partial \alpha}, M\delta = \frac{\partial M}{\partial \delta}, Mq = \frac{\partial M}{\partial q}$$

$$M\dot{\alpha} = \frac{\partial M}{\partial \dot{\alpha}}, M\dot{\delta} = \frac{\partial M}{\partial \dot{\delta}}$$

q is the velocity head $= \frac{1}{2}\rho v^2$
α is the angle of attack
δ is the elevon angle

A procedure for adjusting the circuit to satisfy equations (11) is given in the investigator's report.

10.5.2 Operation

The entire assembly as it was used in studying the performance of the gliders constructed by this contractor included (Figure 11): the test table (center), a servo unit (left) in which torsion rods simulated the aerodynamic loads on the elevons, and the power unit (right). Performance was recorded by a recording oscillograph (Brush Oscillograph, Model OBC). Oscillations in ϕ, α, and δ were recorded for different settings of the minimum angle Φ which saturated the differential amplifier, the gyro rate $\partial L/\partial \alpha$, and $\partial L/\partial \delta$.

10.5.3 Results

In this device, simplicity of construction and neat appearance were achieved by converting the calculated outputs to voltages proportional to the angles to be measured. The advantages are apparent; the longer time required for calibration was more than compensated for by the greater stability once adjustments were made.

With this, as with the others already described, it was determined that slight variation of some of the design factors (Φ, gyro rate, L_α, and L_δ) from the adopted values could produce unsatisfactory oscillation. Here again the time scale was tremendously

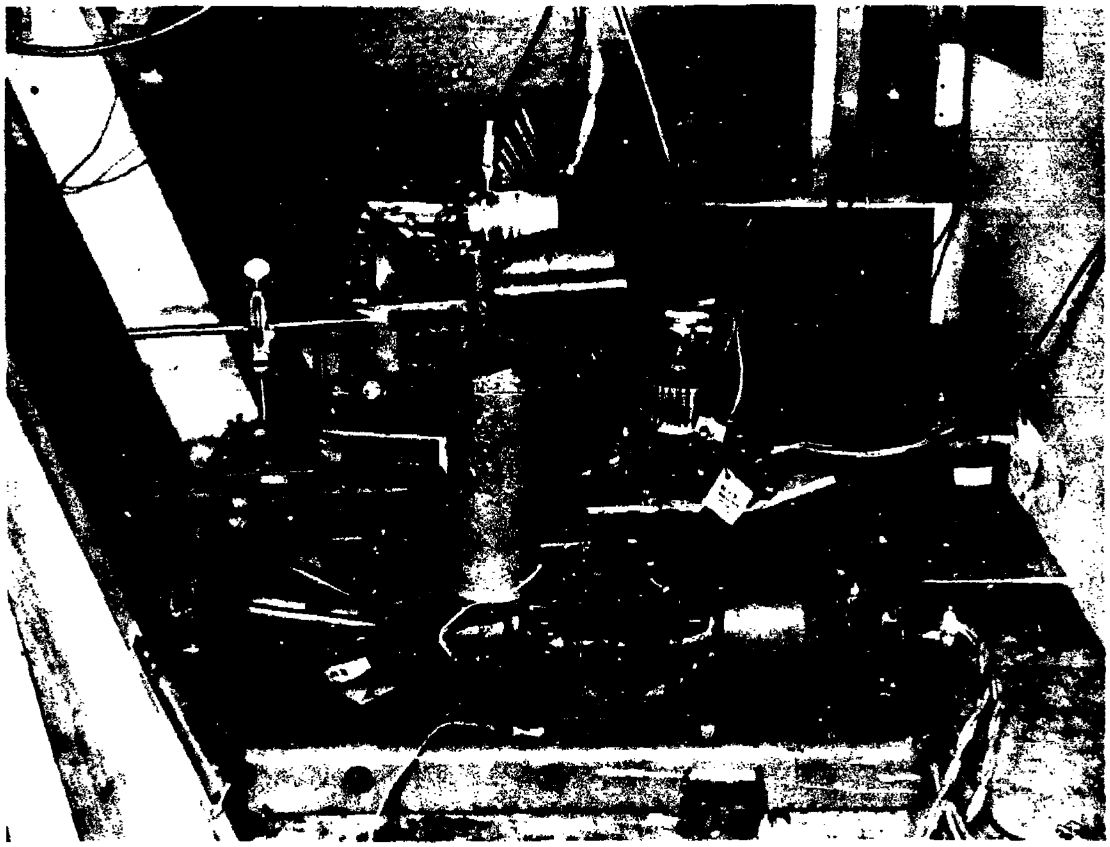


FIGURE 7. Gold Bug calculating machine, rear view.

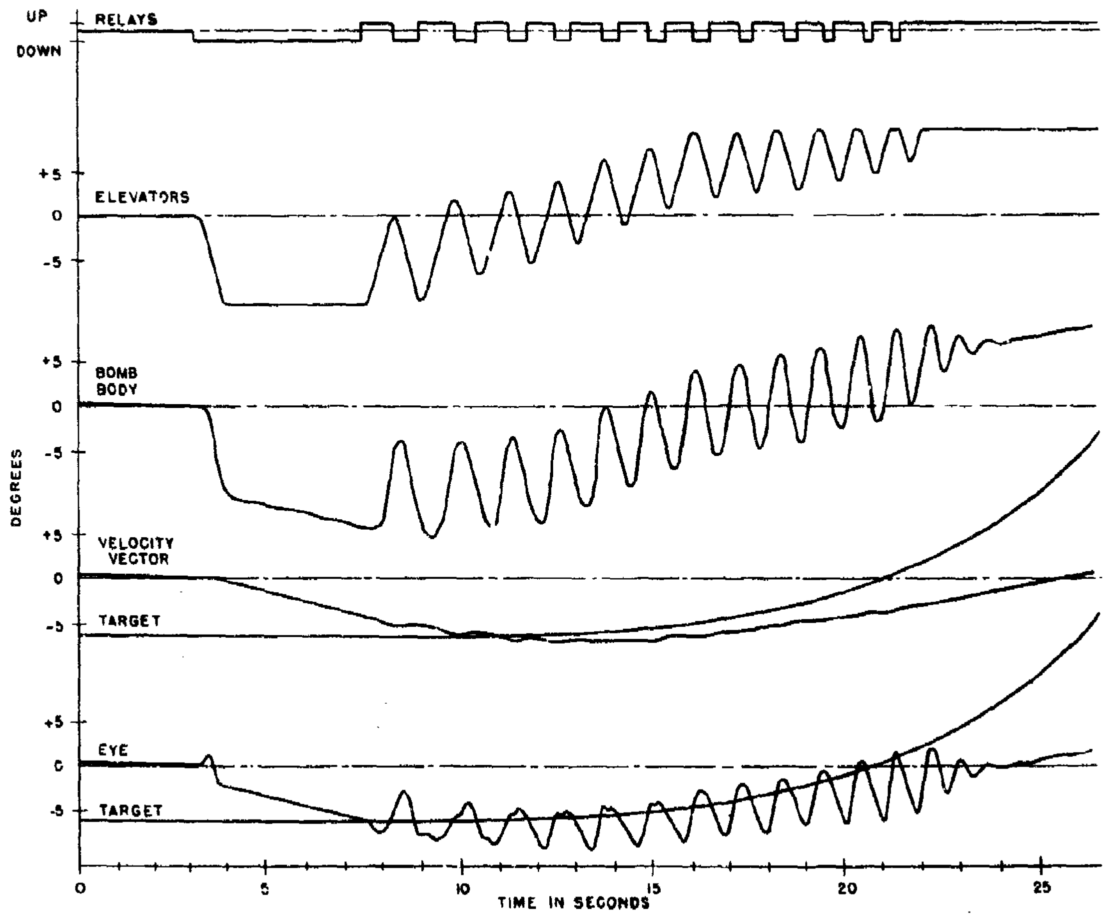


FIGURE 8. Homing curves computed by Gold Bug.

shortened by the transfer of hundreds of "flights" from the test field to the laboratory table.

10.6 PELICAN SERVO TEST TABLE[7]

Chapter 7 included a discussion of the servo system developed at MIT for use in the Pelican series of glide bombs. The stages in the work of this contractor were:

1. Mathematical analysis of a proposed system and determination of the required dynamic and static characteristics of each component;
2. Study of the system on a flight table designed to simulate the more important dynamic and static characteristics of the glider and radar system;
3. Design of components;
4. Dynamic and static checks of each component;
5. Rechecks upon the flight table of the control system comprising the components finally adopted;
6. Flight tests of the complete missile.

Items 2 and 5 entailed the use of a mechanical flight table that actually simulated the Pelican glider but was capable of adjustment for other missiles of similar characteristics. It should be mentioned that this study was the only one in which the entire closed loop was explored as a system, including the servomechanism, airframe, and target seeker.

The flight table as built by this contractor was designed to simulate the missile in roll and in pitch. Figure 12 is a functional diagram of the complete test table with its associated equipment. It will be noted that this bore some similarity to the table described in the preceding section but allowed for the introduction of two additional variables—roll orientation and action of the radar receiver. Rotation of the table top about horizontal and vertical axes simulated roll and yaw motion of the glider, respectively. Up-and-down motion of the target provided for the equivalent of pitch motion.

Portions of the mechanism which were not sensitive to the motion of the table, such as the elevons and their servomotors, were located conveniently near-by.

The equation of motion of the glider in roll was:

$$l_d \delta d - L_p \dot{\phi} = A \ddot{\phi} \tag{12}$$

δ_d = differential displacement of the elevons;
l_d = roll torque for unit elevon displacement;
L_p = damping torque for unit rate of roll;
ϕ = roll angle;
A = moment of inertia about the roll axis.

An exact simulation of equation (12) was obtained by designing the table so that:

A/R = moment of inertia of the table plus its motor and gearing referred to the table;
L_p/R = effective damping of the table;
l_d/R = torque produced upon the table by unit displacement of the simulated elevons;
ϕ = roll angle of the table;
R = a scale factor.

A variable-displacement hydraulic pump whose displacement was a function of the roll angle of the table provided a rate of yaw proportional to the angle of roll. It will be remembered from Chapter 1 that the Bureau of Standards glide bombs were unique among the missiles of the Division in that they turned in yaw only as the result of roll.

The contractor's report[7] describes how the apparatus was arranged to make the above relationships valid. With the flight table, most of the conditions met in flight were adequately represented. Important measurements made with the use of this table were: (1) accuracy with which the glider holds its course; (2) damping of the glider to suddenly applied roll moments; (3) the nature of the response to disturbances in flight direction.

Two general systems were studied, one using rate gyros only for stabilization, and the other using free gyros and rate information obtained electrically. The results eliminated the first type in favor of the second.

10.6.1 Results

Engineering selection of components was based upon their behavior on the test table. In addition, the entire servo system was tested thoroughly before and after installation in the glider. The effectiveness of this procedure was reflected in the performance, as described in Chapter 7.

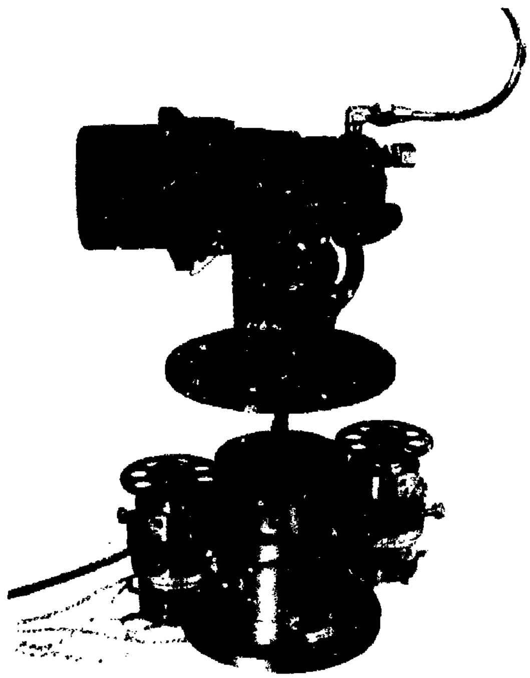


FIGURE 9. Pelican pitch simulator.

10.7 ELECTRONIC SIMULATORS: AZON AND RAZON

Philbrick has discussed[b] the fundamental principles of electronic or mechanical-electronic simulation, and related the history of the collaboration between Division 5 and Division 7 on this subject. It suffices to say here that, as the result of work upon breadboard models at Columbia University[8] under Section 7.2, it was shown that the differential equations for the flight of Azon, Razon, and Roc were amenable to approximate solutions by mechanical-electrical means. Some work at Columbia also showed the feasibility of stable control of the television Roc and the necessity for proportional control for Roc. Reduction of breadboard models to useful training in-

[b] *Aiming Controls in Aerial Ordnance*, G. A. Philbrick Division 7, Volume 3.

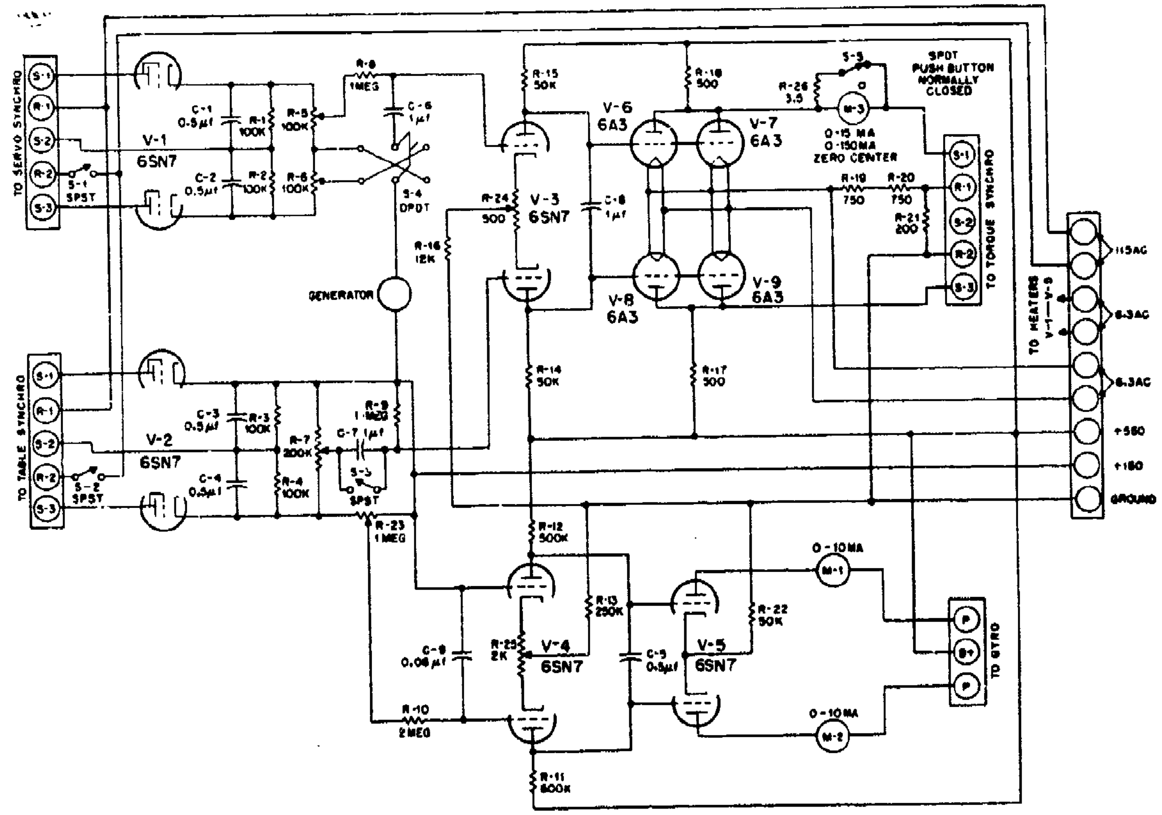


FIGURE 10. Pitch control flight table amplifier unit.

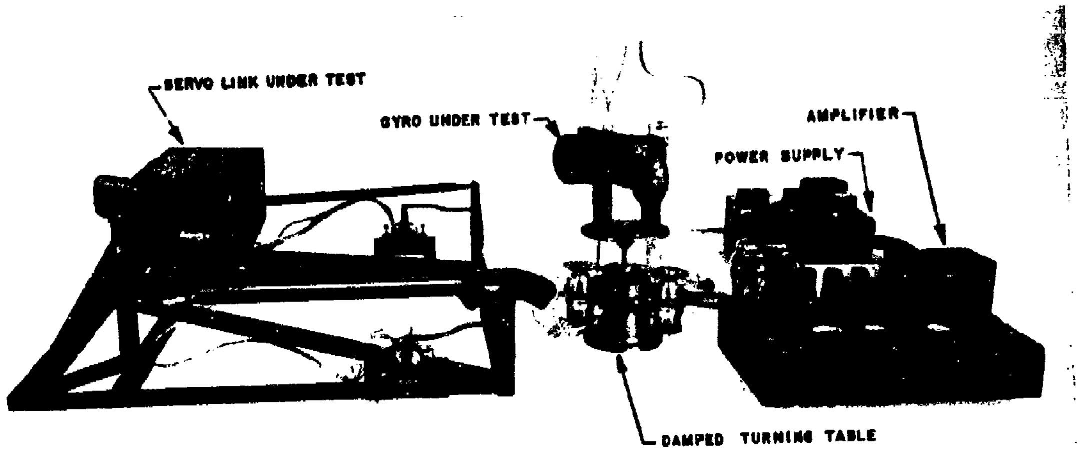


FIGURE 11. Test table assembly.

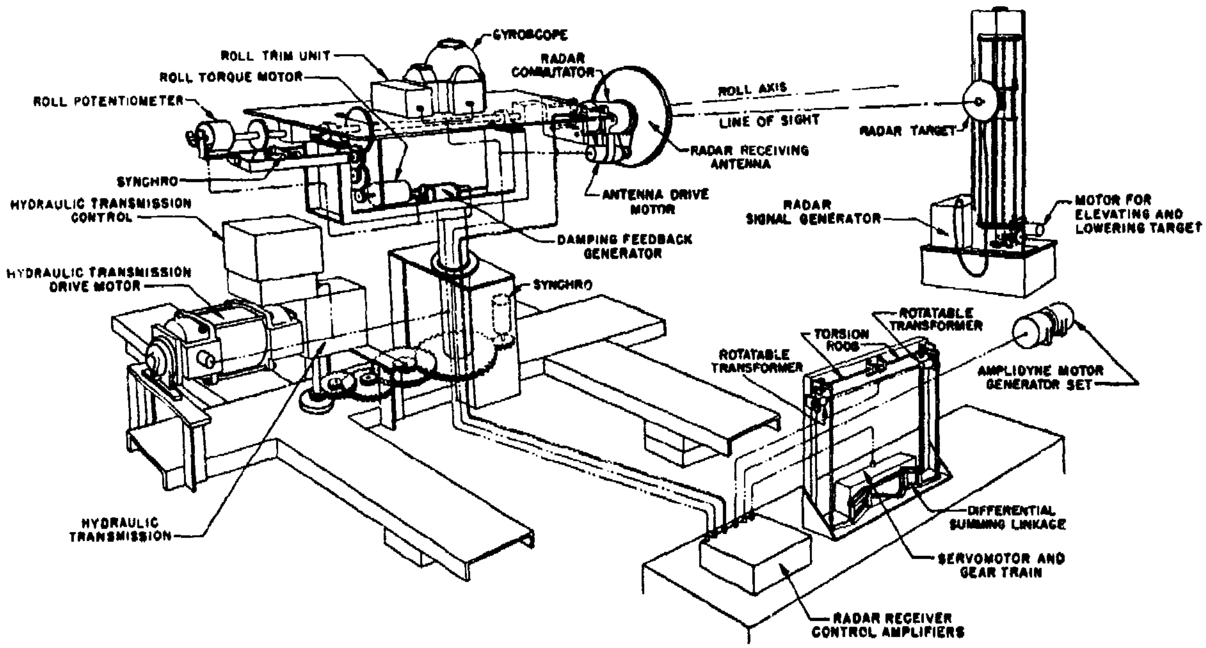


FIGURE 12. Pelican flight test table.

struments was accomplished by Division 5 contractors.

10.7.1 Mathematics

The equations representing the motion of Razon may be expressed (in rectangular coordinates) as follows:

$$\ddot{x} = -\frac{A}{M}\frac{\rho}{2}C_L(\delta_e)V^2\cos\theta \tag{13}$$

$$\ddot{y} = -\frac{A}{M}\frac{\rho}{2}C_S(\delta_r)V^2 \tag{14}$$

x = range coordinate;
y = azimuth coordinate;
A = area of cross section of bomb;
M = mass of bomb;
ρ = air density at altitude h;
V = velocity of bomb tangent to trajectory;
θ = angle between vertical and tangent to trajectory;
$C_L(\delta_e)$ = ballistic coefficient as function of elevator angle;
$C_S(\delta_r)$ = ballistic coefficient as function of rudder angle.

We may simplify these by expressing $\rho V^2 \cos\theta$ and ρV^2 as average functions of time, and by neglecting $\cos\theta$ in order to permit use of the same linkage for both range and azimuth channels. The above equations then reduce to:

$$\ddot{x} = f(t)\delta_e \tag{15}$$

$$\ddot{y} = f(t)\delta_r \tag{16}$$

All the constants in equations (13) and (14) have been absorbed in the time function, which is very nearly a square law, i.e., $f(t) = Kt^2$. Adding the perspective effect, the bomb deflection as seen by the bombardier is, if z = the altitude of drop,

$$\begin{aligned} \theta x &= \tan^{-1}\frac{x}{z-h} \doteq \frac{x}{z-h} \\ \theta y &= \tan^{-1}\frac{y}{z-h} \doteq \frac{y}{z-h} \end{aligned} \tag{17}$$

10.7.2 The Computer

For Azon and Razon a simple on-off control stick was used. Application of control caused the bomb rudder to move at a constant rate of 33 degrees per second to a limiting value of 20 degrees. In the computer this was simulated by applying a voltage of proper polarity to an integrating amplifier and a diode limiter. The output of this amplifier therefore yielded δ_e or δ_r, according to whether range or azimuth was under consideration.

Two different methods were used in inserting the time function. In one, the potentiometers concerned were wound on 10-to-1 taper cards, which approximated the square law reasonably well. Only one manufacturer, however, proved capable of winding potentiometers of the high resistance and steep taper required, and he was unable to supply adequate numbers. For all later models, linear potentiometers were used, driven by the simple *four-bar linkage* (Figure 13) described by Philbrick and so designed as to rotate the potentiometer shaft at a rate proportional to the square of the rate of turn of the synchronous

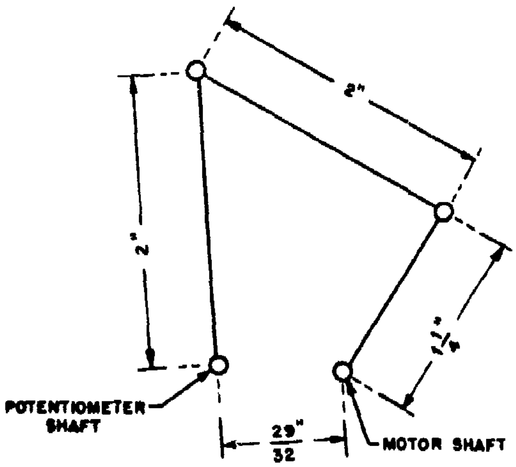


FIGURE 13. Square-law four-bar linkage.

motor driving it (Figure 14). The result is to multiply δ by Kt^2.

x was obtained from $\ddot{x}$ by double integration in integrating amplifiers. The output from amplifier IV was a voltage proportional to the azimuthal displacement of the guided bomb from its unguided trajectory. Lastly, the variable scale factor, which was proportional to the distance between the bomb and the airplane, was introduced. This was also proportional to $f(t)$, so another potentiometer on the same shaft allowed multiplication of the gain of the last amplifier by the factor $1/(z - h) = 1/[f(t)]$.[9]

10.7.3 Model 1010

The output was presented in one of two ways. In the Model 1010 trainer, the output voltage for each coordinate was fed to one pair of field coils of a special galvanometer unit. This unit was a Mark 18 gunsight, modified by the replacement of the standard trail coils with special high-resistance coils. In this unit, a gyroscopically mounted mirror was processed by a voltage applied to the trail coils, the effect being that of a galvanometer capable of motion in two coordinates.

A spot of light reflected by the galvanometer mirror appeared superposed on the target picture provided by an Army A-5 or A-6 bombing trainer (Figure 15). In effect, the bombardier, looking through the Crab sight, saw the bomb flare superposed on the target. Control by the standard stick resulted in appropriate scaled motion of the bomb. Suitable relays permitted automatic stopping of computation (for scoring purposes) at the end of the time of fall, followed by recycling to prepare for another run.

The flare projector, seen enclosed in the vertical rectangular box to the operator's right in Figure 15, is shown in detail in Figure 16. The computer box is shown in Figures 17 and 18.

The A-5 and A-6 trainers simulated the usual procedure of the bombardier in standard bombing, with a target photograph projected upon a white surface for observation through the bombsight. The equip-

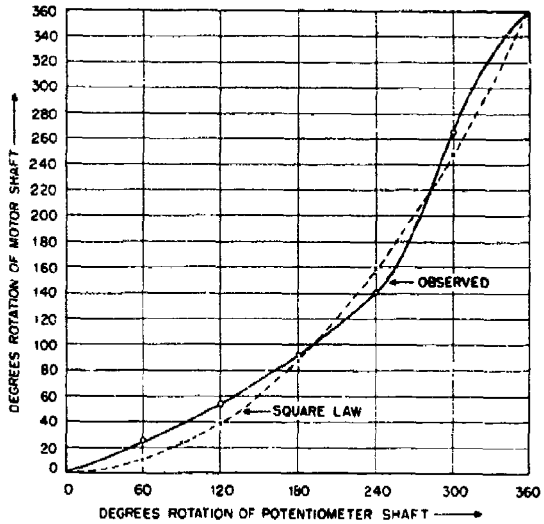


FIGURE 14. Approximation of square law by linkage.

ment for operating the bombsight was standard, and the response of the field of view to the bombardier's controls reproduced the actual target as it would be seen from a moving plane. To superpose the Razon attachment required addition of the flare projector, the control stick, the computer box, and the Crab sight.

Adjustments needed were alignment of the flare projector with the impact light on the trainer, and balancing of the ten amplifiers in the computer box.

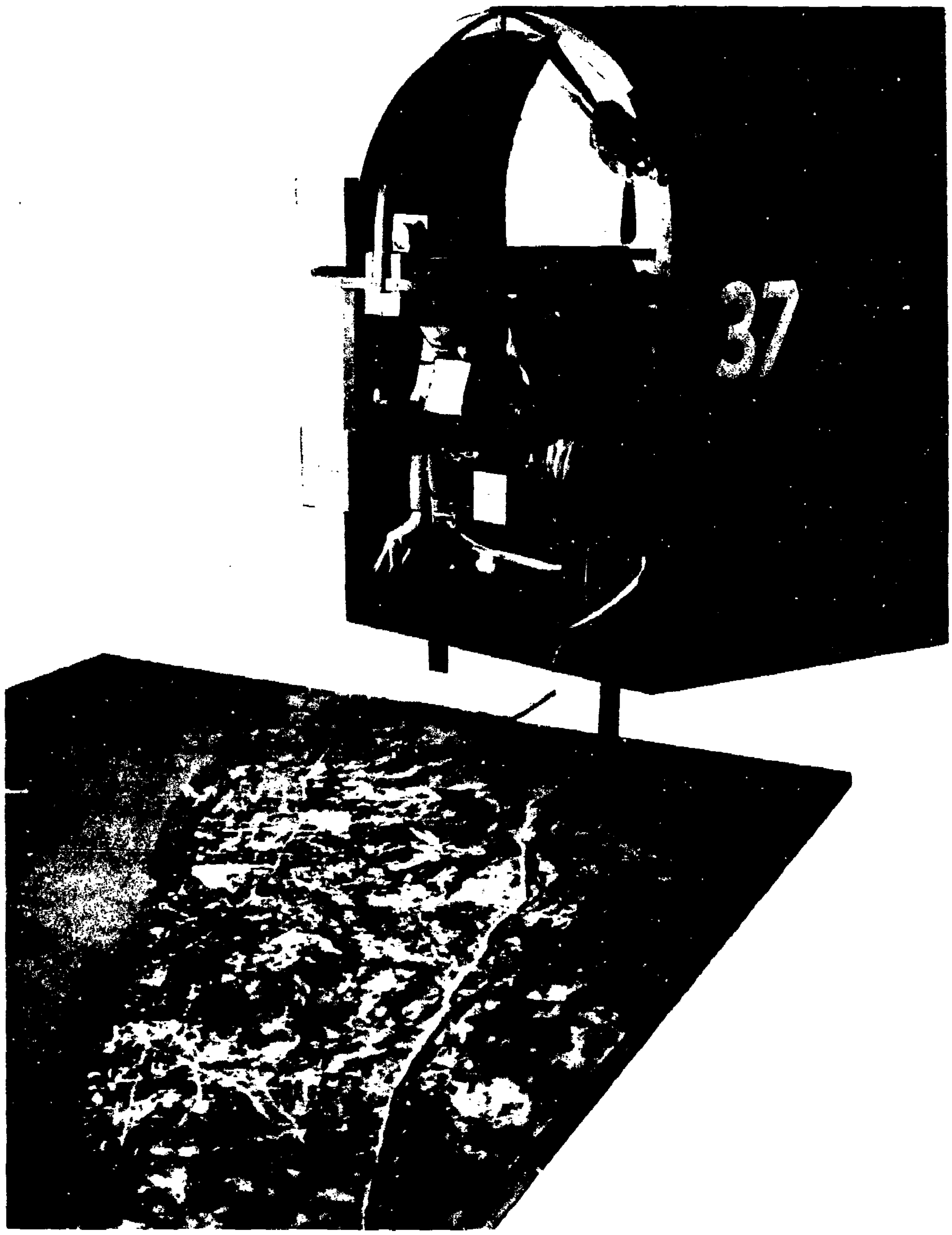


FIGURE 15. Model 1010 trainer in operation.

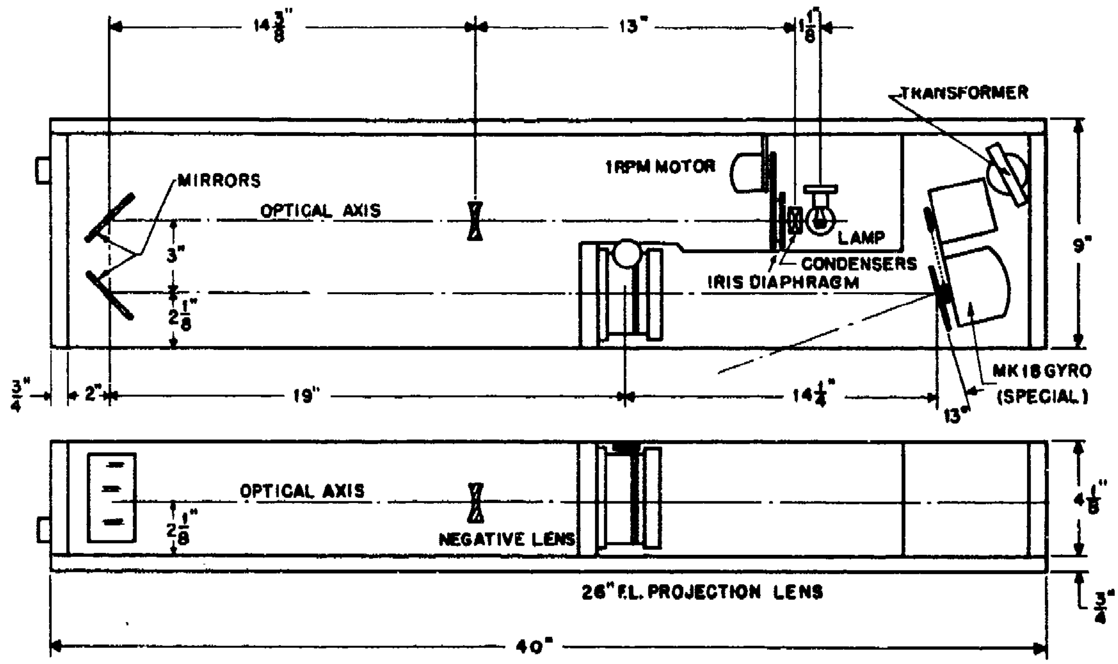


FIGURE 16. Optical arrangement of flare projector.

(Directions for the latter are seen engraved on the face of the computer panel.)

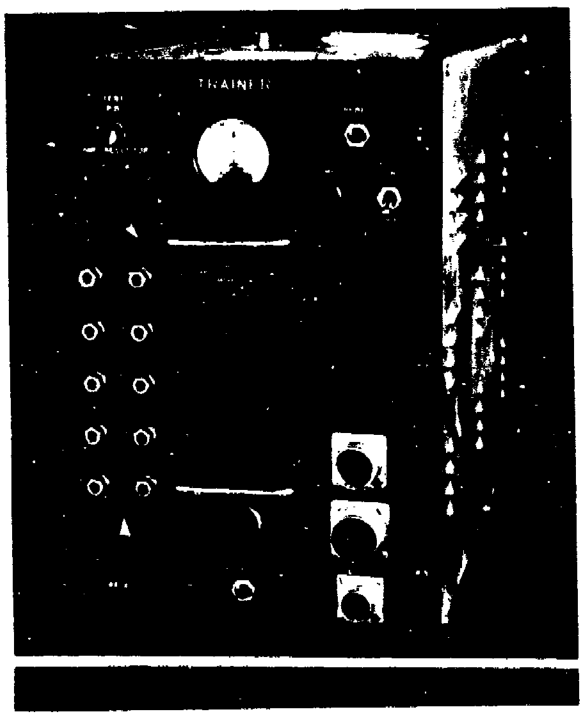


FIGURE 17. Computer box for Model 1010 and Model 1020.

Pushing the "reset" button allowed the motor seen at the bottom center in Figure 16 to drive the linkage to the "zero time" position. From then on, all the operations of the bombardier were identical with those he would perform in combat: setting and synchronization of the Norden bombsight, automatic

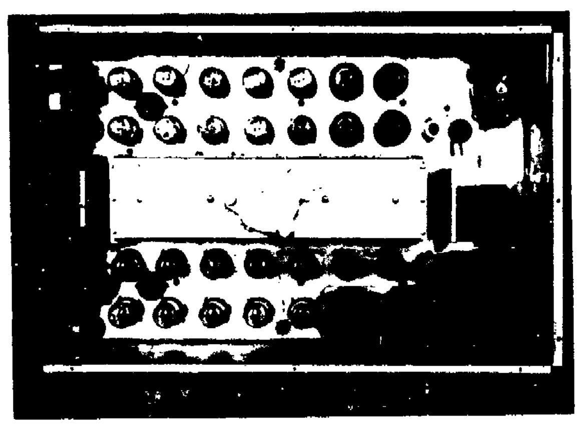


FIGURE 18. Interior of computer box.

bomb release, and use of control stick to keep flare superposed on the target image as seen in the Crab mirror. At impact the flare light remained fixed, indicating where the controlled bomb would have hit, and the impact light showed where the bomb would have hit if uncontrolled. With expert bombardiers the latter point was so near the target that it was frequently desirable to direct the bombardier to synchronize on one target and then steer the bomb to another target.

The dynamics of the moving spot suggested by the trainer in response to control-stick manipulation are very close to those of the apparent motion of the Razon flare as seen from the bombardier's position. Except, therefore, for the discomforts of flight, cramped position, noise, cold, altitude, etc., the Model X1010 is a very realistic trainer. A very short program with this device is equivalent to a good many flying hours. Installed first at Fort Dix and later at the Columbia (S.C.) Air Base, it was used in training Azon and Razon crews. (For Azon, of course, the range section of the device was not used.) A similar trainer has been made available to the Navy and is under analysis by them at Traverse City, Michigan.

10.7.4 Oscilloscope—Model 1020

A portable model was also devised for briefing bombardiers with actual target photographs. In this model (Figure 19) the output voltages from the computer were fed to the deflection plates of a cathode-ray oscilloscope. The target photograph, mounted in the illuminated box seen projecting from the left front of the scope, was rendered coplanar with the face of the scope by the 45-degree semireflecting glass mounted on the front of the scope. The operator pushed the release button on the front of the computer and maneuvered the flare spot to the chosen target. The spot positioner allowed the instructor to insert any desired aiming error.

This device, while less realistic than the Model 1010, was portable and required no special photograph. Any photograph or transparency printed to the proper scale (1 in. = 1,000 ft) could be utilized.

10.7.5 Results

With early versions of this equipment it was determined that: (1) Razon with on-off control was stable; (2) Roc 00-1000-V required proportional control for guidance; (3) bomb-guiding techniques could be acquired within a relatively short training period; (4) the fact that the design involved several approximations militated against its use as a quantitative device, as had been proposed, but did not invalidate the above conclusions.

FIGURE 19. Model 1020 trainer in use.

10.8 MIMO ELECTRONIC SIMULATOR[19]

Remote control of Roc, using television information, was the subject of extended investigation. Preliminary work under Section 7.2, reported by Philbrick, had shown that an unmodified pursuit course must result in a miss of a moving target, but that a "regulator" for converting the pursuit to a collision course would give good results. The Columbia simulator[8] also showed that (1) satisfactory steering was accomplished only after considerable practice, and (2) both experienced and inexperienced operators improved their scores by continued practice.

By the time television equipment for Roc was available, the contractor's representatives had acquired the necessary skill with the aid of their test cart (Section 4.6.2), but it was manifestly impractical to waste both bombs and time training Army bombardiers with the actual matériel. The Division, therefore, arranged for the building of a trainer following the general outline of the Model 1020 Razon trainer, modified to conform to the Roc system of control (proportional) and to present the results from the point of view of the nose of the missile.

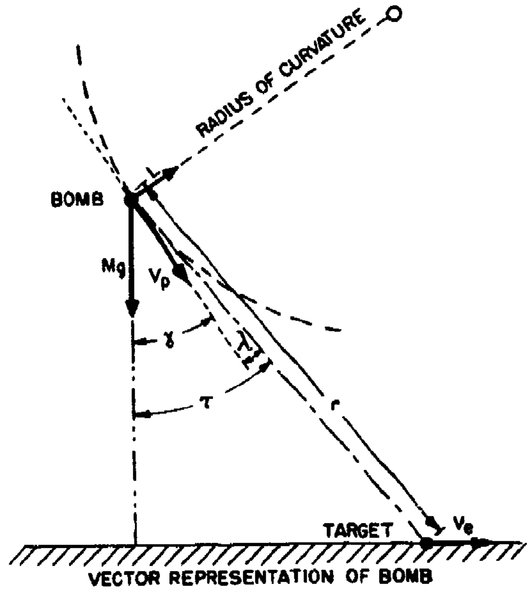


FIGURE 20. Geometry in vertical bomb-target plane.

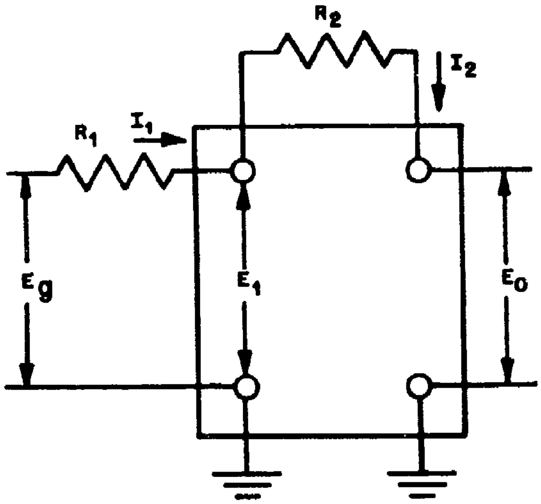


FIGURE 22. Circuit for multiplication and division.

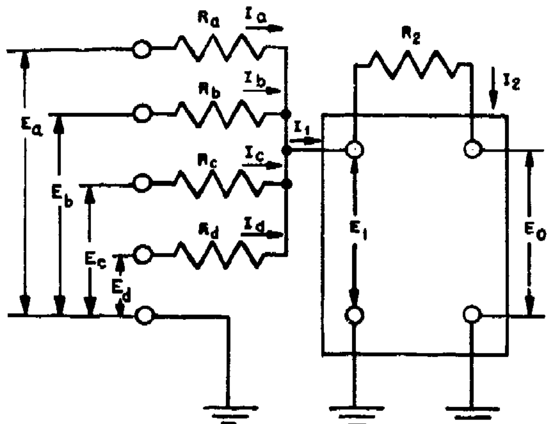


FIGURE 21. Circuit for addition and subtraction.

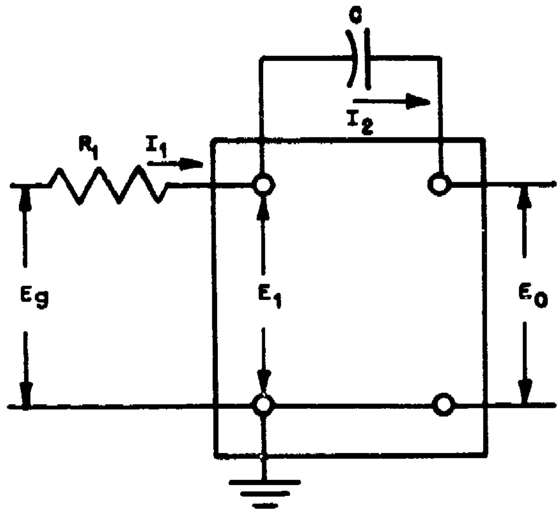


FIGURE 23. Circuit for integration.

10.8.1 General Principles

In Figure 20,

- τ = angle from vertical to line of sight from bomb to target;
- γ = inclination of bomb axis from vertical;
- λ = angle between line of sight to the target and the axis of the bomb;
- r = slant range to the target;
- V_p = bomb velocity in air mass;
- V_e = target velocity in air mass;
- L = aerodynamic lift;
- M = mass of bomb;
- g = acceleration of gravity;
- K = control surface constant;
- δ = control surface angle;
- ρ = air density;
- S = area of control surface.

Then for use in the simulator:

$$\tau = \gamma + \lambda \tag{18}$$

$$\gamma\tau = V_p\lambda + V_e \tag{19}$$

$$\dot{\gamma} = \frac{L}{MV_p} - \frac{g\gamma}{V_p} \tag{20}$$

The above equations are linear, derived from the actual equations[11] by introduction of the following simplifying approximations.

1. (a) $\sin\tau \doteq \tau$ (Equation 19)
   (b) $\cos\tau \doteq 1$ (Equation 19)
   (c) $\sin\gamma \doteq \gamma$ (Equation 20)
2. $\frac{L}{MV_p} = \frac{1}{2}\rho\frac{SV_p^2C_L}{MV_p} \doteq K_L\rho V_p\delta$

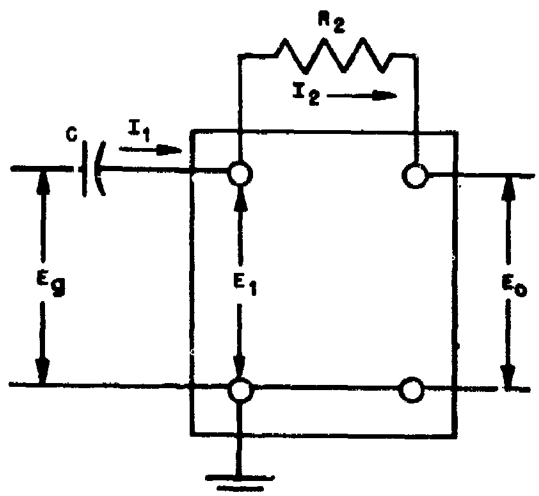
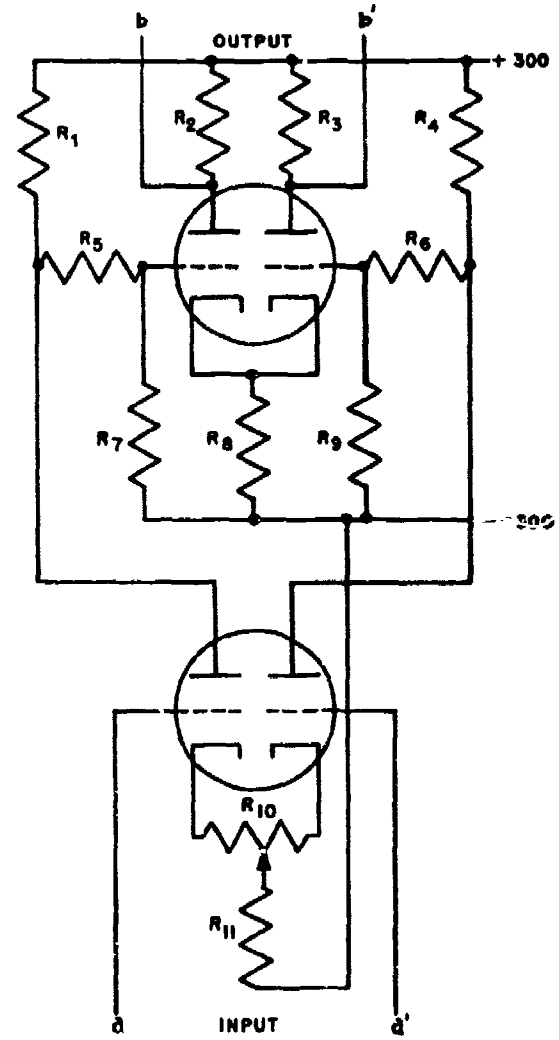


FIGURE 24. Circuit for differentiation.

3. V_p, r, and ρ are linear functions of time after release and are not affected by actual control excursions about the assumed course.

Of the above approximations, 1(a) is valid, since λ is always small; 1(b) seems unjustified, but V_e is so



1 FOR BALANCED OUTPUT, USE b AND b'
2 FOR BALANCED INPUT, USE d AND d'
3 FOR SINGLE-ENDED OUTPUT, CONNECT b OR b' TO GROUND
4 FOR SINGLE-ENDED INPUT, CONNECT d OR d TO GROUND
5 FOR AMPLIFICATION WITHOUT CHANGE IN SIGN (+A) USE d AND b, OR d' AND b'
6 FOR AMPLIFICATION WITH CHANGE IN SIGN (−A) USE d AND b', OR d' AND b

FIGURE 25. Basic amplifier circuit.

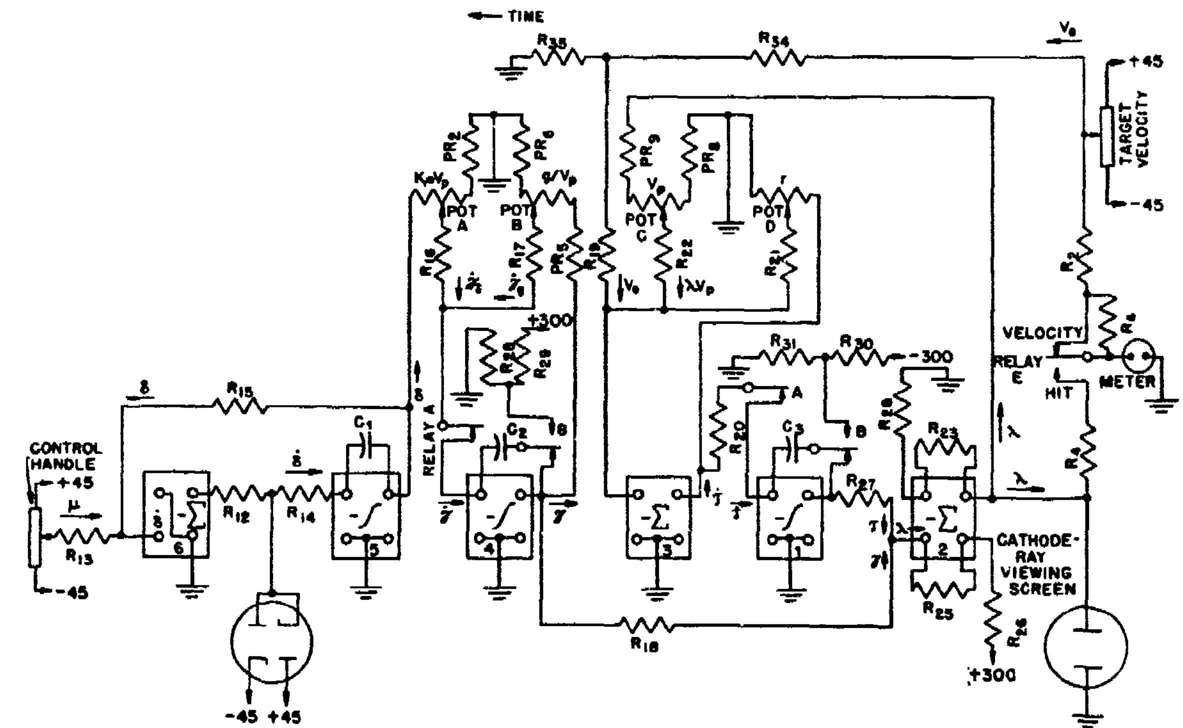


FIGURE 26. Computer schematic for one coordinate.

much smaller than V_p that substitution of V_e for $V_e \cos \tau$ has only a slight effect upon $\dot{\tau}$; 1(c) is subject to similar reasoning—$g\gamma/V_p$ and $g \sin \gamma/V_p$ are both small numbers with little effect upon the first term of the equation.

For simulation, a voltage corresponding to λ was applied to the deflection plates of an oscilloscope.

10.8.2 Electronic Computation

Electronic solution of the above equations and application to the design of the simulator were based upon a few general principles which are not new but are not too well known, so they will be discussed briefly.

10.8.3 Addition and Subtraction

The circuit in Figure 21 may be used either for addition or subtraction, depending upon the polarity of the applied voltages. The block in each of these circuits represents a d-c amplifier, with gain μ.

The exact input-output relationship is

$$E_0 = \frac{-(E_a + E_b + E_c + \cdots)}{1 + \frac{2}{\mu}} \qquad (21)$$

If μ is high enough, this reduces to a simple algebraic summation.

10.8.4 Multiplication and Division

Similarly a single circuit (Figure 22) can be used for multiplication and division. In this case

$$E_0 = -\frac{R_2 E_g}{R_1\left[1 + \frac{1}{\mu}\left(1 + \frac{R_2}{R_1}\right)\right]} \qquad (22)$$

Again, if μ is large, this reduces to the approximation

$$E_0 = \frac{R_2}{R_1} E_g \qquad (23)$$

10.8.5 Time Integration

The circuit for integration (Figure 23) is better known. For this arrangement,

$$E_0 dt = \frac{-\mu}{CR_1(1+\mu)} \int E_g dt - \frac{1}{CR_1(1+\mu)} \int E_0 dt \quad (24)$$

Again, if μ is high enough, and, better, if E_0 reverses occasionally or periodically, this becomes very nearly

$$E_0 = \frac{1}{CR_1} \int E_g dt \qquad (25)$$

10.8.6 Time Differentiation

Interchanging R_1 and C gives the usual circuit for differentiation (Figure 24).

Here the exact statement is

$$E_0 = -\frac{\mu CR_2}{1+\mu}\dot{E}_g - \frac{CR_2}{1+\mu}\dot{E}_0 \qquad (26)$$

If μ is large enough, this becomes the desired differential

$$E_0 = -R_2C\dot{E}_g \qquad (27)$$

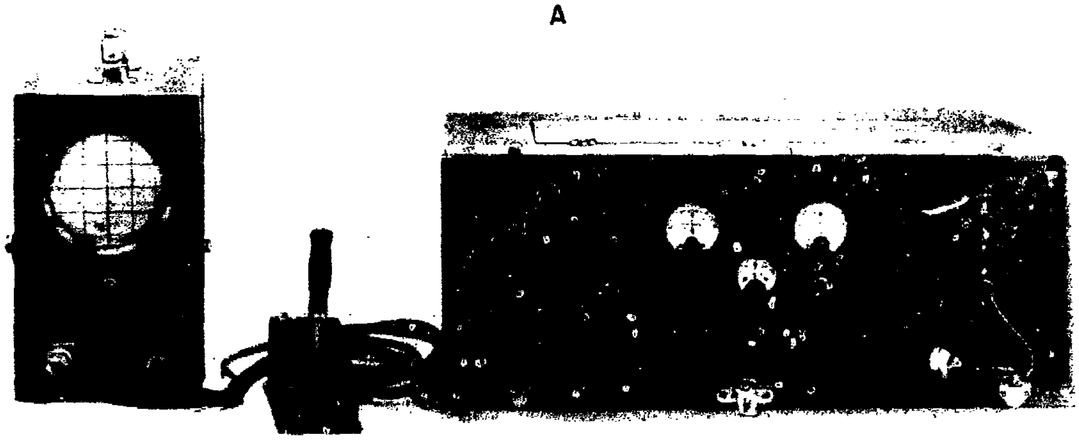
10.8.7 Roc Computer

The principles deduced above indicate that the higher the value of μ, the greater the accuracy of computation. The amplifiers used (Figure 25) had gains of 170 to 500.

Figure 26 shows how these principles were utilized. Amplifiers 5 and 6 simulated the control servo on the bomb. The signal indicating the position of the control handle, combined with δ, the rudder position, determined the speed of the servomotor driving the rudder. The input to amplifier 6 therefore represented $\dot{\delta}$. Limited and summed algebraically, it was applied to amplifier 5.

Integration of $\dot{\delta}$ in amplifier 5 yielded δ. This, multiplied by $K\rho V_p$ in the motor-driven linear potentiometer A, was combined with the g/V_p factor to

A



B

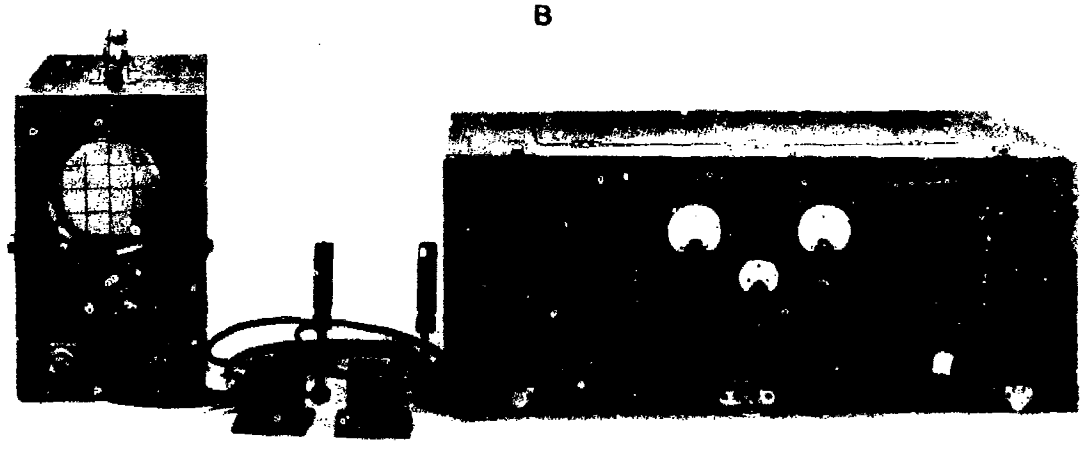


FIGURE 27. Complete simulator model No. 1 with dual control stick (top), with two single-control sticks (bottom).

yield $\dot{\gamma}$, solving equation (20). This, integrated in amplifier 4, yielded γ.

Similarly, $\dot{r}$ was obtained from the summation of λV_p and V_t and division by r in amplifier 3—see equation (19).

Integration of $\dot{r}$ in amplifier 1, followed by subtraction of γ from r in amplifier 2, yielded λ for application to the oscilloscope plates.

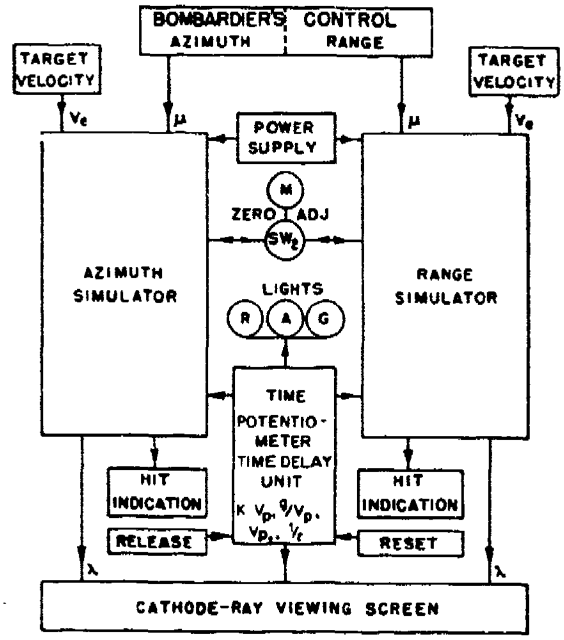


FIGURE 28. Block diagram of two-coordinate television bomb (Mimo) simulator model No. 1 components.

A separate circuit allowed recording of the miss on meters on the computer panel. (Figure 27)

The block diagram (Figure 28) summarizes the above and shows parallel computation for the two coordinates.

10.8.3 Results

This contractor adapted the basic ideas developed by the Division 7 contractor, Columbia University, to the needs of the Roc program. He combined with the basic computer developed at Columbia the principles of sound electronics engineering, so that the resulting apparatus was stable, reliable, and otherwise suitable for training purposes. The report also gives a good statement of the principles to be followed in selection of components for similar computers for other projects.

The presentation is not too realistic. A spot of light on the oscilloscope screen represents the target, its motion corresponding to the motion of the target on the television screen as the bomb falls. The operator gets none of the sensation of target approach produced by increase in size of the image. Nevertheless, a large number of tests run by the contractor have shown that training is necessary to insure good control, and that this simulator could provide such training.

A more serious deficiency in this particular device is the fact that the design is based upon the assumption that the steady-state coefficients are valid in the transient state. Within the existing body of knowledge this was necessary, but as a result the trainer failed to reproduce oscillations which were very noticeable in the actual missile. It was possible to introduce oscillations to match the characteristics of those observed in any given case, but not to determine what oscillations would arise under different conditions. This would be most desirable in future training devices, but is dependent upon nonexistent (at present) wind-tunnel studies of the effects of transients.

The Roc designers built (Section 4.6.2) a computer which was to be mounted on the face of the scope. It was to provide a reticle specifying in two coordinates the desired position of the target in a programmed collision course. The design was analogous to the single-coordinate computer attached to the contractor's test cart.

With the Army preparing to test the Mimo-Roc, the simulator and computer have been supplied to the test group for use in training the bombardiers concerned.

Chapter 11

TRANSITION AND ENGINEERING ACTIVITIES

11.1 INTRODUCTION

In any developmental program the provision of competent laboratory research is not sufficient to produce a finished usable device. This is equally as true in the case of guided missiles or other instrumentalities of warfare as it is with automobiles, aircraft, or any peaceful product. This need is well recognized in normal peacetime industrial endeavors. Indeed, in some large industrial organizations, the research laboratory is supplemented by a general engineering laboratory which is charged with the reduction to practice of the basic principles evolved by the research group. Thus, under ordinary peacetime conditions the research group finds its primary activity in the discovery of new scientific principles in the extension of human understanding.

The engineering group finds its principal activity in the application of the new aspects of human understanding to human use. Even in wartime when research laboratories are more concerned with the development of devices than the establishment of new laws, this need is still acute. The activities of an engineering group in implementing a research organization are manifold. Such a group modifies the basic design established by the research laboratory so that techniques of proved economy and reliability can be applied in production of the new device. It schedules operations during the initial production phases so that the whole project comes to fruition simultaneously. Finally, it is able to make wise compromises between the ideal requirements of each component of a system so that the integrated design of the whole system is at an optimum. It compromises the ideal requirements of the integrated system with the requirements of rapid and economic production.

11.2 GENERAL

The NDRC philosophy as regards this phase of developmental activity envisaged a central office charged with the responsibility for all engineering activity of each of the nineteen divisions and the two panels. This office was to serve as a consulting engineering organization with the divisions and panels of NDRC as clients. The needs of the divisions in some cases, however, outstripped the capacity of this general office to render engineering service, so that Division 5 planned early in 1943 to establish a group of engineers in Division headquarters.

These engineers would be assigned to the several projects within the Division. During the research phases of the project, they would advise the section chiefs as to methods of development which would lead to readily producible items and assist in exploring possible sources of procurement for the device after it had been developed. During this phase of the work their responsibilities were advisory only; that of the section chiefs was fundamental.

The device having been proved in test, these engineers were responsible for directing its development for production. They acted as continual and authoritative liaison between the developmental contractors and Division headquarters. They maintained continuous liaison between the developmental contractors and the section chiefs under whom the research originating the device had been carried out, to the end that none of the basic principles evolved during the research phase of the program would be violated. During this phase of the program their responsibility was fundamental; that of the section chiefs was advisory.

These philosophies were in no sense contradictory. The group of engineers contemplated for the Division headquarters was not intended either as a duplication of or as a substitute for the Central Engineering and Transition Office at NDRC headquarters. Rather, it was the intention that this group, through close liaison with the central engineering organization and by virtue of its continuing association with the projects of the Division, would be able to draw from the headquarters office help and advice necessary to meet the peculiar requirements of each Division problem as it arose. This pattern of operation closely followed that of normal peacetime developmental enterprise.

Pressure of wartime operation thwarted its complete consummation. It was impossible to assemble in the Division headquarters a group of engineers of sufficient size and individual competence to carry to completion each project instituted by the research groups.

There is no question that the failure to organize a sufficient engineering staff to supervise in detail the engineering developments of the programs initiated in laboratories resulted in loss of economy in the Division's operation. The importance of economy in wartime activities is frequently overlooked. It is just as vital in research and development programs in connection with warfare as it is in similar programs of a peacetime nature. Under conditions of war, however, economy is measured in the saving of time. Funds can be made available in very large quantities; time is inexorably limited.

The experience of every industrial enterprise points to the value of lodging responsibility for engineering development in a different group of individuals from those associated with research. The lessons learned from the experience of these organizations is readily transferred to wartime activity. The contract made by the NDRC Engineering and Transition Office with the New England Power Service Company is typical of what can be done to make engineering talent available for the advanced phases of wartime development. Should the Government in the case of another war undertake the mobilization of science, as was done in World War II, a similar procedure should be followed. It should, however, be initiated earlier in the program, and its scope should be broader.

It appears that with a large staff of competent engineers made available in this manner, the work of the entire organization would be benefited. False starts along avenues of unprofitable technique would be avoided through the guidance of mature engineering judgment. Research would be strengthened by eliminating the necessity for diffusing the efforts of research personnel into fields inappropriate to their particular talents.

11.3 GLIDE BOMBS

As has already been stated (see Chapter 1) the basic research on the Pelican missile was carried forward under two cooperating groups. The aerodynamics and servomechanism were developed by the National Bureau of Standards under Division 5; the radar receiver, by the Radiation Laboratory at MIT under Division 14. Similarly with Bat, research was carried forward on the radar equipment by the Bell Telephone Laboratories under contract with the Bureau of Ordnance and the Navy, while the airframe and servo development was carried forward by the National Bureau of Standards and by the Servomechanisms Laboratory of MIT under the direction of Division 5.

The welding of these research programs into a workable missile was in each case an engineering project of some magnitude. Under its contract with Massachusetts Institute of Technology (OEMsr-240) the Division established an engineering group at the National Bureau of Standards known as the MIT Field Experiment Station. While this group had a certain fundamental research responsibility, it was recognized by the Division that the major problems remaining to be solved were technological rather than scientific in nature. Senior responsibility for the activities of the group, therefore, was lodged in an engineer rather than in a research scientist. A small group of associate engineers and a few draftsmen supported him, and under his direction a pilot production line in radar equipment and in servo links was established with Navy cooperation supplying personnel.

This same group undertook and discharged the responsibility for coordinating the design of the airframe with that of the servo link and for seeing that all items scheduled for production met appropriate specifications for performance at an altitude and under conditions of adequate range of temperature and humidity. They developed production designs and checked them on the pilot assembly line. They acted as consultants for the Navy's supply agencies when problems of mass production arose.

They assisted at early flight tests and supervised the tests in the more advanced stages, so that appropriate data obtained in these experimental activities became embodied promptly in the working design. All the field test equipment for the initial squadron that used Bat in combat was designed by this group and fabricated on the production line under its supervision. It provided a competent engineer to accompany the Bat missile into the theater, and it recalled him to supervise its modification and extension to the aircraft equipment as suggested by the initial combat experience with the weapon.

11.4 AZON AND RAZON

For the engineering development of the high-angle dirigible bomb, the Division made contracts with the Union Switch and Signal Company (OEMsr-1081, 1285, and 1415) under the terms of which the contractor was to take the designs developed by the

Gulf Research and Development Company under Contract NDCrc-183 and modify them for production and for combat use. The activities of this contractor were directed from the Division headquarters office. The Division was supported in this work by the consulting engineering service furnished by MIT under Contract OEMsr-240 and particularly by the advice and assistance of the NDRC Engineering and Transition Office. The missile originally designed by Gulf to prove the fundamental principle developed by MIT only approximated the final geometry and loading. It was necessary under this contract for the new contractor to devise means of incorporating the exact payload required by the Services into the dirigible design developed by their predecessor contractors.

Furthermore, the components used by the research group, radio, flare, gyro, and servomotors, had been improvised and had not been necessarily intended for combat use. Union Switch procured an electric-driven gyro to replace the pneumatic-powered one used in the early dirigible high-angle bomb program by MIT and by Gulf. The original radio receiver (see Chapter 6) had been of a type which would produce maximum rudder or elevator deflection in case of loss of the received signal by the missile. Union Switch, through the NDRC Transition Office, procured the development of a superregenerative receiver under subcontract with the General Instrument Company. While this radio receiver was later superseded by a more selective model, it had the property of being "fail safe," so that if radio transmission were lost during a drop, the error of impact would not be increased by virtue of the radio control feature of the missile.

Power for operating the bomb had been obtained from an assembly of batteries—conventional storage batteries for the servomotors and for the aileron solenoid, dry B batteries for the plate supply of the radio receiver. Union Switch procured, through the cooperation of the Navy Coordinator of Research and Development (now the Office of Research and Inventions), a compact, one-shot, expendable lead and sulphuric acid storage battery in a spillproof case (Willard NT-6). This battery had adequate capacity to supply all the power required for the bomb mechanism at the low temperatures likely to be encountered on long high-altitude missions. The radio receiver was provided with a dynamotor so that the plate supply did not require B batteries, whose output voltage at low temperatures is very low.

Early experimental work on the high-angle dirigible bomb program had been dogged by unreliability of the flare by which the bombardier followed the trajectory of the bomb in flight. Under these contracts the contractor investigated other types of pyrotechnic flares, assisted through the Division headquarters office by contractors of Division 11. When a satisfactory design emerged, the Army Ordnance Department was encouraged to undertake its production at the Picatinny Arsenal.

Finally, it was the responsibility of this group to work out all the multitude of compromises necessary to meet the several, and in some cases conflicting, specifications which were deemed to be pertinent.

11.5 FELIX

The NDRC Engineering and Transition Office was the major contributor to the engineering of Felix for production. A group of contracts was made by the Division to procure engineering development of this missile for production. Pressure from the Army Air Forces, suggesting an early operational use of the weapon, prompted the Division to undertake production design before the missile had been completely proved in tests.

Accordingly, one contract (OEMsr-1274) was made with the Norton Company of Worcester, Massachusetts, for the design and sample production of one hundred tails of cruciform structure, although it was well realized that roll stability with this type of structure posed problems not yet fully solved. A succession of contracts with Remington Rand provided for the production design of tail structures having octagonal fins, for nose housings, and for the target-seeking assembly.

Remington Rand subcontracted bolometer supply to Cambridge Thermionic Laboratories, Cambridge, Mass., and to Eppley Laboratories in Newport, Rhode Island. The Heat Research Laboratory at MIT had built bolometers of satisfactory sensitivity and thermal time constant. They had also (see Chapter 5) worked out a spring mounting to keep the bolometer strips under constant tension (see Chapter 3). This mounting had the effect of reducing microphonics. In order to embody the elements of design developed by MIT into a structure suitable for mass production, the Division, with the cooperation of the Vacuum Tube Development Committee, made a contract with the General Electric Company (OEMsr-1348). Under the provisions of this contract the company revised the design of the Heat Research Laboratory, applying the well-known techniques of vacuum-tube manufacturing. These designs were used by the subcontractors just mentioned in manufacturing bolometers for field use. The Division made contracts with the Fairchild Camera and Instrument Corporation for complete scanning units and with the General Instrument Company, in Newark, New Jersey, for scanner amplifiers. The coordination of all of these contracts with the activities of the Heat Research Laboratory at MIT (see Chapter 3) was carried on almost entirely by the Engineering and Transition Office. Personnel who were made available by them to the Division for full-time work undertook activities ranging all the way from supervising field tests to acting as purchasing and procurement agents for the Division contractors and their subcontractors.

Through the contract of the NDRC Transition Office with the New England Power Service Company (OEMsr-1260), personnel in several specialized fields of engineering were made available. These engineers undertook the construction of targets at proving grounds from designs developed by the Heat Research Laboratory. They made a special trip to an arsenal and there designed and built special tools to measure the variation in standard bomb dimensions from approved drawings, allowable tolerances being unavailable from the Ordnance Department. They developed a technique for applying supporting bands to the bomb body, using patch bolts with heads which sheared off at a known loading; thus it was impossible to prestress the holding bolt or supporting band so as to impair the factor of safety against stresses due to impact during landing of an aircraft with a bomb load. They sought out materials impervious to tropical fungi to replace felt gaskets used by the laboratories in early work, and organized and systematized the production layout. They checked many hundred production drawings to ensure that the pilot models would operate in accordance with the scientific principles developed by the MIT Heat Research Laboratory.

Finally, one of the engineers from the NDRC Transition Office continually supported the Division by maintaining a constant liaison between the research laboratory at MIT, the production contractors, and the proving ground so that difficulties as they arose in field tests were promptly referred to the laboratory, corrected, and the correction embodied in the production design without delay.

11.6 ROC AND ITS CONTROLS

The development program of Roc and its controls never reached the stage of production for combat. The situation with respect to this project, however, is sufficiently different from the normal run of a project as carried forward in the Division to its final stage to deserve special mention.

The development agencies were each commercial production units: Douglas Aircraft Company for the missile and its servo links, and Bendix Aviation, Limited for the electronic control equipment. Engineering details, therefore, as well as the development of scientific principles, were assigned to them by the Division. The Division headquarters maintained a supervisory responsibility for both contractors and undertook to coordinate their activities. There can be no question that engineering for production is better accomplished by commercial organizations than by governmental or endowed laboratories, whether devoted solely to research or to research and education. A danger, however, exists in lodging both research and engineering phases of a program in a single contractor. Unless strong supervision is maintained it is easily possible for the Government to lose control of the program. In times of peace this might, perhaps, not be serious, since the personnel of the contractor is almost certainly more competent in detail than any personnel the Government is likely to assemble. In time of war, however, this is not necessarily true. Competent industrial organizations during both World Wars have been heavily loaded with war work, and those projects not operating under strict supervision are likely to be assigned to the least competent staff of the contractor's organization.

This is not to say that the Division experienced this evil in either of the contractors out of which the Roc program emerged. Rather it is a warning against the assumption by a Government agency that the need for strict supervision vanishes just because the contractor's organization is prepared to undertake both basic research and reduction to practice.

11.7 MISCELLANEOUS ENGINEERING ACTIVITIES[1]

In connection with all its guided-missile programs, the Division used consulting engineering services made available to it by MIT under Contract No. OEMsr-240. The activities covered by the engineers assigned by MIT to this contract were extremely broad in character.

11.7.1 Azon Program

In connection with the Azon program, a study of storage batteries was made, resulting in the development by Willard Storage Battery Company of a 12-v, nominal 10-amp lead and acid storage battery. As a by-product of this program, the company was able to increase the capacity of the NT-6 battery used in Azon so that it was adequate to handle the increased load of the 2,000-lb Azon and of Razon.

Increased storage battery capacity was not obtained immediately. Considerable work had to be done by the Willard Storage Battery Company; as a parallel enterprise the project engineers for the Division requested the Division contractor responsible for the missile to redesign the components so that the current drain was materially reduced. Through the combination of these activities the reliability of the missile in long missions, where low temperatures can be expected, was materially increased.

The 2,000-lb Azon VB-2 was engineered for production almost wholly under the supervision of the engineers made available by MIT. They worked closely between Division headquarters and the Division's contractor, the Union Switch and Signal Company. When pilot units became available they supervised drop tests at the Army Air Base at Tonopah, Nevada, reporting continually to the Division. Finally, they cooperated with the Army Air Forces in the performance of evaluation tests by the Army Air Forces Board and assisted in analyzing the data resulting from this testing program.

11.7.2 Razon Program

The activity of these engineers in connection with the Razon program was identical with the service performed by them in connection with Azon. In addition to supervising the production engineering on these units by the Union Switch and Signal Company under Contract No. OEMsr–1415, they performed proof drops at Wendover Army Air Base with the cooperation of the Air Technical Service Command and supplied personnel to cooperate with the Army Air Forces Board for evaluation tests at Orlando, Florida.

The Guided Missiles Subcommittee of the Joint Committee on New Weapons and Equipment of the United States Joint Chiefs of Staff had recommended to the Assistant Chief of Air Staff that the services of NDRC be utilized in connection with the evaluation program at Orlando. Personnel from the Gulf Laboratory instructed Air Forces personnel in the use of the weapon. Personnel from the Applied Mathematics Panel assisted in planning the tests and analyzed their results. The coordination of the activities of both these groups with the activities of the military was handled by the MIT engineers.

11.7.3 Additional Engineering Activities

In addition to carrying a considerable responsibility in the two major programs just mentioned, these engineers were continually occupied with a large number of miscellaneous assignments. A few of them were: expediting the production of fifty Crab attachments to be made available for experimental operational use in the Pacific Theater; the search for more reliable flares of higher intensity and studies of color discrimination with filters for multiple-release operation; the investigation of fuze drives which would not impair the aerodynamic performance of the missile; the elimination of radio noise produced by gyroscope motors; supervision of the procurement of bombing trainers for guided missiles (see Chapter 10).

As World War II closed, the representative of this group had been alerted for overseas service as a scientific consultant to the Thirteenth Air Force. The cessation of hostilities made this mission unnecessary.

PART III

CONTRIBUTIONS FROM INDIVIDUAL INVESTIGATORS

Chapter 12

SOME ASPECTS OF THE DESIGN OF HOMING AERO-MISSILES

12.1 INTRODUCTION

Modern warfare is primarily a warfare of missiles —bullets, shells, rockets, bombs, and grenades. The chief problems are to transport, project or propel, and direct these missiles accurately to strike targets of military importance. Missiles may be transported to the vicinity of a target by men on foot, by mobile artillery, by tanks, by aircraft, or by ships. They may be dropped from aircraft, projected from guns on land, ship, or aircraft, accelerated for all or parts of their trajectories by rocket motors, or they may be self-propelled. Most of the missiles in current use are not under the control of the user after launching. Some form of sighting device is necessary to establish the initial direction of travel in a manner to cause the missile to strike the target. Gunsights, bombsights, and complicated gun directors and computers are mere aids to determine where to point the gun or release the bomb, and after release of the missile no further control is possible.

For many years much thought has been given to the possibilities of guiding missiles after their release to correct for errors in sighting and for evasive action of moving targets. The development of radio communication stimulated inventive activity in this field and even during World War I there were experiments on radio-directed aircraft. There are innumerable patent applications relating not only to radio control but also to other aspects of guided missiles. Particularly attractive has been the idea of missiles which will seek out a target automatically or "home" on the target.

During the present war much serious scientific effort has been devoted to a full exploration of the practicability of guided missiles as useful weapons. The German experiments with Hs 293 and FX and later with V-1 and V-2 stimulated the interest of our military leaders and enlisted their support in the fullest exploitation of the possibilities of this type of weapon.

12.1.1 Classification of Missiles

From the standpoint of the source of control, there are five possible classes of missile. The first, illustrated by the German V-1 and V-2, uses an autopilot to hold the missile on a prescribed course. The missile receives no information relating to the target, and must be launched in the direction required to strike the target. This type is really a kind of long-range artillery, although the missile itself carries a part of the computer.

The second type, illustrated by the Japanese suicide bombers, carries a human pilot in the missile who is expended with the missile. This solution is known, involves no new technical problems, but is not attractive to a nation placing a high value on human life.

The third type, illustrated by the German Hs 293 and FX and the Division 5 NDRC Azon and Razon series, uses a remote human pilot who may (1) see the missile and target visually, aided by flares on the missile and by sighting devices, (2) be guided by television or radar information furnished him by apparatus contained in the missile, or (3) be guided by radar location of the missile in relation to map or radar location of the target.

The fourth type, of which there is no existing illustration, uses some type of beam directed toward the target which the missile automatically follows.

The fifth type is the target-seeking or homing type, illustrated by the Division 5 NDRC Pelican, Bat, and Felix. Such a missile must utilize some physical property of the military target which causes it to stand out from the background. The most commonly suggested property is the emission or reflection of electromagnetic radiation. Separate techniques are available for transforming three major divisions of the electromagnetic spectrum into directional information. Of the three—visible light, infrared, and radio—radio frequencies, for technical reasons, hold the most promise for useful weapons. Radio techniques as developed in radar are directly applicable. Visible light and infrared are useful for certain specific types of targets. Investigations in other suggested properties, such as the emission or reflection of sound, have not given promising results for aero-missiles.

12.1.2 Necessity for Technical Coordination

This chapter is concerned with various aspects of the design of this last type, the homing aero-missile.

The impression is prevalent that scientific advances in many fields have progressed to the point where the development of such a missile is purely a matter of engineering design on the part of the several specialist groups, with the usual coordination as to dimensional requirements, weights, and time of completion. Experience has taught otherwise. Optimistic time schedules based on such an assumption cannot be met. The development of successful homing aero-missiles requires the solution of certain research problems associated with the complete device, involving complex relationships between the performance characteristics of the component parts. There is required a type of overall technical coordination beyond that required in the design of aircraft as ordinarily practiced.

The necessary technical coordination is made difficult by the wide variety of specialists required, each with different scientific and technical backgrounds and accustomed to different vocabularies and habits of thought. For example, in the case of a propelled radar-homing missile there will be represented experts in aerodynamics, aircraft structures, propulsion, servomechanisms, electronics, radar, computers, explosives, and fuzes. Other types of missiles will require experts in radio, optics, infrared radiation, heat, etc. No one person can be expert in all these diverse fields, but the success of the project requires a project engineer who has sufficient knowledge of these fields to be able, with the help of advice from the specialists, to assume technical leadership in the solution of research problems associated with the system as a whole.

In the design of any homing missile, there soon emerges a number of problems which cut across the boundaries of the specialist groups. The particular design which seems best to one group of specialists creates difficult problems for other groups, and the requirements put forth by the several groups as optimum are often contradictory. For example, certain errors are introduced unless the intelligence device "looks" along the direction of motion, i.e., is accurately bore-sighted. The conventional airplane flies at an angle of attack which varies with the position of the elevator. If the aerodynamics specialist adopts a conventional aircraft design with elevator control, the intelligence device must be coupled to the elevator control in such a manner as to compensate for variations of angle of attack for all conditions of flight. However, the designer of the intelligence device might properly suggest that the aerodynamicist design a vehicle which does not change its attitude with application of the controls. It becomes a matter of research to determine which solution gives greater accuracy and hence how responsibility is to be allocated between the two specialists.

12.1.3 Purpose and Background

These broad aspects of the design of homing aero-missiles are treated in this chapter. An attempt has been made to make the discussion general in character and applicable to all such missiles, whether propelled or not. It should be stated, however, that the discussion arises from experience with the radar-homing missiles of the Pelican and Bat series, and this account undoubtedly reflects the solutions there adopted, as well as the problems peculiar to radar homing.

12.2 TARGET DISCRIMINATION AND TRACKING

12.2.1 Limitations of Mechanisms

In visual shooting or bombing, the target is identified by the pattern of optical radiation as perceived by the human eye and interpreted by the human brain. In radar fire control or bombing, the target is identified by the pattern of short-wave electromagnetic radiation exhibited on the screen of a cathode-ray tube as perceived by the human eye and interpreted by the human brain. During the flight of a homing aero-missile these radiation patterns must be made to operate control mechanisms, and the element of interpretation by a human brain is absent. This introduces many problems and severe limitations. A mechanism can perceive only a limited number of physical characteristics of the target pattern and can exercise no judgment in interpreting the received information except of the simplest kind—for example, smoothing over a certain time interval. At present no mechanism is known which will select a given target from an optical image of a complex visual pattern. In their present state of development homing missiles can utilize only simple target situations, the most favorable target situation being that of a small number of ships on a large body of water or, more generally, a few isolated discontinuities in a radiation pattern which is otherwise nearly uniform. From this point of view, aircraft also present favorable target situations.

12.2.2 Principles of Target Discrimination

Except in the case, which seldom occurs, of a single isolated discontinuity in the radiation pattern, the first main problem in designing any homing missile is to determine the method or methods to be used for target discrimination when several targets are present. In the simpler devices the missile homes on the biggest discontinuity within its field of view. In many homing missiles, means are provided to permit the initial selection of the target by a human operator who often has available information supplemental to that given to the control circuits of the missile. Means may also be provided within the missile to keep track of the initially selected target and to respond only to signals from that target. Even in the simpler missiles, the operator attempts to release the missile either with a single large discontinuity within the field or on such a path that a single target comes within the field, and he depends on the precision of the controls of the missile to keep the missile tracking this target.

In order to obtain information about the location of the target, a homing missile must be directionally sensitive. Usually the received intensity of radiation is greatest when the axis of the radiation-receiver is pointed directly at the target. Figure 1 shows a portion of the response curve of the receiving antenna of the radar receiver used in the Pelican project. The relative power is plotted in terms of decibels, a logarithmic unit, but the power ratios are also indicated. The width at $1/2$ power is 23 degrees, and the width at $1/10$ power is 43 degrees. In other words a target at a bearing $21\frac{1}{2}$ degrees from the antenna axis gives $1/10$ as much energy to the receiver as a target on the axis giving the same intensity of radiation.

The radiation pattern shown cannot be used directly because there is no discrimination between right and left or up and down. The usual practice is to scan the field of view, to commutate or phase the received signal intensity with the scanning, and compare right with left and up with down or perform comparisons in some other coordinate system. The on-course indication becomes then an equality of two signals, and a directional sense is provided. In Pelican, conical scanning is used, the antenna axis describing a cone with a half-vertex angle of 11 degrees. A commutator provides the phasing. If there were a variety of targets of equal intensity, every one within a cone of half-vertex angle of approximately 22 degrees would give signals of one-half maximum power or more. This represents one method of stating a figure for the field of view of the receiver, all targets being assumed to return signals of equal intensity.

In Pelican, the target is illuminated by a radar beam, and the directional characteristics of the transmitter antenna provide additional directional discrimination, which is not of interest in this discussion. In Bat, the missile carries the transmitter and the same antenna is used for transmission and reception. The field of view is accordingly smaller than for Pelican.

In other types of intelligence devices, much smaller fields of view are used, the width at $1/2$ power being 10 degrees or less. This is advantageous from the point of view of directional discrimination of targets. Limitation of the field of view is the first general method of securing target discrimination. However,

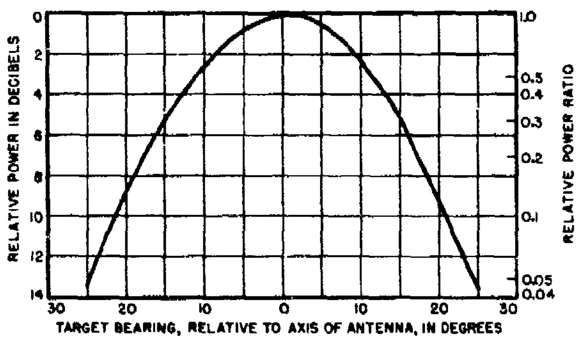


FIGURE 1. Directional sensitivity of antenna of Pelican radar receiver.

a narrow field of view introduces tracking problems, as will be discussed later.

The second method of securing target discrimination is by means of signal strength. This cannot be entirely separated from the directional properties of the intelligence system and permits little choice other than to home on the strongest signal. It is usually necessary to include some type of automatic gain control to obtain directional information at signal levels which may vary more than a billionfold as the missile approaches the target. The strongest signal within the field of view will govern the sensitivity of the receiver through the action of the automatic gain controller.

Target discrimination may also be secured through the selective action of the intelligence device in responding to radiation within narrow wavelength limits. This is best utilized when an intense beam of the desired radiation can be concentrated on the target and the missile made sensitive only to wavelengths within the narrow limits of the transmitted radiation.

In systems in which a pulsed illuminating beam is used, as exemplified particularly in the Pelican and Bat radar-homing systems, another method of target discrimination may be used. This is range selection and synchronization. By making the intelligence system sensitive only for a short period at a predetermined time following the emission of an illuminating pulse, the control information can be restricted to that received from targets lying within certain range limits, say within a zone of ± 250 ft of the actual target range. A given range corresponds to a definite time of transit of the pulse from transmitter to target to receiver. Naturally, such a range selector requires an automatic method of tracking the target in range as the range decreases. The operation of the range selector also requires the synchronization of the receiver and the transmitter. The synchronization is effective in discriminating against reflected radiation originating from other transmitters operating on the same radio frequency but with different pulse rates.

The use of range selection is found to be essential in radar-homing missiles launched from aircraft because of the so-called *altitude signal*, i.e., energy returned from the earth directly below the aircraft. If a reasonable cone of vision is to be maintained, the directional selectivity of the antenna is insufficient to discriminate against the large reflecting area lying beneath the aircraft. A range selector and range-tracking device makes possible the elimination of this signal in the case of glider missiles, since the altitude is always less than the range to the target. Presently available radar-homing devices cannot be used under conditions where the target may appear at the same range as the altitude signal—for example, in air-to-air missiles at ranges greater than the altitude. In the case of ground-to-air missiles using only a receiver, the geometry is more favorable than for the glider, and the range of the target will not coincide with that of the altitude signal. For a send-receive missile, the missile will at some time be at the same altitude as the range to the target and hence may thereafter home on the altitude signal.

It is possible to devise more complex mechanisms to perform more difficult feats of discrimination, for example, to permit the launching of a radar-homing missile at long range without advance selection of a target and to have the range-selection device search for, choose, and lock on a target when the missile has proceeded a definite distance. The limit of performance is set only by the permissible complexity of the mechanism.

The suggestion has often been made that lower animals be used as intelligence devices, since their brains, like human ones, can perform difficult tasks of discrimination. This possibility is perhaps the only one of adequate complexity to deal with the pattern discrimination required to select, for example, a particular building within the complex optical radiation pattern presented by a city. Proponents of this method point out that almost mechanical reliability may be realized in animals by establishing in them a conditioned reflex associated with the object selected for attention.

11.2.3 Relation between Field of View and Permissible Motion of Vehicle

After a target has been selected by the operator before release of the missile or by the mechanism of the missile itself, the target must be tracked, i.e., held within the field of view of the missile during the remainder of its flight. The simplest method of tracking is to have the intelligence control the motion of the missile so that the target remains within the field. If this method of tracking is selected, restrictions are immediately placed on the permissible motions of the vehicle, which must be considered by the aerodynamics specialist. These restrictions depend not only on the aerodynamics of the vehicle and the field of view of the intelligence device but also on target contrast, characteristics of tracking circuits, and behavior of the servomechanism in the absence of homing signals.

When a missile is to be released blind, the aerodynamics specialist can compute trajectories for various release conditions and so provide estimates of the time at which a target in a specific location relative to the point of release will lie within a specified field of view. The relation between field of view, servomechanism, and aerodynamical characteristics must be such that tracking will be preserved. The controls must be sufficiently effective to check any overshoot, or the servomechanism must have a memory to bring the vehicle and field of view of the intelligence device back on the target. For some types of vehicles, the aerodynamic design can be made such that the trajectory with no homing signal will include the desired target within the field of view. The larger the field of view, the easier the task.

Before release of the vehicle, the target must be brought into its field of view and tracking in range established. During launching and thereafter, the motion of the vehicle must be such as to maintain the target within the field of view of the intelligence device. Memory circuits within the intelligence head may allow the signal to fade out for short time intervals and resume tracking in range when the signal level is restored. If during the period of no signal return, the vehicle motion removes the target from the field of view, the intelligence device is unable to secure further information on target direction. The permissible motion will depend upon the intensity of the signal returned by the target. If the target signal is only a small amount of the background signal, the effective cone of vision is reduced (in present radar-homing equipment) to about 70 per cent of its maximum width. Thus a smaller change in attitude will be required to lose directional tracking than if the target signal is much larger than the background. Since the average signal level and its consistency in amplitude depends on target size, target orientation, and meteorological conditions, it is difficult to give definite design rules. However, the smaller the field of view, the smaller the change in attitude required to reduce a low signal to the background level, and from these considerations a large field of view is desirable.

The behavior of the servomechanism in the absence of the signal, or, more exactly, just following fading of the signal, has a definite bearing on the relation between field of view and permissible motions of the vehicle. If the servomechanism maintains the vehicle on the course it was flying, the field of view can be small without risk of losing the target outside this field should the signal fade for a few seconds. If, however, the servomechanism maintains the rates of turn and pitch which exist at the time of signal fading, the target would probably pass outside a small field of view before the signal returned. Either of these types of performance of a servomechanism is somewhat idealized and not accurately obtainable in any actual mechanism. The maintenance of the same course is of advantage when the vehicle is nearly on the desired course and loss of signal is due to fading.

When the vehicle is initially coming on course, it may overshoot by a sufficient amount to lose track. If this occurs, a servomechanism which maintains the course of the vehicle at the time the signal is lost will thereafter give no opportunity for again picking up the target signal. The amount of overshoot permissible will be larger, the larger the field of view and the greater the target contrast.

Some of the restrictions on the motion of the vehicle which are imposed by a narrow field of view can be removed by the use of an intelligence device fitted with automatic directional tracking. In this system the output of the intelligence device is used to drive servomotors to center the field of view on the target independent of the motion of the vehicle. The control of the vehicle itself is then derived from the relative position or rate of motion of the intelligence device with respect to the vehicle, or both. The minimum permissible field of view is then limited only by the precision and speed of response of the servomechanism. The extra degrees of freedom may give rise to more difficulty with the stability of the two servomechanisms—one driving the intelligence, the other the vehicle. There has, as yet, been no field experience with a missile control of this type.

12.2.4 Background Signal

All electronic intelligence devices have a certain internal noise level which cannot be less than that produced by thermal agitation of electrons in the input circuit. The magnitude of this internal noise sets a lower limit to the signal, which can be detected. However, in actual practice there is a much higher background signal, representing the signal return from areas other than that of the target which also lie within the field of view. Thus in a radar-homing device, the background signal is the reflected radar energy from the land, rough sea, or other obstructions that happen to be at the same range as the target. It may be very small or zero when the target is an airplane and the background is cloudless sky. In an optical homing device, the background signal is the reflected or emitted optical energy from land, sea, or sky.

The important attribute of this unwanted background energy is its variability, not only from place to place but also at the same place, especially with weather. Where radar is used against ship targets, the "sea return" depends very greatly on the height and shape of the waves and on the orientation of the wave troughs with respect to the receiver. The performance of a radar-homing missile against a specified target is affected very much by the condition of the sea surface, the permissible range at release being reduced as the sea becomes heavier because the signal returned by the ship is smaller and the amplitude of signal fluctuation is greater. Small targets, regardless of their range, may be lost in the sea return. Similarly, missiles using other parts of the electromagnetic spectrum encounter background signals which usually depend greatly on meteorological conditions.

The ratio of target to background signal may show large short-time variations during the flight of a single missile, and if the target contrast is not sufficient, tracking at long range may be difficult.

12.2.5 Fluctuation of Signal Intensity

As a homing missile approaches its target, the signal intensity and, usually, the background signals increase very greatly, making necessary an automatic gain control in the electronic equipment. The time constant of the gain control must be short enough to take care of the rapid change at the end of the flight but not so short as to obscure the variations of scanning frequency which give the directional information. The reliability of the information obtainable is dependent on the target contrast, which is a function of the strength of both the background signal and the target signal itself. In addition to the slower variation of signal strength as the missile approaches the target, there may also be more rapid variations associated with the changing geometrical relationship between missile and target produced by the motion of the missile and the linear and angular motions of the target. Such fluctuations are always found in radar reflections.

The presence of fluctuating signal intensity and fluctuating background signal means that the missile and servomechanism cannot be designed on the assumption that information as to the angular bearing of the target is continuously available.

The effects of fluctuating signal intensity which must be guarded against are possible resonance effects in the servomechanism, synchronization with the frequency of scanning, and loss of tracking. It is not practical to lay down methods of design. However, in the radar case the MIT field experiment group working on Pelican and Bat have found it advantageous to make photographic records of variations of signal strength of actual targets, to construct a special signal generator which emits variable signals controlled by a cam cut to the observed variations, and to test the effects of such a signal input on the intelligence device output.

12.3 MANEUVERABILITY OF VEHICLE AND OTHER AERODYNAMIC PROBLEMS

12.3.1 The Six Degrees of Freedom

The trajectory of a missile is determined by the force of gravity and the reactions between the missile and the air through which it flies. The force of gravity acts vertically downward through the center of gravity of the missile. It is convenient to represent the resultant of the aerodynamic reactions by three mutually perpendicular force components acting through the center of gravity and three moments acting about the three axes along which the force components are taken. These forces and moments on a given missile are functions of the shape of the missile, the orientation relative to the direction of motion of its center of gravity, the speed, the axis and amount of angular rotation, and the density and other physical properties of the air.

The missile has six degrees of freedom, three linear and three angular. The user of a missile is interested essentially in the three linear degrees of freedom, i.e., in the linear motion of the center of gravity of the missile. The angular motion of the missile is of interest only as it modifies the three force components and thus the trajectory. A spinning or angular hunting motion is of no interest if the missile strikes the target, a result dependent only on the path of the center of gravity. It is generally true for the ordinary bomb, propelled aircraft, or glider that an absence of angular motion gives a more predictable and constant trajectory. But in some other missiles (for example, shells), a spinning motion is deliberately provided to give a more stable and predictable trajectory.

The dynamics of a missile, even if restricted to airplane-like or bomb-like objects, is a very complex subject and hardly appropriate for this chapter. (Readers are referred to *Aerodynamic Theory*[1] for a discussion of airplane dynamics.) Only elementary and general aspects will be discussed here.

The path of the missile can be controlled in a number of ways, but the most usual method is through changes in the aerodynamic reactions by means of changes in the shape of the missile. Other methods may be advantageous in special cases. Thus, the use of rocket motors makes it possible to apply reaction forces on the missile to change its path. This method is effective in the stratosphere, where the air density is very small, and in free space. Control requires the ejection of a part of the missile, a process differing only in degree from the burning of fuel to produce the power that operates other types of control devices. Where other types of control are possible, it is usually more economical to use them.

A missile may be controlled by varying its mass distribution to modify the position of the center of gravity, thus changing the resultant moments of the air reaction—hence the orientation of the missile, which in turn modifies the force components. This was done in early airplanes by motion of the pilot but the method has been little used since that time.

It is possible to use power-driven devices, such as propellers or turbojets, or to use thermal jets to produce forces that modify the path, or to use such devices to apply moments to the missile that change its orientation and thus produce forces to modify the path. It is more common to use these devices as propulsion elements, and some control of the path, especially changes in the vertical plane, is accomplished by varying the propulsion force.

The most common method of control is through changes in shape of the missile which usually alter the moments of the air reaction and change the orientation of the missile in addition to modifying the force components directly. The use of a power-driven propeller may be regarded as a special case of a periodic change in shape. All changes of shape for purposes of control involve the application of power, which may be derived from any of the usual types of power sources. It is obviously desirable that the power required for control be small. This has led to the conventional type of control used on aircraft, in which the primary effect of the controls is to apply moments to the missile, which, in a time determined by the angular moments of inertia and the magnitude of the applied moments, changes the orientation of the missile to the direction of motion of its center of gravity. As a result of the change in orientation, the forces are changed and the path of the center of gravity is modified. It will be seen later that there are advantages, when designing homing aero-missiles, in selecting a change in shape which produces little or no change in moment but does produce directly changes in the force components. Such a method, however, requires greater power for operating the controls than the conventional method.

12.3.2 Equilibrium and Trim

An unpropelled missile can be in complete equilibrium only if the moments of the air reaction about three mutually perpendicular axes through its center of gravity total zero and if the resultant air force is equal to the weight of the missile and acts vertically upward. Such a state does not exclude the possibility of a spiral or spinning motion. In fact the tailspin of an aircraft is a steady motion in which the above conditions are fulfilled. Such motions, however, will not be considered further. Although there is no logical necessity of excluding spinning missiles, the guiding of such missiles would seem to introduce many technical complications.

The equilibrium of a propelled missile differs only in that the resultant aerodynamic force must equal the resultant of the weight and the propelling force.

Practically all missiles now used or under consideration have one or two planes of symmetry and a longitudinal axis which lies within 10 degrees of the intended direction of motion. The exact location of the longitudinal axis is usually chosen to suit the convenience of the specific problems but always in a plane of symmetry. The other mutually perpendicular reference axes are called the lateral and normal axes, and if the missile has only one plane of symmetry, this plane contains the longitudinal and normal axes. In the practical construction of aircraft or missiles it is found impossible to make the device sufficiently accurately to ensure that, when flown or released, the aerodynamic moments about the reference axes will be zero. It is always necessary to apply control moments of suitable magnitude about all three axes, or if it is desired to have the controls in a given neutral position with no force applied to the control levers, to provide adjustable trim tabs. These adjustments are easily made when a human pilot is on board, but other provisions must be made when unmanned missiles are to be used.

For unbalanced moments about the lateral and normal axes, a stable missile compensates by angular rotation to new positions of equilibrium, since displacements about these axes produce restoring moments. The missile would then fly at a somewhat different angle of attack than planned and at an angle of yaw which would give rise to a lateral force producing a lateral drift of the missile. An unbalanced moment about the longitudinal axis, which lies approximately in the direction of motion, cannot be compensated in this way, because rolling about the direction of motion produces no static restoring moment. The only methods known of compensating for this unavoidable and undesired moment arising from lack of symmetry in the actual unmanned missiles involve automatic trimming by control-surface displacements under the control of one or more gyroscopes. The most desirable method is to compensate for the undesired moment directly by displacement of the ailerons. In some cases, for example, the German robot bomb V-1, the autopilot moves the rudder, thus forcing the bomb to travel at an angle of yaw sufficient to produce a rolling moment due to yaw equal to the unbalanced rolling moment. This method of correction gives rise to a lateral drift, which is one source of error contributing to the dispersion. One of the results of the early work on the Pelican and Bat developments was the demonstration that provision must be made in the autopilot for compensating for undesired aerodynamic moments arising from lack of symmetry, i.e., "trimming" the missile, and that a gyro or equivalent reference is essential. It is fairly well known that pendulums or aerodynamic surfaces whose position is controlled by aerodynamic reactions are ineffective for this purpose. In the Azon and Razon developments it has also been found desirable to introduce automatic trim devices to eliminate rolling motions, although not there required for stability reasons, since these missiles have two planes of symmetry. The elimination of the rolling motion in those missiles simplifies the control problem, as will be discussed in the section on coupling between controls.

The state of complete equilibrium is rarely attained in the practical use of missiles. The linear motion of the center of gravity is an accelerated one, the mass times the acceleration being equal to and in the direction of the resultant force. The time required to reach equilibrium is often much greater than the time of flight of the missile. For example, a falling bomb is in complete equilibrium only when it reaches its terminal velocity, a process requiring fall from a great height and many tens of seconds. This long time constant arises from the limited rate at which energy is supplied from the gravitational field. In the case of an aircraft the slow phugoid oscillation arising from interchange of kinetic energy and potential energy has a period of approximately $0.22V$ seconds when V is the speed in ft per sec, i.e., the period is 88 seconds for a missile traveling at 400 ft per sec. The design of servomechanisms and intelligence devices cannot be based on the assumption of equilibrium conditions.

Fortunately the time constants of the angular motions are much shorter, usually of the order of a fraction of a second or at the most a few seconds, increasing somewhat with the size of missile but decreasing with its speed.

12.3.2 Magnitude of Lateral Forces, Angular Rates, and Radii of Curvature

Consider a symmetrical missile falling vertically with its longitudinal axis also vertical. The forces acting are the force of gravity and the air resistance. Because of symmetry there are no lateral forces. The downward acceleration will be equal to the difference between the acceleration of gravity and the ratio of the air resistance to the mass of the missile. The acceleration will ultimately approach zero as the missile approaches its terminal velocity, at which the air resistance equals the weight. At any point along its length the trajectory may be modified only by introducing a lateral force. This force imparts a lateral acceleration which causes the missile to travel in a path which is approximately circular for some time. To move the missile in a path of radius R requires a centripetal acceleration of V^2/R where V is the velocity of the missile. The rate of change of direction of the trajectory $d\theta/dt$ equals V/R.

The usual method of securing a lateral force is to change the orientation of the missile so that its axis makes an angle to the trajectory. The missile does not then travel in the direction of its axis. The change in its direction of motion is dependent on the magnitude of the lateral force produced by the change in orientation in relation to the mass of the missile. If the force is small or the mass is large, the trajectory will be modified very slowly, even though the axis of the missile is at a large angle to the direction of motion of the center of gravity. The missile behaves in the same manner as an automobile traveling on ice when the steering wheel is suddenly turned.

Experience from tests on bombs and airfoils shows that the lateral force produced at a given angle of the missile to its trajectory is approximately proportional to the square of the speed and to the projected lateral area. A reasonable value of the lateral force is about 10 psf on the fins or wings at a speed of 100 ft per sec and about ½ psf on a body of revolution at a speed of 100 ft per sec for angles of yaw of 15 degrees, although with larger angles of yaw still higher values can be obtained. Extremely large angles of yaw give large drag forces which slow up the missile and thus reduce the lateral force. The lateral acceleration to be expected is therefore about $(10A/W)(V/100)^2g$, where A is the area of the fins or wings in sq ft, V the speed in ft per sec, W the weight of the missile in lb, and g is the acceleration of gravity in ft per sec per sec. In any actual design, the lateral acceleration should be determined from wind tunnel measurements on a model of the missile. A radius of curvature R requires an acceleration V^2/R. Hence

$$\frac{V^2}{R} = \frac{0.0322AV^2}{W}$$

or

$$R = 31\frac{W}{A}$$

The rate of change of direction $d\theta/dt = AV/31W$.

For the standard 2,000-lb bomb, A for the standard fins is about 4 sq ft. With a suitable rudder, it may be expected that lateral forces of the above magnitude may be reached, in which case $R = 15{,}500$ ft and $d\theta/dt = V/15{,}500$ radians per sec $= 0.0037V$ degree per sec. In the next 500 ft of fall after the rudder is applied, the bomb would move laterally about 7½ ft.

It is to be noted that for this case of a vertical trajectory, the radius of curvature obtainable with a given fin area does not depend on the speed, since both the required and the available acceleration vary as the square of the speed. However the forces which the missile structure must withstand increase in proportion to V^2/R.

When the trajectory makes an angle to the vertical, the force of gravity has a component at right angles to the trajectory. It is customary to measure the angle from the horizontal and to denote its value by θ. The gravity component is then $g \cos \theta$. The path then curves downward unless a sufficiently large lateral aerodynamic force overcomes the gravitational component. Calling the lateral aerodynamic force L, we have the following equation for the radius of curvature of the path.

$$\frac{mV^2}{R} = mV\frac{d\theta}{dt} = mg \cos \theta - L$$

Consider first the case in which L is zero, i.e., a conventional bomb. We find $R = V^2/(g \cos \theta)$ and $d\theta/dt = (g \cos \theta)/V$. The maximum value of $d\theta/dt$ occurs when the axis of the bomb is horizontal and equals g/V radians per sec. At a speed of 320 ft per sec, $d\theta/dt = 0.1$ radian per sec $= 5.7$ degrees per sec, and $R = 3{,}200$ ft. As the speed increases, $d\theta/dt$ decreases and R increases.

Next assume that the trajectory of the missile is to be approximately a straight line to the target, as is usually desired for a homing missile. In this case the average value of L must equal $mg \cos \theta$. The available control then depends on the changes in L which can be effected by the controls, and the control is the same as for a vertical trajectory. However, the requirement $L = mg \cos \theta$ is the requirement for rectilinear flight, and the speed required is dependent again on the area of the fins or wings. The minimum speed for rectilinear flight, assuming the use of the maximum control, is given by

$$\left(\frac{V}{100}\right)^2 \frac{10.4g}{W} = g \cos \theta$$

or

$$\frac{V}{100} = \sqrt{\frac{W}{A}\frac{\cos \theta}{10}}$$

For the 2,000-lb bomb on a 45-degree trajectory, V is about 600 ft per sec.

At lower speeds than the minimum speed for rectilinear flight, the rate of change of direction is not as great, and the radius of turn is larger. Values for any particular case can be estimated. The control obtainable depends greatly on the ratio of the speed to the rectilinear flying speed, and the rectilinear flying speed is determined mainly by the area of fins or wings.

12.3.4 Nonlifting Missiles

From the aerodynamic point of view the properties of missiles in which the average value of the lateral force is zero are so different from those for which the average value is not zero that the two groups deserve separate treatment. Although an aircraft or glider could be trimmed to give zero lift, its general flight behavior would not be satisfactory, and the nonlifting missile usually takes the form of an elongated object with two or more planes of symmetry and in some cases a body of revolution. The simplest example is an ordinary bomb or rocket stabilized by tail fins. When the axis is inclined, there is a restoring moment because the line of action of the resultant force passes behind the center of gravity. To keep the axis at an angle to provide a lateral force, this moment must be balanced by a smaller force in the opposite direction applied by a rudder at the tail or a spoiler at the nose. The action of the rudder or spoiler must be such that the missile still has sufficient static and dynamic stability about the new position of equilibrium.

Missiles of this type are best adapted to steep trajectories for the following reasons. Launching speeds are usually limited to a few hundred feet per second.

Control against the deflecting action of gravity is effective only near the rectilinear flying speed. The minimum rectilinear flying speed is of the order of $100\sqrt{(W/A)(\cos\theta/10)}$. As the path approaches the vertical, $\cos\theta$ decreases, the minimum rectilinear flying speed decreases, and the control improves.

A decrease in W/A also decreases the rectilinear flying speed and hence improves the control at low speeds. This principle has been used in the Roc project, in which additional surface has been provided to give larger lateral forces for a given angle to the trajectory.

The control of a nonlifting missile in the horizontal plane is of course independent of gravity, and the general considerations discussed for a vertical trajectory apply.

When control moments are applied to missiles of the nonlifting type about two axes at right angles to each other, the resultant air reaction cannot be represented solely by a resultant force. There is also a resultant couple producing rotation about the longitudinal axis. In other words the missile has some of the characteristics of a screw propeller or windmill. It has usually been found desirable to provide ailerons controlled by gyro elements to keep the missile from rolling. Such a control is desirable to permit easy separation of right-left from up-down controls of the missile.

It is inferred from the successful use of the German V-2 rocket, which is a nonlifting missile, that the problems of controlling missiles of this type at supersonic speeds will not be too difficult.

12.3.5 Lifting Missiles

The nonlifting missile follows the normal type of approximately parabolic trajectory except when the controls are operated. The fins or wings ordinarily exert no lateral force. If, however, the vertical control is held deflected so that the longitudinal axis of the missile is maintained at an angle to the trajectory, the missile will ultimately reach equilibrium as a glider traveling at constant speed (the terminal speed for this orientation) in a straight path which is inclined at an angle to the vertical. If propelled, the path may be inclined upward. Even if the controls are maintained in the neutral position, the missile will finally approach an equilibrium state of unaccelerated fall vertically downward at its terminal speed. For an ordinary bomb or other missile of high wing loading the time required corresponds to a fall through a very great height.

The lifting missiles are intended to follow an approximately straight flight path, which for powered missiles may be horizontal or inclined upward. We shall consider first an unpowered missile, i.e., a glider.

The only forces acting on a glider in flight are the force of gravity and the resultant air force. It is customary to consider the resultant air force in terms of its components perpendicular and parallel to the direction of motion, the lift and the drag. In equilibrium gliding flight the resultant of lift L and drag D must balance the weight and hence must act in the vertical direction. The flight path is therefore inclined downwards at an angle θ such that $\tan\theta = D/L$. The resultant force R is usually expressed in terms of the dimensionless coefficient C_R defined by $R = C_R A \frac{1}{2}\rho V^2$, where A is the wing area, ρ the air density, and V the flight speed. Since at equilibrium the resultant equals the weight W, the equilibrium speed of the glider along its flight path is determined by the relation

$$V = \sqrt{\frac{W}{A}\,\frac{2}{\rho C_R}}$$

For an airplane the value of C_R increases from a small value at zero degrees or some small negative angle of attack, depending on the shape of the wing section, nearly linearly up to angles of the order of 12 to 15 degrees, reaches a maximum value of the order of 1.2 to 1.4, and then slowly decreases. The ratio of lift to drag reaches a rather sharp maximum value at some angle between 5 and 10 degrees and then decreases rapidly. The slowest equilibrium gliding speed corresponds to the maximum value of C_R near the stalling angle, and in this region of angle of attack the glide angle changes rather rapidly but with only small changes in equilibrium speed. As the angle is reduced, the glide angle becomes flatter, and the equilibrium speed increases. On passing the angle of maximum L/D the glide path again becomes steeper, and the equilibrium speed increases still more. The steepest path is the vertical dive, in which the equilibrium speed reaches its maximum value, the terminal speed at which the weight is balanced by the drag.

The preceding description applies solely to steady-state conditions, i.e., those which occur after the lapse of a sufficient interval of time. It is important to observe that an increase in angle of attack at angles beyond that of maximum L/D at first flattens the angle of glide or even causes a temporary ascent, and the steeper glide angle is obtained only after the lapse of sufficient time.

Let us suppose that while the airplane is gliding steadily at some angle of attack, the angle is suddenly changed to a new value. The lift at angles below the angle of attack for maximum L/D is changed much more than the drag, and the principal effect will be to produce an unbalanced force nearly perpendicular to the direction of motion, which will curve the flight path. Ultimately of course the unbalanced drag force will modify the speed but this process requires some time. Suppose the lift coefficient corresponding to the steady, straight flight at the instantaneous altitude and speed is C_{L° and the actual lift coefficient is C_L. The unbalanced force is then $(C_L - C_{L^\circ})A\frac{1}{2}\rho V^2$, and hence the lateral acceleration will be $[(C_L - C_{L^\circ})A\frac{1}{2}\rho V^2]/(W/g)$. The radius of curvature of the path will be $W/(C_L - C_{L^\circ})Ag\frac{1}{2}\rho$. This corresponds to the value $31W/A$ given earlier, if $C_L - C_{L^\circ}$ is taken as 0.84. For a given wing loading and air density, the radius of curvature of the flight path depends on the difference between the actual value of the lift coefficient and the value which would be necessary in steady flight.

The minimum radius is obviously obtained with $C_{L^\circ} = 0$ and C_L equal to the maximum lift coefficient, i.e., with a nonlifting missile. The use of a lifting missile increases the minimum radius of curvature and hence gives lower maneuverability.

For angles of attack beyond the angle of maximum L/D, the effect of the drag may predominate, and the speed may be reduced so rapidly that the lift force is not increased, although the lift *coefficient* is greater.

The foregoing discussion applies to control of the path of the missile in a vertical plane. The lifting missile usually has larger surfaces, i.e., wings for support and control in the vertical plane. For right-left steering the lifting missile is usually designed to use the airplane method, i.e., banking or rolling the missile to obtain a component of the force on the large wing surfaces in the desired direction. The turns which can be produced without banking are of very large radius. An airplane with dihedral angle will automatically bank if the rudder is turned and ailerons are not moved, and will turn to right or left if the airplane is rolled either by deflecting the ailerons or by turning the rudder.

Turns of a glider are descending spirals. If the inclination of the spiral flight path to the horizontal is θ and the radius of the spiral is r, the radius of curvature R of the flight path is $r/\cos\theta$. Call the angle of bank ϕ and the lift L. The available force is then $L\sin\phi$ and hence

$$L \sin \phi = \frac{W}{g}\frac{V^2}{R}$$

V being the flight speed, W the weight of the aircraft, and g the acceleration of gravity. Setting $L = C_L\frac{1}{2}\rho A V^2$ and solving for R

$$R = \frac{2}{\rho}\frac{W}{A}\frac{1}{C_L g \sin\phi}$$

The radius of turn can be decreased by increasing C_L as the glider is banked. This is the method commonly used in aircraft to make a tight turn. If C_L is zero, i.e., a nonlifting missile, banking does not give rise to a turn, R being infinite. If C_L is not zero, i.e., a lifting missile, banking gives rise to a turn even if C_L is not increased by action of the longitudinal control. This is one of the essential differences between the aerodynamic properties of lifting and nonlifting missiles. The right-left steering of lifting missiles by banking will be discussed further in Section 12.4.

It is quite possible to design a lifting missile which could turn without banking. A large vertical surface would be needed, and various practical difficulties would arise.

Nonlifting missiles will probably have less difficulty with compressibility effects at high speeds. The chief difficulty with the lifting missile arises from the fact that the missile is unsymmetrical about the plane of the wings, and the orientation is maintained by reactions on wings and tail whose moments about the center of gravity are equal and opposite. Compressibility effects first appear on the wings, usually producing diving moments and large changes in attitude. The nonlifting missile, on the other hand, is symmetrical, and both body and fin moments are zero, except when control is applied. Thus the trim position of the nonlifting missile is not likely to change with speed in the absence of control. The control will undoubtedly be modified by compressibility effects.

At the present time aerodynamic data at supersonic speeds are quite limited, consisting mainly of information on the drag of projectiles obtained in firing tests. Adequate supersonic facilities are now being provided, and within the next year or two a great deal of the necessary basic research should be completed.

12.3.6
Powered Missiles

The control of powered nonlifting missiles requires little further discussion. When no control is applied, the propulsive force acts in the direction of motion. Variation of the propulsive force changes the speed but not the direction of motion. When control is applied, the orientation may change, in which case the propulsive force has a component at right angles to the direction of motion of the center of gravity, increasing the lateral force available for control. This effect is usually not large.

In the case of powered lifting missiles, variation of the propulsive force constitutes a second and independent method of control in the vertical plane. Under equilibrium conditions the speed is approximately independent of the value of the propulsive force, satisfying the equation

$$V = \frac{2W \cos \theta}{A \rho C_L}$$

For horizontal flight the propulsive thrust T is equal to the drag D. If T is greater than D, the missile climbs at angle θ such that $T = D + W \sin \theta$. The angle θ may be negative, corresponding to descent if T is less than D. For a more complete discussion, reference should be made to one of the many books on the subject of airplane performance.

12.3.7
Homing Missiles

In homing missiles, the apparatus contained within the missile locates the target with reference to some axis fixed in the missile. The information so obtained is not adequate, unless this reference axis is always in a known relation to the flight path of the center of gravity of the missile. The simplest solution is obviously to make the reference axis coincide with the flight path, i.e., to have the intelligence device "look" along the flight path. The installation is especially simple if the application of control does not change the orientation of the missile with respect to its flight path. The securing of this result is one of the aerodynamic problems peculiar to homing missiles. The solution used in the Pelican and Bat projects was to change the lift of the wing by trailing edge flaps and so to locate the center of gravity of the missile and a fixed tail structure that the downwash effects on the tail produced moments counterbalancing the moments produced by the flap deflection. The Roc project adopted the same solution.

In the flight of an unpowered homing missile in still air against a stationary target, the flight path is approximately rectilinear. The initial speed is usually much less than the terminal speed in the straight glide path, and hence the speed increases. To maintain the rectilinear flight, the lift must be maintained constant and equal to $W \cos \theta$. As the speed increases, the lift coefficient must be decreased by the action of the controls.

It appears desirable to operate unpowered homing missiles within the range of lift coefficients lying between zero and that for maximum lift-drag ratio. As is well known, the equilibrium flight path first flattens and then steepens as the lift coefficient is increased. There is accordingly a reversal of control as regards the final effect when past the maximum lift-drag ratio. Missiles are not usually in equilibrium on their flight path, and computation shows that the first effect of control is always that of the change in lift. If, however, the lift-drag ratio at the maximum lift coefficient permitted by the controls corresponds to a slope of path steeper than the actual path slope to the target, the control proceeds to its limit and stays there. The intelligence calls for a higher lift. A higher lift coefficient is obtained as the control moves toward its limit, but a higher drag coefficient also results. The drag reduces the speed so that the actual lift does not increase very fast, and the flight path is corrected very slowly, if at all. It is probably desirable that powered homing missiles should also be operated in the region between zero and maximum lift-drag ratio.

If the homing missile is powered, various combinations of control are possible. For example, the propulsive thrust might be controlled by a speed-sensitive device to maintain a constant speed in the later stages of the flight.

12.3.8
Stability Problems

In theory a homing missile might receive sufficient control information to give stable flight without inherent stability of the missile in the absence of control. In practice, a missile must have satisfactory stability to maintain its flight in periods of intentional or unintentional absence of control information.

It is not practical to review the many aspects of the stability of missiles. The disturbed motions of a stable airplane-like missile in the absence of homing control consists of various combinations of a rapid, heavily damped, longitudinal motion (in which the angular pitching motion is most prominent), a slow oscillation (the previously mentioned phugoid oscillation, in which the missile rises and falls with the speed decreasing and increasing), a rapidly damped rolling and yawing oscillation, and a slow spiral motion.

Under certain conditions the missile may pass from steady rectilinear flight to a steady spin. In a true spin, as distinguished from the spiral motion referred to above, the wing surface is stalled, i.e., it meets the air at a large angle. The spinning motion is, however, a steady motion with the following balance of moments and forces:

1. The stalled wing rotates of itself at such a speed that the rolling moment is zero. (A wing at normal angles offers resistance to rolling; a stalled wing is in unstable equilibrium at zero rate of roll.)
2. The aerodynamic pitching moment that tends to reduce the angle of attack is balanced by the centrifugal pitching moment that tends to increase the angle of attack.
3. The aerodynamic yawing moment is balanced by the centrifugal yawing moment. The spinning characteristics are greatly affected by the angle of yaw at which this balance occurs.
4. The airplane descends at such a rate that the vertical component of the air force equals the weight.
5. The horizontal component of the air force gives the requisite centripetal acceleration of the center of gravity towards the spin axis.

A missile can be made difficult to spin by a suitable disposition of tail surfaces to give large aerodynamic pitching moments and a favorable antispin equilibrium angle of yaw.

When a homing device is applied to an airplane-like missile, the disturbed motions take on a somewhat different character. For example, if only the longitudinal stability is considered, the slow phugoid oscillation disappears and is replaced by a damping of any disturbance of the velocity along the flight path; the period and damping of the fast angular pitching oscillation are controlled in part by the static longitudinal stability of the missile and in part by the power of the control surface and the lag of the servomechanism; and there arises a second angular pitching oscillation of longer period, which may in some cases degenerate into two aperiodic motions. As the missile approaches the target, the frequencies and damping constants change somewhat, and an additional mode appears.

In a similar manner the slow spiral motion associated with the lateral stability of the free-flying missile disappears. There are short- and long-period, combined rolling and yawing oscillations, where damping may be positive, zero, or negative, and the long-period motion may degenerate into aperiodic motions.

Some aspects of the stability of homing missiles will be discussed briefly in Section 12.5.

12.4 COUPLING BETWEEN CONTROLS

12.4.1 Interdependence of Controls

A missile in flight has six degrees of freedom, but if it follows conventional aircraft design it has only three controls—unless it is propelled, in which case it has also a throttle or equivalent thrust control. The three controls are usually movable surfaces to control the moments about three mutually perpendicular axes, and there is no direct control of the linear motions. Unfortunately the three controls do not give independent effects. Thus the rudder produces a small rolling moment as well as a yawing moment which turns the aircraft to right or left. When the missile is yawed, a much larger indirect rolling moment results, arising from the aerodynamic reactions. The ailerons produce yawing moments as well as rolling moments, and the yawing moments may be either favorable or "adverse," i.e., the resultant yaw may produce a rolling moment in a direction opposite to the desired rolling moment. In extreme cases the ailerons may turn the aircraft to right or left without rolling it, or the rudder may roll the aircraft with little yaw. The effects may change sign for the same aircraft at different speeds, i.e., at different angles of attack or at different lift coefficients. The interaction between the rolling or yawing motion and the pitching motion is fortunately very small.

In the case of nonlifting missiles, operation of the left-right and up-down controls simultaneously produces rolling moments, and hence it has been found that a nonlifting missile must have ailerons if rolling motions are to be avoided.

12.4.2 Intelligence Coordinates and Controls

The intelligence devices generally available for use in homing aero-missiles give information on the bearing of the target to the right or left and up or down from some reference axis, i.e., an essentially two-dimensional presentation. In the case of radar devices, range information can also be obtained if desired. The missile, however, has three controls if unpropelled and at least four if propelled. There is evidently a problem in connecting the two-dimensional output of the intelligence device with the control system of the missile.

In the case of a nonlifting missile, the obvious method of connecting the controls is to connect the two channels of the intelligence device to two control surfaces producing moments about two mutually perpendicular lateral axes, which are aligned with the intelligence device. While the two control surfaces may be designed to give independent action about the lateral axes, the application of control about both axes simultaneously will produce rolling moments about the longitudinal axis. If the aerodynamic design were such that the longitudinal axis remained in the direction of motion, the roll would not be objectionable, unless the rate was so high that the lag in the control system introduced phase errors. However, most missiles of the zero lift type change orientation as the controls are applied. The roll takes place about the axis of the missile and introduces incorrect error signals in the intelligence device. A better solution is to stabilize the missile in roll by means of ailerons controlled from a suitable gyro system. Thus in the simplest method, the roll control is governed by a gyro, and the other two by the channels of the intelligence device.

There have been many ingenious suggestions for connecting the controls of a nonlifting missile to permit continuous rotation of the missile. It does not seem profitable to discuss them here. For remotely controlled as distinguished from homing missiles, such devices become computers, often of complex design, for transforming from fixed to rotating axes, and metering the degree of control to be given by each of the two control surfaces.

In the case of a lifting missile of the airplane type, turns are accomplished by banking the airplane, and it is therefore not desired to prevent roll. It is necessary either to reduce the number of control surfaces from three to two, or to couple two of the control surfaces together to be controlled from a single intelligence channel. If the missile is powered, the throttle or equivalent power plant control may be arranged to be controlled by airspeed, altitude, or some quantity associated with engine performance as for example, mixture ratio, peak pressure, temperature, etc. Combinations may be used but it has not been customary to use the throttle for up-down control of the flight path.

The more common two-control airplanes use the elevator-rudder or the elevator-aileron combinations. Both methods have been used in the design of missiles. With proper design reasonably satisfactory turns can be made either with ailerons or with rudder. For homing missiles, aileron control is believed to give somewhat smaller errors, since out-of-trim rolling moments can be balanced without introducing yaw. In either case, the use of two controls alone makes possible independent connections of the two intelligence channels.

It has already been pointed out that a gyro is required for trimming the missile in roll. It is desirable that this gyro also limit the maximum angle of roll; otherwise the missile is likely to turn over on its back when a control signal is continued for some time.

In automatic pilots for aircraft, the rudder and aileron are often controlled together for turns. Such a coordination is possible for one flight condition or, at most, a narrow range of conditions. For missiles intended to operate over a considerable speed range, the rudder displacement for a given aileron displacement varies both with airspeed and angle of attack, and it has not seemed necessary to attempt the design of the necessarily complicated control. By suitable aerodynamic design of a two-control missile, the sideslip during turns can be made reasonably small.

12.4.3 Effect of Roll on Error Signals

The lifting missile of the airplane type banks during a turn. The reference axes of the intelligence device are fixed with reference to the missile and hence rotate with the missile. The axis of rotation of the missile does not usually coincide with the direction of motion of the center of gravity of the missile. Hence the intelligence device no longer measures the up-down and right-left errors with respect to axes fixed with respect to the vertical.

It has been previously pointed out that an airplane is made to turn in its tightest circle by banking and then pulling back on the stick to increase the lift coefficient to its maximum value. The coupling between the up-down and right-left controls produced by banking automatically gives an error signal to the elevator or elevons in a direction to increase the lift coefficient and thus accelerates the turn. At the same time the increased lift bends the trajectory of the center of gravity upward. The exact behavior of the system depends on the characteristics of the intelligence device, servomechanism, and missile.

The error angles are readily computed for idealized motions. If the missile rotates about the direction of motion of the center of gravity, the effects amount simply to rotation of the axes of reference of the error signals. If the error angles referred to the original axes are δ_e in elevation and δ_a in azimuth, and if referred to axes rotated through an angle ϕ they are δ_e' and δ_a', the relations are

$$\delta_a' = \delta_a \cos\phi - \delta_e \sin\phi$$
$$\delta_e' = \delta_a \sin\phi + \delta_e \cos\phi$$

If, however, the rotation occurs about an axis making an angle δ_{e_0} with the direction of motion of the center of gravity

$$\delta_a' = \delta_a \cos\phi - (\delta_e - \delta_{e_0}) \sin\phi$$
$$\delta_e' = \delta_a \sin\phi + (\delta_e - \delta_{e_0}) \cos\phi$$

In the general case the dynamics of a rigid body with six degrees of freedom and the aerodynamic characteristics of the control must be considered. Thus the axis of torque varies with the displacement of the control surfaces. The body rotates not about the axis of torque, unless this axis is also a principal axis of inertia, but about an axis intermediate between the axis of torque and a principal axis. Thus the instantaneous axis of rotation travels in the body, and an integration process is necessary. Because of these complications it is not very practical to correct for these effects by inserting a computing device between the intelligence and the controls. One of the important consequences of the foregoing effects is that when there is an elevation error angle and the true azimuth angle is zero, an azimuth error is passed on to the controls equal to $-(\delta_e - \delta_{e_0}) \sin\phi$. To illustrate, suppose that the target is high, so that $\delta_e - \delta_{e_0}$ is positive, and that the airplane rolls as for a right turn (positive ϕ). A negative azimuth error is then given to the controls, which tends to oppose the right turn. If, however, $\delta_e - \delta_{e_0}$ were negative, i.e., true elevation error is zero but axis of roll above flight path or target is low, the azimuth error given to the controls would assist the turn. In the first case there would be a damping effect on oscillations; in the second, a destabilizing effect which would promote hunting. In the usual lifting missile the effect is on the average a destabilizing one.

12.4.4 Effect of Angle of Attack or Yaw on Error Signals

In the nonlifting missile, the application of controls pitches or yaws the longitudinal axis so that the intelligence no longer looks along the flight path. Using the same notation as before, the effect is given by the relation

$$\delta_e' = \delta_e - \delta_{e_0}$$

The same relation applies to the elevation control of a lifting missile. It is in theory possible to interconnect the controls with the intelligence device to move the reference axes of the intelligence device to compensate for this effect. If it is undercompensated there will be a stabilizing action against oscillations; if it is overcompensated a destabilizing action.

12.4.5 Methods of Reducing Coupling between Controls

The methods of reducing both the interdependence of the controls and the undesired effects of the angular motions on the error signals are still in the early development stages, and much additional aerodynamic research is required. A homing missile can be made to work with all these effects present in some degree. It would seem fruitful, however, to attempt to make the normal flight path coincide with the longitudinal principal axis of inertia for all control positions, and to do further research on reducing interactions between controls.

12.5 SYSTEM STABILITY OR HUNTING PROBLEMS

12.5.1 Illustration of Hunting

Perhaps the most difficult of the special problems associated with the design of homing missiles is that of securing a satisfactory stability of the complete system, since the overall stability depends on the characteristics of the missile, intelligence, and servomechanism and especially on their interrelations. To illustrate the problem there are shown in Figures 2, 3, and 4 the observed motions of three homing missiles. In Figure 2 it is seen that the missile rolls and yaws in increasing oscillations of about a 10-second period until the missile strikes the ground. In extreme cases, such a missile may turn completely over on its back, lose track of the target and descend in a steep

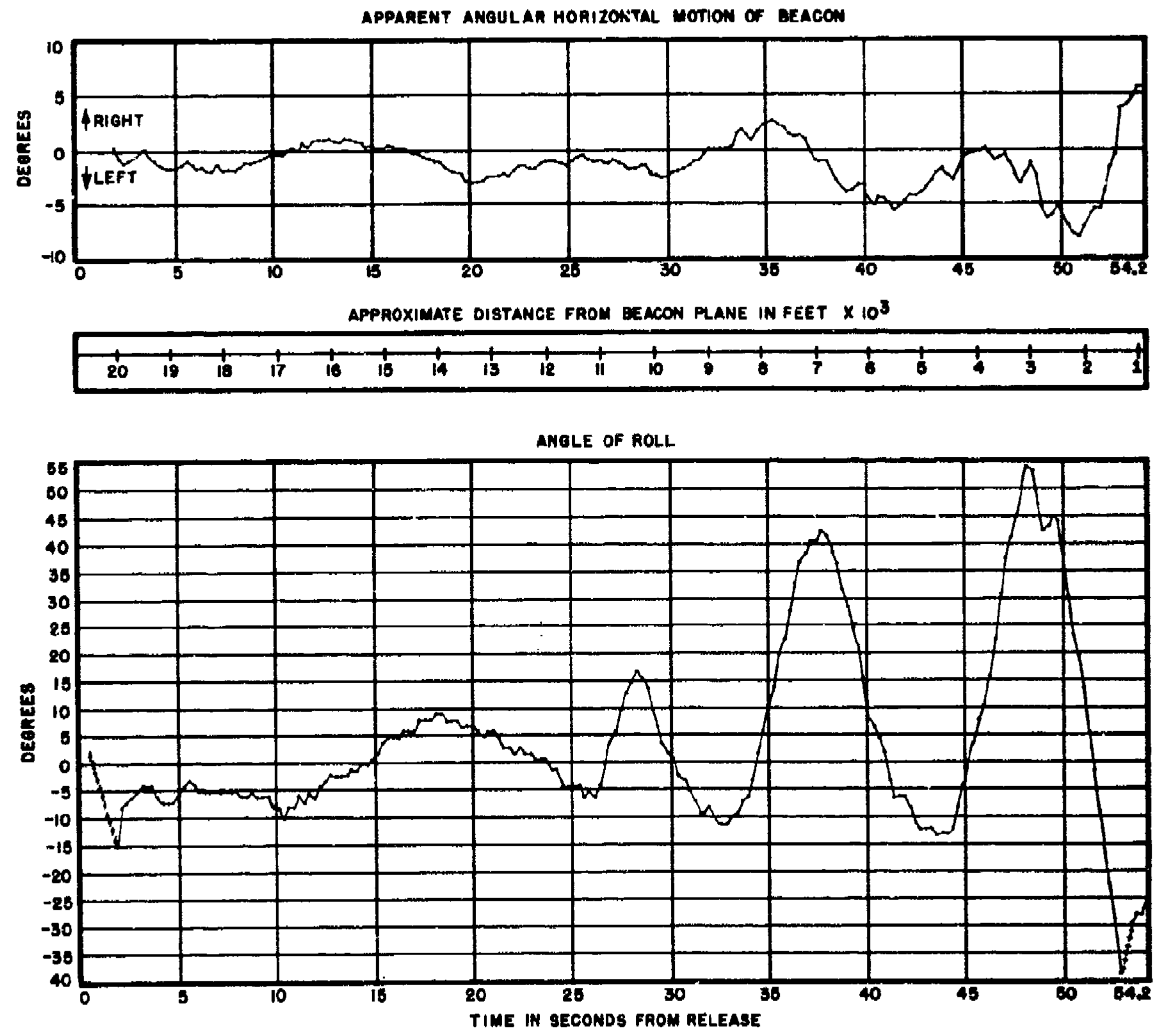


FIGURE 2. Unstable oscillation of homing missile.

spiral. In Figure 3, the missile pitches in a steady oscillation of nearly constant amplitude and a period from 5 to 7 seconds. Figure 4 shows a rolling and yawing oscillation which is damped as the flight progresses. The period of the main oscillation is approximately 10 seconds but there is superposed a rapid roll oscillation of about 4 degrees amplitude and 1¼-second period.

The steady hunting motions illustrated in Figures 3 and 4 are objectionable only as they affect the path of the center of gravity of the missile. The unstable motion of Figure 2 usually, but not always, results in complete failure of the missile and a wide miss.

The effect of a given hunting motion on the trajectory may be estimated as follows. The error angle is equal to the ratio of the velocity dy/dt of the missile transverse to the flight path to the velocity V of the missile, provided the missile looks along its flight path. If this angle oscillates sinusoidally with maximum amplitude θ_0, the motion may be represented by

$$\frac{dy}{dt} = V\theta_0 \cos \frac{2\pi t}{T}$$

where T is the period. The lateral displacement y is then given by the formula

$$y = y_0 + \frac{V\theta_0 T}{2\pi} \sin \frac{2\pi t}{T}$$

where y_0 is the mean value of y. The maximum excursion from the trajectory is then $V\theta_0 T/2\pi$. For

$V = 400$ ft per sec, $\theta_0 = 3$ degrees $= 1/20$ radian, and $T = 2\pi$ seconds, the flight path oscillates approximately 20 ft. On the other hand, if $T = 1$ second, the flight path oscillation is only 3 ft.

These simple computations underestimate the error since the actual missile does not look accurately along the flight path under dynamic conditions. This effect is, however, greatest for the short-period oscillations where the errors are small.

12.5.2 Factors Leading to Instability

The presence of error signals from a homing device would seem at first sight to remove most of the sources of instability and to supplement the aerodynamic damping forces which are present in any normal design. The element which introduces difficulty is the unavoidable lag between the presence of an error angle and the application of the corrective

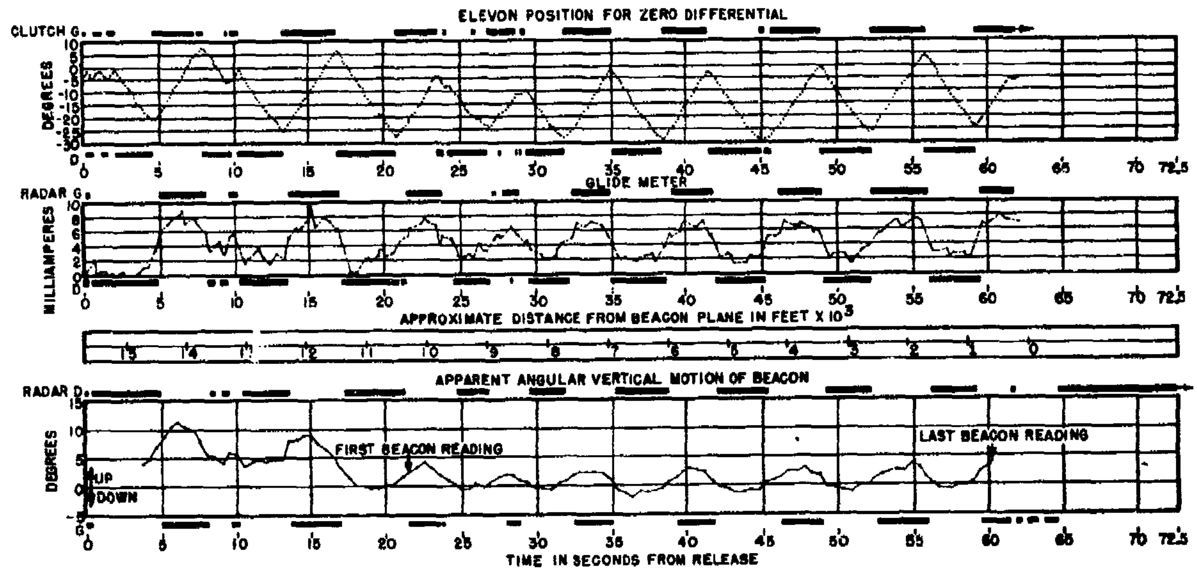


FIGURE 3. Undamped oscillation of homing missile.

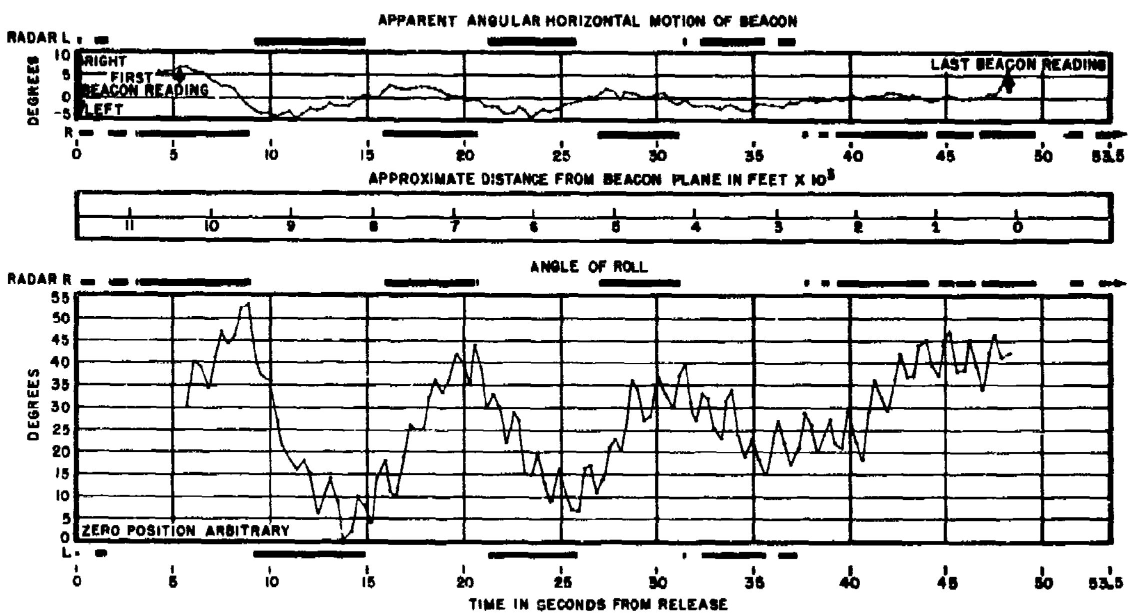


FIGURE 4. Damped oscillation of homing missile.

forces and moments to the missile. The lag may arise in the mechanical and electrical parts of the intelligence device, control system, or servomotor, or it may be introduced by the motion of the missile responding to the controls in such a manner as to introduce errors in the measurement of the error angle by the intelligence device.

The physical effect of the lag in producing hunting may be appreciated by considering the missile displaced from the correct flight path toward the target but being returned to it by the action of the controls. As the error angle approaches zero, the control surface deflection is approaching zero and should reach zero at the same instant as the flight path intersects the target. If the control is of the on-off type, reversal should occur at the instant the flight path intersects the target. If this could be effected, the aerodynamic damping forces would absorb some of the kinetic energy present, and the next crossings would be made with successively decreasing speed until the missile reached equilibrium on a steady trajectory. Because of the inevitable lag present, the control surface remains deflected in a direction to increase the error angle of the missile for a short time and thus feeds energy into the oscillatory motion. Equilibrium is reached at an amplitude of oscillation such that the amount of energy fed in is equal to that absorbed by the aerodynamic damping. It is possible that the energy fed in does not equal the energy absorbed for any amplitude, in which case the oscillation builds up until the missile capsizes.

The amount of energy fed in is directly proportional to the time lag, and to the overall sensitivity, i.e., to the magnitude of the correcting forces and moments produced by a given error angle. This overall sensitivity is dependent on such factors as the area of the control surfaces, the speed, altitude, and attitude of the missile, the deflection or rate of deflection of the control surface for a given electrical input to the servomechanism, and the sensitivity of the intelligence device.

The aerodynamic damping is a function of altitude and airspeed as well as of relative areas of various parts of the missile and of the amplitude of oscillation.

The time lag in the intelligence device is usually determined by the amount of integration or smoothing found desirable to give a reasonably steady output signal from the intelligence device. For the radar-homing systems used so far, the time lag has been within the range from 0.05 to 0.25 second.

The time lag of the usual electromechanical servo system is of the order of 0.10 to 0.15 second, but considerably smaller values can be obtained by special design.

Either a time lag or a time advance may be introduced by the relations between the motions of the missile, the axis of the intelligence device, and the direction of motion of the center of gravity of the missile, as discussed in Section 12.4.3. In the usual design, the axis of roll lies between the longitudinal axis of the missile and the direction of motion of its center of gravity, and a time lag is introduced. For example, if a disturbance rolls the missile for a right turn, a false azimuth error is indicated in a direction to aid the turn and amplify the effect of the disturbance. From the point of view of lag, if the missile is off course to the left and is being corrected to the right, the centering or reversal of control is delayed until the missile moves off course to the right a sufficient amount to bring the rotated reference axis on the target.

The use of automatic lead computers to reduce errors associated with wind and moving targets often leads to a difficult stability problem, as discussed later in this chapter.

12.5.2 Antihunt Devices

Since hunting indicates a phase lag between the error angle and the application of corrective forces and moments, the remedy is obviously the introduction by some means of a phase advance which is greater than the lag. As the missile comes on course, the control must be reduced or removed *before* the error is actually zero. The most common method of accomplishing this result is to incorporate a rate term in the control, i.e., to make the position or speed of the control dependent in part on the error and in part on the rate of change of the error.

A compensating or antihunt circuit can often be introduced in the amplifier or output circuit of the intelligence device itself. It usually takes the form of a suitable condenser-resistance network which may be considered either as a phase-advancing device for sinusoidal signals or as introducing a rate component for arbitrary signal variation. Difficulties often arise with such a circuit if the input signals are "rough" (fluctuating in magnitude for a given error angle), as, for example, is the case for radar reflections from many types of targets. Because of the antihunt circuit, the higher frequency "roughness" is amplified much more than the slower variation as the missile comes on course. A further characteristic of this anti-hunt circuit is that good performance is obtained only with considerable attenuation of the input signal, so that additional amplification is required.

The rate term may be introduced by a gyroscopic turn indicator which measures the angular rate at which the missile comes on course. This method has been found completely effective in obtaining system stability. It has the disadvantage that winds or moving targets require a steady rate of turn, which introduces a control signal. The presence of this signal, in effect, limits the maximum rate of turn and thus increases the errors associated with winds and moving targets.

12.5.4 Time to Come on Course

One of the important characteristics of the control system is the time required for a missile released with an initial error angle to come on its proper course. The time can be controlled to some extent by the overall sensitivity of the control system. It has already been pointed out that increasing the overall sensitivity increases the amount of energy fed into the system when a time lag is present. Even if the system is stable, the missile may come on course with a damped oscillatory motion, and the damping is small if the sensitivity is too great. A return without oscillation can be secured with suitable values of the control parameters. Both experience and theory show that it is necessary to make a compromise between the stability characteristics and the time to come on course. In most cases it is necessary to make the time to come on course about 10 seconds or more.

12.5.5 Effect of Wind Gusts

Wind gusts introduce disturbances which excite the natural modes of motion of the complete system. The effects persist for times which depend on the periods or time constants of the natural modes, and the disturbed motion at any instant depends on the history of disturbances over comparable past periods of time. Exclusive of the effects of changes in speed along the trajectory for which the time constant is very large but which in themselves do not cause the missile to miss the target, there usually exist modes for which the time constant is of the order of 10 seconds. Hence gusts in the latter part of the flight path introduce errors which cannot be wholly corrected in the time available.

Experience has shown decreased dispersion in tests of homing missiles over water as compared with tests over land, an effect which is probably to be attributed to the decreased gustiness over water. In one instance over land, a severe disturbance was noted from the sharp boundary between a heated layer of air at the ground and a cold air mass aloft. While the designer of a missile can vary the frequencies of the natural modes of motion through small limits, it is practically impossible to change their order of magnitude. Fortunately the errors in the trajectory decrease as the rectilinear flight speed increases.

12.5.6 Methods of Analysis

The problem of the design of stable systems has been approached by several methods of mathematical analysis and by experiments on mechanical, electromechanical, or electrical models. If sufficient information is available from tests of the component parts, the choice of control parameters to assure system stability can be made by any of these methods of analysis. The purely mathematical methods require more or less idealized representation of the performance of the component parts of the system and are most useful for systems whose performance is described by linear differential equations. The various methods using models have the advantage that some of the actual components can be incorporated as part of the model, so that nonlinear control mechanisms and on-off or step controls whose mathematical analysis is often difficult can readily be investigated.

The control system of a homing missile constitutes a closed-cycle control system or servomechanism. The chief difference from ordinary servomechanisms is that the parameters of the system are not constant but vary through considerable limits during the flight of a single missile. More specifically, the parameters associated with aerodynamic forces and moments are functions of the airspeed, air density, and attitude of the missile and its control surfaces. If these variations are taken into account, the usual methods of analysis of servomechanisms may be applied. These involve a study of the response of the system to certain standardized conditions, the two most useful conditions translated in terms of a homing missile being a sinusoidal displacement of the target at various frequencies or a sudden permanent displacement of the target. If the system is a linear one, its performance is completely known when the performance under either of the above conditions is known.

Readers who are interested in the details of the mathematical procedures are referred to reference 2. This paper describes the application of the sinusoidal analysis to the design of linear servomechanisms with continuous control. An example of analysis using suddenly applied disturbances may be found in reference 3. The same laboratory has developed this method of studying the control of certain types of missiles.

The preceding methods of analysis lend themselves to a complete study of the performance of the system, including not only the question of whether the system is stable or not but all questions of the magnitude of the errors. For determination of stability, one may apply the method of small oscillations commonly used in airplane stability problems. This method as applied to an airplane without automatic pilot is described in great detail in reference 1a. The method, in effect, determines the period and damping of the natural modes of oscillation and the damping of the natural aperiodic motions. If the damping constant turns out to be negative, the corresponding mode is unstable.

The mathematical methods are in practice limited to systems described by linear differential equations and find some difficulty in the treatment of actual servo systems with friction, "dead" regions, and time lag. For this reason models have been found useful. These range in complexity from systems representing a single degree of freedom of the missile to more complete flight tables, which include the three angular components of the motion or the "phantasmagoria" which simulate one or two components of the linear

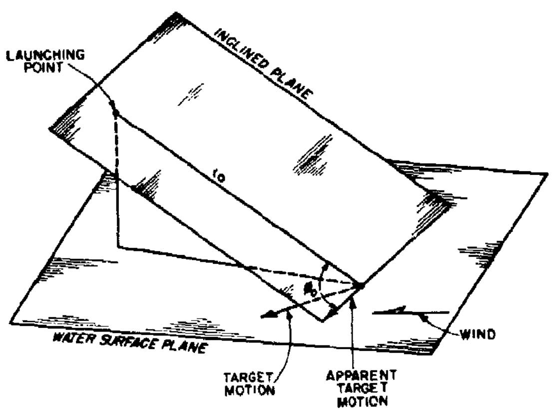


FIGURE 5. Diagram of launching variables determining pursuit curve errors.

motion. As an example, methods of automatic roll stabilization may be investigated with the actual gyro and servo elements by using a mechanical system (damped pendulum or damped rotor) to simulate the inertia and damping of the missile about its roll axis. A system of this type and a more complicated electromechanical model of the longitudinal motion were used in the study of the Pelican and Bat control systems. In addition, the Servomechanisms Laboratory, Massachusetts Institute of Technology, developed a flight table in which the pitching, yawing, and rolling motions of the missile with proper cross coupling were fully simulated and on which an overall test could be made of the complete control system including the intelligence unit, gyroscopes, and servomechanism. This flight table was extremely useful in determining the best adjustments of the several parameters of the control system.

Comparison of these models with actual flights of homing missiles shows that they reproduce the angular motions encountered in flight extremely well. Designers of homing missiles will find that the use of this method of studying system stability and overall performance will save much time in the development of a stable system and in adjusting it for best performance.

12.6 PROBLEMS ARISING FROM WIND AND MOVING TARGETS

12.6.1 Pursuit Curves

If the target is moving or there is a natural wind, a flying missile which always heads toward the target follows a path known as a pursuit curve or homing curve, depending on whether the motion is referred to the air or to the ground. The radius of curvature of the pursuit curve becomes very small as the target is approached and becomes infinitely small for the idealized case of a point target. The maneuverability of the missile is limited, and hence the missile will not hit a moving point target or a stationary target in a cross wind. The magnitude of the miss depends on the speeds of the missile, wind, and target, on their relative directions, on the range, and on the maneuverability of the missile as expressed by its minimum radius of curvature.

This problem in idealized form has been studied by the Statistical Research Group, Division of War Research, Columbia University, under the direction of the Applied Mathematics Panel. For convenience, the effect of wind and target motion are combined to give an apparent target motion of speed v. (See Figure 5.) The azimuth ϕ_0 of the launching position referred to the direction of apparent motion of the target, the launching radius r_0, the ratio n of the apparent target speed v, (the resultant of wind effect and target motion) to the speed of the missile V, and the minimum turning radius ρ_m of the missile are the quantities determining the miss for the case of the point target. Constant velocities of target and missile, direction of launching toward the target, and missile continuing along an osculating circle when the minimum radius of curvature is reached are assumed.

The computed miss M is shown in Figure 6 in the form of a plot of M/ρ_m vs ϕ_0 for $n = 0.1, 0.2, 0.3$, and 0.4 and $r_0 = 6\rho_m$, $10\rho_m$, and $14\rho_m$. The essential points to notice are: (1) that the maximum miss varies but little with launching radius; (2) that the maximum miss is approximately equal to $\frac{1}{2}\rho_m n^2$; and (3) that

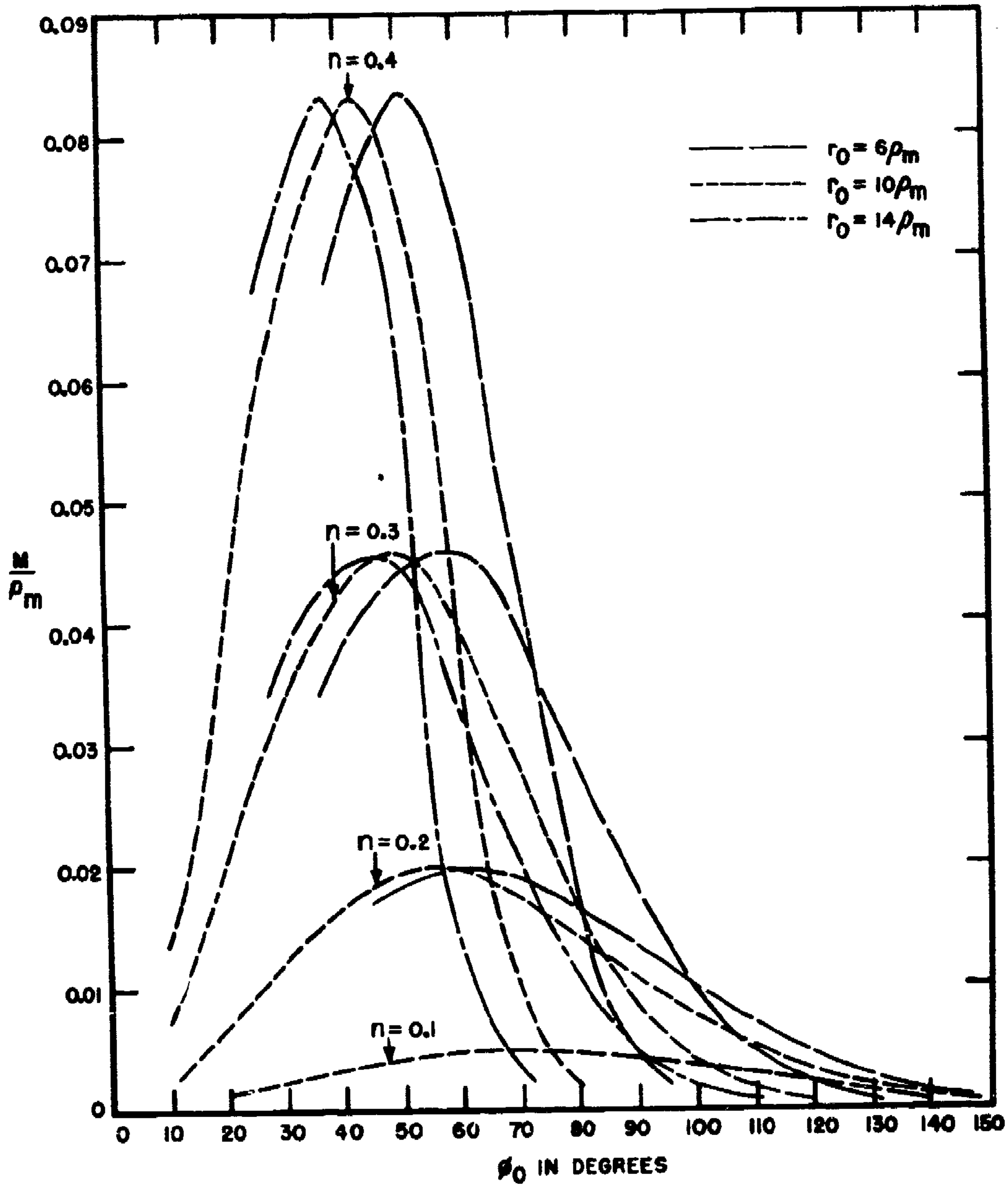


FIGURE 6. Pursuit curve errors due to effects of wind, target motion, and limited maneuverability of missile.

the miss becomes very small for ϕ_0 between 140 and 180 degrees. The only factors within the control of the designer of the missile are the speed of the missile and its minimum turning radius. The speed ratio should be as small as possible and the minimum turning radius as small as possible to minimize pursuit-curve errors. The user of the missile may reduce the error by making his attack on a course such that ϕ_0 is approximately 145 degrees. In the case of ship targets this course gives a good compromise between the magnitude of the error and the projected length of the ship, which determines the permissible error that still yields a hit.

12.6.2 Computers

The essential feature of the pursuit curve is that the missile moves along a path which makes an angle $\tan^{-1}(n \sin \phi_0)/(1 + n \cos \phi_0)$ with the line joining the missile and target. If the axis of the intelligence device were rotated with respect to the longitudinal axis of the missile by this amount in the opposite direction to the apparent target motion, the path with respect to axes fixed in the target would be straight, and the missile would travel on a collision course. If the user of the missile has the necessary data to compute n and ϕ_0 and the means of offsetting the axis of the intelligence device by the computed amount, and if the variations of n and ϕ_0 may be neglected, the pursuit-curve error may be eliminated.

It is, in theory, possible to design a computer which automatically offsets the axis of the intelligence device by the required amount. The simplest scheme, in theory, is to equip the intelligence device with a separate servo system which always keeps the axis of the device centered on the target. If the missile flies a collision course, the bearing of the target will remain constant; hence the angular velocity of the intelligence device will be zero. If the controls are so arranged that the missile is guided to make the angular velocity zero, the course followed should be the desired collision course. In practice, a high precision is required, since the rate of change of bearing for a small offset is very small at long ranges. Furthermore, the missile is subject to numerous disturbances of attitude, and it appears that an accurate, linear-integrating, angular-velocity meter would be required. It is not known whether the scheme would work or not; it has not yet been tried on a missile.

Another possibility which amounts to integrating the angular velocity is to determine the angular displacement of the axis of the missile after a certain time or distance by means of a free gyro which maintains a fixed direction in space. A knowledge of the angular displacement and the range at the beginning and end of the displacement permits a computation of the desired offset. This computation also assumes a constant value of n throughout the flight.

Still another possibility is a continuously integrating angular-velocity meter which continuously sets in the appropriate offset.

Study shows that the roughest sort of correction reduces the pursuit-curve errors, even though a true collision course is not obtained. Hence it is worth while to experiment with the simplest conceivable computers—for example, those dependent merely on the relative frequency and length of error signals in the two opposite directions.

The chief bar to the general use of computers lies in their effect on system stability; in fact, the automatic devices described cannot be used because they produce excessive hunting. The computer essentially puts in a lead on a moving target. If the missile, as a result of a disturbance, rotates to increase the lead, the angular velocity developed acts to increase the lead still further and thus builds up an oscillation of increasing amplitude. The computer cannot distinguish between angular velocity arising from disturbances and angular velocity caused by the missile following a pursuit curve. Consequently an automatic lead computer is an inherently destabilizing device.

The two methods of solving the stability problem are: (1) to feed in only a fraction of the correct lead angle, or (2) to introduce a time constant in the integration process which is long compared to the natural period of oscillation of the homing missile. In the first case, the permissible fraction is dependent on the stability reserve of the complete system of the intelligence device, servo control, and missile. In the second case, the time constant must be of the order of at least 20 or 30 seconds for missiles exhibiting natural periods of the order of 1 to 8 seconds.

The computer problem is susceptible of mathematical analysis for any specific missile and control system, and it is not too difficult if all elements of the system are linear. Actual experience with computers on a homing missile is not yet available.

12.7 BORE-SIGHT ERRORS

If the axis of the intelligence device does not coincide with the direction of motion of the center of gravity of the missile, there arises an error which may be termed the bore-sight error. Let us confine our attention to the case where the intelligence device is not equipped with a computer or other means of introducing an offset angle, i.e., the axis is fixed with respect to the missile. The missile then flies at a fixed angle to the line joining the missile and the target and hence follows a logarithmic spiral whose equation in polar coordinates is $\rho = \rho_0 e^{-(\theta-\theta_0)/\tan\epsilon}$, where ρ_0 and θ_0 are the coordinates of the release point and ϵ is the bore-sight error. As the missile approaches the target, the radius of curvature decreases and finally becomes equal to and would be less than that which the missile can follow. The radius of curvature of the path is equal to $\rho/\tan\epsilon$ or, if ϵ is small, to ρ/ϵ. Thus if ρ_m is the minimum radius of turn of the missile, this value is reached at a value of r equal to $\rho_m\epsilon$. This value of the range to the target at which the radius of turn becomes ρ_m will be designated R_m. If it is assumed that the missile continues to travel in a circular path of radius ρ_m, the miss is readily computed to be $\frac{1}{2}\rho_m\epsilon^2$. If the path were straight, the miss would be $R_m\epsilon = \rho_m\epsilon^2$ and the circular path produces a correction $\frac{1}{2}\rho_m\epsilon^2$, leaving a residual miss of $\frac{1}{2}\rho_m\epsilon^2$. For $\rho_m = 10{,}000$ ft and $\epsilon = 1$ degree, $R_m = 167$ ft, and the miss is only 1.4 ft. The miss increases as the square of the bore-sight error.

Bore-sight errors arise from many sources in addition to the obvious one of inaccuracy in construction of the vehicle and of the mounting brackets of the intelligence device. Both mechanical and electrical imperfections of the intelligence device may produce bore-sight error. Thus, in a radar-homing device the electrical axis of the antenna system may not coincide with the geometrical axis because of unsymmetrical distribution of dielectric or conducting material near the antenna. The output circuits may be unbalanced in such a manner that the output is not zero when the target is on the axis of the antenna. The servo control system may contain elements which are not balanced when the input signal is zero; for example, the pick-off of a rate gyroscope may be displaced from the correct zero position. Errors from these and similar causes may be controlled by careful inspection tests of the individual components, and an overall check of an installed system can readily be made. The reference axis of the vehicle can be oriented with respect to the target until the indicated output is zero, in which case the angular displacement of the target from the reference axis gives the bore-sight error.

The most difficult problem is to determine that reference axis of the vehicle which lies in the direction of motion of the center of gravity of the vehicle in free flight. In fact a vehicle designed like a conventional airplane travels at different attitudes for different positions of the control surfaces. Particularly in the vertical plane, the angle of attack varies with the elevator setting. Thus, there is a variable bore-sight error which might amount to as much as 10 degrees or more.

A similar error may occur in the horizontal plane when rudder and elevator control are used, for in this case the rolling moment due to any lack of symmetry of the missile about its longitudinal axis must be balanced by application of the rudder to yaw the missile, which then flies at an angle to its longitudinal axis.

Two methods have been used to reduce bore-sight errors from aerodynamic causes. The first and most satisfactory is to design the missile so that the change in attitude with application of control is as small as possible. This requires aileron-elevator control rather than rudder-elevator control, so far as the horizontal motions are concerned. In the vertical plane the aerodynamic design should be such that the lateral forces are modified without change in attitude. One method is to use flaps on the trailing edges of the wings to change the lift and to balance the pitching moments so produced by pitching moments from the tail arising from changes in the downwash angle. This can be done by proper choice of tail size and location of tail and of center of gravity of the missile.

The second method which has been used to reduce bore-sight errors from angle of attack changes is to mount the intelligence device on trunnions and couple it to the controls in such a manner that the reference axis of the intelligence device is rotated to compensate for changes in angle of attack. This compensation can be made perfectly for steady-flight conditions, but there are residual errors under dynamic conditions. In addition a stability problem arises, as in the case of computers, and usually only a partial compensation can be made if hunting troubles are to be avoided. In some instances, such a coupling of intelligence device to controls has been used as a means of damping, as previously discussed. In such a case the bore-sight error is not completely eliminated.

A final source of bore-sight error is the inevitable inaccuracy in construction of the internal shape of the vehicle. The axis of zero moment, i.e., the direction of travel, will vary somewhat from one missile to another of the same intended shape. Such errors can be measured in a suitable wind tunnel, but only with great expenditure of time, and the requirements for uniformity of flow in the wind tunnel are difficult to meet. In the case of Pelican and Bat missiles, errors of about 0.8 degree were found from this source.

With sufficient care and exclusive of actual equipment failures, it should be possible to reduce the bore-sight error to the order of magnitude of 1 degree.

12.8 SENSITIVITY, LAG, AND MINIMUM RANGE

The preceding discussion of pursuit curves and bore-sight errors has assumed certain ideal characteristics of the intelligence device and has not taken into consideration (1) that the intelligence device must look away from the target to produce error signals and (2) that it has a certain lag.

Let us consider first an intelligence device without lag which gives an output signal proportional to the error angle up to a certain angle σ_m and which gives a constant output for angles greater than σ_m. The maximum output signal gives the minimum radius of curvature of the path ρ_m. For any error angle σ smaller than σ_m it will be assumed that the radius of curvature ρ_c is given by $\rho_c/\rho_m = \sigma_m/\sigma$; i.e., the radius of curvature is infinite for $\sigma = 0$. If then the discussion of the pursuit curve is reexamined, it is seen that the axis of the intelligence device must point away from the target by an angle σ when the radius of curvature is ρ_c.

An exact solution of this problem is difficult and has not been carried out. We have already seen that the pursuit-curve error is entirely analogous to a bore-sight error of magnitude $\tan^{-1}(n \sin \phi_0)/(1 + n \cos \phi_0)$, where n is the ratio of the apparent target speed to the speed of the missile and ϕ_0 is the azimuth of the missile referred to the direction of apparent motion of the target. This equivalent bore-sight error varies during the flight of the missile along a pursuit curve because ϕ_0 varies, and the pursuit-curve calculations are complicated by the determination of ϕ_0 as a function of the initial azimuth, initial range, and n. It will be instructive, however, to consider the simpler problems of the effect of the value of σ_m on the miss arising from a constant bore-sight error ϵ.

This problem has been worked out by Skramstad (unpublished) for the case where ϵ is small, the lateral displacement y of the missile from a line joining the release point to the final target position is small compared with the initial range $x_0 - x$, and the slope of the trajectory dy/dx to the same line is small compared with 1. The differential equation is found to be

$$\frac{1}{\rho_c} = \frac{d^2y}{dx^2} = \frac{\sigma}{\rho_m\sigma_m} = \frac{1}{\rho_m\sigma_m}\left[\left(\frac{y}{x - x_0}\right) - \frac{dy}{dx} + \epsilon\right]$$

The solution of this differential equation was found to be

$$y = \epsilon(x_0 - x)\left[\log\frac{x_0}{x_0 - x} - \frac{H(x_0/\rho_m\sigma_m)}{x_0/\rho_m\sigma_m}\right] + \epsilon$$

$$\frac{dy}{dx} = \epsilon - \epsilon\log\left[\frac{x_0}{x_0 - x} - \frac{H(x_0/\rho_m\sigma_m)}{x_0/\rho_m\sigma_m}\right]$$

$$\frac{d^2y}{dx^2} = \frac{-\epsilon}{x_0 - x}$$

where

$$H(x) = 1 + \frac{1}{x} + \frac{2}{x^2} + \frac{6}{x^2} + \cdots$$

For practical values of x_0, ρ_m, and σ_m, the second term in the brackets is entirely negligible. If, at a range $x_0 - x = R_m$, the missile is assumed to follow a circle of radius ρ_m, the miss M is given by

$$M = y + R_m\frac{dy}{dx} - \frac{1}{2}\,\frac{R_m^2}{\rho_m}$$

Whence

$$M = \epsilon(R_m + \rho_m\sigma_m) - \frac{1}{2}\,\frac{R_m^2}{\rho_m}$$

The range R_m at which $\sigma = \sigma_m$ or $\rho_c = \rho_m$ is equal to $\rho_m\epsilon$,

since

$$\frac{1}{\rho_c} = \frac{d^2y}{dx^2} = -\frac{\epsilon}{x_0 - x} = \frac{-\epsilon}{R}$$

Hence the miss is given by

$$M = \rho_m\sigma_m\epsilon + \tfrac{1}{2}\rho_m\epsilon^2$$

If we assume $\sigma_m = 1/15$ we obtain the following values:

ϵ	$\dfrac{M}{\rho_m}$
0.05	0.0046
0.10	0.0117
0.15	0.0213
0.20	0.0333
0.25	0.0480

The effect of the value of σ_m is zero if $\epsilon = 0$. Thus, if the missile travels a collision course and the bore-sight error is zero, there is no error from limited sensitivity of the intelligence device. When ϵ is not zero, the effect of σ_m is to give an error term proportional to ϵ, whereas the miss due to bore-sight error alone is proportional to ϵ^2. Hence the effect of σ_m predominates at small values of ϵ.

It is possible to use the formulas previously given to compute the pursuit-curve errors by means of an equivalent bore-sight error for the azimuth angle ϕ_0 of the missile, referred to the direction of the apparent position of the target, changes from ϕ_0 to $\phi = \phi_0 - dy/dx$. By introducing the value of dy/dx in the expression for equivalent bore-sight error, there is obtained

$$\epsilon = \frac{\sin\left(\phi_0 - \epsilon + \epsilon \log \frac{x_0}{\rho_m} + \epsilon \log \frac{1}{\epsilon}\right)}{n + \cos\left(\phi_0 - \epsilon + \epsilon \log \frac{x_0}{\rho_m} + \epsilon \log \frac{1}{\epsilon}\right)}$$

This transcendental equation can be solved for ϵ as a function of ϕ_0, n and x_0/ρ_m, and with the expression for M in terms of ρ_m, σ_m, and ϵ the values of M/ρ_m as a function of σ_m, ϕ_0, n, and x_0/ρ_m can be found. The accuracy is not very good when $|\phi - \phi_0|$ exceeds about 0.3.

Since large pursuit-curve errors correspond to large values of ϵ, the term in σ_m is the smaller, but for $\sigma_m = 1/15$ corresponds to increasing the miss by 50 to 100 per cent.

The effect of a time lag τ in the intelligence device may be estimated in a qualitative way by considering this effect also as an equivalent bore-sight error. The error signal actually present at a range R is that appropriate to a range $R + V\tau$, where V is the speed of the missile. This may be regarded as caused by an error angle at range R differing from that actually present by an equivalent additional bore-sight error equal to the change in the error angle between $R + V\tau$ and R. This is readily seen to be

$$\rho_m\sigma_m\epsilon\left(\frac{1}{R} - \frac{1}{R + V\tau}\right) = \frac{\rho_m\sigma_m\epsilon V\tau}{R(R + V\tau)}$$

The total equivalent bore-sight error is then

$$\epsilon\left[1 + \frac{\rho_m\sigma_m V\tau}{R(R + V\tau)}\right].$$

The range at which $\rho_c = \rho_m$ is then given by

$$R_m' = \rho_m\epsilon\left[1 + \frac{\rho_m\sigma_m V\tau}{R_m'(R_m' + V\tau)}\right]$$

This can be solved for R_m' and introduced in the equation previously given to find the corrected miss. For most cases the total equivalent bore-sight error may be approximated in practice by

$$\epsilon\left(1 + \frac{\sigma_m V\tau}{\rho_m\epsilon^2}\right)$$

The magnitude of the additional error is not large.

If the intelligence device overloads as the target is approached, the directional information may disappear completely, or the error signals may even be reversed in sign. Furthermore, certain types, such as radar, have a minimum range within which no error signals are given. If the minimum range is R_m, the missile in this case continues in a straight line and the miss is given by

$$M = y + R_m\frac{dy}{dx} = \epsilon(R_m + \rho_m\sigma_m) \quad ,$$

For example, if $R_m = 2{,}000$ ft, as was found in one design of intelligence device, $\rho_m = 10{,}000$ ft, $\sigma_m = 1/15$, and $\epsilon = 1/30$, the miss is 89 ft. If R_m is reduced to 200 ft, the miss is 29 ft, of which 7 ft is associated with the minimum range and 22 ft with the radar sensitivity σ_m.

12.9 STRENGTH PROBLEMS OF HOMING MISSILES

The structural design of a missile is in most respects entirely analogous to that of an aircraft. It is desired here to call attention to only two design conditions peculiar to missiles.

For rocket or jet-propelled missiles it is often inefficient to design the power plant of sufficient size to include the take-off condition. It is better to use assisted take-off by means of a catapult or by special launching rockets. In German experience with antiaircraft and long-range missiles, accelerations from $2g$ to $16g$ have been used in launching. The missile structure must be designed to withstand the inertia loads produced, and so must all the parts of the intelligence device and control system.

The second design condition peculiar to missiles is that of full control application at maximum speed. Because of the bore-sight error which may be present, the intelligence device will call for the maximum rate of correction. The missile must be able to withstand the loads so produced, or some automatic device must be used to limit the acceleration which may be imposed.

12.10 LAUNCHING PROBLEMS OF HOMING MISSILES

Some discussion has been given of launching problems in the discussion of the relation between the field of view and the permissible motions of the missile. The target must come within the field of view and remain there. A sighting device or computer may be required for determination of the proper release time.

A special problem encountered in the release of missiles from aircraft is that of avoiding maneuvers which cause contact between missile and aircraft after release. It appears essential to keep the homing device disconnected from the controls until the missile is at a safe distance from the aircraft. The choice of airspeed and attitude at release can be made after the study of computed trajectories confirmed by experimental tests. In general the airspeed must be lower than the horizontal flight speed of the missile, the amount by which it should be lower depending somewhat on the drag-weight ratio of the missile. In some cases interference effects between the missile and the aircraft may cause an unfavorable trajectory. However, no such effects have been encountered for missiles of high wing loading.

12.11 CONCLUSION

A survey has been given of some aspects of the design of homing missiles for flight through air, primarily to place on record that part of the experience in the study of the radar-homing glide bombs, Pelican and Bat, which is likely to be of value in the future development of homing missiles. None of the topics have been treated in detail in this chapter, but it is believed that the discussion is sufficient to indicate the nature of the problems and possible methods for their solution.

Chapter 13

THE DESIGN OF HIGH-ANGLE DIRIGIBLE BOMBS

13.1 DESIGN PROBLEMS

13.1.1 General Considerations

In general, the structural configuration and dimensions of high-angle dirigible bombs are sufficiently restricted by tactical considerations to preclude any extensive liberty in their design. Except for exceptional cases, they must be carried within the bomb-bays of airplanes which are designed primarily for carrying standard bombs comprising only the explosive case and sufficient tail-fin area to provide reasonable weathercock stability of the bombs in flight. Thus the bomb-bays, including the carrying racks, are designed to pack a maximum number of compact explosive cases, with very little additional space for anything except the most rudimentary type of fin surface at the tail. Moreover, there existed an almost unsurmountable resistance on the part of the military to accept a dirigible bomb design which would not pack in existing bomb-bays in numbers equal to the number of standard bombs normally carried. This point of view will undoubtedly be changed to a reasonable degree when in the future such special weapons have proved their comparative worth in terms of potential effectiveness. However, during the recent period the design of special bombs was definitely handicapped by this understandable but nonetheless disconcerting viewpoint, which necessarily dominated developments.

A few simple basic principles are involved in the aerodynamic design of dirigible bombs, and the discussion which follows is intended to outline in the simplest possible nontechnical terms certain major considerations which suffice to cover the broad aspects of the problem.

Control of a bomb in flight requires first of all control of forces at right angles to the direction of flight so that the bomb may be deviated sideways, in any direction, from its normal trajectory. Since the dirigible bombs contemplated here do not include the use of any internal power source such as jets, there remain only aerodynamic forces to accomplish the maneuvering of the bomb. Aerodynamic forces imply lift surfaces of adequate area to generate the desired forces, and means whereby these lift forces may be controlled at will. As to the method of obtaining lift forces from such surfaces as may be placed on a high-angle bomb, dimensional limitations leave no alternative but to yaw or pitch the entire bomb so that it attains a trim angle of attack in the airstream. Since the lift force increases in proportion to the angle of attack, it is desirable to make it as large as possible, but drag forces increase disproportionately and soon reach the point where the ballistics of the bomb become intractable, so a compromise is required. Moreover, the rudder surfaces start stalling seriously at around a 20-degree angle of attack, so that other problems are introduced if very large yaw angles are contemplated. Experience indicates that it is not desirable to maintain trim angles in excess of 15 degrees, and hence all dirigible bombs designed in this project have been held closely to this value.

13.1.2 Mass vs Maneuverability Relations

The lift force generated by any aerodynamic surface having an angle of attack in an airstream at velocities below the critical velocity at which the airflow regime changes because of compressibility effects may be expressed as:

$$\text{Lift force per unit area} = C_L \rho \frac{V^2}{2}$$

or

$$\text{Lift force} = \text{Area} \cdot C_L \cdot \rho \frac{V^2}{2}$$

where V = velocity of the airstream;
ρ = density of the air;
C_L = a numerical constant characteristic of the aerodynamic surface.

The $\rho V^2/2$ term is, of course, something over which we have no control, but it is of interest in the case of high-angle dirigible bombs because, in spite of the ever-increasing velocities of a falling bomb, the V^2 factor results in a practically constant maneuverability. That is, if control is applied continuously throughout the drop, the radius of curvature of the resultant deviation path in space is substantially a constant.[a] This arises from the fact that, whereas the total velocity of the bomb along its trajectory is

[a] The radius of curvature of the VB-1 is about 27,000 ft; for the VB-2, approximately 32,000 ft; and for the VB-3, about 19,500 ft.

steadily increasing under the constant acceleration of gravity, the lift or deviation force is increasing as V^2. Geometrical considerations will show a resultant deviation of practically constant radius. Thus, to the extent that the fin surfaces retain their effectiveness at high velocities, the maneuverability of a dirigible bomb will be practically constant anywhere in its flight. This, of course, is a very pertinent characteristic.

The lift coefficient C_L is a dimensionless constant describing the effectiveness of the bomb body and its fins in producing aerodynamic lift. Its numerical value is determined by actual measurements, either by wind-tunnel tests on scale models or by actual drop tests of full-size bombs. However, here we are concerned with the broad fact that lift forces generated aerodynamically are proportional to the area of the airfoil. This is of interest in verifying an intuitive guess that the more fin area applied to a bomb, the greater the lift or maneuverability, but it is more important in indicating that the *size of bomb which may be maneuvered effectively with a given type of fin configuration is definitely limited.*

In considering the maneuverability of a bomb we are concerned with the rate at which it is deviated from its normal path when control is applied; that is, maneuverability depends upon the sideways or deviating *acceleration*. Since $a = F/m$, the deviation acceleration is equal to the total lift force divided by the mass of the bomb. From the above, since the lift force is proportional to the area L^2, and since mass is proportional to L^3, it is found that, for bombs of similar design and density factor, deviation acceleration is proportional to L^2/L^3, or $1/L$.

Thus for a particular design of bomb and fins, the maneuverability of the bomb decreases in proportion to the increase in lineal dimensions, if the density factor remains constant and the dimensions of all parts simply increase proportionately. In terms of weight, the decrease in maneuverability with increased size is shown in the following table.

Wt. of bomb	Lineal dimension factor	Maneuverability factor	Inertial moment about c.g.	Period of oscillation
1,000	1.0	1.0	1.0	1.0
2,000	1.26	0.79	3.18	1.26
8,000	2.0	0.50	32.0	2.0
12,000	2.29	0.44	63.0	2.29
22,000	2.8	0.36	172.0	2.8

Hence, if it is assumed that a 1,000-lb bomb case has been supplied with a controllable fin structure whose area and aerodynamic effectiveness are such as to produce adequate lift for a certain desired maneuverability, then the same design in a 2,000-lb bomb will have only 79 per cent as much maneuverability as the smaller unit. In the larger sizes such as the 12,000-lb, the loss in maneuverability to 44 per cent of the 1,000-lb unit becomes very serious and for really satisfactory performance would require an increase in lift-surface area amounting to about 2.25 times the area provided by merely scaling the 1,000-lb bomb to the larger size. This is a fundamental difficulty in designing dirigible bombs which prohibits unlimited expansion into large sizes without major modification of the design. In particular, it requires an ever-expanding area or lift surface to maintain a fixed maneuverability. This circumstance must be borne in mind carefully in considering the application of the dirigible bomb principles to larger and larger bombs. The current development of a 12,000-lb bomb (Tarzon) is illustrative, for after using all available space for the most efficient lift surface distribution practicable, the maneuverability is down to about 40 per cent of that obtainable with the 1,000-lb VB-3. While this may still be quite satisfactory for azimuth steering, its adequacy for range steering is seriously questioned and will require actual trial to provide any satisfactory conclusions about the practicability of this bomb.

13.1.3 Mass vs Yaw Oscillation Characteristics

Another aerodynamic feature characteristic of high-angle dirigible bombs having broad implications in the application of controls to very large bombs pertains to the yaw and pitch oscillations induced when control is applied.

As already mentioned, the necessary lift forces are obtained by applying rudder or elevator to the control surfaces, which yaw or pitch the bomb into a trim angle of attack of about 15 degrees, whereby the desired aerodynamic lift forces are brought into play. The application of the yawing moment by the rudder induces an overshoot of the bomb beyond its normal trim angle, and the steady-state trim angle is approached only by a damped oscillation about the trim position. Unfortunately, the aerodynamic damping induced by such oscillation is rather small; hence care must be taken in the application of rudder or elevator so as to limit the initial overshoot of the yaw angle as much as possible. It can be shown that, if the small damping term is neglected, when rudder is applied instantaneously from neutral position, the initial yaw angle will be double the normal trim angle, and the yaw angle will be greater by far when the change involves immediate deflection from full rudder in one direction to the opposite angle. It will also be evident that a *very* slow application of control will inhibit overshooting; in fact, no hunting will occur if the rudder application is in phase with the yawing angle. Thus the rate at which rudder is applied must be limited to a value somewhat comparable to the natural period of the bomb oscillation about its center of gravity. In the 1,000-lb VB-3 having periods ranging, because of ever-increasing velocity, from about 2.5 seconds at release to 0.7 second near the end of a 15,000-ft drop, experience has indicated that reasonable suppression of oscillation is obtained with rudder speeds of about 1.2 seconds for travel from neutral to full deflection. By way of comparison, the 12,000-lb Tarzon design indicates a period of about 1.75 greater than the VB-3; hence, the maximum rudder speed must be reduced to about 2.0 seconds from neutral to full deflection. Moreover, this reasonably short period for the 12,000-lb bomb oscillation is achieved only by increasing the weathercock stability of the bomb relative to that of the VB-3, a compromise which is obtainable only at a sacrifice in effective lift for a given area of fin surface. The details regarding this inherent loss of lift with increasing weathercock stability are beyond the scope of this discussion. However, it is mentioned merely to indicate that the increased moment of inertia of larger bombs leading to embarrassingly long oscillation periods cannot be compensated for by indiscriminately increasing the stiffness or weathercock stability by greater tail stabilization. It might appear that slowing up the rudder action arbitrarily to handle the long-period problem is sufficient. Such a device will, in fact, serve to keep the yaw oscillations within reasonable bounds.[b] However, it must be remembered that the high-angle steering problem also demands reasonable speeds in response to controls; otherwise, accurate steering would be impossible. The optimum design is one of compromises throughout, and great care must be taken that the whole purpose of the control feature is not vitiated.

The above discussion, while far from complete, is intended to point out forcefully that there are limitations to the practicable weight of dirigible bombs, unless the space made available for the aerodynamic surfaces is allowed to expand disproportionately. One cannot cope with the area vs mass relationship, or the moment of inertia vs mass stability problem without some additional freedom in the design of the aerodynamic surfaces other than mere uniform expansion of dimensions.

13.1.4 The Roll Torque Problem

Dirigible bombs of the type discussed here all require stabilization of the bomb in roll about its longitudinal axis. This basic requirement that the roll orientation be fixed throughout the flight of the bomb will be evident on considering the necessity of defining the plane of action of the rudders and elevators with respect to azimuthal and range coordinates in space. Thus the rudders must be maintained parallel to the vertical or azimuthal reference plane, and the elevators to a horizontal or range reference plane. The use of a suitable gyro control acting through roll-stabilizing ailerons has accomplished the required stabilization in the Razon-type bomb, VB-3.

Throughout this chapter the importance of this roll control problem has been stressed, and particular attention has been called to the difficulties encountered in attempting to stabilize the flat-fin cruciform-type empennage. Indeed, reliable performance was never attained with this type of structure when it was subjected to simultaneous yaw and pitch control, although attempts to "brute-force" stabilization with larger and larger ailerons were carried to the point at which practical considerations of power and space limitations called a halt to further attempts. At the same time, considerable effort was made to analyze the problem from a quantitative aerodynamic viewpoint by means of wind-tunnel tests designed to measure the roll torques generated when a bomb equipped with a cruciform-fin structure was exposed to simultaneous pitch and yaw. Such tests were made in several wind tunnels, but reliable quantitative information was found very difficult to

[b] An alternative method might be devised whereby artificial damping is introduced by properly controlling the speed and phase of rudder applications, or by applying some kind of aerodynamic brake. While considerable thought has been given to this problem, it has not yet appeared amenable to solution without an excessive amount of auxiliary equipment. In addition to added power requirements for special controls, it appears to require at least two or perhaps four additional gyro controls. Such devices might be found practicable for the very large bombs, such as the VB-13, but it is questionable whether the added complexity and accompanying decrease in reliability of the instrumentation would be warranted, except as a last resort.

obtain. However, numerical data were secured which, qualitatively, showed the typical roll torque characteristics that were anticipated from the early cursory visual consideration of the structure. Quantitatively, the data were of no great value. On the contrary, they were misleading to the extent that in some quarters they encouraged the belief that the roll torque problem was less serious than seemed evident from actual drop tests. In large measure, these deceptive data were responsible for the illusive hope that sufficiently large ailerons could be applied to the structure to assure roll stabilization.

Although this is not the place to discuss the aerodynamic aspects in detail, the importance of the problem, in view of future work on dirigible missiles, warrants brief consideration of the source of the roll torque phenomenon. Indeed it seems imperative, for even now development work appears to be under way using cruciform-type empennage designs with too little consideration for the seriousness of the problem. It is as if this contractor had never been plagued with the roll problem or, if so, had labored under delusions regarding its seriousness.

As regards the source of the roll torques developed when a flat-fin cruciform-type tail is subjected to the cross wind associated with combined pitch and yaw angles of attack, a cursory study of a model will provide all the qualitative information required.

The first and simplest consideration is that the structure comprises flat radial surfaces; hence, any unbalanced lifts produced on these surfaces represent roll torques whose magnitude is merely the product of the unbalanced force and the radial distance to its effective center of pressure. It is pertinent, then, to examine the conditions which will give rise to unbalanced lift forces.

If we assume that there are no interference effects, that is, no shading of one surface by another due to an asymmetrical wind, unbalanced lift forces (and therefore torques) will be produced, except when the direction of the wind vector is such that its projection in the plane of the lift surface is parallel to the axis of the empennage. In other words, any flat surface constrained on a central axis will always orient in a fluid stream so as to expose a maximum surface at right angles to the stream. It will be clear that, if a missile carrying a tail surface comprising a single flat fin is yawed in the windstream, it will roll on its axis until the plane containing the wind vector and the axis is normal to the surface; that is, it will roll until a maximum area is exposed to the wind. If such a missile is yawed in azimuth, it will be stable if the fin is vertical; but if given a pitch angle of attack, it will be stable in roll only if the fin is horizontal. In the case of an empennage having two flat fins at right angles, as in the cruciform structure, it will be evident from similar considerations that it will be stable in roll if subjected to pure yaw or to pure pitch, but a combination of the two will develop a roll torque. This stability characteristic explains why the cruciform structure is reasonably practical in the VB-1, which is controlled in azimuth only (or in range only, if desired), but is impractical for a Razon bomb steered in both range and azimuth.

On the other hand, if the vertical and horizontal fins have unequal areas, the assembly will behave like the single-fin structure to the extent that the two sets of fins are of unequal size. This effect was observed to a pronounced degree in actual bombs when an experimental attempt was made to use unequal fin areas to obtain greater maneuverability in range than in azimuth. Hence, the Azon empennage carries horizontal and vertical fins of equal size.

The above discussion can be summarized by stating that the roll torque characteristics of the cruciform structure are inherent because the projected area of the assembly varies with the angle of roll; that is, the structure is not radially symmetrical as regards exposed area. Obviously, the area asymmetry could be improved by increasing the number of fins from, say, four to eight, but other practical considerations preclude such a design. Moreover, the simple explanation of roll torque considered thus far is only one part and not necessarily the major part of the roll torque problem.

Thus far we have ignored the effect of interference or shading of one fin on another or of the body of the missile on the fin surfaces. We have also ignored the effects due to the shape of the body section of the empennage to which the cruciform fins are attached. The shape of the body lying within the cruciform structure can markedly affect the roll stability pattern in both magnitude and angular distribution of the stability angles. Details regarding the latter effects can be obtained only from wind-tunnel studies.

However, the shading effects may be considered profitably in a qualitative manner by recalling that any unbalanced lift forces on the radial fins of the cruciform structure will generate a roll torque. Moreover, it is evident that any aerodynamic shading affecting the several fin surfaces unequally will necessarily result in unbalanced lift forces.

Consider a bomb equipped with a cruciform tail having elevator and rudder flaps on the trailing edge of each of the horizontal and vertical fins. In normal flight the tail section is subject to the wash of the bomb body, so that the inner portions of the surfaces may be exposed to very disturbed air while the fin areas at some greater radial distance outward may be in relatively smooth air. However, since all four fins are symmetrically disposed with respect to the cone of rough air behind the bomb body, and in normal flight the surfaces have no angle of attack, no roll torque of appreciable magnitude should develop.

Now suppose that elevators are applied so that the bomb attains a trim angle of attack (15 degrees upward pitch for typical Razon bombs). The frontal area of the bomb body has now increased because of the attack angle, and the area of the disturbed wake will likewise increase, accompanied by even greater turbulence. Obviously, this will result in an increased shading of the upper half of the vertical fin, accompanied by a decreased shading of the lower half; but since the vertical fin is still parallel to the wind stream (no rudders applied) no lift will be developed and no roll torque. Similarly, the right and left sections of the horizontal fin are symmetrically disposed in the wake, and no torque should result. Thus, in pure pitch or yaw alone the bomb should be stable in roll.

When the elevator angle of attack is maintained and right rudder suddenly applied, consider the aerodynamic reaction due to the rudder application *before* the bomb has yawed to any appreciable extent in response to the rudders. It will be apparent that, as described in the preceding paragraph, the upper section of the vertical fin in the tail of the bomb (the nose of which is tilted upward 15 degrees in its elevator trim position) is heavily shaded within the wake of the bomb body, while the lower section is in smooth air. Since the rudder flaps on the vertical fins are deflected, the lift force generated will appear as a thrust directed to the left on the vertical fins. However, since the lower fin is more efficient aerodynamically than the shaded upper fin, the lift forces are not balanced, and the excess thrust on the lower vertical fin will generate a clockwise roll torque. As the bomb yaws into its proper trim position, it will be observed that a similar shading effect will be exhibited by the horizontal or elevator fins; but the resulting roll torque will be counterclockwise, tending to cancel the torque from the rudders. Thus, it would appear that if the yaw and pitch response of the bomb was always in trim with the rudder and elevator applications, roll torques due to shading effects might be relatively unimportant.

However, yaw and pitch oscillations of a bomb are very poorly damped (the coefficient of damping is approximately 0.25 for the Razon bomb) so that, because of randomly imposed control applications, it is easy to induce transient angles of attack 1.5 or even 2.0 times the normal trim angles. Moreover, as a result of such oscillations, it is possible that the angle of attack of the bomb may at times be the opposite of that called for by the rudders or elevators. Should this occur, then the shading effects on the rudder and elevator will not cancel as in the case considered above; their roll torques will be additive, and the resultant magnitude will depend only upon the asymmetry in the lift forces induced by shading. It should also be remembered that this roll torque is a phenomenon due to control-flap action coupled with aerodynamic shading effects and is distinct from and, depending upon the phase of the events, may be additive to the torques due to radial asymmetry of the fin structure discussed earlier. It is also likely that it is the more important of the two.

The qualitative description of these sources of roll torque, characteristic of the radial-fin cruciform structure, indicate conclusively that the torques are strongly impulsive in character. But, however short their duration, the energy will be exhibited as a roll acceleration of the bomb, which must be balanced by an equal and opposite acceleration produced by the roll-stabilizing ailerons, which for practical reasons are necessarily limited in capacity. It will also be apparent that the magnitude of the transient roll torques will depend to a large extent upon the fortuitous coincidence of certain combinations of yaw or pitch oscillations together with control applications, with the result that the occurrence of excessive torques will be a random event. Both the impulsive and unpredictable occurrence of the phenomenon have been observed repeatedly in actual drop tests.

Finally, it may be said that the magnitude of the torques due to control asymmetry resulting from aerodynamic shading on a cruciform structure will be directly proportional to the lift forces produced by the control, to the area of the disturbed wake in which the fins are emersed, and to the degree of turbulence within the wake which gives rise to the deleterious aerodynamic effects resulting in asymmetrical lift forces. It will be clear, therefore, that at low velocities the net effect may be small, but with increasing velocity the disturbed wake behind the bomb body will increase in diameter and in degree of turbulence, with a resultant rapid increase in the aerodynamic asymmetry of the fin surfaces. Thus, failure of roll stabilization may not occur until the velocity of the missile attains a critical value. Doubtless the failure of wind-tunnel studies to produce a reliable quantitative analysis of the roll torque problem consistent with the phenomena actually observed in drop tests is due to the lack of wind-tunnel tests at sufficiently high velocities. It is a well-known fact that it is quite impossible to extrapolate low-velocity observations involving especially the type of phenomena referred to here as shading since the flow regime undergoes marked changes beyond certain critical velocities which are a function of the aerodynamic shape of the structure.

Indeed this effect has been clearly observed in nose-camera motion pictures wherein, occasionally, bombs of the VB-1 type carrying cruciform fins have been observed to develop spurious trim angles of attack up to 5 degrees or more near the end of a 15,000-ft drop, even though no control was applied. This is a direct result of the blanking of the stabilizing fins by the turbulent wake of the bomb body. Similar effects have been observed visually in the last several thousand feet of 15,000-ft drops of standard 1,000-lb bombs. In these cases the effect was observable because of a slow rotation deliberately imposed by very small ailerons on the standard bombs for the purpose of eliminating dispersion. The effect was exhibited occasionally by the sudden initiation of a conical wobble of the bomb and an accompanying visible increase in trail angle compared with others in the group.

Two obvious sources of roll torques in radial fin structures have been considered. There are more complex effects, such as mutual interference of the fin surfaces themselves, that should be considered. However, this very qualitative and cursory discussion should serve to emphasize that the use of radial-fin structures on dirigible missiles should be contemplated with caution. True, the shading effects may be ameliorated by the use of far better streamlining of the aft portion of the missile than was possible in the design of the high-angle dirigible bombs. Moreover, the roll torques due to all causes fade out rapidly as the angles of attack required for adequate maneuverability are reduced below the large values necessary in the dirigible bombs. But no empennage remains well-streamlined when large angles of attack are involved; and if these angles are kept small, maneuverability must be sacrificed in proportion unless larger lift surfaces are permissible. But if it is assumed that cleaner design of the empennage may be attained than was possible in converting to a dirigible type the aerodynamically inept standard bomb, it must be remembered that such gains may, to a large extent, be vitiated at the very high velocities contemplated for some of the proposed highly maneuverable missiles. Hence, a careful study of the problem is warranted.

The Division is well aware of the compactness and particularly the attractively "clean" aerodynamic features of the radial-fin structures which recommend them, particularly for high-speed missiles. In the case of the dirigible-bomb project, time did not permit an exhaustive study of the roll torque problem and this definitely precluded the use of radial fins in the Razon-type bomb. The alternative was immediate adoption of a type of structure inherently free of the problem. Thus, the use of cylindrical shroud surfaces eliminates any possibility of a serious roll torque problem, since such surfaces have radial symmetry and are so disposed that any lift forces produced act radially and cannot generate a roll torque. Hence, from the roll torque aspect the structure is inherently free even of the aerodynamic shading problem. The practical requirement of suitable radial supports for the shroud apparatus does introduce some radial asymmetry. Likewise, simplicity of design calls for a modification of the ideal circular shroud to an octagonal shape which facilitates the use of simple control flaps. But these modifications result in only minor asymmetry and present no serious problem in roll stabilization. For use on missiles whose velocity range is within the permissible limits for this type of structure, their adoption may be contemplated without serious worry about the roll stabilization problem, and reliable performance may be assumed with confidence. This obvious advantage of the shroud-type control and lift surface over the radial-fin type for highly maneuverable missiles warrants some extensive study to determine the practical limit of velocity for which they are applicable.

13.2 FUTURE APPLICATIONS OF DIRIGIBLE BOMB TECHNIQUE

13.2.1 Alleviating Limitations on Size of Dirigible Bombs

The above discussion is intended to outline the salient features of high-angle dirigible bomb design which impose inherent limitations on the weight of bombs which may be controlled in the manner of the VB-1, -2, and -3 units. It is indicated that in the 12,000-lb VB-13 we have already passed the point at which truly effective control is obtainable—effective in the sense that these bombs are intended to permit accurately directed maneuvers of 1,500 to 2,000 ft in order to secure hits on targets executing evasive action.

These considerations lead to the inevitable conclusion that specifications for very large dirigible bombs must allow for a disproportionate increase in the size of the aerodynamic surfaces as compared with the 1,000- to 2,000-lb sizes. Alternatively, the use of some type of controlled jet-power units must be contemplated, provided adequate side thrusts are obtainable with compact units of a type which can be turned on or off as occasion requires.

13.2.2 High-Velocity Dirigible Projectiles

The success of high-angle dirigible bombs might lead one naturally to the conclusion that similar aerodynamic methods of control are applicable to other types of projectiles. Aside from the weight considerations mentioned above, there are also limitations on the velocity at which such aerodynamic controls may be reliable. The extent to which the velocity of the VB-3 may be increased without loss of control is not yet established by experience. It is known from high-speed wind-tunnel tests that the drag coefficients on all structures start increasing rapidly above a speed of about 800 ft per sec. This corresponds approximately to the terminal velocity of a 15,000-ft drop. The VB-3 has been tested at 20,000 ft with no indications of failure, and it is felt that at 25,000 ft it should be quite satisfactory. However, while the Division has no data on drag coefficients above the critical velocity mentioned above and hence cannot calculate the probable terminal velocity, there is little reason to expect a terminal velocity much above 1,000 ft per sec with the small bombs. Because of lack of adequate information at present, the performance of the aerodynamic controls, either aileron or directional, is an unanswered question when the terminal velocity due to aerodynamic drag has been reached. This is especially true of the complete lift shroud-control shroud assembly of the VB-3 or VB-13 type. However, it will be recalled that this type of design was used because it was amenable to roll control whereas the more orthodox cruciform-fin design was not. While the latter design is undeniably a "cleaner" and more compact aerodynamic structure and amenable to higher speeds, its use must be envisaged only with great caution in regard to its unfavorable characteristics.

In addition to the roll control problem introduced by the use of the cruciform fins, certain additional features should be mentioned. It will be recalled that one of the attractive features of the cruciform-fin design is its compactness as ordinarily fitted into a bomb-bay. As applied to the standard 1,000- and 2,000-lb bomb cases in the VB-1 and -2 designs, only about half of the fin area projects beyond the diameter of the bomb body. It is of interest that a successful cylindrical or octagonal control shroud for these bombs cannot be made unless its diameter is greater than the bomb diameter. The standard bomb cases used in these bombs have such a short tail that no real streamlining of the aft portion is possible, and even at low velocities normal airflow breaks away behind the main section of the bomb. At very high velocities one would expect a complete break-away at this point, with a resultant decrease in effectiveness of the airfoil within this diameter. Low-speed tunnel tests cannot show this effect, but the Division has direct evidence, from trajectory photographs, of the cruciform-type VB-1 which shows that near the end of flight these bombs evidence changes in their aerodynamic behavior. Similarly, in the case of standard bombs with standard tail fins, the evidence shows that they have lost some of their normal weathercock stability. This experience clearly indicates that if a cruciform-type fin structure is used, it should be placed on a well-streamlined conical section having only a gradual taper from the bomb body, in order to minimize break-away of the airstream and particularly to minimize shadowing of the fin structure by the bomb body when the bomb is yawed.

It is believed that both the roll torque and shadowing effects discussed above are sufficient to justify discarding the cruciform-fin structure from any consideration for projectiles having the general proportions of the VB-1, -2, or -3 types, particularly if the aerodynamic control requires yaw angles of the order of 10 to 15 degrees. It is felt that these structures will be unreliable for such projectiles at velocities in excess of about 800 ft per sec. With a longer tail section, providing possibilities of streamlining the empennage better, these objections might be materially mitigated, especially if only small angles of yaw or pitch are involved, but the problem deserves very serious study in any case.

13.2.3 Jet Control of Bombs or Projectiles

The use of aerodynamic lift surfaces on very large bombs entails inherent limitations as to the weight of the bombs, unless the area of the aerodynamic surfaces is increased proportionally. Questions regarding velocity limitations also require study. Moreover, as high-velocity bombs are intended to attain deep penetration on impact, the effect of a 15-degree or greater angle of attack at impact must be considered. In using the VB-3, for example, there were observed a few cases in which the bomb had control applied just before impact, and the bomb deflected upward after entering the ground. Thus, any use of such bombs contemplating a semi-armor-piercing type requires further study.

These problems all lead to the consideration of some means other than aerodynamic forces to achieve control of the trajectory. Moreover, certain contemplated types of high-speed controlled projectiles require a degree of maneuverability hardly amenable to an aerodynamic solution. The only evident alternative at present is some type of jet power, applied radially without introducing roll torques. While the contractor is not sufficiently informed regarding either rocket or fuel-injection rocket-type jets, it would seem that the latter have attractive possibilities for controlled missiles.

Rocket or jet-propelled missiles have been built in which control has been applied by means of deflectors in the high-velocity jet stream, resulting in a change in direction of the thrust. If this thrust is applied aft of the aerodynamic center of pressure, then the component of thrust normal to the axis which is induced by the deflectors serves to yaw the missile into a trim angle of attack, with a resultant change in course due to aero-dynamic lift. But the maneuverability obtainable by aero-dynamic forces is distinctly limited by practical limitations in surface dimensions. If mechanical problems can be met, it seems not impracticable to apply the lateral component of the jet thrust at or perhaps slightly forward of the center of gravity, in which case the full benefit of jet thrust can be used to deflect the course of the missile, aided by the incidental aerodynamic lift induced by any yawing of the bomb since this lift will be in the same direction as the jet thrust.

Thus it would seem that the ideal controlled missile would be propelled by an annular jet slightly forward of the center of gravity of the missile. This jet would be directed rearward at an angle of 45 degrees or less from the axis of the missile, depending upon the degree of maneuverability desired. If this jet is of the fuel-injection type, so arranged that the annular distribution of the fuel may be controlled, the direction of the net thrust and hence the direction of flight would be controlled at will. Such control could apply a large fraction of the total thrust as a deviating force. Moreover, if such a scheme could be developed, the control of fuel distribution could be accomplished with relatively simple, fast-acting, and compact control devices, well adapted to automatic control equipment. While such a self-propelled, controlled missile may appear rather fantastic, and, indeed, may be relegated immediately to the realm of the impractical on the basis of already known properties of jets, other mechanical and performance features are very attractive. Initial acceleration to high velocity may be obtained by means of a rocket which could be released from the tail when expended. Above all, such jets appear to be the only means of circumventing the maneuverability limitations of aerodynamic methods for missiles requiring a very high degree of maneuverability, such as either ground-to-air or air-to-air antiaircraft weapons.

A missile of the above type would be designed with a high degree of weathercock stability to minimize yaw. This would minimize the roll control problem, which is one of the really serious problems in all dirigible missiles. Alternatively, if the annular-jet power distribution is amenable to simple and rapid control, the missile may be allowed to rotate at a reasonable and controlled rate, with only the control apparatus stabilized in roll. Certain types of homing devices involving rotary scanning might make effective use of such a scheme.

These rather futuristic suggestions are offered primarily to stress the fact that the contractor's four years of experience in the development of high-angle dirigible bombs has rather impressively indicated some of the limitations of normal aerodynamic solutions to the controlled missiles problem. In view of some of the weapons which have been visualized, it is considered that a substitute for the completely aerodynamic methods is imperative. The great weight of some of the contemplated bombs, the high velocity, and particularly the very high maneuverability desired in *some* of these weapons do not appear amenable to the usual aerodynamic controls. Fuel-injection rocket-type impellers to provide the necessary deviation forces appear to be the only solution. If developed to the point of practicability as a power source, such units will offer attractive possibilities for simplification of control mechanisms, especially of the automatic or target-seeking type. For these reasons an intensive study of such methods not only is justified but is an urgently needed program. Indeed, if present airplane speeds are even marginally close to vitiating aerodynamic controls for antiaircraft missiles, such methods are then already obsolete for future use. Yet some method must be devised whereby control of the missile between the launching point and target is made possible, however fantastic it may appear at this moment.

13.2.4 High-Angle Armor-Piercing Bombs

The current development work on the VB-13 (12,000-lb dirigible bomb) is indicative of the importance of controlling very heavy bombs of the semi-armor-piercing type. The difficulties in providing maneuverability without decreasing the available penetration have already been mentioned. Such heavy bombs require large control surfaces with resultant aerodynamic drags that seriously limit the terminal velocities. Moreover, aerodynamic controls require yawing of the bomb, which will seriously affect penetration; yet one cannot handicap the accuracy of control by prohibiting steering at the end of flight where it is most needed for precision control.

As a solution to some of these problems, it has already been suggested that rocket accelerators might be used at the end of flight. It has occurred to the contractor that perhaps a shaped-charge bomb with a follow-through missile might be more practical. It is suggested that a 36-in. diameter shaped charge about 48 in. long would penetrate 16 ft of concrete and leave an opening through which 200 to 300 lb of follow-through explosive would be projected. Such a bomb would also serve against steel armor. There remains the question about the influence of impact angle on the effectiveness of the shaped charge. The follow-through charge would not appear to present insurmountable difficulties in view of the solution of a similar smaller-scale problem.

A bomb of the above type would be smaller than the VB-13 and hence more adaptable to the dirigible type. It would have a penetrating power on some targets equal to the VB-13 and could be more destructive for certain purposes. Since the only evident problems are the two mentioned above, both of which should be readily solved without a prohibitive amount of research, it would seem that such a bomb is well worth investigation.

Chapter 14

PROJECT ROC IN RETROSPECT

14.1 INTRODUCTION

THE PRESENT CHAPTER was prepared for the purpose of collecting some of the lessons and experiences that were learned by a group engaged in the development of a family of guided missiles designated Roc.

Chapter 12 covers some of the broad aspects and fundamental philosophy of the design of guided flying missiles with particular reference to experience gained with projects Bat and Pelican. Since most of the conclusions and recommendations presented there express the corresponding sentiments of the Roc group most admirably, there is no need to recapitulate the entire subject matter here. The present note will therefore be restricted to such supplementary remarks as appear appropriate to convey or preserve incidental bits of experience which were peculiar to Roc, to its developmental history, or to the personnel engaged in the project.

Of the five types or categories of missiles enumerated by Dryden, namely, (1) autopilot-launched, (2) suicide-pilot directed, (3) remote-vision guided, (4) beam-borne, (5) self-homing, Roc started out as a project of type 4 (beam-borne); it was then developed toward type 5 (self-homing) and finally built as type 3 (remotely guided), adapted to a variety of intelligence devices. While the advantages of versatility under conditions of rapid changes of the fortunes of war are impressive, it must not be overlooked that the price of versatility is compromise of performance. The best device for any particular purpose is likely to be the one specially designed for it and nothing else. The best procedure, however, is not necessarily to lay down a utility specification and then have someone else meet it, but rather to make a careful study of the prospective merits and penalties of variations of any tentative specification.

Many viewpoints of a technical, tactical, and strategical nature have to be reconciled. This requires the close cooperation of specialists in many fields, who should have some understanding of the realms of neighboring fields. The necessity for intimate coordination at the research and design levels has already been stressed in Chapter 12. Equally close coordination is needed between design and preliminary research on the one hand and flight testing on the other. In fact, flight testing might well be considered more as a part of the research activity than as a function of proof testing, involving as it does technical problems of considerable magnitude in itself.

Flight testing in the Roc project was the responsibility of the same organization as research and design. The advantages of this union were keenly and frequently felt. So was (while it lasted) the relative proximity of the testing range to the location of the engineering organization.

Guided missiles have been classified according to a great variety of viewpoints. One of these is that of the trajectory slope. Distinction can be made between (1) bombs falling essentially in a ballistic trajectory corrected only by a small fraction of the height, (2) bombs beginning to fall in a ballistic trajectory but possessing aerodynamic devices to deflect them appreciably from a passive trajectory through a distance commensurable with the height, and sufficient to make an accurate bombsight approach unnecessary, (3) glide bombs which develop enough lift to carry their own weight in a steady glide and travel a distance several times the height of release, and (4) propelled missiles capable of climbing to considerable altitudes.

Of these, the Roc project was deliberately assigned to fill category (2), the moderately steep dive bomb. Tactically, it is closely related to category (1), the steep high-angle bomb, from which it differs essentially by the concession of a wing system which exceeds the caliber-circumscribed box so that more lift can be generated than by any system wholly contained within the dimensions of such a box.

14.2 WING SYSTEM

When a wing system is to be attached to the bomb body, the problem arises of how it should be arranged. One school of thought favors an arrangement after the manner of an airplane, with the wings in one plane generating lift normal to that plane only; this requires banking of the vehicle into such an attitude as to tilt the lift into whatever direction is desired. This is the natural configuration for flat-flying or gliding bombs, which have to develop lift to balance gravity at all times and may require only secondary and occasional corrections in other directions.

On the other hand, missiles designed to fly steep paths (or, for that matter, those required to generate lift amounting to multiples of the path-normal component of gravity) may be called upon to develop lift quickly in any direction. This may demand large and rapid changes of roll attitude of a monoplane vehicle and therefore require a powerful aileron system. In a conventional airplane, the span and hence the available aileron leverage are large, the roll damping is appreciable, and the moment of inertia against rolling is relatively small. If, however, the wing system of a missile is of small span compared to the radius of gyration, and if the aileron loading is of necessity high, as in a dive bomb, then it is more difficult to generate and control large rolling moments to initiate a rolling motion and to stop it in time. This problem becomes particularly severe when the lift demand drops to or near zero, only to increase again in the opposite direction without much of a lateral component present. It is here that the advantage of providing wings in all directions makes itself felt, and this is why arrangements of three radial wings at 120 degrees to each other and of four cruciform wings at 90 degrees were tried and a universally jointed ring wing finally adopted in project Roc. The extra drag of the wing component not needed at any one time can usually be tolerated on a gravity-propelled device. As to the extra apparatus, it is a question of weighing it against the more powerful and elaborately controlled aileron system otherwise required.

It is interesting to note that the Germans, independently, seem to have come to a similar conclusion; their steep-angle guided bomb, Fritz X, was equipped with cross wings, originally at an obtuse dihedral angle, later at 90 degrees to each other. In steep-climbing antiaircraft rockets, the drag of the extra wing may be more serious. The Germans had not settled this question; of their four foremost antiaircraft and two air-to-air missile projects, Rheintochter, Wasserfall and X-4 had cruciform wing systems while Enzian and the Schmetterling missiles were banking monoplane structures. It is interesting to note that the former were under development by ordnance experts, the latter by airplane manufacturers.

14.2.1 Roll Stabilization

The problem of wing configuration around the projectile axis is intimately linked with the problem of roll stabilization. With cross wings or their equivalent it is possible, though not necessary, to stabilize the missile in some particular roll attitude relation. Such stabilization is advantageous where it is desired to maintain a certain geometrical correlation between a remote control gear on the one hand and range and line response of the missile on the other.

This was the case of Roc 00-1000V[a] when controlled towards a collinearity program by direct vision in the Carp sight; a suitable type of roll stabilization gyro system, already developed for Azon and its descendants, was therefore adopted for Roc 00-1000. Other types of roll stabilization, however, can also be adapted to Roc or the Roc missile to them, provided the guidance system is emancipated from geometrical correlation with the original target orientation and is based either on a televised image or is wholly automatic and bird-contained.

One such roll stabilization system may be evolved from a gyroscope aggregate arranged to maintain the elevator axis horizontal. This has a certain advantage when it comes to compensating automatically for the computed gravity effect on path curvature, because then only the elevator system need be equipped with the gravity compensator; the rudder remains entirely unconcerned with gravity. This type of roll control may be advantageous when guidance is wholly by automatic target seekers or by television, not by direct vision or any other remote-control system which would lack recognition of vehicle orientation. In all other roll stability or control schemes, gravity will generally deliver a component into each of two orthogonal control planes, which may be aerodynamically equivalent (as with cruciform and annular wing systems) or which may perform different pitch and yaw functions (as in a truly banking vehicle).

Where the gravity components are not to be computed but are expected to take care of themselves because the missile's control system is designed to sense higher derivatives of path errors, roll control can be relaxed. In fact the vehicle may be permitted to roll without preference for any particular attitude,

[a] Roc 00-1000 is the designation of the Roc missile with ring wing and ring tail and 1,000-lb warhead; "-V" denotes the version adapted for direct vision guidance, "-T" denotes the version guided by television; Roc-X was the earlier experimental model with cruciform wing and empennage.

but prevented from rolling too fast and making its intelligence "dizzy." This system, in the opinion of many, exacts lesser demands of the gyro-dynamic apparatus than that of positive roll attitude control. Roll attitude remembrance, however, is necessary for a commutator to distribute the proper instantaneous pitch and yaw components where guidance is by remote control, or where gravity correction[b] is to be properly accomplished (without recourse to a televised horizon[4]). In the German antitank missile X-7, Max Kramer went so far as to make a monoplane vehicle deliberately roll at about 2 turns per second while flying on an essentially horizontal path; thus, antigravity lift was made only half the time, and a very fast response of the aerodynamic controls to the commutated signals was required. For this purpose he advocated the flow spoiler type of "interrupter" controls, which absorb remarkably little power. It would appear that this device conjures up a number of new difficulties for any precision intelligence system and for the dynamic response speed of the entire missile. Nevertheless, the fact that the design trend toward deliberate rolling of the missile was adopted in at least two groups of German projects[c] toward the later phase of the war, even though these projects were sponsored by individuals of considerably different background, is notable.

There is also another possibility of providing effective roll control without attitude control of the body of the missile, namely, by articulating the wing system on the body so that the one can roll with respect to the other, stabilizing the wing system only but letting the body assume whatever roll attitude it may. This system has merits where the wing or lift controlling system is very compact (more so than on Roc) and of relatively low moment of inertia in roll. No such device seems to have been developed by the Germans.

The free-flying missile has six degrees of freedom, which may be defined as three components of translation and three components of rotation. When referred to an airborne system, the three rotation components are not of equal significance for the guidance of the missile; rolling rotates only the vector of aerodynamic force generated by the missile, whereas any angular motion in pitch immediately produces changes in the magnitude of the force and thus affects the path curvature in its own plane directly. In yaw the situation corresponds to that in pitch if the wing is not a monoplane structure but cruciform, annular, or otherwise effectively symmetrical around the longitudinal body axis.

14.2.2 Lift Control

If the (main) wing is entirely rigid and fixed to the whole vehicle, then its lift can be varied by merely controlling the angle of attack of the vehicle; this is usually done by means of a separate aerodynamic control element (elevator) at some leverage from the center of gravity producing a trimming moment. In order to achieve a stable motion under control, the wing and empennage system must be so controlled that a restoring moment is evoked by the accrual of an angle of attack until moment equilibrium is attained against the deliberately produced trimming moment of the elevator. However, the tilting of the vehicle from the flight path takes time after the elevator has been applied; inertia comes into play, and a pitch oscillation is initiated, the dynamic stability of which requires investigation. The heavier the wing loading of the vehicle in comparison to the velocity head, and the shorter the coupling, the more serious this dynamic problem is likely to become. The leverage of the control surfaces may be positive or negative, corresponding to a Canard type of head controls on the one hand and to conventional airplane tail controls on the other. In the former the control-surface lift is additive to the wing lift; in the latter, subtractive.

In high-speed missiles the tendency is for the wing span to be limited and not large in terms of fuselage width, as compared to conventional manned aircraft. Hence, in such a missile the lift generated by the body or fuselage when riding at an angle of attack is appreciable, like the dynamic hull lift of a dirigible airship. It is therefore possible to equip such a missile with a tail-less wing system and yet provide a fair leverage for control. Since an elongated body or fuselage is inherently unstable in attack, these tail-less wings must be positioned aft of the center of gravity and perform the duties of fins as well as wings ("fings"). The speed of response in attaining the attack attitude commanded and the dynamic damping of the ensuing pitching motion here become problems of special significance.

[b] In the early experimental Roc-X missiles, primary gravity correction of flight path was not attempted; hence no position gyro and no commutator were provided.

[c] X-3, X-4, X-5, X-6, X-7, Rheintochter-3.

In Roc the original plan was to forgo the lift contribution of the fuselage or body and generate the lift exclusively by the main wing system as close to the center of gravity as possible, and to provide sufficient arrow stability to force the vehicle to ride at zero angle of attack of the fuselage. It was believed that this would simplify the control of self-homing and television guidance to such a degree as to justify the moderate sacrifice in maneuverability otherwise attainable. Encouraging results were obtained with experimental Roc-X missiles which had cross wings, radial interdigitated fins, and generous span at moderate wing loading. However, when it came to designing the heavier production article, clearance-space limitations for it underneath the wing of the Navy's carrier airplanes led the design compellingly to the adoption of an annular wing as a more compact lift-generating device; because larger moments of inertia resulted, an equivalent dynamic stability was not retained.

14.2.3 Trim Stability

The trim-stability characteristics of Roc 00-1000 are such that an initial trim disturbance would, according to calculations and extrapolations from wind-tunnel tests decay in the form of a weakly damped oscillation, the frequency of which may vary from about 0.25 c at low airspeed and density, to about 0.75 c at high airspeed and density, while the amplitude would subside to about 60 per cent per cycle. In actual flight drop tests, oscillations of approximately the computed frequency have been observed but the story of their subsidence is not so simple. Occasionally the oscillations seem to decay slowly; on other occasions, however, they seem to persist, or even to increase temporarily. Whether these anomalies were the result of casual disturbances or a symptom of conditional or quasi-instability has not been definitely established. It is possible that trim stability is dependent upon and sensitive to localized downwash, wake, flow detachment, and interference effects which may vary intricately with wing incidence in pitch and yaw as well as with Reynolds and Mach number, especially because of the flow constraint between the wing ring and the fuselage. The influences may be more pronounced in the regime of higher speeds than those explored in the wind-tunnel tests that were made. It is also possible, in self-homing or television guidance, to fan such oscillations by involuntarily introducing a phase lag between oscillation and control. Any attempt at avoiding such fanning by smoothing out the control, or the missile's response to it, over the period of a cycle or more is tantamount to a delay in control which may sacrifice precision of interception. On the other hand, it should be possible to damp the oscillation greatly and speed up its frequency by anticipation. A suitable device may take the form of an autopilot boost system responsive to gyroscopically (or optically) determined pitch rotation, or better yet the form of an automatic elevator servo boost responsive to the local angle of attack at the tail, in order to increase both the decrement and the frequency of the oscillation.[d] The booster must then be adapted to actuate an elevator at reasonable long leverage to the center of gravity.

In Roc 00-1000 the entire wing ring is articulated in a Cardan joint. The moment of inertia of the wing system constitutes about 3 per cent of that of the entire missile; hence, according to the law of conservation of angular momentum, the execution of a wing incidence command of 0–13 degrees would, aside from all aerodynamical trim effects, tend to produce an angle of attack of −0.4 degree. This may not be serious but theoretically it means that, to a small extent at least, incidence control will also superimpose a slight attack disturbance.

14.2.4 Incidence Control

With an annular wing, tilting the rigid ring as a whole on a universal joint is obviously the mechanically simplest method of incidence control, whereas with radial wings many other methods besides tilting the whole wing have merits; two have been considered and tried on experimental Roc-X models—full-span flaps with internal and external balance. The choice between these and other possible incidence-control methods is mainly governed by aerodynamic considerations: (1) the lift coefficient should be a smooth, nearly linear function of the control displacement in the entire speed range; (2) the torque required to produce the displacement should be low in the entire speed range; (3) whether the torque is a monotonic function of the displacement or not is not necessarily of much importance so long as the control system is irreversible or gustproof by virtue either of

[d] Such a booster will be even more important on guided antiaircraft missiles which have to be precisely controlled in much thinner air than guided bombs.

friction or of the servo circuit chosen. A small unstable torque at low deflection is easily tolerable if it helps to keep the maximum restoring torque at high deflection a bit lower, provided the system is free from backlash.

In the development of Roc, the design of the control balance was based essentially on computation. Attempts were made in the wind tunnel to obtain rough checks of the adequacy of the servomotor drive to provide the necessary torque, but these efforts were seriously handicapped by the relatively low speed of 185 mph available in the wind tunnel and the uncertainty regarding the behavior of Reynolds number and Mach number effects at speeds higher than the test speed. The flight drop tests made with the finished Roc model revealed much useful information but they were not sufficient in number to afford opportunities to explore all the factors governing control efficiency and adequacy. Therefore, thorough wind-tunnel tests at full scale and full speed and numerous systematic drop tests with complete instrumentation cannot be too highly recommended where scientific procedure is not overruled by the pressure of military exigency.

14.2.5 Maximum Lift Demands

The maximum amount of lift to be demanded of a missile has been the subject of a good deal of controversy. For a given design the maximum lift that can be generated is determined by the velocity head, the wing loading, and the stalling characteristics of the wing configuration; the stalling characteristics, however, may themselves be influenced by the Mach number. The maximum lift which can be borne by the structure without failure in strength or velocity may limit the permissible incidence at high velocity; brakes may be installed to safeguard against excessive loads. The highest maneuverability demands of any guided missile are likely to occur during the last phase of the flight in an effort to convert a miss into a hit. In a bomb (contrary to an antiaircraft projectile) this phase lies in the region of highest velocity head and hence highest maneuverability. Because both lift and centrifugal force evoked in a deflected path are proportional to the square of the velocity, the geometric effectiveness of an aerodynamic lifting device can be expressed independently of velocity V, in terms of path curvature $1/r$ forced upon a missile of mass M by a wing system of effective wing area A and at an incidence producing a lift coefficient C_L (in the absence of a gravity component—for instance, as deflection from the vertical); that is,

$$\frac{MV^2}{r} = \tfrac{1}{2}\rho A V^2 C_L$$

hence

$$\frac{1}{r} = \tfrac{1}{2}\rho A \frac{C_L}{M}$$

but it remains proportional to the air density ρ. Roc 00-1000 was designed to have a performance equivalent to a path-curvature radius of 7,500 ft from the vertical at sea-level density. At a terminal velocity of about 700 ft per sec, the centrifugal force evoked by such a turn amounts to approximately $2g$. Computations of sample trajectories had shown this amount of agility necessary to execute a sail-dive program according to the Carp technique to attain early collinearity at release speeds of the order of 200 mph and altitudes of 15,000 feet and still leave a fair margin for the superimposition of manual remote corrective control.

With television control, however, there is no compelling reason upon which to base a prediction of how much maneuverability will be necessary; such factors as field of vision encompassed, orientation of optical axis, wind or target speed to be overcome, and distance from which interception maneuver is to be begun, all have a bearing upon the maneuverability required to score a hit. To accomplish circular interception with controls full-over, the minimum distance at which leading must start is $R_0 = 2rU/V$; hence for $r = 7{,}500$ ft and $V = 600$ ft per sec,

U =	20	40	60	ft per sec
R_0 =	500	1,000	1,500	ft

aside from any gravity component which may be impeding in a rear- or up-wind attack, or aiding in a head-on or down-wind attack.

14.2.6 Lift Control Rate

The following questions now arise. How fast must the controls be capable of changing lift, say from zero to full-over, and should this rate be fixed or controllable? If controllable, then should the integration of the control speed, i.e., the determination of the control angle, be accomplished on the guider's station or on the bird? This latter question asks whether it is the control speed or the wing incidence angle that should be signalled. In the experimental Roc-X missiles, control speed was signalled because the bird was permitted to roll and no means were provided to ascertain the instantaneous roll attitude; hence, none were available to compute the proper incidence angles to allow for gravity.

These points have been made: (1) the actual physical quantity which it is desired to control in order to achieve interception is the position of the missile in space; (2) velocity components, acceleration components, and jolt components are the first, second, and third derivatives of position; (3) the higher the order of the derivative controlled, the greater the delay in executing the maneuver and in relaying the information of its success to the guiding agency. Hence, it should be desirable to guide by operating on as low a derivative as possible. Rudder or wing incidence essentially defines the transverse-path acceleration of the vehicle (second derivative of position), rudder speed the jolt (or third derivative of position). Deliberate control of the former thus appears faster but it requires knowledge of other accelerations (for instance the gravity components) present. There is no doubt that incidence-angle control is mechanically simpler, more foolproof, and intrinsically more efficient from a power-conservation viewpoint than incidence-speed control.

As to the speed attainable in moving the control element, it depends upon the servo power available and on the degree of balance of aerodynamic forces achieved; Roc's control speed was not so fast as to make the inertia of the controlled mechanisms a significant factor. On vehicles controlled from the tail, secondary influences, such as downwash wakes and aerodynamic interferences, make it difficult to achieve high-precision balance over a large range of incidences with simple mechanisms (except possibly with spoiler types of control). Obviously the torque balance problem is more severe when the main wing, which generates the whole lift, is to be controlled than when only an elevator is controlled, which generates only the small forces needed to serve as an air-impelled servo device and to operate on the main wing via the fuselage leverage. The advantage of direct wing-incidence control which is bought with the more precarious torque balance or power penalty should be a greater response precision of the vehicle as a whole, provided it is thereby relieved of disturbances due to angle of attack. Therefore, to fully justify the type of wing control of Roc, it would be desirable to complete the investigation into the origin of observed attack oscillations and into the prospects of devising means to prevent them.

14.2.7 German Lift-Control Systems

Some of the German designers have favored "trembling" spoiler controls, in which the amplitude of the control movements are almost always in excess of those needed and the speed of the control movement is also much faster than any response desired, the missile smoothing out the response by the effect of its own inertia in the course of integration over sensible periods. Even if the trembling is done at natural resonance frequencies, it would seem that this artifice is predicated upon precise balance and upon indirect control via elevator and fuselage angle of attack.

The Germans also devoted a great deal of study to the theory of the so-called *Black-White* or *Yes-No* type of key control, in which the signals are not quantitatively modulated but pulsed, the length of each pulse governing the accumulation of response at a definite servo rate. The mathematical treatment of Yes-No types of control, especially when lags are taken into account, becomes rather involved because linearizing simplifications become treacherous. The advantages of intermittent control signalling systems presumably lie in greater simplicity and jamproofness of the receiver decoder for radio remote control. It would seem, however, that their application should be limited to devices whose tremble frequencies are a good multiple of the natural response frequency and whose torque requirements are not critical.

14.3 ROC GUIDANCE

14.3.1 Roc Radar Beam Rider

As to the type of intelligence to which Roc was to be adapted, there have been repeated revisions of opinion during the course of the development. Roc started out as a vehicle for a radar beam rider. Later it was intended as a radar-homing bomb. Subsequently, other homing target seekers were considered, among them acoustic and heat-homing; photoelectric target seekers were actually tried out in drop tests. In 1944 a serious effort was made to press Roc into service for direct collinearity vision radio control. Simultaneously it was developed as a vehicle for television control. These changes of policy were dictated by the advancement and delays in the development of the intelligence devices and by encouraging or discouraging results obtained with them. Varying strategic considerations also bore an influence on the program as World War II progressed.

The beam-riding bomb project was shelved in 1943 because it was believed (1) that it would be difficult to train the beam from the parent airplane on the target and to lock it thereon so precisely and steadily that the bomb would not be constantly subjected to excessive and abrupt control commands by the beam jitter; (2) the precise transmission of roll-phase information down a slanting beam from a parent airplane executing evasive maneuvers was deemed a difficult task at the time; (3) the accelerations imposed upon the bomb when the parent airplane executes evasive maneuvers was appreciable, and considerable maneuverability would be required of the vehicle if it was to meet this contingency. It was then thought that the development of a radar target seeker responsive to an echo from a target illuminated from the parent airplane or another airplane farther behind would be a less ambitious task.

Later experience indicated that this conclusion may have been fallacious. Although success was achieved in feeding the output of a radar-beacon-homing receiver into a differentiating and smoothing amplifier suitable to actuate the controls of Roc-X, flight tests aimed at measuring the reflection from foreign-illuminated target ships at sea gave discouraging results in that reception from the upper quarters from which a moderately-steep-angle bomb would approach was handicapped by sea return clutter. Until a new way could be found by the radar experts to get around this difficulty, radar homing seemed limited to flying or gliding vehicles coming in on a flat approach path.

14.3.2 Heat Homing

While no attempt has been made to equip Roc with heat-homing devices for drop tests, it would seem to be reasonably certain that Roc should be at least as suitable a vehicle for heat homing as the Gulf bomb is in project Felix if there is any tactical advantage in the greater inherent maneuverability of Roc.

14.3.3 Remote Guidance

Any kind of automatic target seeker must comprise a discriminator element which recognizes the target as such and distinguishes it from its background and environment. Camouflage, decoys, and other ruses complicate the technical problem of target discrimination. It is therefore desirable to leave this part of the job to the human brain which still can apply judgment in a more versatile and delicate manner than any man-made machine characterized by anticipation and standardization. To apply judgment on the spot means either a suicide pilot or a guider close at hand but at a (relatively) safe distance, transmitting his services by radio from the parent airplane (or from an advanced ground station) to the falling bomb.

14.3.4 Guider Station Control

From the viewpoint of economy of the expendable article, it is naturally attractive to dispense with all target-sensing apparatus on the bird and to rely entirely on the recognition and intelligence directly available at the guider station. Fundamentally, this amounts to tracking both the target and the missile from the guider station and guiding the missile in such a manner that the two tracking rays coincide either at or prior to impact. Theoretically, for this purpose it should suffice to treat the missile as a mass point, provided its attitude is a unique function of the control-command history. Since unaided and undisturbed ocular vision from aircraft has a discriminating power of approximately ½ mil, it is tempting to rely on direct vision of bomb and target from the parent airplane for aim. However, it would be over optimistic to expect that the potential hitting accuracy would be equal to the visual acuity in detecting an error in aim. To arrive at a more reasonable expectancy, it is necessary to assess the accuracy with which the aim can be held continuously for some time prior to impact. On the other hand, some improvement of resolving power can be attained by resorting to moderate optical magnification in the sighting device, provided the telescope is gyrostabilized against vibration. A prerequisite of any point-aiming scheme is that the parallax between target and missile, during the critical guiding period at least, is either quite small or else rather accurately computed and subject to derivative measurement in control. An encouraging amount of success has been achieved by some techniques of collinearity or three-point-alignment guidance. This principle, including the stabilized telescope, was exemplified in this country by the Azon and Razon projects and the Franklin Institute's bombsight projects Crab and Carp, and in Germany by both Max Kramer's X-bomb projects and H. Wagner's Henschel glide-bomb projects.

14.3.5 Carp Apparatus

Roc was brought into this picture as a compromise. It promised to have enough maneuverability to attain target collinearity after a sail-and-dive Carp program without imposing serious zoom-and-slow-down restrictions upon the parent airplane. On the other hand Roc's potential feature of riding at or near zero angle of attack of the fuselage was wasted on a remote-vision technique in which the missile was treated as a mass point only. In fact still more lift per wing diameter can be attained if the fuselage is permitted to assume an appreciable angle of attack; a Gulf type of bomb with a fixed ring wing and a controllable tail would accomplish this purpose in a simpler manner than Roc with its more expensive Cardan-jointed wing ring. However, the pending development of Roc as a television vehicle seemed to promise a fairly maneuverable missile to become available for Carp technique sooner and as a by-product, so that this course of action was adopted.

Actually the development of the optical, navigational, and practical aspects of the Carp apparatus and technique turned out to be a much larger project than was anticipated by its proponents. To expedite its completion would have required a more generous assignment of test missiles and research manpower, as well as a deliberate advance development of all component parts of the system (flare, Carp sight, radio link, roll stabilization, and bird mechanism) before attempting to test the complete article. That a good solution for the collinearity-guided bomb would be of considerable interest there can be no doubt, especially in view of the fact that in antiaircraft techniques there is a definite trend toward making full use of the collinearity-aiming principle. The Germans claim to have achieved considerable success with it in drop and glide bombs. However, the problem of stabilizing the bird in roll so as to retain correspondence or range-and-line correlations on the bird and on the guide station will be aggravated when the guide-station carrier is allowed to perform evasive action to outmaneuver antiaircraft defenses.

14.4 TELEVISION CONTROL

14.4.1 The Observer's Task

The advent of Mimo television equipment small enough to be accommodated on a vehicle such as Roc raised the problem of how to interpret the television picture and how to govern the control command to be given in response to it. The observer of the television screen has to perform the duty of the discriminator; he chooses and holds a target that can be recognized on the screen by the human eye but does not necessarily have such outstanding features that fully automatic apparatus could follow it while its image appears to change in size and perspective. Otherwise the guider's function is but a link in the chain of an automatic regulator loop, though he may, depending on his understanding, experience, and skill, also introduce corrections to allow for known deficiencies of the remote control and regulating circuits.

Attempts have been made to steer unmanned aircraft and automatic flying missiles by radio remote control toward a target seen by a television camera carried on the missile and observed on a television receiver elsewhere. These experiments have taught that to direct the missile into the vicinity of the target is one thing—to score a hit is another and much more difficult task. The reasons for the difficulty are not obvious. In fact it has been argued by some that steering the vehicle by watching the television screen should be no more difficult than to fly an airplane while looking through a small windshield and gunsight; even the apparent enlargement of the target image upon approach should not complicate the task beyond that of the pilot of a dive or suicide bomber.

It seems that there are several major differences, to wit: (1) the pilot in a manned aircraft has a much greater field of vision, whereby he receives a great deal of helpful information, mostly subconsciously, partly by perspective, partly by reference landmarks; (2) the pilot receives vitally important secondary information from other than the visual sense regarding acceleration and rotation, which have an influence upon the coordination between what he sees and what controls he has to apply to effect any desired course changes; (3) the pilot undergoes elaborate training in spot landing so that he can practice the whole maneuver, except the very last suicidal phase;[c] (4) in conventional aircraft, lift is made in one direction, and it is necessary to roll and then to "unroll" at the proper orientation. The rolling maneuver can be readily learned in nearly horizontal flight and in nearly vertical dive, but it is much more

[c] It is understood that a remarkable number of Japanese suicide attacks missed their targets, indicating that pilots were insufficiently trained in the final phase.

difficult to learn in moderately steep phases. In Roc this difficulty is altered in that the pilot has to learn to coordinate pitch and yaw instead of elevator and aileron controls, but the gravity component influence remains confusing.

That training of the operator of television remote control is important has also been recognized, and simulators have been built in which the trainee sees a target area photograph gradually enlarge and move when the conventional control stick is manipulated, more or less as he would expect the image in a real flight to behave, while an instructor may introduce various disturbances. When operating such a simulator one begins to appreciate the magnitude of the task of learning how to parry these elusive disturbances.

14.4.2 Aiming Aids

There are reasons to believe that the job of learning the technique of steering to hit the target can be vastly facilitated by relieving the operator of as much of the estimating, anticipating, and parrying as possible, in exactly the same manner as a gunner is helped by a lead-computing gunsight and aided tracking. This can be accomplished by inserting a regulator in the reaction chain which leads from the operator's perception of the chosen target as some spot on the television scope screen to the application of a quantitatively metered-out amount of aerodynamic elevator and rudder control. In a conventional aircraft control system, the control stick primarily governs the rates of turn of the vehicle but it causes secondary displacements of the image by virtue of the banking necessary to veer and of the change of angle of attack accompanying any changes of lift. Wind and target evasive maneuvers introduce unknown disturbances which conjure up the complications of interception of moving targets in space. In any vehicle descending at a steep slope angle, like Roc, information about the amount of trajectory deflection due to the gravity component normal to the path tangent is not well conveyed by the television image; therefore, it appears as an unknown disturbance.

In this connection it is interesting to note that during Mimo-Roc tests observers were led to experiment with two-man control, each taking care of the aim in one component direction only. This was meant to be a temporary expedient while operations were still hampered by various troubles. The Germans also experimented with two-man operation, though in a different manner: in collinearity guidance of a glide bomb, one man would roughly aim a master telescope while the other would sight through a repeater telescope and operate the remote control of the missile. Otherwise the Germans went to great trouble to render one-man operation more convenient and effective by developing means for training in proper coordination. Matters of this kind, involving psychological and physiological problems, cannot be solved dogmatically by theoretical analysis alone. It is for their solution that the advent of simulators is of particular significance.

Definite advantages are seen by some in the idea of providing the bomb guider with a control device that reduces his job from that of a flier piloting an aircraft to that of a gunner aiming a gun or turret. The underlying philosophy is that this is much more a gunner's than a flier's job and that it is neither necessary nor natural to fly an aircraft in an aerobatic maneuver. In the ideal device, all the estimating, extrapolating, and leading would be relegated to a regulator or computer so that the gunner's task would be reduced to maneuvering a reticule or bead onto the chosen target image.

Suitable steering equipment will then comprise a reticule or bead system which is directly or indirectly movable over the surface of the television receiver screen. As to the most convenient method of moving this reticule, there are two schools of thought.

In one, manipulation is accomplished by means of a direct mechanism, after the manner of a pantograph pointer or a telautograph tracing a pattern; this method is most directly borrowed from the idea of aiming a gun towards a target and is particularly convenient when the inertia of the apparatus is negligible and where jerkiness of manipulation is inconsequential or self-averaging. The linkage of the mechanism can be equipped with suitable electric pickups which feed into an electric computer. The latter computes the control values to be signalled to the missile via the radio link.

The other idea is to motorize the movement of the reticule and to control it after the manner of a motor control, speeding it up or slowing it down to "go after the target" or intercept it in due time. The latter method requires a little more indoctrination to master but it has the advantage of lending itself better to a mechanization of the pickup of the reticule speed.

An optical beam projector can be made to serve the same purpose as a mechanical reticule holder. This projector can be mounted in a universal joint or it may comprise two coordinate-line projector elements, throwing a luminous image of a reticule pattern upon the scope screen from the outside of the oscilloscope but within the hood. The light can be of a color contrasting with the fluorescent target image.

Eventually an electronic reticule image can be developed, for instance, by producing a couple of bright (or dark) spots on one vertical scan line. The vertical lead motion would move the spots along the line, and the horizontal motion would select an earlier or later scan line. The aiming point could be the virtual center between the two pip spots so that the target itself is not blotted out by them.

14.4.3 Camera Installation

At a relatively early stage of the Mimo-Roc, it was arbitrarily decided to mount the Mimo television camera (fixed coaxially in the Roc head) looking forward. It was hoped that the advantages of flying at zero angle of attack would reduce the reasons for a squinting or nodding eye. It was realized that several disadvantages would have to be suffered as a consequence of this design choice: (1) navigational lead would have to be limited to half the field angle encompassed by the camera, (2) the target would not come into view until after about the first third of the fall time had elapsed, and (3) any tendency of the vehicle to suffer disturbances in angle of attack would have to be effectively subdued.

As to the first of these three penalties, it was felt that a reasonable compromise could still be achieved with a field angle of 20 degrees, at which a properly led target having 20 per cent of the missile speed comes close to the image edge. As to the second problem, a removable down-view prism was developed which afforded a view of the target during the flight approach before release, so that target contrast and television reception could be checked directly. The first phase of the drop would then be blind for about 12 seconds. In order to enhance the probability of the target then coming into view, an unorthodox bomb-run-approach technique was developed which tended to minimize the crab angle. Similarly a variety of methods of choosing the release angle can be considered:

1. One is defined by the ballistic trajectory of the passive missile i.e., with controls zero, and determined in a conventional bombsight-tracking procedure; this obviously affords a maximum of physical possibilities of correcting random bad aims.

2. Another method utilizes a late drop, requiring some early diving results in a very steep or nearly vertical impact which may be tactically desirable against certain types of targets and which has the advantage of minimizing the path-deflecting effect of gravity, possibly to the point where the effect can be neglected; the tactical disadvantages of a late drop are belated arrival of the target proper in the field of television and greater exposure of the parent aircraft to antiaircraft defense of the target.

3. A sail-dive program, after a sufficiently early release, has the same advantages without the excessive exposure to antiaircraft, but it may increase the chance of the missile veering too far off laterally.

4. An early release with a relatively flat glide toward the target is a favorable technique as far as early television of the target and minimized exposure are concerned, but it requires more careful treatment of the path-deflecting gravity component, extends the flight time, reduces the impact speed and angle, and encroaches upon the forward-range-correction tolerance.

14.4.4 Compensation for Wind and Target Motion

Obviously it would be strategically most desirable to provide the missile with the equipment necessary to accomplish all these tactics and to leave their choice to the individual mission crews. Sufficiently precise gravity correction would have to be provided for this purpose. The question of what should be done to take care of the influences of wind and target motion, which are functionally equivalent, has come in for a great deal of attention.

If a missile is so controlled that it tends to center the target in the field of a fixed eye, then an approach develops into a pursuit curve, and the question arises of how far the missile will miss under typical conditions of target or wind speed not being compensated for by navigational interception. The bird will miss if it does not lead the target because, in a pursuit approach at large speed ratio, the rate of turn required to keep the aim of the target is small at first but increases toward the end phase until it finally exceeds the agility of the missile. The redeeming feature is that while the missile can at best wind up in its tightest circle osculating the pursuit spiral, the total miss may not be so large as to be objectionable, nor even larger than the inevitable errors due to other causes, especially when the wind or target speed is moderate. A rough idea of the order of magnitude of the miss can be readily given on the slightly optimistic assumption that the link and servo system lag is negligible.

Under this assumption the miss is defined as the difference between the distance Ut yet to be traveled by the target at speed U and the deflection of the

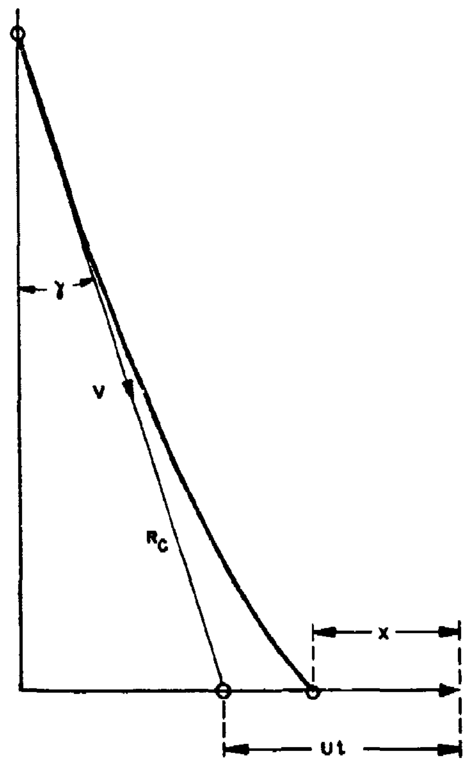


FIGURE 1. Angular relations in range-vertical projection of pursuit curve.

path from the last tangent at which maximum available control was attained, i.e., at the critical range R_c, under the combined influence of the path-normal accelerations due to this control and due to gravity. (See Figure 1.) The available control is characterized by the minimum turning radius $r = V\dot{\gamma}$, so that the acceleration due to it is $\dot{\gamma}V = V^2/r$; the acceleration due to the effective gravity component is $g \cdot \sin\gamma$.

Hence, as soon as the path-curvature demand $(U\cos\gamma)/Vr$ exceeds the available maneuverability due to aerodynamic control, namely $1/r$, plus (or minus) that due to gravity, namely $(g\sin\gamma)/V^2$—that is, after passing the critical range $R_c = (UV\cos\gamma)/(V^2r + g\sin\gamma)$—a miss of magnitude $x = \frac{1}{2} R_cU/V$ is incurred.

The following table gives an idea of these critical ranges and misses for various values of target (wind) speed U and terminal path slopes γ_c.

		Critical range R_c in feet			Miss in feet		
	Degrees	$U = 20$	40	60	20	40	60
Tail-wind or bow attack	75	167	333	1,000	18	17	25
	30	225	450	675	11	23	34
	15	285	570	855	14	29	43
	0	350	700	1,050	18	35	53
Head-wind or stern attack	−15	410	820	1,230	20	41	61
	−30	455	910	1,365	23	45	68
	−45	420	840	1,260	30	42	63

It would seem that a quasi-scopodromic approach without automatic navigational lead is probably adequate for target and wind speeds up to about 40 mph. Some deliberate lead can perhaps be applied by the bombardier, aiming for the bow of a moving ship, or to the windward in case smoke indicated a strong wind in the lower strata.

The Mimo-Roc drop tests were conducted without benefit of a lead-computing device, although the need for some such device has been recognized and emphasized. It had been recommended that under reasonably favorable weather conditions none might be needed, at least until the television and control functions of the missile had proved practicable. As it turned out, about half of the drops were hampered by television troubles and the rest by angle-of-attack oscillations of the bird, either of which would have interfered with any precise lead computation, which, so far as it aims at interception of target motion or wind, depends upon a measurement of a rate of change of the target bearing as seen from the missile. This rate can be picked up directly from the target image speed as seen on the television receiver screen, provided the optical axis of the television camera remains pointed in the direction of the missile's airspeed vector. The most direct method of accomplishing this measurement consists in forcing the vehicle to ride at zero angle of attack, like an arrow. Whether Roc can be made to avoid unfavorable angles of attack, either by moving the center of gravity far enough forward or by auxiliary stabilizing controls automatically responsive to the least angle of attack and more effective in wiping out any disturbance than the fixed empennage now provided, remains to be explored. Theoretically this should be possible, but the apparatus required may turn out to be burdensome.

14.4.5 Compensation for Angle of Attack

If angle-of-attack oscillations and appreciable trim angles are not eliminated from the vehicle, then there are several possibilities of compromise.

1. The control command, or its execution, is made so sluggish as to smooth out the pitch and yaw oscillations, either by making it impossible for the guider to follow them with a geared-down manual control element (like the knobs tried out on the last two Mimo-Roc drop tests made thus far), or by means of electrical-mechanical smoothing devices inserted in the chain between the guider's manipulation and the command execution. Whatever artifice of this kind is resorted to, it will of necessity reduce the alertness of the response to the real target bearing derivative and introduce a time constant of the order of the period of the attack oscillation which is to be averaged.

2. The Germans were very conscious of the angle of trim because the vehicles on which they tried television were controlled by more or less conventional elevator systems. They experimented with television cameras mounted in a swivel joint on a sailplane and tilted mechanically by means of a pitch wind vane. For guided missiles they were sold on the idea of controlling at least the pitch angle of the optical television axis by a prism or mirror system governed by a pitch wind vane. In yaw, however, they believed that a banking monoplane missile could be endowed with sufficient arrow stability to avoid adverse yaw oscillations. In a vehicle possessing aerodynamical axial symmetry, like Roc, alignment of the optical axis with the flight path tangent, independent of trim oscillations, would necessitate mounting the camera in a universal joint[f] permitting several degrees of movement in any direction, and providing a means to govern the nodding motion by what amounts to a vector wind vane. Instead of building a mechanical wind vane, which has inertia and tends to oscillate itself, aside from being disturbed by the airflow past the vehicle, a three- or four-orifice pitch-and-yaw meter may prove easier to develop as a means to govern the alignment of the optical axis, and it can be made more rugged and serviceable.

3. If the camera were mounted in a Cardanic suspension on the vehicle, but so softly sprung like a seismometric mass that it will not appreciably participate in the oscillation, then it would of necessity also lag behind the rate of turn of the missile in its curved trajectory, possibly frustrating the advantages of such suspension.

4. In Germany, the DVL (Deutsche Versuchsanstalt für Luftfahrt) developed a pendulum scheme for orienting an optical system (a photoelectric contrast seeker, not a television camera) parallel to the flight-velocity vector. The scheme is based on the idea that the direction of the resultant airforce (vector sum of lift and drag) is a unique function of the angle of attack, presumably known from wind-tunnel tests. The optical system is mounted on a pendulum which is articulated on the missile by resting on a (three-dimensional) evolute cam body. It seems that some means to damp the evolute motion will be required to make this system practical; its self-containedness and freedom from aerodynamic appendages are distinct advantages.

5. A more indirect method of allowing for the angle of attack of the missile is also conceivable. It provides a pitch-and-yaw meter on the vehicle and transmits its readings to the guider or computer station via television or radio. If this is done via television, then the observer is burdened with having to read or interpret two pairs of coordinates from the screen, that of the target and that indicating the airspeed vector. If it is done by a radio signal, though possibly within the television channel, the data can be picked up and digested by a computer without bothering the observer.

14.4.6 Interception

If a computer is to be provided at all, then it is obviously desirable to make it do as much of the job as has a significant influence upon the hitting accuracy. The theory of interception by means of automatic target seekers has been studied by many investigators. There are various ways of effecting interception of a moving target. The theory must recognize and introduce the various influences which affect the giving of a control signal, the control effected thereby, and the result of the ensuing maneuver showing up on the scope screen and inviting further correction of the signal. The geometry of the orientation of the seeker with respect to the flight path has a dominating effect upon the presentation

[f] A pitch and yaw mirror or prism system would be very clumsy at best.

of a television picture and hence upon the guider's reaction. Various methods of changing, biasing, and regulating the orientation of the seeker's axis with respect to the vehicle's flight path have been proposed and tried by different investigators; they may introduce an artificial, mechanically controlled angle of squint between the axis of the seeker and the fuselage and may have to take account of whatever angle of trim of the fuselage axis against the flight path in air may remain unsuppressed; or else they may control the orientation of the seeker in space by gyroscopic means and measure the space orientation of the vehicle independently by similar means.

As to the interception maneuver to be executed by remote guidance, several alternatives offer themselves.

1. The least that can be done is to make the missile turn early enough so as to intercept before the turning requirements exceed the agility of the missile.

2. The geometrically most perspicuous proposition is to distribute the turning evenly over the entire flight path; this implies approach along a circular arc path. It is the path of least peak curvature and accomplishes the greatest path deflection for a given maneuverability. In the horizontal plane this is obviously also the method of least aerodynamic effort; in the vertical plane no similar criterion exists because gravity and density variation confuse the issue, the aerodynamic effort required being but the sum or difference of the force required to produce the geometric path curvature and of the variable gravity component already tending to produce some path curvature.

3. If ample agility is available, then it may pay to do the turning early, so that less turning is required later, and the path soon settles down toward a straight-line collision course which may be repeatedly or gradually corrected to frustrate evasive action by the target.

The geometry of interception can be conveniently expressed in terms of the angular velocity of the line of sight in a coordinate system to be anchored in the flying medium, oriented in such a manner that the angles to the line of sight τ and to the line of flight ω are measured from the normal to the line of target motion of presumably constant speed U with respect to the medium, viz.,

$$\dot{\tau} = \frac{(U\sin\tau - V)\sin(\omega - \tau) + U\cos(\omega - \tau)}{R} \tag{1}$$

which, for small lead angles $\omega - \tau$ and for large speed ratio V/U, can be approximated by the first order terms:

$$\dot{\tau} = \frac{-V(\omega - \tau)}{R} + \frac{u}{R} \tag{1a}$$

where V is the speed of the missile and $u = U\cos\tau$, the target speed component normal to the instantaneous slant range R.

The angular acceleration of the line of sight is then

$$\ddot{\tau} = \frac{(V\dot{\tau}R - V\tau\dot{R} - V\dot{\omega}R + V\omega\dot{R} - u\dot{R})}{R^2} \tag{2}$$

The range shrinks essentially at the rate

$$\dot{R} = -V$$

which condenses the above into

$$\ddot{\tau} = \frac{(2\dot{\tau} - \dot{\omega})V}{R} \tag{2a}$$

This means that the angular acceleration grows large, hyperbolically as the range R shrinks to nothing when

$$\frac{\dot{\omega}}{\dot{\tau}} < 2 \tag{3a}$$

$\dot{\omega} = 2\dot{\tau}$ makes $\ddot{\tau}$ vanish and produces a constant rate of turn $\dot{\omega}$. If the proportionality factor $\dot{\omega}/\dot{\tau}$ of control is not 2 but K, such that

$$\dot{\omega} = K\dot{\tau} \tag{3b}$$

then the choice of $K < 2$ causes the turning to lag and grow late, whereas $K > 2$ causes the turning to overdo at first and to diminish forthwith. A very large K leads quickly into a straight collision course.

To accomplish control according to equation (3a) or (3b) would require the measurement of the angular velocity $\dot{\tau}$ of the line of sight against a reference direction fixed in the medium or in terrestrial space. A practical method known to measure $\dot{\tau}$ directly consists of gimballing the eye on the bird, locking it on the target, automatically in the case of a target seeker or via radio remote control in the case of television and measuring its rotation gyroscopically, for instance, by governing the rotation through precessor motors or otherwise influencing a free gyroscope carried on the eye gimbal system.

After $\dot{\tau}$ is measured, the required angular velocity of the line of flight is thus determined in proportion. The amount of aerodynamic force to be generated in order to produce the rate of turn $\dot{\omega}$ can then be computed (if all ambient factors are known).

If the eye is not gimballed but fixed in the bird, as was the case in the Roc missiles, then angular velocity of the line of sight is not directly measurable with reference to terrestrial space but only that of the lead angle between the line of sight to the target and the bird axis, which latter is represented by the center of the television screen. The lead angle λ, is correlated to the absolute sight-direction angle τ by the identity

$$\tau + \lambda = \omega + \alpha \tag{4}$$

where α is the angle of attack, as illustrated in Figure 2. If the latter is forcibly kept zero then

$$\lambda = \omega - \tau \tag{4a}$$

is the current lead angle. Equation (3b) then becomes

$$\dot{\omega} = K\dot{\tau} = K\dot{\omega} - K\dot{\lambda}$$

hence

$$\dot{\omega} = \frac{K}{K-1}\dot{\lambda} = n\dot{\lambda} \tag{3c}$$

By way of examples:

$K = 1$	corresponds to $n = \infty$,	pursuit course
$K = 2$	corresponds to $n = 2$,	circular interception
$K = \infty$	corresponds to $n = 1$,	immediate turn into straight collision course

Any automatic control scheme based on equation (3c) directly would become unstable whenever K dropped below 1, as this would imply a negative value of n. This difficulty can be overcome by designing the automatic control regulator so as to take into account the fact that any deliberate change in $\dot{\omega}$ will entail an identical change in $\dot{\lambda}$, because such a change will not immediately affect $\dot{\tau}$, which is $\dot{\omega} - \dot{\lambda}$. Hence, the change $\Delta\dot{\omega}$ necessary to establish compliance with equation (3c) from a condition of non-compliance $(\dot{\omega}_1, \dot{\lambda}_1)$ for any chosen value of n is

$$\Delta\dot{\omega} = \frac{\dot{\omega}_1 - n\dot{\lambda}_1}{n-1}$$

whereupon the new image velocity $\dot{\lambda}$ indeed becomes

$$\dot{\lambda} = \frac{\dot{\omega}_1 - \dot{\lambda}_1}{n-1}$$

This means the servomotor system of an automatic regulator should be arranged to tend to reduce any difference between the existent value of $\dot{\omega}_1$ and a presently computed value $\dot{\omega} = K(\dot{\omega}_1 - \dot{\lambda}_1)$.

If n is some value other than 2, then λ does not tend to be constant, but

$$\dot{\lambda} = \frac{n-2}{n-1} \cdot \frac{V}{R} = \frac{cV}{R} \tag{5}$$

as can be seen by inserting equation (4a) into equation (2a). Consequently, since

$$R = R_0 + \dot{R}t = R_0 - Vt$$

$$\lambda = \lambda_0\left(\frac{R_0}{R}\right)^c \tag{6}$$

and

$$\frac{\lambda + u/V}{\lambda_0 + u/V} = \left(\frac{R}{R_0}\right)^{n/n-1} \tag{7}$$

but for $n = 2$, $\lambda = \lambda_0$ and

$$\frac{\lambda + u/V}{\lambda_0 + u/V} = \frac{R}{R_0} \tag{7a}$$

which states that an incidental lead angle has to approach the collision-course angle linearly as the range shrinks during the approach. When $n > 2$ the turning has to be done earlier, and for very large n it degenerates into the collision course. For n between 1 and 2 the turning has to be delayed, and the approach degenerates toward pursuit. For very strong negative n the pursuit tends to become clinodromic, i.e., it tends to maintain any existing lead λ_0 unchanged.

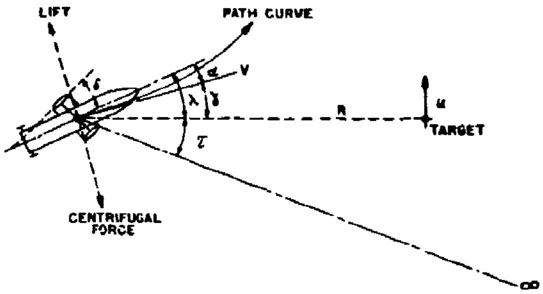


FIGURE 2. Angular relations in Roc trajectory.

The question of how the image speed $\dot{\lambda}$ can be picked up from the screen has already been touched upon. It can be done either by manipulating a reticule to coincide with the target image and measuring the derivative of its position or by motoring the reticule after the target image and measuring the motor speed directly, always provided no angle of attack α exists to enter into equation (4), or that such angle of attack is suitably determined and its rate of change subtracted from $\dot{\lambda}$.

Assume, now, that by this procedure and by suitable choice of the interception factor K or n, the desired rate of turn $\dot{\omega}$ is determined. The knowledge of $\dot{\omega}$ itself does not, however, suffice to determine the amount of aerodynamic control as governed by the wing incidence angle α and the lift coefficient C_L correlated with it. The latter is determined by the equations

$$\tfrac{1}{2}\rho A V^2 \frac{C_{L_P}}{M} = g \sin \omega_P + \dot{\omega}_P V \tag{8}$$

if ω_P is measured from the vertical, for a wing control component so oriented that its lift is in the pitch plane defined by the vertical and the flight path, while

$$\tfrac{1}{2}\rho A V^2 \frac{C_{L_Y}}{M} = \dot{\omega}_Y V \tag{8a}$$

without the gravity effect for the wing control component in the yaw plane, i.e., normal to the former. Hence

$$C_L = \frac{2M(\dot{\omega} + \sin \omega_P \cdot g/V)}{\rho A V} \tag{8b}$$

(the parenthesis term in pitch only).

If the elevator and rudder planes are not roll-stabilized with respect to gravity, then each of them will be affected by a component of g times the sine and cosine respectively of a roll angle suitably defined with respect to the horizon.

Since aerodynamic action depends upon air density and airspeed, the control sensitivity to λ should vary with these parameters. In other words, as the bomb drops into denser air and gains speed, the control commands should be attenuated, the λ term inversely proportional to ρV. Some German authors have emphasized the desirability of such progressive attenuation. Against it, the opponents of the idea have adduced the argument that since some leeway broadens the choice of the interception factor n, it ought to suffice to select a fair value for the middle run, condone some weakness of response in the early stage of the fall, and reap the benefit of sharper control toward the end of it.

There is, however, a solution which evades part of the issue by operating on the centrifugal force so that no knowledge or estimate of the air density is necessary. This scheme consists in signaling not a definite control-surface angle but the desired accelerational load factor n_p in pitch and n_y in yaw, viz., $n_p = \dot{\omega}_p V/g + \sin \omega_p$ and $n_y = \dot{\omega}_Y V/g$ respectively. Two servomotors are arranged to move the controls until two accelerometers match the signaled values. The airspeed still enters the picture. So does the method of roll stabilization.

As to the influence of gravity upon the missile's path, it can readily be seen that to compensate for it alone the bird should develop a lift coefficient

$$C_{L_g} = \left(\frac{2W}{\rho A V^2}\right) \sin \omega \tag{9}$$

upon which the lift demand for curving the path $\dot{\omega}/V$ must yet be superimposed. (W is the weight of the missile.) Equation (9) applies to that plane of the vehicle which contains the gravity vector. There are several schools of thought regarding how the variable values of ρ, V, ω should be determined and entered into the control-regulator system.

14.4.7 Mimo-Roc Computer

One school of thought prefers to arrive at the answer by means entirely contained on the parent aircraft so that no expendable apparatus need be installed on the missile for this purpose. The computer developed by Division 7, NDRC, for Mimo-Roc belongs in this category. The scheme amounts to an integration of the motion of the bird under an assumed or recorded history of the control commands given or not given. Such integration is afflicted with some uncertainty because of the accumulation of inevitable inaccuracies of zero setting and command execution. This inaccuracy, if it is of any consequence at all, can theoretically be reduced by telemetering the velocity head $\frac{1}{2}\rho V^2$ and attitude ω on the missile by means of an airspeed indicator and a free gyro. Whether a greater precision might actually be realized in this manner is doubtful in view of the difficulties attending any scheme of telemetering, whether it is accomplished by existing television or by a separate radio channel.

It has also been proposed to take care of the gravity influence by a series of trial-and-error glide-angle changes in which a straight collision course would eventually be reached after several discrete steps. The Germans tested this principle on one of their flat-glide bombs. The success of the scheme (which has a correlate in surface navigation) depends upon the time available and the precision of the determination of $\dot{\omega}$ and λ. In dive bombs it is hampered by variations of air density and airspeed, and by the brevity of time.

14.4.4 Computation on the Missile

Another method requires some expendable devices on the bird but has certain merits, especially that of being entirely independent of the television and command-transmission system—in fact of the entire command and lead-computing system. The gravity connection is separately computed on the bird and applied there. If it is to be done during all phases of the flight, an airspeed indicator must be provided to measure the velocity head $\frac{1}{2}\rho V^2$ and a free gyro to furnish ω and thus sin ω. The quotient of these quantities is then fed into the bird's amplifier or servo system so as to superimpose the value indicated by equation (9) upon whatever command arrives.

It so happens that the speed of the missile tends toward the condition of equilibrium between the drag and the axial component of gravity, viz.,

$$W \cos \omega = \tfrac{1}{2}\rho A_D V^2 \tag{10}$$

Substituting $2W/\rho V^2$ from equation (9) into equation (8) makes

$$C_{L_g} = \left(\frac{A_D}{A}\right) \tan \omega \tag{11}$$

where A_D is the equivalent drag area of the missile, which is approximately known (except for the induced drag, which depends on the lift coefficients).

Equation (11) shows that the correction is essentially governed by the slope angle ω. It tends toward zero near the vertical dive but would be large if the path were flat. Fortunately, in Mimo-Roc flat-flight path, phases are of no concern because the target is not yet in the field of view. It probably suffices to apply this correction for angles of ω greater than 45 degrees.

The angle ω can be measured by means of a bird-borne free gyro which is uncaged upon release. Unfortunately, the standard Schwien gyro aggregate, as it is installed in the direct-vision-controlled Roc-V, is not adapted to measure ω because its free rotor rotates as a wagon wheel with its axis in an unsuitable orientation.

The job can be done by means of a free gyro which has its spin axis vertical, a tan ω potentiometer on the outer gimbal, and roll-stabilizing contacts on the inner gimbal. The potentiometer could be so connected to the circuit of the present elevator-actuator follow-up potentiometers that it would bias the elevator radio signal by just the desired amount and make the actuator find the position, which is defined as the sum of the control command received by the radio link and the gravity-component correction. In this event the wagon-wheel gyro rotor can be dispensed with, the new spinning top rotor replacing the former and thus accommodating the whole gyro system in the same standard Schwien gyro housing. The roll-rate check gyro has to be retained. Although it cannot easily be coupled mechanically to the free gyro, the coupling can be accomplished electrically. The action of this new aggregate would not differ much from the conventional system in the early phases or so long as the flight path did not become very steep. If the missile came within a few degrees of a vertical dive, slight pitch or yaw control deflections might call for large roll adjustments to keep the elevator axis horizontal. This might overtax the ailerons and confuse the observer. Since in this condition the gravity correction would be very small anyhow, no harm is probably done by preventing rapid rolling through the roll-rate gyro.

The possibility of coping with roll stabilization by means of the standard Schwien gyro unit and of solving the gravity correction by means of a supplemental free gyro with vertical axis, transverse inner gimbal axis and fore-and-aft outer gimbal axis also presents itself. In this case the tan ω potentiometer would be driven between the gyro frame and the gimbal frame, and a sinometer between the gimbal and the bird itself. The sinometer would directly furnish the sine and cosine of the roll angle ϕ as the bird rolls with respect to the horizon when it is called upon to veer from the original heading, so that range and line control remain as originally oriented, while the elevator axis does not stay in a horizontal plane. A suitable circuit would then have to be devised to supply tan ω cos ϕ to the elevator bias and tan ω sin ϕ to the rudder bias.

14.5 Tests and Conclusions

In view of the multiplicity of methods and devices and techniques of steering a guided missile via television toward a target, too much emphasis cannot be placed upon the desirability of trying them out in nondestructive tests which duplicate or simulate the essential theoretical and practical aspects involved. The Germans recognized this need quite some time ago and spared no efforts to develop mechanical-electrical simulating devices. In connection with the Mimo-Roc venture a similar effort was made in two directions: one with an all-electronic simulator for the study of the fundamental principles, the other with a test cart on which two-dimensional interception problems with lead-computing control could be run. The lessons learned on these devices were most instructive. The history of this effort began at an early stage of Roc's development, when the missile was still meant to fly without definite roll-orientation control. Here the spontaneous change of orientation posed a complex simulator problem for the solution of which a rather ambitious project of a model missile test range was at one time seriously considered. In the meantime the NDRC group at Columbia University developed electronic simulators of guided missile trajectory geometry to the point where the misses of individual runs could be quantitatively demonstrated without reproducing the physical motion of the missile by airborne carriage. In fact such a simulator was put to practical use in training operators who were to participate in the drop tests of visually controlled Roc 00-1000-V using the Carp technique. It afforded valuable opportunities to convey some of the dynamic response characteristic of the operation. That the Roc-V tests were nevertheless hampered by practical difficulties of guiding should not reflect on the potential value of such simulators as training devices; rather it was due to the omission from the simulator system of the disturbing factors. This brings to mind that a simulator to be universally useful in the experimental stage of such a project must be versatile and equipped to add factors and influences that turn out to be more significant than was anticipated.

While the Columbia University group was working toward the development of more universal electronic simulators and of simulators adapted to the representation of television guidance, the Roc group undertook the construction of a mechanical model range suitable to simulate the most urgent problems of television guidance. In this model range the missile was represented by a steerable cart, moving at a speed of approximately 1:100 scale over a smooth floor toward a target independently movable on a cable track. Motion in only one plane was simulated, and roll was not represented, but devices were provided to approximate the path deflection by gravity when desired. Experiments were made with the real television camera mounted on the remotely steered cart. The bulk of the investigations into various guidance techniques was made without television, the guider (and an observer) riding the cart and observing the target space through equivalent optics. It is interesting to note that a similar training cart was developed by the Germans.

No provision has as yet been made on the cart to simulate trim oscillation, although this was seriously considered. The cart was therefore applied mostly to the clarification of practical aspects of guiding with and without lead-computing aids. Various more or less primitive tracking aids or schemes were cursorily tried on the cart for educational purposes, but one scheme, for which the theory had been advanced under a project of Division 7, NDRC, was investigated more thoroughly. This scheme comprised an electronic computer which would allow for target motion and gravity influence in one plane and aid the guider by means of a motorized reticule system. This device was built and operated on the cart under a variety of conditions. After some practice had been obtained, results were sufficiently convincing to encourage the construction of an airworthy prototype of the computer, which is available to be installed in the test airplane for future test drops. This procedure brought home the value of simulators of this kind as a means to iron out bugs or to dispel uncertainties regarding new and complex devices which have to perform as a link in a chain or regulatory loop. Appreciation of the simulator experience is not dimmed by the realization of the fact that some of the significant features were not portrayed in the model range, especially the behavior in trim and roll.

It would be premature at the present stage of the cart studies to judge the relative merits of various computer schemes proposed or considered for application in conjunction with television. This much, however, can be safely concluded: the Division 7, NDRC, computer and reticule scheme does perform in any one plane as calculated and is far enough advanced to be tried out in practical drop tests. Aside from this, it is felt that simulator and cart tests should by all means be continued and extended to cover various refinements and to afford training to those resuming flight-test operations.

If an attempt is made to summarize the lessons learned in the pursuit of the Roc project, it must be borne in mind that this project was but a cog in the gearworks of a variegated guided-missile development directed by NDRC and not a rival of but rather a supplement to other missile projects. There seem to be enough different tactical merits in missiles traveling to their targets on differently inclined flight paths to warrant the development of specialized missiles. The definition of the border lines of their various applications may be somewhat arbitrary, but some overlapping among them can be accomplished by a judicious compromise between versatility and specialization.

The aerodynamics of missiles deserves to come in for more scientific investigation when higher speeds are to be attained. The supersonic regime, especially, is becoming a new field of expanding knowledge in which the pursuit of guided-missile projects is bound to be in the forefront and to have an influence upon the progress of the entire art, including the design of manned aircraft for high speeds. The choice of a suitable aerodynamic configuration for guided missiles is dictated by considerations peculiar to them and inseparable from the guidance scheme and its tactical implications. This complex network constitutes a regulatory loop, the satisfactory solution of which can be achieved only by close coordination between the specialists in the fields of aerodynamics, regulation, and intelligence. Because of the importance of coordination between these fields, it is believed that the responsibility for the coordination should be placed at an industrial level upon a prime contractor for the entire system.

The need for facilitating the dissemination of mutually pertinent data among the workers in this and associated fields has been impressed upon the personnel working on the Roc project. Since the ending of hostilities and resulting relaxation of security measures, the exchange of information has brought to light some cases of duplication, but, more important, it has answered questions on unsolved problems and posed questions on important new problems. It is felt that a system which will allow the exchange of information in this field of endeavor under wartime restrictions must be developed.

The flight testing of guided missiles is likely to become a discipline of ever increasing importance and scope. Here again the usefulness of close cooperation between those responsible for the conduct of the tests and the recovery of instructive information, those responsible for the design of the missile and its controls, and those who determine its tactical purposes and performance specification cannot be overemphasized. In order to facilitate this cooperation during the flight testing of the missile, it is believed that adequate flight test facilities should be developed, with satisfactory housing and laboratories necessary for maintaining a high scientific standard in these intricate and significant tests.

In closing, one is tempted to reaffirm the belief that the missile, its payload, propulsion, stabilization, controls, guiding, and launching and all the apparatus necessary to make it operate, constitute an integral system which must be considered and treated as a whole.

Appendix A

INTERCEPTION AND ESCAPE TECHNIQUES AT HIGH SPEED AND HIGH ALTITUDE[a]

During 1941, under contract from the U. S. Army Air Forces, Douglas Aircraft Company undertook a study to determine the effects of high speed at high altitudes on the problem faced by fighters when attacking bombardment aircraft. The report which arose from that work comprises the body of Appendix A. The problem of maneuvering a fighter plane against a high-speed bomber so as to bring the fixed guns to bear is one of flying a pursuit course. The work of Douglas, therefore, involved a searching analysis of the dynamics of pursuit curves, and although the content of the contract involved no work on guided missiles, its outcome has become a fundamental classic, which has been invaluable to all the Division's contractors concerned with the development of homing missiles. [EDITOR]

The study which led to the essay, *Interception and Escape Techniques at High Speed and High Altitude*, was originally undertaken in 1941 in conjunction with a design study of a fast long-range bombardment airplane in an effort to arrive by theoretical analysis at some judgment of the merits of a design trend toward safety through high performance which was then beginning to take shape in the minds of visionary engineers. The idea was still a bit ahead of contemporary concepts of immediate necessities of the military situation, in which England was seen as hard pressed and in need of relief while America was not yet actively embroiled in the world conflict. The high-performance bomber project was shelved at the time, but the principle was eventually incorporated in the later development of the B-29 bomber.

The report on interception and escape techniques was written at the time as a part of the project proposal and not intended to be published by itself or to pose as a comprehensive treatise on the subject. It is indeed but a very incomplete part of a survey of the field that could be covered or implied by the title.

In retrospect, presentation of the report without a bibliography of the subject matter which has been a fruitful field for many investigators would seem somewhat presumptive. As a matter of fact, no time at all was allowed for a literature search in view of deadlines for the submittal of the project proposal.

This fact also contributed to the decision of coining code words for technical terms which are peculiar to the science of pursuit, and for which more common words were in rather lax and ambiguous usage, though some of them (e.g., pursuit curve, dog curve, squinting, vector sight, and many others) have since been adopted more generally, while others have entered the language of gunsight, radar, and antiaircraft fire-director techniques. The "Greek" words introduced in the present report were not proposed for universal adoption but merely to fix the ideas until coordination with the nomenclature of related techniques could be accomplished.

An admirable bibliographic survey of mathematical treatments of pursuit problems has since been prepared for the Special Devices Division, Research Section, Bureau of Aeronautics, U. S. Navy Department, by Tufts College Mathematical Research Project. It is entitled *Project RM-6, Mathematical Analysis of Ordinary and Deviated Pursuit Curves.* A survey of some pertinent German papers produced during the war is expected to become available in the near future.

In Sections A.3 and A.5 various conclusions were drawn regarding the tightest turns that could be flown in combat maneuvers. The analysis did not take into account the possible variability of the maximum lift coefficient of wings with Mach number. In the light of knowledge and experience gained in the meantime regarding this variability, some of the conclusions drawn may require revision. Whether the pursuer or the pursued is likely to be more hampered by premature stalling or flight stability difficulties will depend upon aerodynamical details of either craft.

Section A.8, which deals with problems familiar to artillery experts but unfamiliar to the aeronautical engineer, is particularly sketchy. It was meant to be elaborated after consultation with experts in this field, but the report had to be concluded before the necessary information could be gathered. This section must therefore be considered as a mere collection of thoughts and an enumeration of problems rather than their solution.

Section A.9 must also be forgiven as somewhat cursory in view of the vast amount of study which other agencies concerned with the training of pursuit pilots have actually devoted to the task of simulating, teaching, and practicing pursuit and interception flight techniques, even though the author did go to the trouble of verifying some of the statements made by improvised flight tests.

Occupation with the thoretical aspects of air-to-air interception at the time the investigation was carried

[a] Written October 23, 1941.

out gave the organization a background which served it in good stead when it was called upon to contribute to the development of guided missiles, and particularly of Project Roc.

A.1 SUMMARY

The purpose of the following investigation is to anticipate and analyze the armament requirements for a radically new bomber project designed for such high speed and altitude that its own performance would render it extremely hard to intercept. The study envisages performances that may sound fantastic but they can be shown by proven aerodynamic methods to be entirely within the realm of immediate realization; they are probably no more in advance of the aircraft now in service than the latter are of those of but a few years ago.

The results of the present study bear out the contention that the need for defensive armament of a high-altitude bomber decreases as its speed approaches the value at which air compressibility influences begin to impede further progress seriously.

Limitations of Interception

A raider entering enemy territory in the stratosphere, safe from ground fire, can penetrate enemy territory to a considerable depth before he can be challenged by interceptor aircraft which have to be designed to match the raider's high ceiling. The chances of being found by an interceptor depend on the latter's climb and speed advantage, which can at best be small, and on an excellent, alert, detecting, warning, dispatching, and control organization on the ground.

Interception vs Straight Escape

Even the fastest interceptor has very little chance to pour effective fire into an almost equally fast bomber, except in a straight tail chase. Therefore, rear armament covering a moderate tail-cone field is all the armament definitely necessary on the bomber. High accelerations and unfavorable leading conditions hamper or thwart any close approaches from blunt angles. Unless he is far out of range, the pursuer has to turn so fast to keep his bead on his quarry that the accompanying high accelerations would greatly impair his aiming accuracy, or even cause him to black out. A variety of aiming and approaching techniques are studied in detail. The practical limits depend on speed and effective firing range but it is shown that for a very fast, high-performance bomber an interceptor cannot practically bring fixed forward-firing guns to bear on the target closer than 500 yd from angles greater than about 30 degrees, or even closer than 1,000 yd from more than 60 degrees off the tail of the target without suffering more than $3g$ acceleration.

Attacks from dead ahead appear to be extremely unlikely because of the terrific speed of approach, which leaves but a few seconds for recognition and decision, less than one second for fire at effective range, and but a fraction of a second to maneuver out of the way to avoid collision.

The influence of properly leading the target is investigated. It is shown that this refinement must be taken into account in order not to overestimate the acceleration suffered in the homing approach. However, it is also revealed how complicated a job is the accurate determination of the factors governing the aim correction in any homing maneuver but the tail chase. These considerations may help justify the limitation of the bomber's defense gunnery to a rear field cone.

It is shown that cross-passage combat phases are theoretically possible at all angles without the interceptor suffering acceleration loads. However, it is also shown how utterly brief such encounters would be, how few bullets could possibly sweep through the target, and how difficult it would be for the interceptor, in the few seconds available, to determine and attain the best intersection course which would bring him into effective range just at the correct instant.

The only way for the interceptor to challenge the high-speed, high-altitude bomber effectively from appreciable angles off the tail, and thus require him to defend himself there, is by mounting slant guns. Turrets would probably cost too much drag, reduce the speed advantage of the interceptor, and defeat their own purpose. Moreover, even pursuers with fixed oblique guns cannot very well attack effectively from very large angles because of their own maneuvering problems and windage influences.

Combat Maneuvering Techniques

It is shown that the bomber, if equipped with effective tail defense, can maneuver so as to force an attacker into a tail chase in which the bomber has an aerodynamical and tactical advantage. Also, he can, if he so elects, assume the initiative in a combat; it is shown under what conditions the bomber can frustrate or delay an attack by certain dogfight maneuvers.

Multiple Interception

In a study of the possibility of multiple interception, the difficulties of accurate coordination of the interceptors at high speed appear formidable so that on this score the bomber would not seem to require increased fire coverage in space. Simple escape maneuvers are likely to force simultaneous attackers into the same tail quarter to be resisted by the tail gunnery as they come into range.

Mass Raid Techniques

Consideration is given to mass formation flights and to the influence of mass formation tactics upon the armament requirements. While even in this case a tail defense is probably adequate, the tactical advantage of equipping at least some of the bombers with forward-firing fighter guns is brought to light.

Considerations of Effectiveness of Fire

An investigation into the data required to establish some sort of probability calculus for the chances of receiving fire from definite quarters leads, although not to any rigorous calculation, at least to qualitative confirmation of the overwhelming predominance of the tail chase if the attacker is equipped with fixed forward-firing guns. The appearance of interceptors equipped with oblique guns pitched within reasonable limits would favor a proportional increase of the angular coverage of the tail cone.

Mock Interception to Scale

Some rules are established for the interpretation of practical studies of high-speed interception problems by means of reduced-speed mock-maneuver flight tests which may serve to practice various interception phases and to throw some light on their respective practicality and seriousness.

A.2 LIMITATIONS OF INTERCEPTION

The present study was prompted by an endeavor to find answers to the query: To what extent is a long-range, high-altitude, ultra-high-speed bomber safe from attack by conventional defense means, or what specialized defense means and technique would have to be devised to combat it?

A.2.1 Bomber's Speed and Altitude

The advocates of ultra-high performance of the bomber as its best protection contend that armor and armament can be sacrificed or at least reduced to protection from very limited critical quarters for the benefit of speed and ceiling to the point where it can escape any effective defense against it that can be developed in the time before it becomes obsolete. To fix the idea, assume that the bomber approaches the enemy area in the stratosphere, say at 40,000-ft altitude, at a speed of $V = 450$ mph, so high and so fast that any attempt at ballistic ground defense would be ineffective and useless. As to air combat, the idea is to fly the bomber so fast that it approaches the speed limit set by compressibility burble drag so closely that the interceptor, who is of necessity subject to similar limitations, is left but little speed advantage with which to catch up with his prey before he runs out of fuel; his pursuit maneuvers are further handicapped by the high load factors which accompany any turns at high speed.

A.2.2 No Standing Patrol

If the defender were compelled to set up continuous aerial standing patrols of pursuit airplanes at high altitude, he would require a fleet of many thousands of airplanes constantly devoted to no other duty than this waiting job, a gigantic waste that might surpass in drain of resources the potential bomber damage it is set up to avert. One can try to estimate the size of such a curtain defense fleet, but for the time being the idea will be dismissed as fantastic.

A.2.3 Defense Detector System Assumed

Disregarding the possibility of the development of radically new weapons as yet unknown, we shall assume that both the bomber and the interceptor are equipped with directive radio detectors enabling them to spot and locate enemy aircraft in the air within a range of several miles (say 5 to 20), and that the defenders possess a highly organized scanning and warning system on the ground along their border by means of which they can detect and identify any invading bomber force while it is still at a distance D of many (say 30) miles away. The possibility of disabling the detectors by jamming (or electric camouflage) may be admitted for close range in the air but it can probably be dismissed as far as the ground warning system is concerned.

A.2.4 Interceptor's Climb Required

In order to be able to intercept the bomber before it reaches the shore or boundary of the defender, the time T_H available and the average climbing speed $\mathbf{C}$ required from the instant of detection to the arrival at the invader's flight level in the stratosphere (altitude H above the defender's take-off field) are determined by the equations $T_H = D/V = H/\mathbf{C}$. If V is taken in mph, D in miles, and H in feet, then T_H and $\mathbf{C}$ have to be multiplied by 60 in order to give the time in minutes and the average rate of climb in conventional units of feet per minute. Table 1 gives an idea of the magnitude of these quantities for $V = 450$ mph. These figures bring home to what degree the interceptor is handicapped by pressure of time, even if no time were lost in transmitting all necessary information and dispatching the pursuit formations.

TABLE 1

	D (miles)	15	30	45	60
H (ft)	T_H (min)	2	4	6	8
30,000	C (fpm)	15,000	7,500	5,000	3,750
35,000	C (fpm)	17,500	8,750	5,833	4,375
40,000	C (fpm)	20,000	10,000	6,667	5,000

A.2.5 Undefendable Zone vs Climb Time

As a reasonable example, if the detection distance is 30 miles, that $T_0 = 7$ minutes (time lost in transmitting the message and in take-off preparations), and that the actual climbing time to 40,000 ft will be $T_c = 20$ minutes, there remains an undefendable zone of over 200 miles into which the bomber may penetrate unchallenged. For various other conditions, the depth D_u of this undefendable zone, as determined by the relation $D_u = V(T_0 + T_c) - D$, is given in Table 2. The last column of Table 2 indicates to what extent the detection range will have to be increased to assure defense preparedness right up to the border.

TABLE 2

$T_0 + T_c$ (min)	Range of detection D (miles) 60	45	30	15		Range of detection required for complete defense (miles)
20	90	105	120	135	Undefendable zone	150
24	120	135	150	165		180
28	150	165	180	195		210
32	180	195	210	225		240
36	210	225	240	255		270

A.2.6 Interception Maneuvers Required

However, even after the interceptor arrives at the altitude of the bomber and finds it, he still has to maneuver into position for attack. The success of this maneuver will depend greatly on the conditions and technique of this approach. Consideration will be given to a variety of such conditions and techniques; although this survey may not be complete, it is intended to cover at least the critical phases.

A.3 INTERCEPTION VS STRAIGHT ESCAPE

In this part of the investigation it will be assumed that the bomber crew, because of their high speed, feel so secure and invulnerable that they fly serenely on toward their objective on a straight and level path without paying any attention to enemy efforts at challenging or intercepting them. This assumption will be dropped later in this appendix, but it is at once apparent that it is much to the advantage of the bomber if it can afford to minimize any departures from its direct course towards its objective or at least toward a feint objective.

A.3.1 Homing Pursuit (Scopodrome)

Let it first be assumed that, after the interceptor has located and chosen his quarry, he pursues his target in a homing pursuit curve, aiming his airplane constantly at his victim without leading his target.[b] The maneuver winds up asymptotically in a stern chase. The pursuit pilot holds his fire until he has arrived at close enough range and close enough on the tail to require but negligible target lead.

This scopodromic concept of flying in the direction toward the target represents an idealized technique, introduced here for the sake of mathematical simplification, close enough to be fruitful but predicated upon several artificial assumptions. One of these is the supposition that the interceptor is equipped with a sight which tells its pilot the direction of its instantaneous flight path. In the past, airplanes were not so equipped. Their gunsights were bore-sighted with respect to their guns, which usually were installed parallel to the normal speed flight path in straight flight. In a turn, however, the angle of attack is increased to overcome the centrifugal force, and this variation was not revealed by the conventional gunsight. An estimate of the influence of the angle of attack with a fixed gun and fixed gunsight will be made separately.

INTERCEPTOR'S SPEED CONSTANT

Assume that the interceptor approaches at constant airspeed v, neglecting the fact that as he turns his

[b] Reasons for not leading the target may be that (1) at long range he may be uncertain as to the enemy's flight direction and (2) later at moderate range because he may want to evade the complication of allowing for a variable lead vector as he banks in the approach turn while still beyond firing range. The term "homing" is not any too apt here, though derived from beam-flying technique with wind. It may be well to coin special words to identify the various approach techniques for ready reference. The term "scopodromic" is proposed for the present method; the word signifies "driving so as to move toward the visible target."

drag must increase. (An estimate of this neglected influence will be introduced later.)

Horizontal Plane Scopodrome

Further assume that the pursuer either does not attempt to dive on his prey or that any advantage derived from such a dive can be expressed as a slight increase in his speed advantage over the bomber.

Range vs Azimuth

The polar equation of this horizontal scopodromic pursuit curve in terms of instantaneous range r and azimuth α of the pursuer's position off the pursued's tail can be written:

$$r = r_T \cdot \frac{\left(\tan \frac{\alpha}{2}\right)^{\epsilon}}{\sin \alpha} \tag{1}$$[c]

$\epsilon = v/V$, the speed ratio of pursuer to the pursued, which is here assumed slightly greater than unity, say 10:9 for a 500-mph interceptor or a 450-mph bomber; r_T is the range at which the pursuer was headed at right angles to the flight path of his quarry. If he does not take up the chase until he is in a rear quadrant at an azimuth α_0 and at a range r_0, then r_T may be reconstructed by following the process in reverse, or else the same curve can be expressed in terms of any coordinated initial values of α_0 and r_0, namely:

$$\frac{r}{r_0} = \left(\frac{\tan \frac{\alpha}{2}}{\tan \frac{\alpha_0}{2}}\right)^{\epsilon} \cdot \frac{\sin \alpha_0}{\sin \alpha} \tag{2}$$

As the pursuit approaches the tail chase for which α nears 0, equation (2) approaches its first order term, namely,

$$\frac{r}{r_0} = \left(\frac{\alpha}{\alpha_0}\right)^{\epsilon - 1} \tag{3}$$

Typical approach curves of this character are shown in Figure 1 in a coordinate system assumed traveling with the pursued aircraft for speed ratios of pursued to pursuer $1/\epsilon = 1.1$, 1.0, 0.9, 0.8, 0.7, 0.6, and 0.5. Of these, 1.0 is a limit case because, with speeds equal, the pursuer never catches up with the pursued; he can approach him no closer than $\frac{1}{2} r_T$. The case of $V : v = 1/\epsilon = 0.9$ is a practical example.

Accelerations

The question now arises: What centrifugal "accelerations" and what load factors would be suffered by the pursuer in such a scopodromic approach and what consequences will they have? The centrifugal acceleration in terms of a horizontal load factor n_η is simply the product of the tangential and angular velocities of the pursuer; thus, $n_\eta g = -v\,d\alpha/dt$. The angular velocity, however, is $-d\alpha/dt = V \sin \alpha / r$, so that

$$n_\eta g = \frac{vV}{r} \cdot \sin \alpha \tag{4}$$

This is constant for constant $r/\sin \alpha = vV/n_\eta g$, which is the diameter of a Thales circle, tangent to the pursued's path at the pursued's instantaneous position. Such Thales circles are *isobars*, i.e., loci of equal load factors for the pursuer. A family of such circles, with the corresponding resulting load factors

$$n = \sqrt{1 + n_\eta^2} \tag{5}$$

annoted, are shown in Figure 2, together with scopodromic pursuit curves and range circles for the examples $v = 500$ mph and $V = 400$ mph ($1/\epsilon = 0.8$) and $V = 450$ mph ($1/\epsilon = 0.9$). Table 3 shows at what ranges and azimuths certain load factors would be suffered in scopodromic approach. If the pursuer enters the innermost $n = 5$ circle, he would probably black out.

Table 3. Range in yards ($v = 500$ mph) for various pursuer's resultant load factors and azimuths.

V	α	n / n_η	2 / 1.732	2.5 / 2.29	3 / 2.83	3.5 / 3.35	4 / 3.87	4.5 / 4.39	5 / 4.90
450 mph	90°		2,895	2,190	1,773	1,497	1,295	1,142	1,023
	60°		2,510	1,897	1,535	1,297	1,123	989	887
	56°17′		2,405	1,820	1,472	1,243	1,077	948	851
	45°		2,045	1,547	1,252	1,058	916	807	723
	30°		1,447	1,095	887	˙749	648	571	512
	15°		749	567	459	388	336	296	265
400 mph	90°		2,570	1,945	1,575	1,330	1,152	1,015	910
	60°		2,225	1,687	1 365	1,152	998	879	788
	51°19′		2,005	1,518	1,228	1,038	898	792	709
	45°		1,840	1,375	1,113	940	813	718	643
	30°		1,285	973	788	665	576	508	455
	15°		666	504	408	345	299	263	236

For any given resultant load factor n, the diameter of the Thales circle or cross-path range is:

$$r_T = \frac{vV}{\sqrt{n^2 - 1}} \tag{6}$$

The banking angle ϕ required to execute the turn with the resultant load factor n is, of course,

$$\phi = \sin^{-1} \frac{1}{n} \tag{7}$$

By substituting the range r from equation (1) into equation (4), the centripetal acceleration at any azi-

[c] For derivations see Section A.4.1.

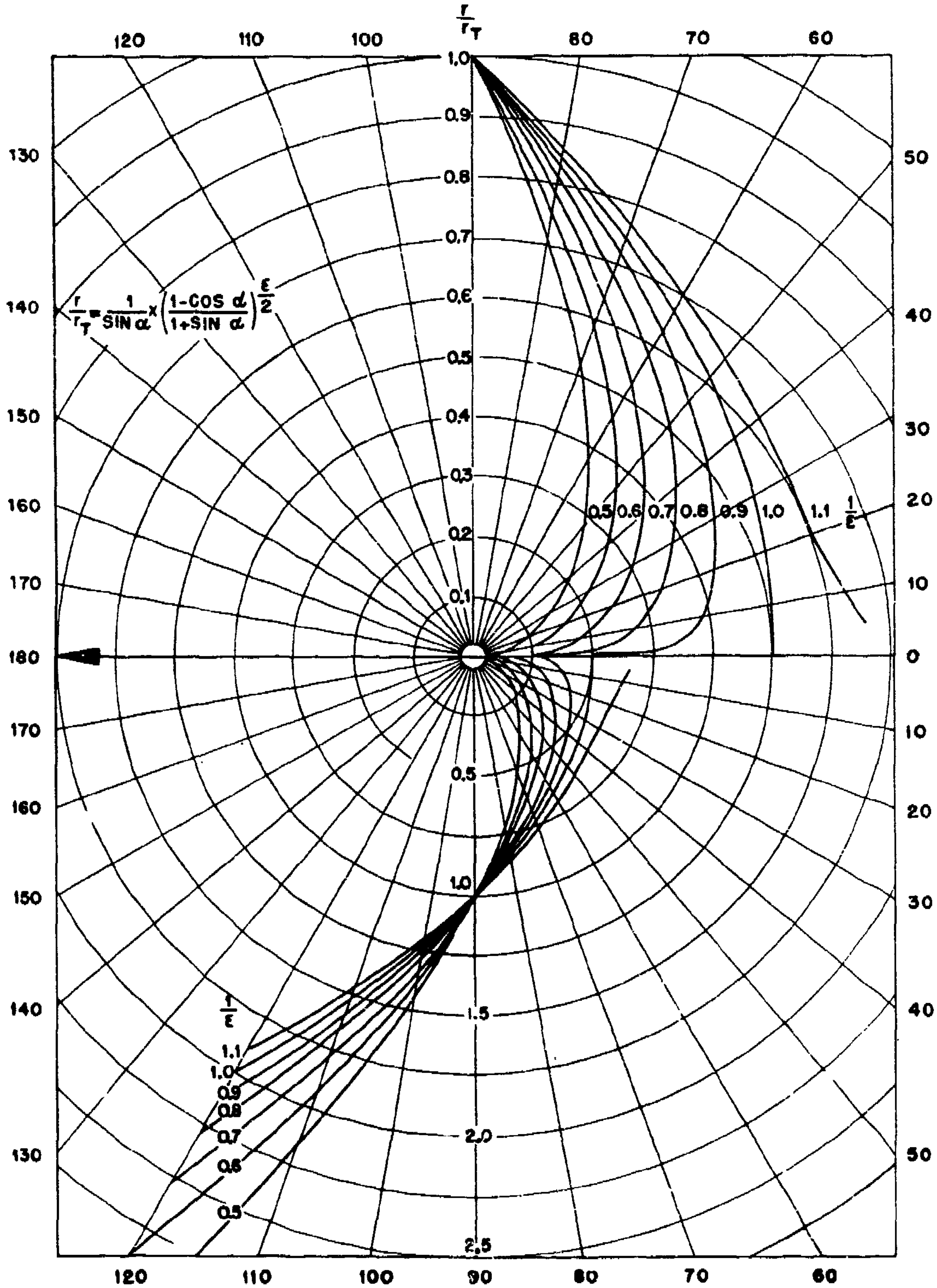


FIGURE 1. Scopodromic approach.

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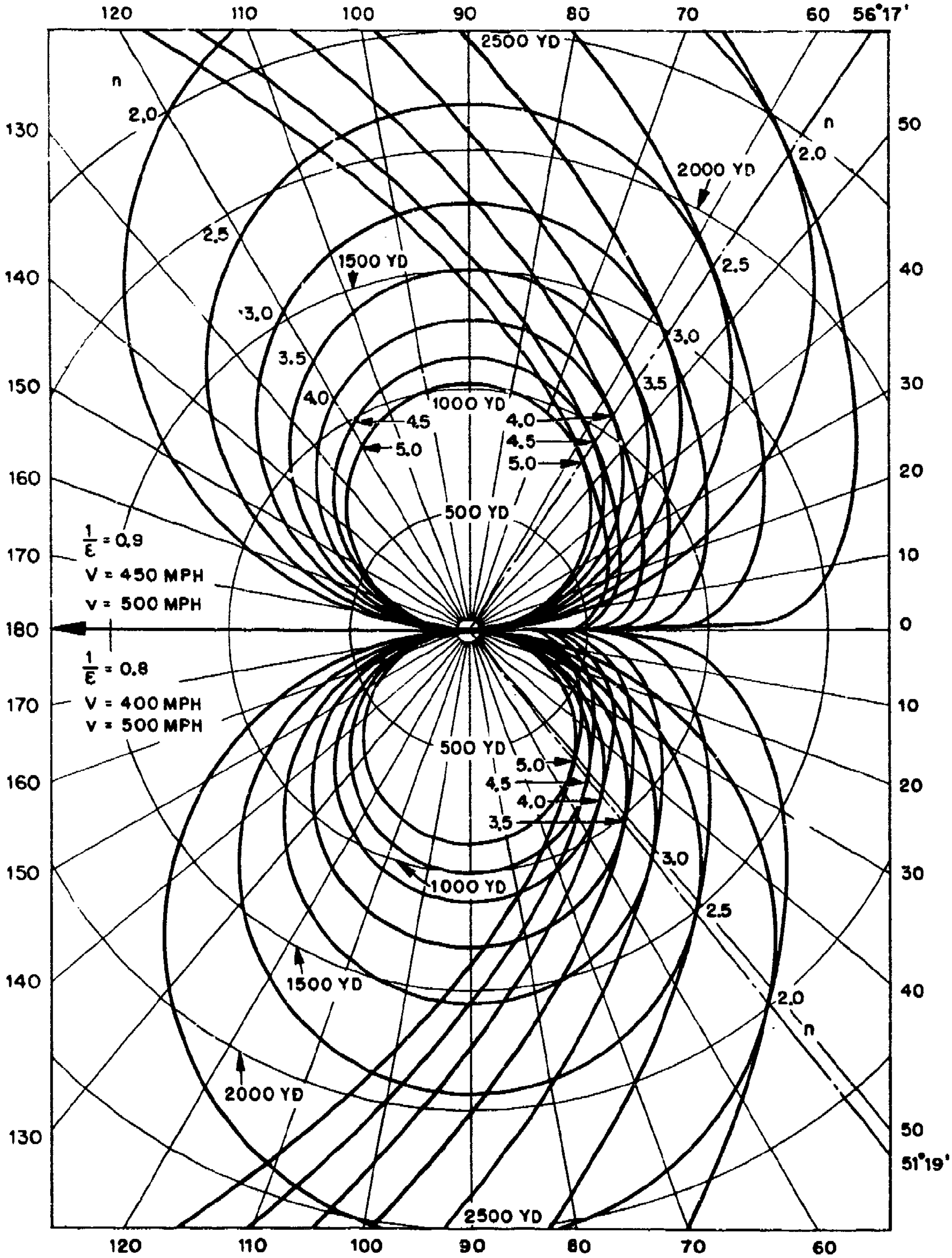


FIGURE 2. Scopodromic approach curves with lines of constant load factor.

muth point α of a definite pursuit curve can be expressed as

$$n_\eta g = \frac{vV}{r_T} \cdot \frac{\sin^2 \alpha}{\tan^\epsilon \frac{\alpha}{2}} \tag{4}$$

At some place along the curve this acceleration becomes a maximum. This critical place is defined by $\cos \alpha_c = \epsilon/2$, a remarkably simple result.[d] The critical angle α_c and the resultant load factor n_{max} are shown on Figure 3. In a polar chart (Figure 4) the

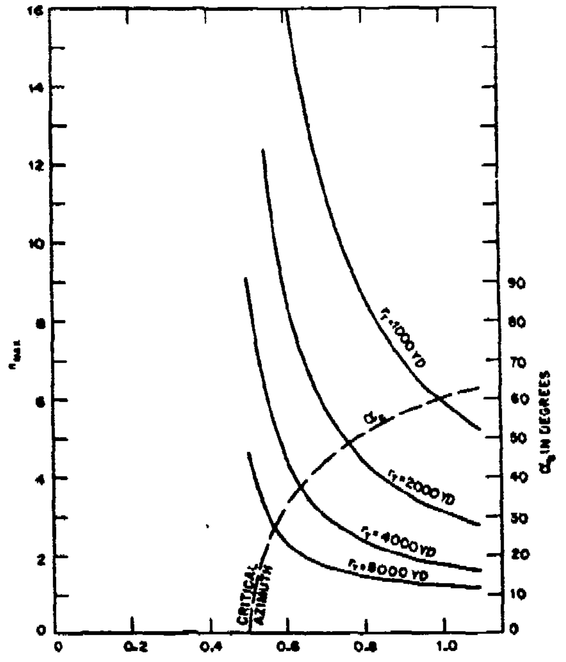


FIGURE 3. Load factor peak in horizontal scopodromic approach.

critical azimuth is indicated by a straight line. It shows clearly how, for large speed ratios near 2:1, the banking is concentrated in the last phase of the combat, whereas for speeds nearly equal it occurs near a 60-degree azimuth.

The magnitude of the horizontal load factor component peak depends also on the proximity of the approach, as expressed by the cross-path range r_T, namely:

$$n_{\eta max} = \frac{vV}{g r_T} \cdot \left(1 + \frac{\epsilon}{2}\right)^{1+\epsilon/2} \cdot \left(1 - \frac{\epsilon}{2}\right)^{1-\epsilon/2} \tag{4a}$$[d]

and the resultant load factor peak is then

$$n_{max} = \sqrt{1 + n_{\eta max}^2} \tag{5a}$$

[d] For proof see Section A.4.2.

The critical range r_c at which the maximum load factor occurs is, according to equation (1),

$$r_c = r_T(\sin \alpha_c)^{(\epsilon-1)} \cdot (1 + \cos \alpha_c)^{-\epsilon} \tag{6a}$$[d]

and the steepest banking angle ϕ_{max} is

$$\phi_{max} = \tan^{-1}\left[\frac{vV}{r_T g}\left(1 + \frac{\epsilon}{2}\right)^{(1+\epsilon/2)} \cdot \left(1 - \frac{\epsilon}{2}\right)^{(1-\epsilon/2)}\right] \tag{7a}$$

All these values typically grow quickly with the product of the two speeds. Table 4 gives α_c, $n_{\eta max}$, n_{max}, r_c, and ϕ_{max} for a v = 500-mph pursuer going after a bomber flying at speeds of $V = v/\epsilon$ from 350

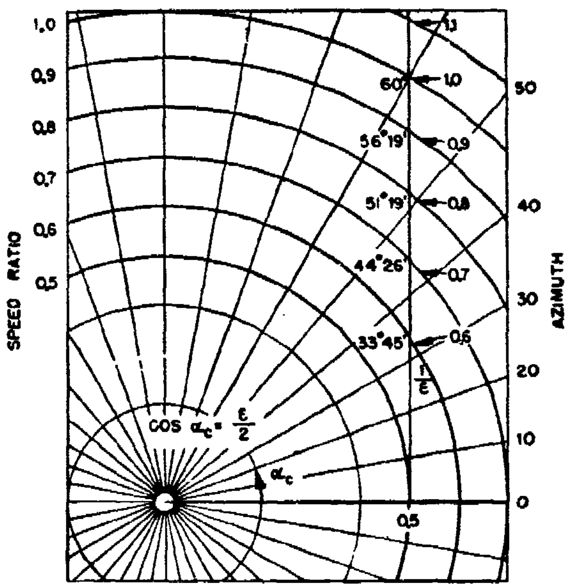


FIGURE 4. Azimuth of greatest load, scopodromic.

to 450 mph; and also for a 450-mph bomber with three different pursuit speeds. The proximity parameter r_T indicates the distance at which the pursuer passes abeam of the bomber. It is a parameter of the scale of the scopodromic curve and fully characterizes the path.

Table 4, as well as Figure 2, gives a vivid picture of the load factor limitations of the pursuer's approach. It is readily seen that no aiming (scopodromic) approach can be carried into firing range while still on a forward quadrant without entailing excessive load factors which would not only impair the aiming accuracy but also slow down the pursuer. The critical azimuth α_c, which is 56¼ degrees for a speed ratio of $1/\epsilon = 0.9$, is of some significance for the armament coverage of the bomber because from any greater angle the pursuer is hampered by the load factor's increasing as he approaches. Once the pursuer has negotiated this critical azimuth, the load

TABLE 4. Critical approach phase of interceptor in scopodromic pursuit.

Bomber speed V (mph)		350	385	400	450	450	450
Pursuit speed v (mph)		500	500	500	563	500	450
Speed ratio $1/\epsilon$		0.7	0.77	0.8	0.8	0.9	1.0
Critical azimuth angle		44°21′	49°32′	51°19′	51°19′	56°15′	60°
r_T (yards)							
8,000	$n_{\psi max}$	0.863	0.848	0.85	1.075	0.867	0.7313
	n_{max}	1.322	1.311	1.313	1.468	1.323	1.239
	r_c (yards)	3184	3856	4104	4104	4820	5333
	ϕ_{max}	40°47′	40°18′	40°22′	47°4′	40°56′	36°10′
4,000	$n_{\psi max}$	1.725	1.696	1.70	2.15	1.735	1.4625
	n_{max}	1.984	1.969	1.972	2.37	2.000	1.77
	r_c (yards)	1592	1928	2052	2052	2410	2666
	ϕ_{max}	59°54′	59°29′	59°32′	65°3′	60°3′	55°38′
2,000	$n_{\psi max}$	3.45	3.393	3.40	4.30	3.47	2.925
	n_{max}	3.59	3.535	3.545	4.42	3.62	3.09
	r_c (yards)	796	964	1026	1026	1205	1333
	ϕ_{max}	73°50′	73°35′	73°37′	76°54′	73°55′	71°8′
1,000	$n_{\psi max}$	6.90	6.785	6.80	8.60	6.94	5.85
	n_{max}	6.97	6.850	6.875	8.66	7.05	6.65
	r_c (yards)	398	482	513	513	602	666
	ϕ_{max}	81°45′	81°37′	81°38′	83°22′	81°48′	80°18′

factor eases up again, and he becomes more dangerous. This need not mean that the tail guns of the bomber must cover a field extending 56 degrees off the tail axis, because the range at the critical point is still large; for our 500-mph vs 450-mph example, it is 850 yd for $5g$ or 1,070 yd for $4g$, and the azimuth diminishes rapidly with further approach (to 30 degrees when the range has shrunk to 512 yd for $5g$ and 648 yd for $4g$ on the limit circle, or 655 yd for $5g$ and 825 yd for $4g$, respectively, along the critical approach curve).

It is interesting to note that for a given pursuit speed, the maximum load factor suffered in scopodromic pursuit varies but little with the speed of the quarry, and is almost entirely determined by the distance at which the approach arrives at any definite azimuth. As a matter of curiosity, it may be mentioned that for a given pursuit speed, the least maximum load factor is attained at $\epsilon = 1.3$, $1/\epsilon = 0.77$, i.e., where the bomber's speed is 30 per cent slower than the pursuit.[e]

TIME ELAPSED

The time it takes the pursuer to gain on the target from any initial azimuth angle is appreciable. According to the simple scopodromic concept, at constant airspeeds, the elapsed time, counted backwards from the instant of catching up, is

$$t = \frac{r_T}{2V}\left[\frac{\tan^{(\epsilon-1)}\frac{\alpha}{2}}{\epsilon-1} + \frac{\tan^{(\epsilon+1)}\frac{\alpha}{2}}{\epsilon+1}\right] \qquad (8)^{f}$$

The progress of the approach can thus be plotted on a time scale. This has been done in Figures 5, 6, and 7 for the example $V = 450$ and $v = 500$ mph. The plots refer to three initial positions (defined by

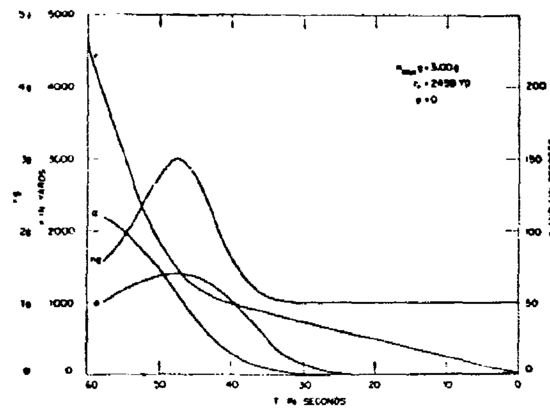


FIGURE 5. Scopodromic approach against time; $n_{max}g = 3.00g$, $r_T = 2{,}455$ yd, $\psi = 0$.

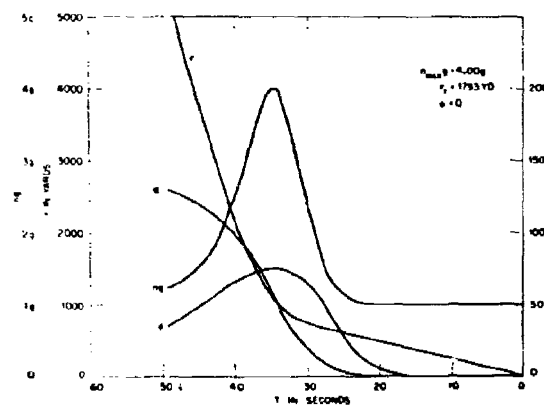


FIGURE 6. Scopodromic approach against time; $n_{max}g = 4.00g$, $r_T = 1{,}793$ yd, $\psi = 0$.

r_T) so chosen as to reach load factor peaks of 3, 4, and $5g$ which occur 47½, 34½, and 27½ seconds, respectively, before catching up. The graphs show the gradual approach in range and azimuth toward the tail and the sudden surge of load factor and banking angle. For instance, it appears that the interceptor has to be banked and releveled very accurately; the rolling speed has to attain peaks of the order of 6, 8½, and 11 degrees per second. The maximum load

[e] See Section A.4.3 for proof.

[f] See Section A.4.4 for derivation.

factors occur at ranges of 1,500, 1,080, and 840 yd, respectively. A factor halfway between 1 and the maximum is exceeded for 12.6, 9.6, and 7.9 seconds, respectively. Figure 8 is a synopsis, showing that the final approach phase proceeds practically independently of the sharpness and proximity of the chase turn.

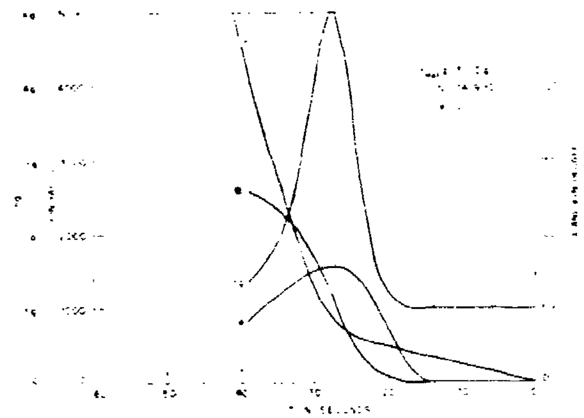


FIGURE 7. Scopodromic approach against time; $n_{max}g = 5.00g$, $r_T = 1{,}419$ yd, $\psi = 0$.

SPEED LOSS

However, it must be remembered that the idealized scopodromic approach is a theoretical simplification and the time history as shown here is but an approximation of any real combat maneuver. For one thing, as has been pointed out, in reality the pursuer loses some of his theoretical speed advantage because, as he banks, the extra lift required to overcome centrifugal force entails induced drag, which slows him down. The order of magnitude of the retardation thus occasioned is

$$g \cdot \frac{D}{L} \cdot \frac{n^2 - 1}{\lambda^4 + 1} \qquad (9)^{e}$$

where D/L is the glide ratio at high speed, n is the load factor, and $\lambda = v/v_{(L/D)_{max}}$ is the ratio of the flight speed over his best glide speed. If, for example, $D/L = 1:14$, $\lambda = 1.7$, and an average n of 3, the deceleration would be 2 ft per sec per sec. This would consume all the speed advantage of the interceptor in 10 seconds, and half of it in the 5 seconds it would take him to creep in from 90 degrees to 56 degrees, the worst part of the approach. Allowance for this retardation would have to be made step by step if pursuit maneuvers of this character were to be studied in greater detail. As an additional refinement, the extra drag due to aileron deflection while changing the bank angle may be taken into consideration.

[e] For proof see Section A.4.5.

VERTICAL AND OBLIQUE SCOPODROMES

Let us now allow the interceptor to attack from a different flight level so that he has to maneuver in space, and his flight path has curvature components both in horizontal and vertical projection, to be denoted by the indices η and ζ in bomber's flight coordinates. Theoretically, the mathematics of the scopodromic pursuit curve are the same for either component, as well as in the resultant slanting approach plane defined by the pursued's flight path and the line of sight between the two craft at some "initial" condition. The main differences between the general case of oblique and horizontal approach are the load factor and the retardation suffered.

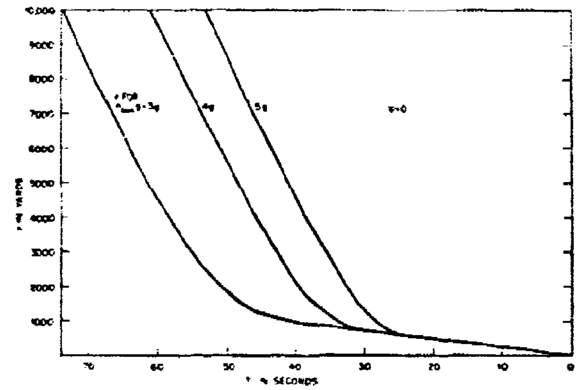


FIGURE 8. Scopodromic approach, range against time.

The total load factor n is now not merely $\sqrt{n_\eta^2 + 1}$, as for horizontal turns, but $n = \sqrt{n_\eta^2 + n_\zeta^2}$. With γ the angle of the slant-flight path plane against the horizon, this is determined by

$$n^2 = \left(\frac{c}{g} \sin\gamma + \sqrt{1 - \sin^2\alpha \sin^2\gamma}\right)^2 + \left(\frac{c}{g}\cos\gamma\right)^2 \qquad (10)$$

where $c = V\Omega$ is the centripetal acceleration and Ω the angular velocity of the interceptor's axis in space during the oblique turn.

The steeper the descent in the turn, the more severe is the extra load factor because a given rate of turn produces only $n = \sqrt{1 + (c/g)^2}$ when c is horizontal and the path is horizontal, but $n = 1 + c/g$ when c is vertical, and the path is horizontal. At a centrifugal force of $4/3\,g$ the load increase gets twice as great in a vertical dive zoom ($n = 7/3$) as in a horizontal turn ($n = 5/3$). The higher the centrifugal force, the less difference the slope of the flight path makes.

As to the retardation, the aerodynamical extra drag is also slightly greater for the descent turn in proportion to the effect of the increased resultant load factor n, but a gravity component $-g \sin \gamma$, helpful for negative γ, readily offsets the induced drag. A descent of 4 degrees in the phase of the previously adduced example would suffice to balance completely the induced drag due to the turn. Steeper descents would actually help in boosting speed were it not for the bugaboo of the compressibility burble. In an attack from below, on the other hand, the gravity component becomes a serious retarding factor, but the load factor diminishes slightly.

Pitched Gun (Clinoscopodromes)

In certain combat phases a gun installed at an appreciable angle to the flight path may have certain advantages (despite obvious ballistic and less obvious maneuvering disadvantages). If the gun were mounted at a skew angle, the phoronomy of the approach would become mathematically rather complicated. The same is true if the gun were mounted at a fixed angle of pitch or yaw only, because as the interceptor banks, the displacement of the trajectory rotates around the flight-path tangent, and the latter degenerates into a bent skew spiral. The description of such a "helicodromic" path would require the solution of two simultaneous differential equations between the range and the pursuer's position azimuth and latitude. Considerations of trajectory drop and angle-of-attack variation with load factor further complicate the mechanics of such an approach. If necessary, a step-by-step construction beginning with any given set of initial conditions can of course be executed, though it will at best be tedious and involved.

One particular case is amenable relatively easily to an explicit solution, namely, the attack in a vertical plane with a vertically elevated (or depressed) gun. In this "clinoscopic" case the approach does not require banking, and with α the apparent elevation of the pursuer as seen from the pursued and β the pitch angle of the interceptor's gun with respect to its air path, the differential equation of the approach becomes

$$\frac{dr}{r} = \frac{\epsilon \cos \beta - \cos \alpha}{\epsilon \sin \beta + \sin \alpha} \cdot d\alpha \qquad (11)$$

For constant gun (and sight) inclination β this equation is solved by

$$r = r_T \cdot \frac{a}{a - 1 + \sin \alpha} \left[\frac{1 + \sqrt{\frac{b}{a}} \tan\left(\frac{\alpha}{2} - \frac{\pi}{4}\right)}{1 - \sqrt{\frac{b}{a}} \tan\left(\frac{\alpha}{2} - \frac{\pi}{4}\right)} \right]^{\frac{\epsilon \cos \beta}{\sqrt{ab}}} \qquad (12)^{h}$$

where $a = 1 + \epsilon \sin \beta$ and $b = 1 - \epsilon \sin \beta$. Here r_T indicates that hypothetical range at which the pursuer would have been vertically above (or below) the pursued (and upside down) had he begun the approach that far away. Some sample approaches are pictured in Figure 9 for a speed ratio $1/\epsilon = 0.9$ and for gun inclination angles of 5, 10, 15, and 20 degrees up and -5 and -10 degrees down, load factor and azimuth being plotted against range.

The load factor built up by virtue of the gradual "pull-out" is simply

$$n = \cos(\alpha + \beta) - \frac{v}{g} \cdot \frac{d\alpha}{dt}$$

which is

$$n = \cos(\alpha + \beta) + \frac{vV}{gr} \cdot (\sin \alpha + \epsilon \sin \beta) \qquad (13)$$

The loci of equal load factors are apple-shaped curves also shown in Figure 10.

It is significant that, with the gun pitched, the pursuit terminates asymptotically in an approach from an angle α_t slightly greater than the negative gun pitch angle β, viz., $\sin \alpha_t = -\epsilon \sin \beta$. During the end phase, the pursuer slowly creeps up from below (if gun is pitched up) or stalks from above (if gun is pitched down) with negligible path curvature and acceleration left at close firing range.

A.3.2 Leading Pursuit (Ballodrome), Gun Parallel to Path

It must be realized that all scopodromic pursuit maneuvers thus far studied, although automatically winding up in a stern chase, fail to make allowance for leading the target. In order to hit the target from such an approach while the azimuth is at all appreciable, the gun would have to be flexibly mounted in the interceptor with automatic or semiautomatic lead correction control. Obviously, the mechanical complication of such a system would be appreciable. It is much easier to apply the lead correction to the gunsight, either by automatic or semiautomatic control, or even by "guess and experience." This alternative, however, complicates the mathematical treatment of the approach maneuver. It transforms the simple homing or scopodromic interception curve into one that, for the sake of descriptive identification, will be denoted as "ballodromic" (meaning "to drive so as to hit"). Its characteristic is that the interceptor does not head directly for the target but leads it by an ever diminishing lead angle in the plane of approach which is defined by the line of sight and in the target flight path (aside from the elevation correction for trajectory drop due to gravity).

[h] For derivation see Section A.4.6.

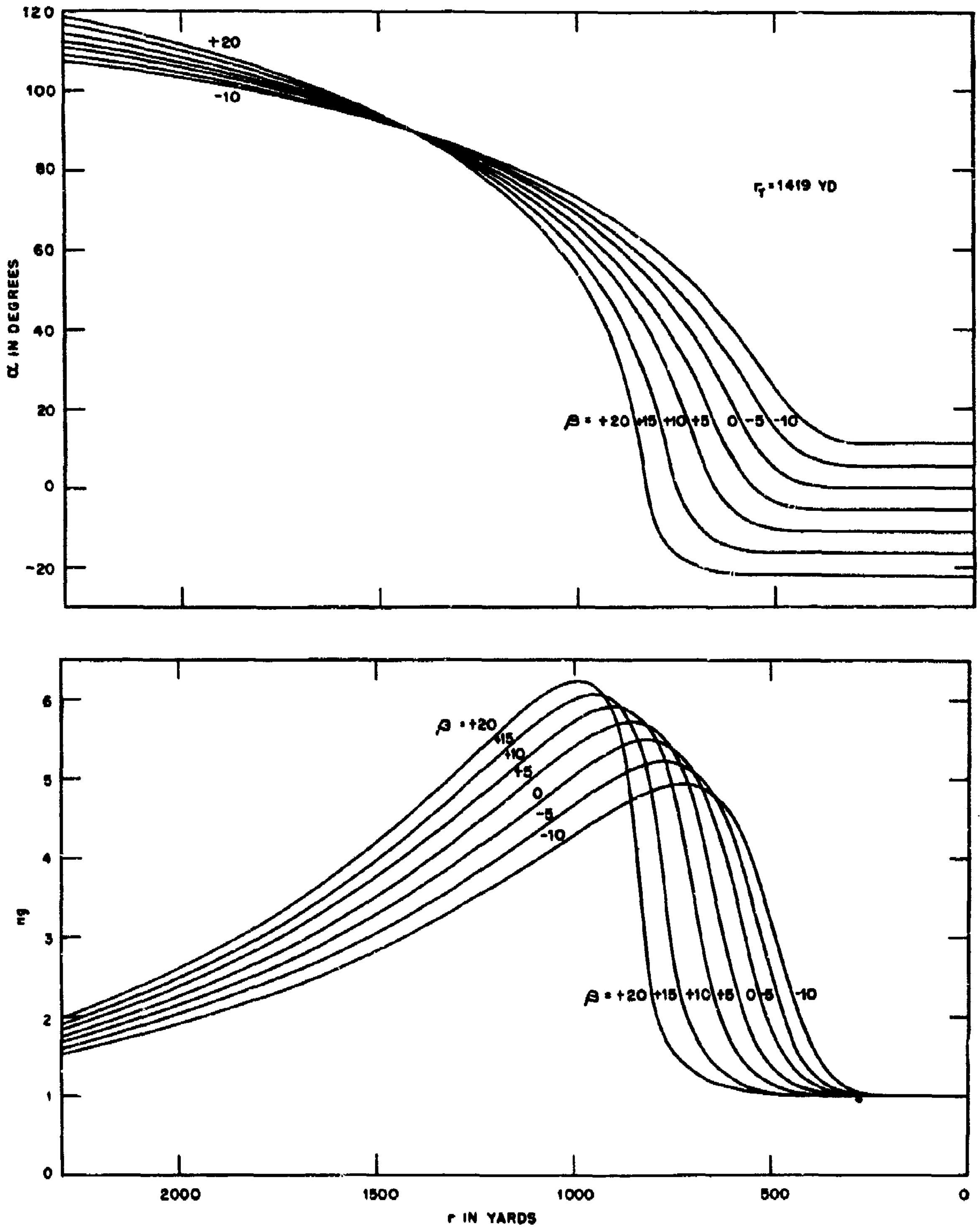


FIGURE 9. Clinoscopodromic approach.

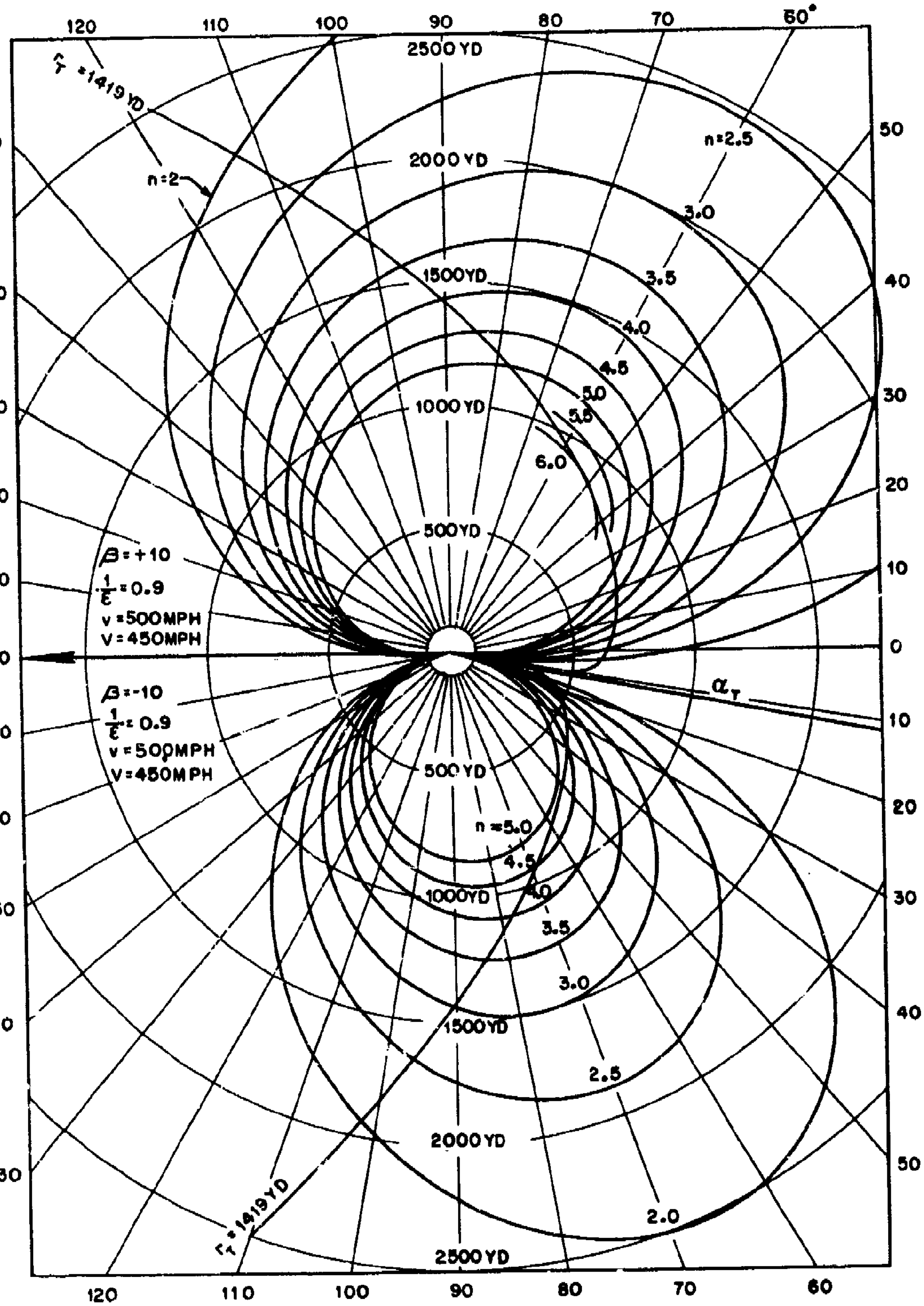


FIGURE 10. Clinoscopodromic approach with lines of constant load factor.

Range vs Azimuth

If the gun elevation is controlled by a device at least compensating for airspeed (angle of attack) and trajectory drop so that the bullet trajectory chord is parallel to the straight flight path, then the lead correction angle is determined by a "refraction" relation

$$\frac{\sin \delta}{\sin \alpha} = \frac{V}{u + v} = \frac{1}{\kappa + \epsilon} = \psi \tag{14}$$

where u is the average bullet speed with respect to the muzzle or κ is its ratio to the pursued's airspeed. This can be directly derived from the bullet, interceptor, and target speed triangle.[i] The polar differential equation of the ballodromic curve is thus:

$$\frac{dr}{r} = \frac{\epsilon\psi \cot \delta - \cot \alpha}{1 - \epsilon\psi} \cdot d\alpha$$

$$= \frac{\epsilon\sqrt{\csc^2 \alpha - \psi^2} - \cot \alpha}{1 - \epsilon\psi} \cdot d\alpha \qquad (15)^{j}$$

The ballodromic equation is amenable to integration, so that the range can be expressed as a function of the azimuth by

$$r = r_T \cdot \left[\left(\frac{\cos \delta + \psi \cos \alpha}{\cos \delta - \psi \cos \alpha} \right)^{\epsilon\psi/2} \cdot \left(\frac{\cos \delta - \cos \alpha}{\cos \delta + \cos \alpha} \right)^{\epsilon/2} \cdot \frac{1}{\sin \alpha} \right]^{1/(1-\epsilon\psi)} \qquad (16)^{j}$$

Ranges with $\sin \delta = \psi \sin \alpha$ from equation (14) have been computed for a representative value of speed ratio ϵ and muzzle velocity ratio ψ. The results are tabulated in Table 5 and shown in Figures 11, 12, and 13.

Acceleration

As to the banking angles and load factors, it is significant that in the ballodromic approach they are somewhat less severe than in the scopodromic approach because the whole path is cut shorter. The entire maneuver takes several seconds less time. (The scopodromic maneuver may be regarded as a special case of the ballodromic with infinite muzzle velocity, i.e., $\psi = 0$.)

An accurate evaluation of load factors $n = \sec \phi$ in ballodromic approach (still with the gun assumed in the direction of the flight-path tangent) can be derived from the rate of change of the pursuer's course, which is defined by the difference of the two azimuths $\alpha - \delta$, viz.

$$n_v = \tan \phi = \frac{v}{g}\left(\frac{d\alpha}{dt} - \frac{d\delta}{dt}\right)$$

$$= \frac{vV}{gr} \cdot (1 - \epsilon\psi) \cdot \sin \alpha \left(1 - \psi \cdot \frac{\cos \alpha}{\cos \delta}\right) \qquad (17)^{k}$$

and hence the total load factor (if the approach takes place in a horizontal plane) is $n = \sqrt{1 + n_v^2}$.

The loci of equal load factors are ovals, slightly distorted from the scopodromic circles of equal load factors. These ovals and ballodromic approach curves, as they appear in a polar coordinate system flying with the bomber, are shown in Figure 11. The equation for these ovals is

$$r = \frac{vV(1 - \epsilon\psi)}{g\sqrt{n^2 - 1}} \cdot \sin \alpha \frac{\cos \delta - \psi \cos \alpha}{\cos \delta} \tag{18}$$

TABLE 5. Ballodromic approach.

$1/\epsilon = 0.9$ $V = 450$ mph $v = 500$ mph $r_T = 1,419$ yd

Azimuth α (degrees)	$\psi = 0.225$; $u = 2,200$ fps: Lead angle δ (degrees)	Range r (yards)	Bank ϕ (degrees)	Load factor n (g)	$\psi = 0.183$; $u = 2,875$ fps: Lead angle δ (degrees)	Range r (yards)	Bank ϕ (degrees)	Load factor n (g)
150	6.5	32,300	4	1.00	5.2	20,870	6½	1.01
140	8.3	11,110	15	1.04	6.8	9,934	16½	1.04
130	9.9	6,118	28½	1.15	8.1	5,649	31	1.17
120	11.2	3,806	43½	1.38	9.2	3,570	46½	1.46
110	12.2	2,580	56	1.78	9.9	2,494	58	1.89
100	12.8	1,865	64	2.29	10.4	1,840	65	2.38
90	13.0	1,419	69½	2.83	10.6	1,419	70½	2.90
80	12.8	1,124	72½	3.32	10.4	1,140	73½	3.50
70	12.2	921	74	3.67	9.9	941	75	3.87
60	11.2	776	75	3.85	9.2	790	76	4.10
55	10.6	719	75	3.85	8.6	743	76	4.06
50	9.9	670	75	3.80	8.1	696	75½	4.00
45	9.2	627	74	3.68	7.4	652	75	3.90
40	8.3	589	73½	3.54	6.8	614	74½	3.73
35	7.4	555	72½	3.32	6.0	581	73½	3.49
30	6.4	525	71	3.05	5.4	550	72	3.22
25	5.4	497	68½	2.73	4.4	522	69½	2.88
20	4.4	470	65	2.38	3.6	496	66½	2.49
15	3.4	433	60½	2.03	2.7	467	61½	2.08
10	2.2	412	51	1.59	1.8	437	52½	1.64
5	1.2	369	34½	1.21	0.9	394	36	1.23
3	0.7	341	24	1.10	0.6	365	25	1.10
1	0.2	290	10	1.02	0.2	313	10½	1.02
⅓	0.1	245	4	1.00	0.1	198	5½	1.01

Time Elapsed

The time elapsed between passing any particular position α_1 and catching up has been determined for

[i] Attack from below, however, cannot very well be accomplished without loss of speed, whereas the assumption of no gain in speed in attack from above is not so far off because of the compressibility drag

[j] For proof refer to Section A.4.7.

[k] For derivation and explanation see Section A.4.7.

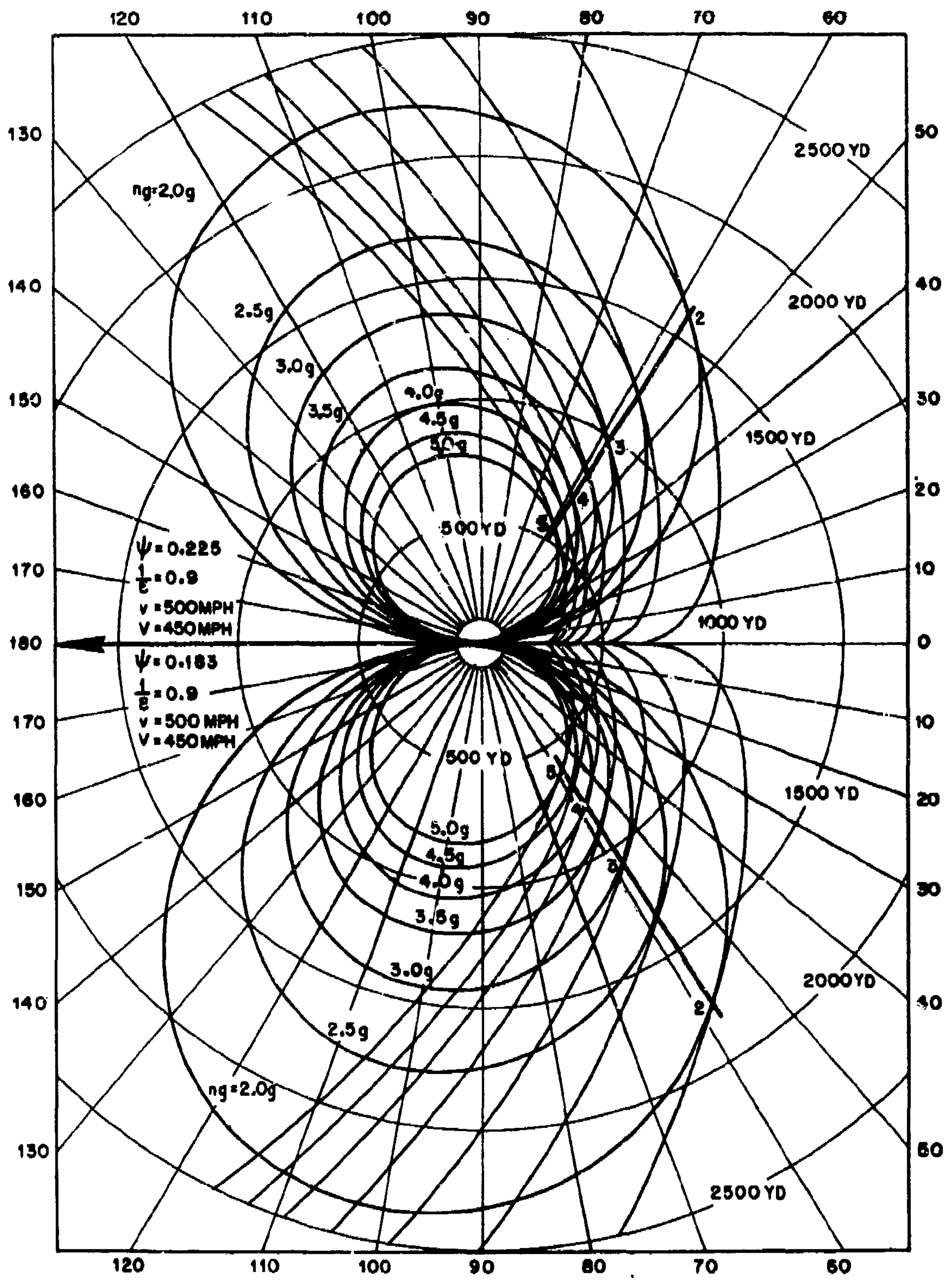


FIGURE 11. Ballodromic approach with lines of constant load factor.

several sample conditions by graphical integration after having computed n_τ from equation (17) and according to equation (14) for suitable steps of azimuth α. Figures 12 and 13 are time scale plots of ballodromic approach examples thus derived. These are interesting to compare with the corresponding scopodromic chart, Figure 7, which refers to the same "initial" position, namely, 1,419 yd abeam. While scopodromic pursuit from this initial position leads to a maximum load factor of 5, the ballodromic examples reach $4.1g$ and $3.85g$ for two different muzzle velocities, namely 2,875 and 2,200 fps, respectively. The critical azimuth angle at which the maximum load factor is reached is practically the same, 56 to 57 degrees, independent of the aiming technique. The time elapsed from the abeam to the critical position is 3 seconds scopodromically and 4 seconds ballodromically; the time from there to theoretical collision is 27½ vs 24 seconds.

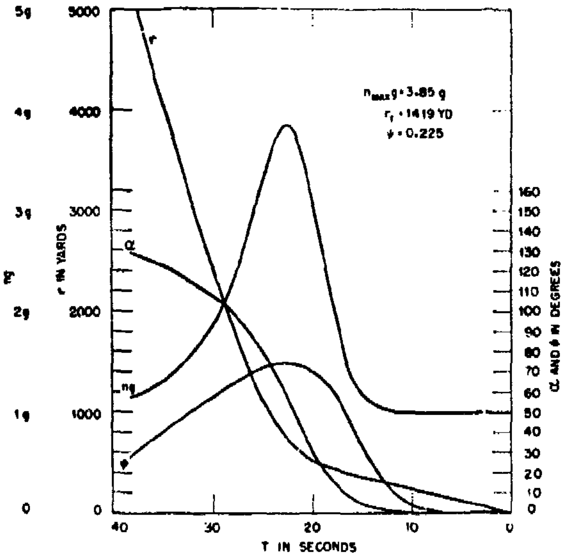


FIGURE 12. Ballodromic approach against time; $n_{max}g = 3.85g$, $r_T = 1{,}419$ yd, $\psi = 0.225$.

A.3.3 Leading Pursuit (Ballodrome), Gun Fixed

Thus far it has been assumed that the gun is automatically elevated to the tangent of the flight path of the interceptor. This assumption, however, is somewhat strained during the strongly banked phase of the ballodromic chase, where the high load factors induced by centrifugal force require larger angles of attack of the aircraft than in normal high-speed straight flight. With the gun fixed in the airplane, any change of angle of attack of the airplane is equivalent to an elevation or depression of the gun with respect to the flight-path tangent in straight flight as well as in turns.

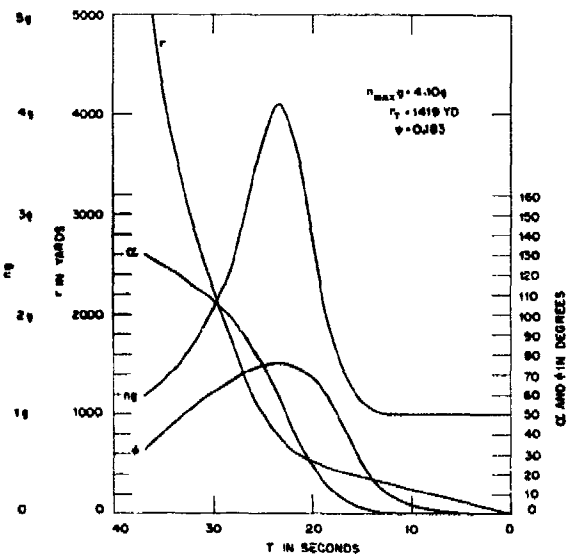


FIGURE 13. Ballodromic approach against time; $n_{max}g = 4.10g$, $r_T = 1{,}419$ yd, $\psi = 0.183$.

INFLUENCE OF ANGLE OF ATTACK

The possible effect of this apparent gun-vs-path elevation upon the ballodromic approach phoronomy can be estimated. If the gun is fixed with the barrel axis parallel to the flight path in straight level flight at high altitude and high speed v and the excess angle of attack θ of the aircraft varies essentially in proportion to the load factor, i.e., $\theta = i(n - 1)$. The factor i is defined as the quotient of the lift coefficient of straight level flight to the slope of the lift-coefficient-vs-angle-of-attack curve of the interceptor; i is of the order of a degree or two. The maximum value of the excess angle of attack may be of the order of $\theta = 5$ to 8 degrees, and this is about half of the maximum lead angle δ.[1]

In a horizontal turn the banking angle ϕ is defined by $n = \sec\phi$. The excess angle of attack has a horizontal component of $\tau = \theta\sin\phi = i(\tan\phi - \sin\phi)$, which is the angle to be deducted from the lead angle δ to arrive at the flight path. The vertical component $\theta\cos\phi = i(1 - \cos\phi)$ may be disregarded; it would merely subtract itself from the trajectory drop correction which, at a large banking angle, appears as a lateral or yaw displacement. Yet, an analytical calculation of the refinement, even under the further

[1] Explained in Section A.4.8.

simplifying assumptions of constant speed, leads to unmanageable expressions.

APPROACH BETWEEN SCOPO AND BALLO

As a first approximation it cannot be far off to expect the resultant path and history of load factors to fall between the scopodromic and ballodromic curves corresponding to the same initial position, about halfway, in the phase of highest load factors, between $\alpha = 90$ degrees and 30 degrees azimuth, and closer to ballodromic in the early (obtuse) and late (acute) phases. As a more accurate approximation a step-by-step correction method can be devised by determining successive correction angles. (See Section A.4.8.)

At any rate the maneuvers studied give a fair insight into the difficulties with which a high-speed chase at small-speed advantages is fraught.

A.3.4 Intersection Passage Without Banking

The approach maneuvers discussed in the preceding chapters are by no means easy to execute. They require an utterly precise banking technique, not only for the sake of preventing black-out but also for keeping the bead on the target. Thus, any type of approach requiring steep banking within the firing range may be impractical. Following is a study of what techniques of approach the interceptor could resort to in order to emancipate himself from the shackles of high load factors at firing range. Obviously, the trick is for him to do most of his turning while he is still so far away that it can be done at moderate angular velocity and then to approach so that by the time he arrives within firing range he has sufficiently straightened out to minimize banking and load factors.

COLLISION COURSE (TOMODROME)

As a hypothetical maneuver, because of its aid in the treatment and presentation of the analysis, and not because of any particular tactical effectiveness, the study will first consider what may be called a "tomodromic" approach (meaning "driving so as to cut or intersect"), namely, leading to collision on intersecting straight-flight paths. This condition can be devolved from the ballodromic equation (11) by letting $u = 0$ or $\psi = 1/\epsilon$. This makes the denominator zero, which indicates that the azimuth does not change when the proper lead

$$\sin \delta = \frac{1}{\epsilon} \sin \alpha \qquad (19)$$

is attained.

Table 6 is a list of values of this proper lead angle for various azimuths and speed ratios. Figure 14 shows them in a polar diagram.

TABLE 6.

α (deg)	$1/\epsilon$ 0.5	0.6	0.7	0.8	0.9	α (deg)	$1/\epsilon$ 1.0	1.1
0	0°	0°	0°	0°	0°	180	0°	0°
10	4°59′	5°59′	6°59′	7°59′	8°59′	170	10°	11°01′
20	9°51′	11°50′	13°51′	15°52′	17°56′	160	20°	22°05′
30	14°29′	17°27′	20°29′	23°35′	26°45′	150	30°	33°22′
40	18°45′	22°05′	26°45′	30°56′	35°19′	140	40°	44°59′
50	22°50′	27°23′	32°25′	37°48′	43°38′	130	50°	57°28′
60	25°40′	31°20′	37°18′	43°52′	51°16′	120	60°	72°22′
70	28°01′	34°20′	41°09′	48°41′	57°34′	110	70°	
80	29°30′	36°14′	43°35′	52°00′	62°23′	100	80°	
90	30°00′	36°52′	44°26′	53°08′	64°09′	90		

(A column for $1/\epsilon = 1.1$ is included here to show what limited chance a slow interceptor has when his speed is 10/11 that of his target; he has to attack from a forward sextant or else he would be left behind.)

TOMODROMIC APPROACH RATE

The actual rate of approach in the tomodromic maneuver is

$$-\frac{dr}{dt} = V\left[\epsilon - \cos\sqrt{1 - \left(\frac{\sin\alpha}{\epsilon}\right)^2} - \frac{\sin^2\alpha}{\epsilon}\right]$$
$$= \gamma V \qquad (20)$$

Table 7 gives values for the bracket expression γ which indicates the rate of approach as a fraction of the bomber's get-away speed. Figure 15 is a hodographic chart of it.

TABLE 7.

α (deg)	$1/\epsilon$ 0.5	0.6	0.7	0.8	0.9	1.0	1.1
0	1.000	0.667	0.429	0.250	0.111		
10	1.004	0.671	0.430	0.251	0.111		
20	1.0155	0.678	0.435	0.253	0.111		
30	1.037	0.692	0.443	0.256	0.112		
40	1.0685	0.710	0.456	0.262	0.114		
50	1.115	0.745	0.475	0.274	0.118		
60	1.174	0.791	0.507	0.290	0.123		
70	1.2565	0.856	0.553	0.318	0.133		
80	1.364	0.946	0.624	0.367	0.151		
90	1.500	1.068	0.729	0.450	0.211		
100	1.660	1.226	0.976	0.581	0.325	0.0602	
110	1.860	1.420	1.069	0.770	0.499	0.234	
120	2.076	1.645	1.302	1.010	0.749	0.500	0.235
130	2.299	1.887	1.561	1.351	1.048	0.826	0.532
140	2.518	2.130	1.824	1.576	1.364	1.173	0.910
150	2.713	2.344	2.065	1.844	1.660	1.500	1.357
160	2.867	2.518	2.260	2.060	1.900	1.764	1.652
170	2.966	2.635	2.386	2.201	2.057	1.940	1.843
180	3.000	2.667	2.429	2.250	2.111	2.000	1.909

Slant Tomodrome

Whether the plane of tomodromic intersection is horizontal or vertical, as in a glide approach from higher up or slant, the results are the same. Only the speed ratio is affected. The speed gain derived from a glide angle γ at a given power is a matter of aerodynamics near the compressibility burble limit and may have to be left to a step-by-step investigation of typical examples if of sufficient interest.

A.3.5 Interception Passage (Brachydrome)

The tomodromic approach would be suicidal if carried to the end, which is collision. It is theoretical also on the count that never during this approach is a fixed gun aimed at the proper lead angle; it would always fire ahead of the target. It is therefore necessary for the pilot, before he arrives at the desired firing range, to abandon the true tomodromic approach line and cut in behind the tail of his quarry. At close range he cannot afford to change over into the nearest ballodromic curve as this would entail an S-turn requiring extremely rapid aileron action, entailing high load factors and probably winding up in as much of a tail chase as a ballodromic approach from the beginning would have. To avoid this dilemma, all the pursuer has to do is to make an imperfect version of the straight slant approach, yet not to intersect but to miss the collision—in other words, slightly short. Such a maneuver will be denoted as "brachydromic" ("driving short"). This maneuver may attack the victim from vulnerable angles. However, the pursuer's firing rate must be very high, for he will have his guns aimed correctly only during one instant of the passage and he may not be certain just at what range this will occur.

The technique of this approach begins very much like the true intersection from initial azimuth α_0, except that the initial lead angle δ_0 is now chosen slightly less than the tomodromic lead angle of equation (19). The choice of this new initial lead angle δ_0 will be to a great extent a matter of training and experience. Once it is attained, the interceptor proceeds essentially straight and observes how the target gradually creeps up toward the firing lead angle δ^* which is identified by the ballistic triangle, namely $\sin \delta^* = \psi \sin \alpha^*$, while the azimuth off the target's tail will have diminished slightly from α_0 to α^*. The idea is to begin firing just before arriving at the proper range and lead and to continue firing until the target appears dead ahead. It must then have flown through a hail of bullets (provided proper allowance for trajectory drop was made). The pursuer need not swerve from his course and he is sure to fly through the wake of the victim, missing a collision.

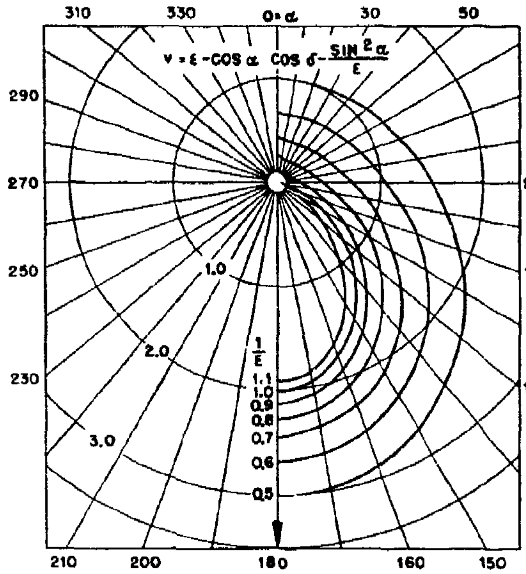


FIGURE 15. Tomodromic approach rate.

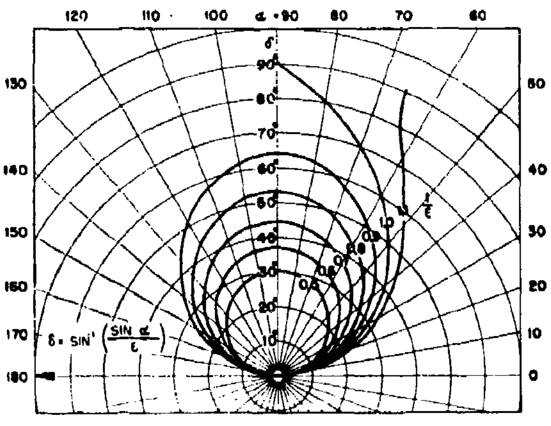


FIGURE 14. Tomodromic lead angle.

Brachydromic Approach

The range equation governing the brachydromic passage is

$$\frac{r}{r_0} = \frac{\epsilon \sin(\theta - \alpha_0) + \sin \alpha_0}{\epsilon \sin(\theta - \alpha) + \sin \alpha} \tag{21}$$

where r_0 and α_0 are any given initial conditions and θ is the angle at which the two courses cross. If σ denotes the "shortness," i.e., the range at which the enemy crosses dead ahead, then

$$\frac{r}{\sigma} = \frac{\sin\theta}{\epsilon \sin(\theta - \alpha) + \sin\alpha} = \frac{1}{\epsilon} \cdot \frac{\sin \alpha_\infty}{\sin(\alpha_\infty - \alpha)} \tag{22}$$

The rate at which the range changes is:

$$\frac{dr}{dt} = V[\cos\alpha - \epsilon\cos(\alpha - \theta)] \tag{23}$$

and in bomber's polar coordinates

$$\frac{dr}{d\alpha} = \sigma \cdot \frac{\sin\theta\,[\cos\alpha - \epsilon\cos(\theta - \alpha)]}{[\epsilon\sin(\theta - \alpha) + \sin\alpha]^2} \tag{24}$$

The azimuth α_∞ at which the approach would have begun from $r = \infty$ is identified by:

$$\cot\alpha_\infty = \cot\theta - \frac{1}{\epsilon}\sin\theta \tag{25}$$

The closest approach ever reached occurs at an azimuth of $\alpha_\infty - 90$ degrees.

Table 8 and Figures 16, 17, and 18 show how the range, expressed in terms of the dead-on "shortness" (which is not the closest passage distance), varies in the maneuver.

In polar coordinates the paths appear as straight course lines intersecting the enemy course at the initial azimuth angle α_∞ while the pursuer is actually headed in the direction θ as shown by the sample silhouettes.

Brachydromic Firing Range and Lead

The firing range at which the lead is correct is attained at a firing azimuth α^* for which:

$$\tan\alpha^* = \frac{\sin\theta}{\cos(\theta - \psi)} \tag{26}$$

TABLE 8. Brachydromic interception approach at course intersection angle θ.

α (degrees)	r/σ for $1/\epsilon = 0.5$: $\theta = 30°$	60°	90°	120°	150°	α (degrees)	r/σ for $1/\epsilon = 0.6$: 30°	60°	90°	120°	150°
0	0.500	0.500	0.500	0.500	0.500	0	0.600	0.600	0.600	0.600	0.600
10	0.583	0.507	0.466	0.422	0.343	10	0.672	0.597	0.551	0.498	0.389
20	0.727	0.531	0.450	0.375	0.267	20	0.791	0.595	0.523	0.437	0.308
30	1.000	0.577	0.4485	0.346	0.224	30	1.00	0.650	0.515	0.399	0.257
40	1.685	0.653	0.460	0.332	0.198	40	1.415	0.714	0.521	0.379	0.237
50	6.10	0.779	0.488	0.327	0.183	50	2.55	0.821	0.532	0.371	0.208
60		1.000	0.536	0.333	0.178	60	15.15	1.000	0.589	0.375	0.197
70		1.472	0.615	0.350	0.172	70		1.33	0.662	0.391	0.194
80		2.88	0.751	0.382	0.174	80		2.085	0.785	0.413	0.196
90			1.00	0.433	0.183	90		5.18	1.000	0.472	0.205
100			1.565	0.519	0.199	100			1.438	0.557	0.221
110			3.91	0.674	0.221	110			2.71	0.705	0.244
120				1.000	0.268	120			33.0	1.00	0.294
130				2.06	0.345	130				1.86	0.374
140					0.506	140				11.87	0.536
150					1.000	150					1.000
160						160					9.62
α_∞	53.8°	90.0°	116.6°	139.1°	159.9°	α_∞	62.0°	96.6°	121.0°	141.8°	161.2°

α (degrees)	r/σ for $1/\epsilon = 0.7$: $\theta = 30°$	60°	90°	120°	150°	α (degrees)	r/σ for $1/\epsilon = 0.8$: 30°	60°	90°	120°	150°
0	0.700	0.700	0.700	0.700	0.700	0	0.800	0.800	0.800	0.800	0.800
10	0.755	0.684	0.634	0.572	0.458	10	0.831	0.765	0.707	0.639	0.511
20	0.847	0.688	0.595	0.495	0.348	20	0.894	0.756	0.659	0.543	0.385
30	1.000	0.721	0.576	0.450	0.288	30	1.000	0.769	0.632	0.472	0.316
40	1.265	0.766	0.576	0.423	0.252	40	1.172	0.808	0.625	0.456	0.275
50	1.798	0.854	0.594	0.411	0.230	50	1.475	0.881	0.637	0.443	0.248
60	3.03	1.00	0.633	0.412	0.218	60	2.07	1.000	0.680	0.442	0.236
70	22.7	1.25	0.700	0.426	0.213	70	3.68	1.197	0.731	0.453	0.229
80		1.74	0.810	0.450	0.215	80	18.5	1.55	0.833	0.481	0.231
90		3.02	1.000	0.505	0.223	90		2.31	1.000	0.530	0.240
100		12.92	1.347	0.588	0.240	100		4.78	1.303	0.609	0.257
110			2.41	0.706	0.269	110			1.95	0.745	0.286
120			6.56	1.000	0.316	120			4.15	1.000	0.335
130				1.67	0.395	130				1.57	0.418
140				5.59	0.561	140				4.00	0.582
150					1.000	150					1.00
160					5.32	160					4.00
α_∞	71.6°	103.0°	125.0°	144.2°	162.3°	α_∞	82.5°	108.5°	128.7°	146.3°	163.3°

TABLE 8 (*Continued*)

α (degrees)	r/σ for $1/\epsilon = 0.9$				
	$\theta = 30°$	60°	90°	120°	150°
0	0.900	0.900	0.900	0.900	0.900
10	0.903	0.837	0.790	0.709	0.570
20	0.934	0.821	0.721	0.601	0.419
30	1.000	0.821	0.683	0.535	0.342
40	1.110	0.846	0.669	0.496	0.297
50	1.294	0.903	0.676	0.476	0.269
60	1.605	1.000	0.704	0.471	0.253
70	2.21	1.16	0.758	0.481	0.246
80	4.20	1.43	0.849	0.507	0.246
90	14.70	1.94	1.000	0.554	0.255
100		3.20	1.262	0.631	0.272
110		11.7	1.786	0.764	0.302
120			3.22	1.000	0.352
130			19.2	1.51	0.436
140				3.29	0.598
150					1.000
160					3.35
α_∞	93.9°	114.1°	132.0°	148.2°	164.2°
α (degrees)	r/σ for $1/\epsilon = 1.0$				
	30°	60°	90°	120°	150°
0	1.000	1.000	1.000	1.000	1.000
10	0.969	0.922	0.864	0.777	0.612
20	0.969	0.879	0.780	0.653	0.451
30	1.000	0.866	0.732	0.577	0.366
40	1.065	0.879	0.710	0.532	0.315
50	1.180	0.922	0.710	0.508	0.285
60	1.367	1.000	0.732	0.500	0.268
70	1.668	1.13	0.780	0.508	0.259
80	2.28	1.35	0.864	0.532	0.259
90	3.73	1.73	1.000	0.577	0.268
100	11.1	2.53	1.233	0.653	0.285
110		4.98	1.67	0.777	0.315
120			2.73	1.000	0.366
130			8.14	1.462	0.451
140				2.88	0.612
150					1.000
160					2.97
α_∞	105.0°	120.0°	135.0°	150.0°	165.0°
α (degrees)	r/σ for $1/\epsilon = 1.1$				
	$\theta = 30°$	60°	90°	120°	150°
0	1.10	1.10	1.10	1.10	1.10
10	1.03	0.995	0.936	0.850	0.66
20	1.00	0.935	0.843	0.701	0.582
30	1.00	0.908	0.777	0.615	0.388
40	1.03	0.908	0.746	0.563	0.336
50	1.10	0.937	0.741	0.537	0.301
60	1.21	1.000	0.757	0.524	0.282
70	1.40	1.108	0.799	0.530	0.272
80	1.73	1.285	0.875	0.552	0.273
90	2.34	1.585	1.000	0.596	0.280
100	3.57	2.16	1.21	0.669	0.297
110	11.1	3.55	1.59	0.788	0.328
120		10.96	2.42	1.000	0.379
130			5.49	1.423	0.464
140				2.61	0.624
150				18.8	1.00
160					2.72
α_∞	115.1°	124.7°	137.7°	151.6°	165.7°

and the lead angle at this instant is $\delta^* = \alpha^* - \theta$ for which:

$$\sin \delta^* = \psi \sin \alpha^* \quad \text{or} \quad \tan \delta^* = \frac{\psi \sin \theta}{1 - \psi \cos \theta} \tag{27a}$$

or

$$\tan \delta^* = \frac{\tan \delta}{1 + \frac{u}{v} \cdot \cos \delta \left[\cos \delta \pm \sqrt{\left(\frac{1}{\epsilon}\right)^2 - \sin^2 \delta} \right]} \tag{27b}$$

where u/v is the ratio of the muzzle velocity to the interceptor's own airspeed.

When the pursuit pilot does not know and cannot estimate the course of the quarry, he can, theoretically, so maneuver that he finds at what lead or crab angle δ he can fly straight without the target changing its apparent angular position during the approach. He knows his own bullet-to-flight speed ratio u/v. This would suffice to solve the ballistic triangle, except that the inaccurately known enemy-to-own speed ratio $1/\epsilon = V/v$ enters in equation (27b) as a slight correction.[m] The resulting ballistic lead angle required to hit the target is, however, ambiguous. The larger one corresponds to the case of encounter, the smaller one to that of overtaking. The values of proper lead angles for various tomodromic approach crab angles δ_t and a series of bullet-to-pursuit speed ratios $u/v = 2.7, 3.0$, and 3.3 times the pursuit speed are given in Table 9 and plotted in Figure 19 and a cross plot for $u/v = 3$ in Figure 20.

Table 10 and Figures 21 to 25 give a synopsis of values of proper lead angles and ranges in brachydromic interception for a series of course intersection angles θ in steps of 30 degrees and for various speed ratios ϵ and ψ.

EXAMPLE

To quote an example, take the case of $\psi = 0.225$, which may correspond to a $v = 500$ mph interceptor ($1/\epsilon = 0.9$) and $u/v = 3$ (effective average muzzle velocity $u = 2{,}200$ fps). If this interceptor pilot wanted to so intercept a $V = 450$ mph bomber as to hit at, say, $r^* = 400$ yd, he would have but a few seconds for the several phases of such an attack, and less than a second of effective fire. Table 11 shows for various course angles θ how much time

$$t_1 = \frac{r^*}{V} \cdot \frac{\sin \delta^*}{\sin \theta} = \frac{r^*}{u + v} \cdot \frac{\sin \alpha^*}{\sin \theta} \tag{28}$$

[m] A torpedo-directing technique can be developed from this method of tomodromic approach and brachydromic interception.

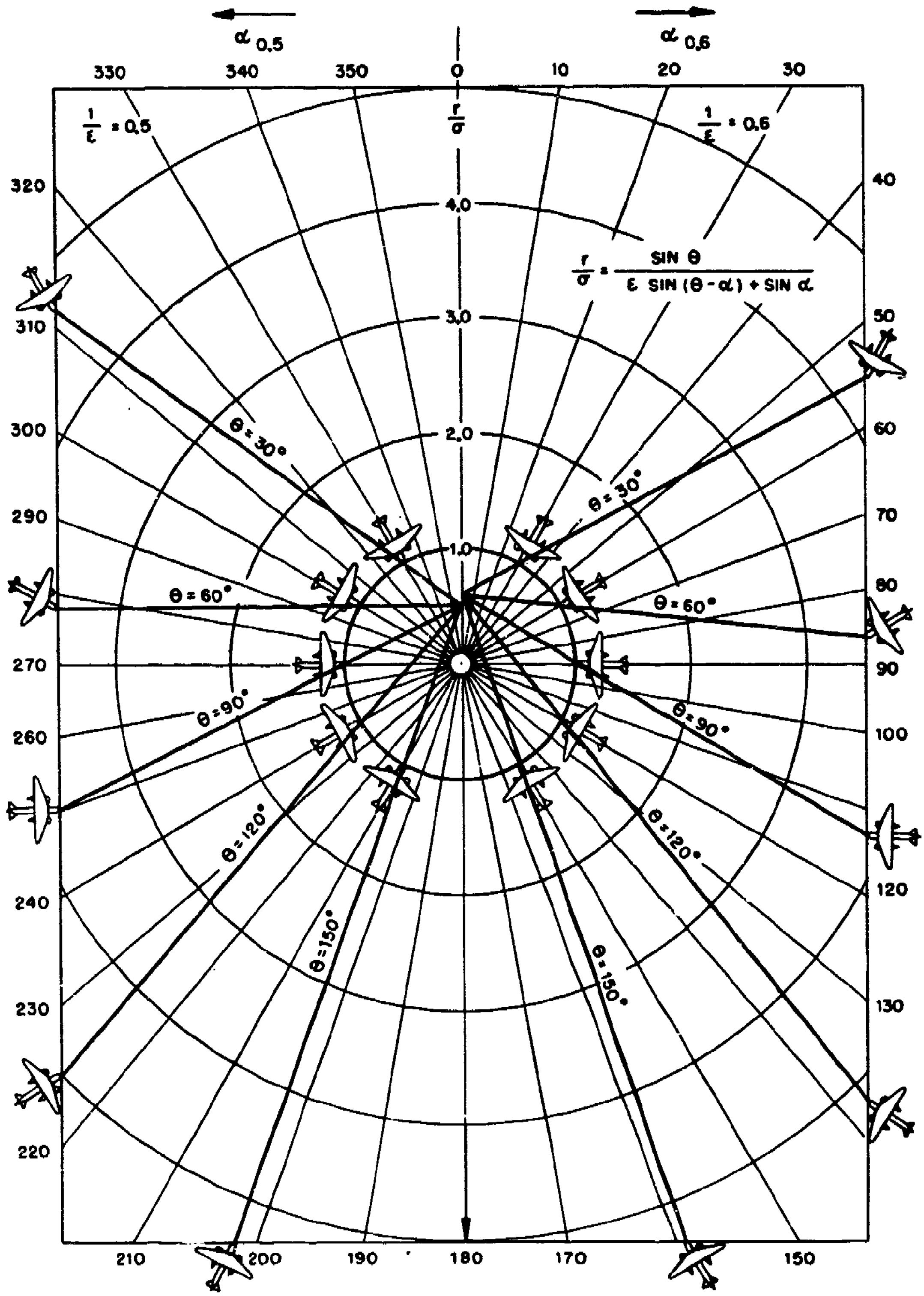


FIGURE 16. Brachydromic passage, $1/\epsilon = 0.6$.

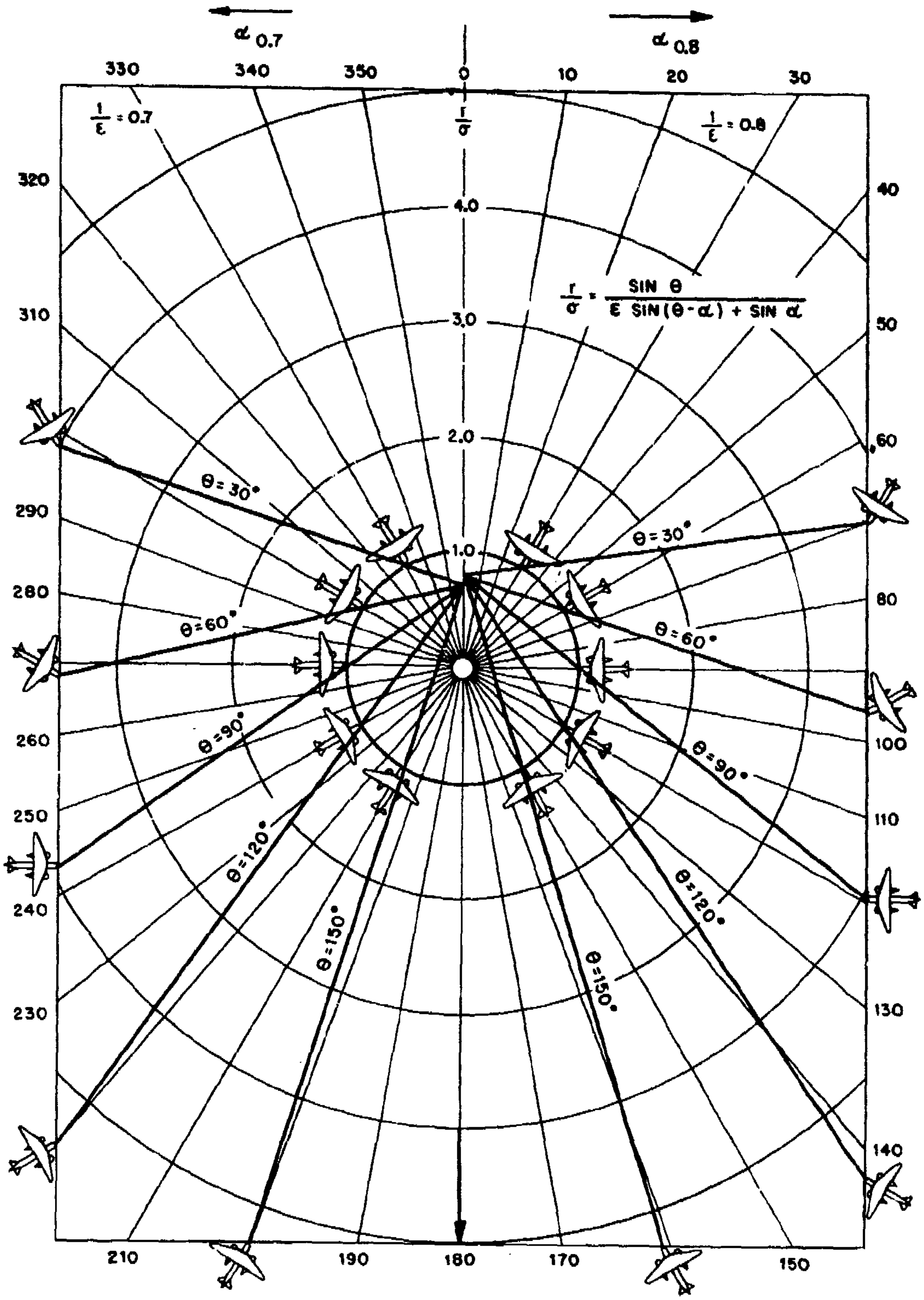


FIGURE 17. Brachydromic passage, $1/\epsilon = 0.8$.

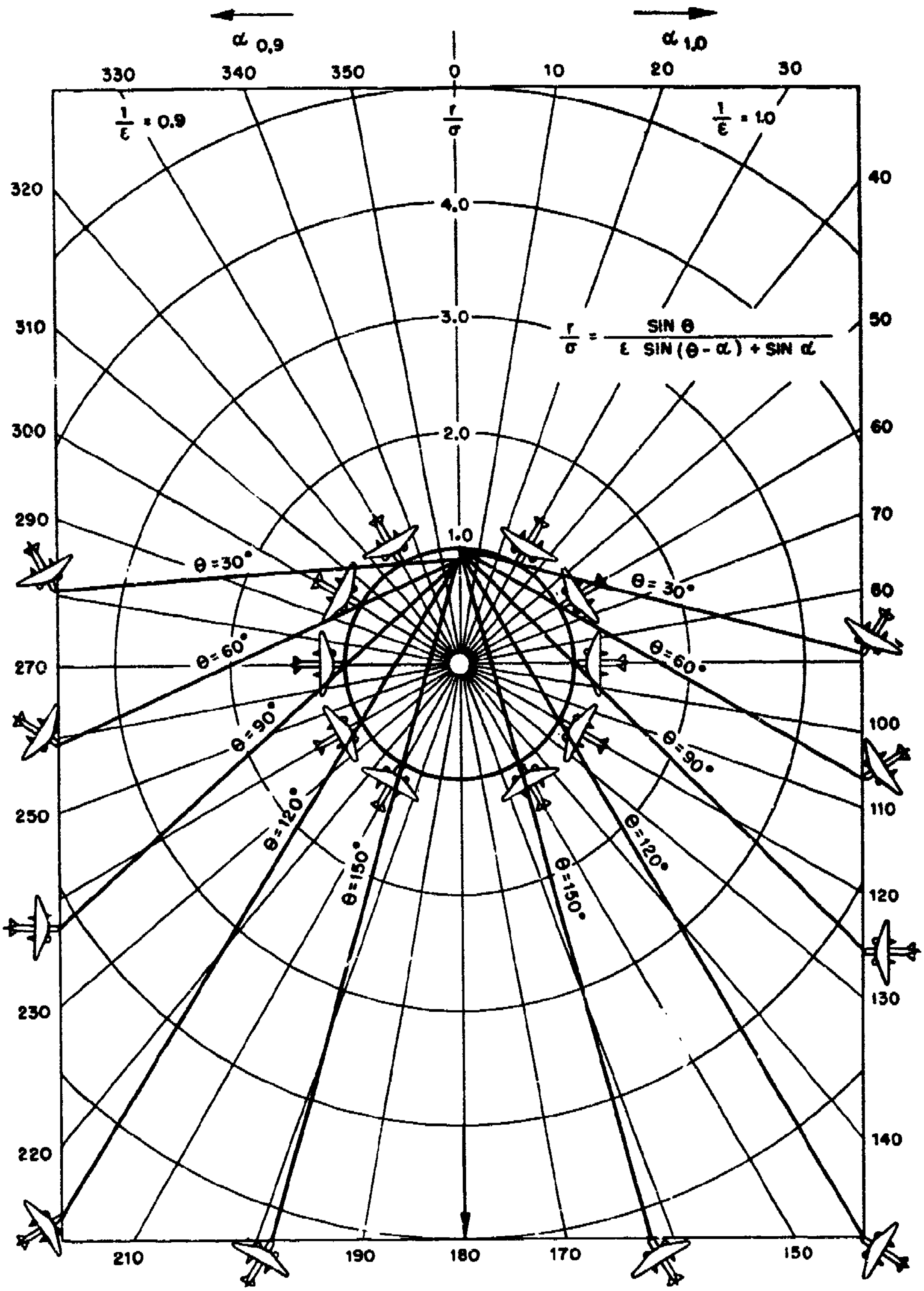


FIGURE 18. Brachydromic passage, $1/\epsilon = 1.0$.

TABLE 9. Proper brachydromic lead angle δ^* after tomodromic approach at crab angle θ.

δ	$u/v = 2.7$ δ_1^*	δ_2^*	$u/v = 3.0$ δ_1^*	δ_2^*	$u/v = 3.3$ δ_1^*	δ_2^*
	For $1/\epsilon = 0.7$					
10°	3°49′	1°1′	3°34′	0°56′	3°21′	0°51′
20°	7°18′	2°9′	6°49′	1°57′	6°22′	1°47′
30°	9°56′	3°33′	9°11′	3°13′	8°37′	2°58′
40°	10°50′	5°50′	10°01′	5°20′	9°18′	4°54′
44°26′	8°51′	8°51′	8°05′	8°05′	7°28′	7°28′
	For $1/\epsilon = 0.8$					
10°	3°57′	0°42′	3°42′	0°38′	3°24′	0°35′
20°	7°36′	1°28′	7°07′	1°20′	6°40′	1°13′
30°	10°36′	2°23′	9°52′	2°10′	9°14′	1°59′
40°	12°18′	3°39′	11°25′	3°18′	10°37′	3°02′
50°	11°35′	6°06′	10°39′	5°33′	9°51′	5°05′
53°08′	8°55′	8°55′	8°13′	8°13′	7°24′	7°24′
	For $1/\epsilon = 0.9$					
10°	4°5′	0°22′	3°50′	0°20′	3°37′	0°18′
20°	7°54′	0°45′	7°24′	0°41′	6°57′	0°37′
30°	11°09′	1°13′	10°26′	1°06′	9°46′	1°00′
40°	13°23′	1°47′	12°28′	1°37′	11°35′	1°28′
50°	14°02′	2°41′	12°57′	2°25′	12°01′	2°12′
60°	11°52′	4°27′	11°01′	4°02′	9°57′	3°40′
64°10′	7°45′	7°45′	7°01′	7°01′	6°24′	6°24′
	For $1/\epsilon = 1.0$					
10°	4°13′	0°	3°58′	0°	3°44′	0°
20°	8°12′	0°	7°41′	0°	7°14′	0°
30°	11°39′	0°	10°53′	0°	10°13′	0°
40°	14°15′	0°	13°17′	0°	12°24′	0°
50°	15°35′	0°	14°25′	0°	13°23′	0°
60°	15°10′	0°	13°52′	0°	12°51′	0°
70°	12°21′	0°	11°14′	0°	10°19′	0°
80°	7°12′	0°	6°30′	0°	5°54′	0°
90°	0°	0°	0°	0°	0°	0°

elapses between the arrival at proper lead angle δ^* and zero lead (dead-on) and how far the bullets of any one machine gun firing at the rate of, say, $b = 20$ rounds per second would be spaced on the moving target, along the target's longitudinal axis

$$s = \frac{u}{b} \cdot \psi \tag{29}$$

and laterally with respect to the sighting line

$$s_v = \frac{u}{b} \cdot \psi \sin \alpha^* \tag{30}$$

BULLET DENSITY

It is immediately apparent that for any interception passage at appreciable crossing angle θ only one or two bullets per gun will have a chance of hitting a vital part of the airplane. The fact remains that the slanting or brachydromic attack can be pressed home

TABLE 10. Values of r^*/ϵ for ψ = 0.175, 0.200, 0.225, and 0.250, and for θ = 30°, 60°, 90°, 120°, and 150°. $1/\epsilon$ = 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.10.

$\theta =$	0°	30°	60°	90°	120°	150°	180°
	$\psi = 0.175$						
α^*	0	35°54′	69°27′	99°55′	127°58′	154°21′	0
δ^*	0	5°54′	9°27′	9°55′	7°58′	4°21′	0
$1/\epsilon$ = 0.5	1.27	1.315	1.425	1.56	1.69	1.78	1.81
0.6	1.175	1.205	1.31	1.43	1.56	1.64	1.675
0.7	1.10	1.14	1.235	1.35	1.47	1.55	1.57
0.8	1.055	1.09	1.185	1.30	1.41	1.48	1.505
0.9	1.025	1.06	1.15	1.26	1.37	1.43	1.46
1.0	1.00	1.035	1.12	1.23	1.34	1.40	1.425
1.1	0.98	1.015	1.10	1.21	1.31	1.37	1.40
	$\psi = 0.200$						
α^*	0	36°55′	70°54′	101°18′	128°56′	154°51′	0
δ^*	0	6°55′	10°54′	11°18′	8°56′	4°51′	0
$1/\epsilon$ = 0.5	1.33	1.38	1.53	1.70	1.85	1.95	2.0
0.6	1.20	1.24	1.37	1.53	1.66	1.76	1.80
0.7	1.12	1.17	1.29	1.43	1.55	1.64	1.68
0.8	1.07	1.11	1.22	1.36	1.48	1.56	1.61
0.9	1.03	1.07	1.18	1.31	1.43	1.51	1.55
1.0	1.00	1.04	1.15	1.27	1.39	1.47	1.50
1.1	0.98	1.02	1.12	1.24	1.36	1.44	1.47
	$\psi = 0.225$						
α^*	0	37°58′	72°22′	102°41′	129°56′	155°25′	0
δ^*	0	7°58′	12°22′	12°41′	9°56′	5°25′	0
$1/\epsilon$ = 0.5	1.41	1.48	1.65	1.87	2.05	2.19	2.23
0.6	1.24	1.30	1.45	1.64	1.80	1.94	1.96
0.7	1.14	1.20	1.34	1.51	1.66	1.78	1.81
0.8	1.08	1.13	1.26	1.43	1.57	1.68	1.70
0.9	1.03	1.08	1.21	1.37	1.50	1.61	1.64
1.0	1.00	1.05	1.17	1.32	1.45	1.55	1.58
1.1	0.97	1.02	1.14	1.29	1.42	1.51	1.54
	$\psi = 0.250$						
α^*	0	39°05′	73°53′	104°02′	130°54′	155°53′	0
δ^*	0	9°05′	13°53′	14°02′	10°54′	5°53′	0
$1/\epsilon$ = 0.5	1.50	1.59	1.76	2.08	2.30	2.47	2.50
0.6	1.28	1.36	1.52	1.77	1.47	2.11	2.14
0.7	1.17	1.24	1.38	1.61	1.78	1.92	1.95
0.8	1.09	1.15	1.30	1.50	1.67	1.79	1.82
0.9	1.04	1.10	1.24	1.43	1.58	1.70	1.73
1.0	1.00	1.06	1.19	1.37	1.53	1.64	1.67
1.1	0.97	1.03	1.16	1.33	1.48	1.59	1.62

if the quarry pursues a straight course. The success of this type of interception is, however, very problematical because it depends on (1) rapid fire power to assure that enough bullets will hit the target, (2) prompt alignment on an interception path that will bring him within the desired range, and (3) early detection and identification of the enemy and his flight direction.

The first condition is necessitated by the fact that the bullet stream sweeps or saws through the target. This may be an advantage inasmuch as it mitigates

TABLE 11. Firing opportunity for $r^* = 400$ yd, $b = 20$ rounds per sec, $\psi = 0.225$, $v = 500$ mph, $V = 450$ mph, $u = 2{,}200$ fps, $s = 25$ ft.

θ	Time to dead-on t_1 (sec)	Lateral spacing s_y (ft)
30°	0.52	15½
60°	0.45	23½
90°	0.40	24
120°	0.35	18½
150°	0.29	9

any inadvertent horizontal aiming error, but it may also be a weakness if the bullets are spaced too far apart, especially in a near broadside attack where the scatter is greatest. The interceptor must, of course, be equipped with several guns adapted to be fired syncopatingly.

As to the second problem of prompt alignment, the maneuver is more difficult than an early phase of a scopodromic turn. The trick is to straighten out into a near tomodromic intersection approach and to correct the interceptor's course quickly so that the crab angle (θ) appears to remain nearly constant until the firing range is approached. Then, instead of swerving toward the wake of the target, the interceptor need merely throttle slightly to let the target creep up close to the proper lead angle δ^*, which can be derived from the previously observed crab angle θ according to Table 9 and Figure 19, if only the speed ratio ϵ can be estimated with sufficient accuracy. As soon as the target has arrived at the proper lead angle δ^*, or slightly before, the interceptor may open the throttle wide again and fire.

It will be noted that the final maneuver is free from turning and involves no increased load factors while in or near the firing range, but the actual combat time is much shorter than in the ballodromic tail chase. The question remains whether there is enough time to determine the constant crab angle θ and the corresponding firing lead angle δ^*. The computation of the latter can be automatized by means of a cam device set to the proper value of the speed ratio ϵ as

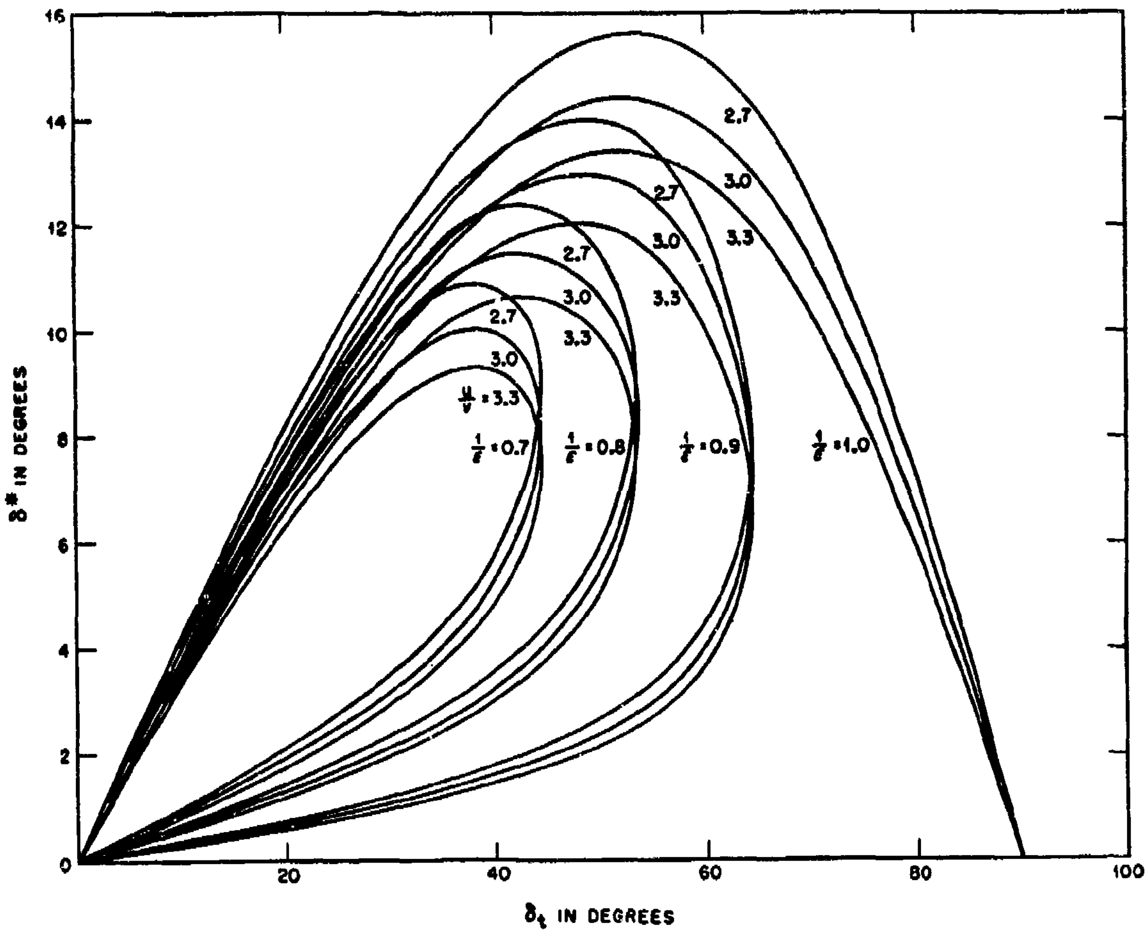


FIGURE 19. Brachydromic lead.

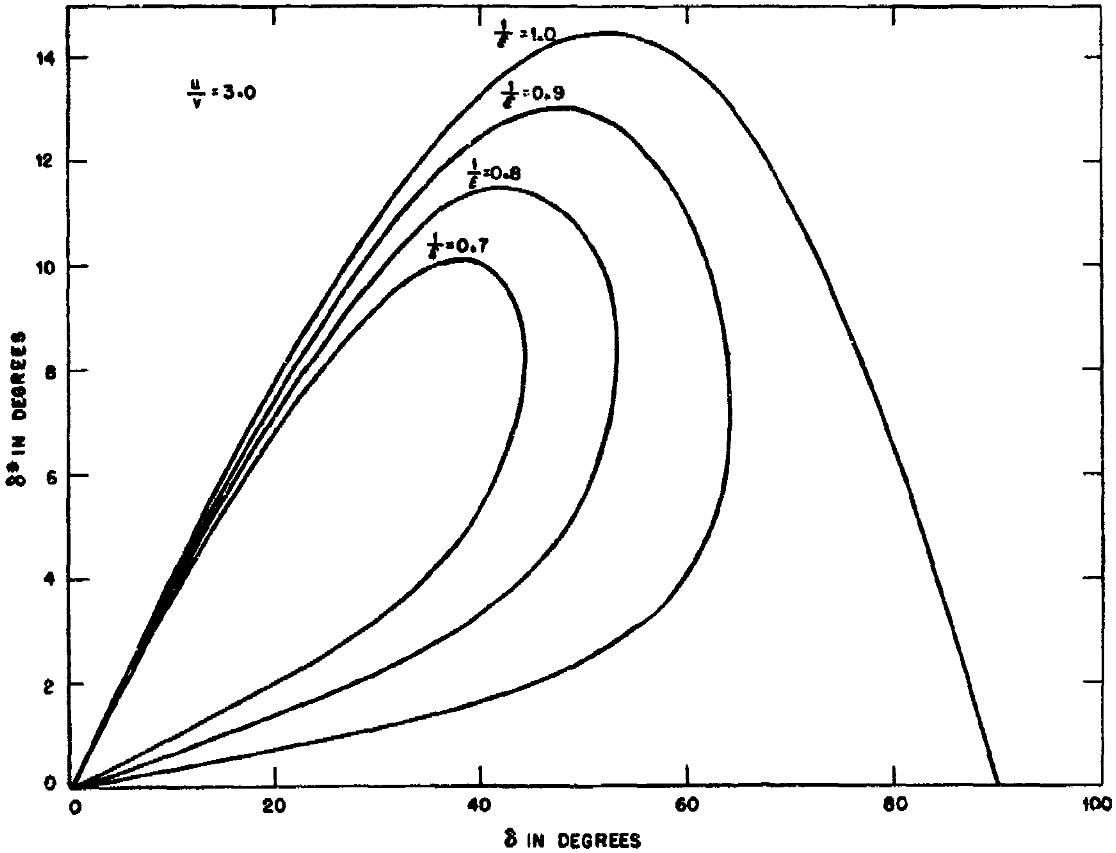


FIGURE 20. Brachydromic lead, for $u/v = 3.0$.

soon as it is estimated. The pilot would merely adjust a diopter toward the target during the tomodromic approach phase with constant crab angle. This would automatically cam the proper correction into his reflector gunsight, ready for use when he is ready to "cut short."

However, it is possible that the maneuver can be learned and practiced even without such a device by allowing for the lead to diminish from the tomodromic value which is sure to be too large, to zero (dead-ahead) which is sure to be too small. The probability of a hit, however, remains small at best.

The third problem, prompt detection and identification of the quarry, is aggravated for the interceptor by the shortness of the time available (1 to 2 minutes) to obtain and digest any information received from the ground, and the time (but a few seconds) to maneuver into any other than a tail chase position.

SLANT BRACHYDROME

The brachydromic interception can be executed in a sloping path as well as in a horizontal plane. The descent yields a speed advantage which, though small, is constant and easy to compute.

A.3.6 Outlook

The protagonist of minimum defense on the fast bomber may concede that interception from blunt or even obtuse angles is possible but he may justly argue that such attacks will be rare, because of the early decision required to prevent the encounter from developing into a stern chase, and that at best they will be weak or ineffectual because of the brief time of combat fire. Should the first attack miscarry, then a second one by the same attacker would inevitably wind up on the tail. The more blunt or obtuse the first attack, the greater the chance of the bomber to run away because of the speed drop of the pursuer in his turn to resume the chase. In fact, the latter may risk losing his quarry altogether. For example, if the paths crossed at 90 degrees and if the pursuer made an immediate quarter-turn at $4g$ with his speed dropping down to the same (450 mph) as the bomber's, he would drop about 1,300 yd behind. On the

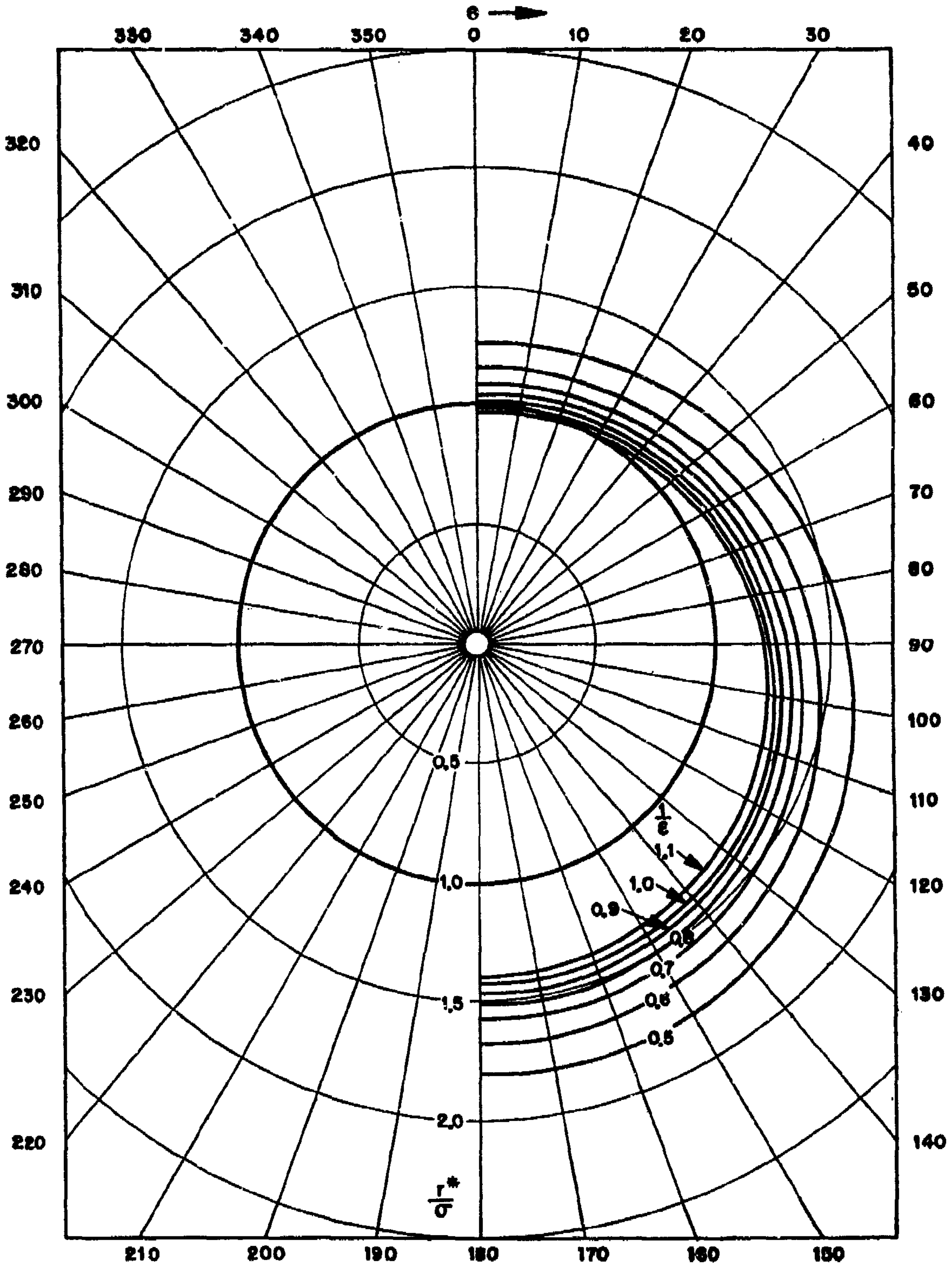


FIGURE 21. Brachydromic firing range, $\psi = 0.175$.

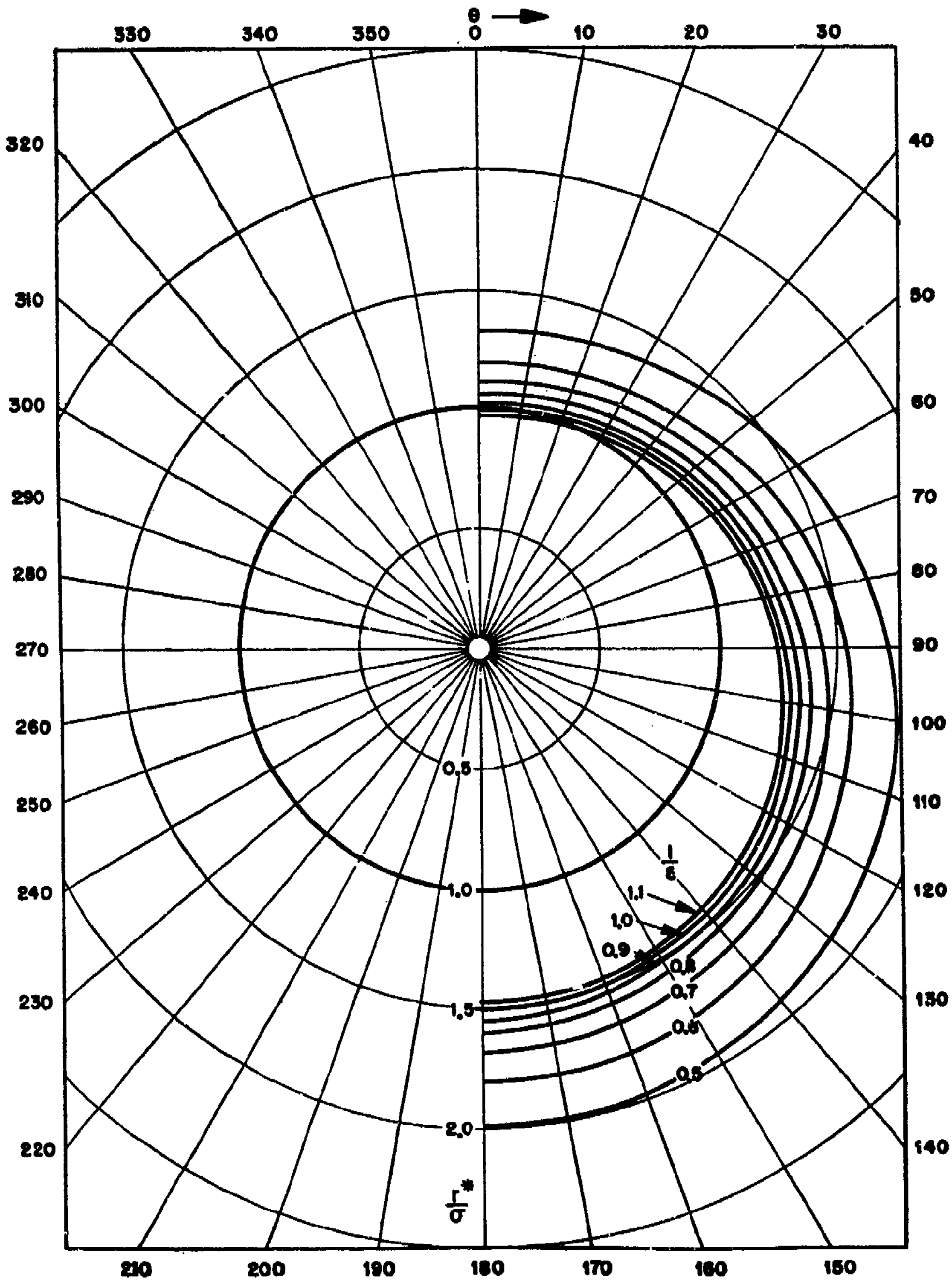


FIGURE 22. Brachydromic firing range, $\psi = 0.200$.

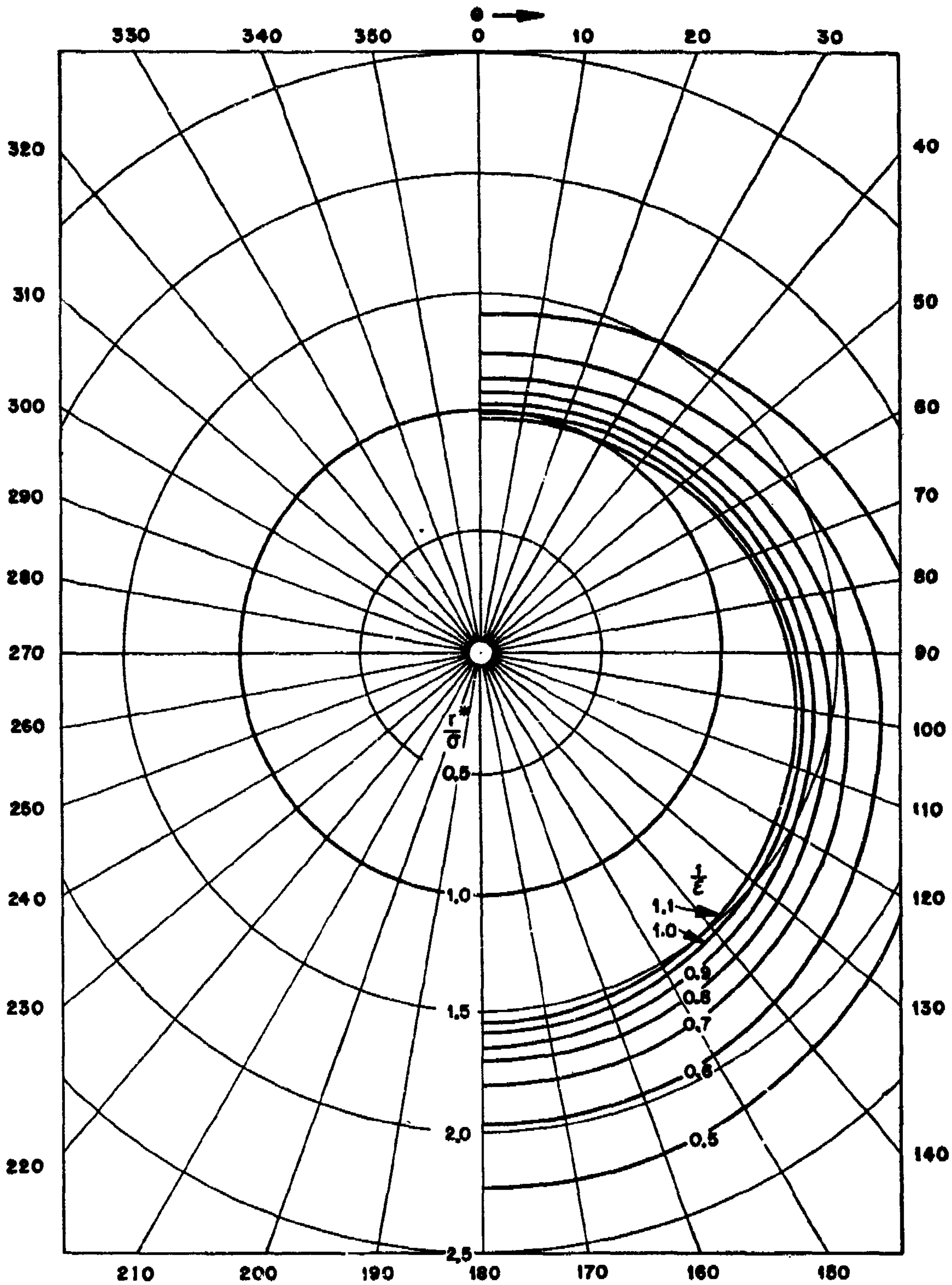


FIGURE 23. Brachydromic firing range, $\psi = 0.225$.

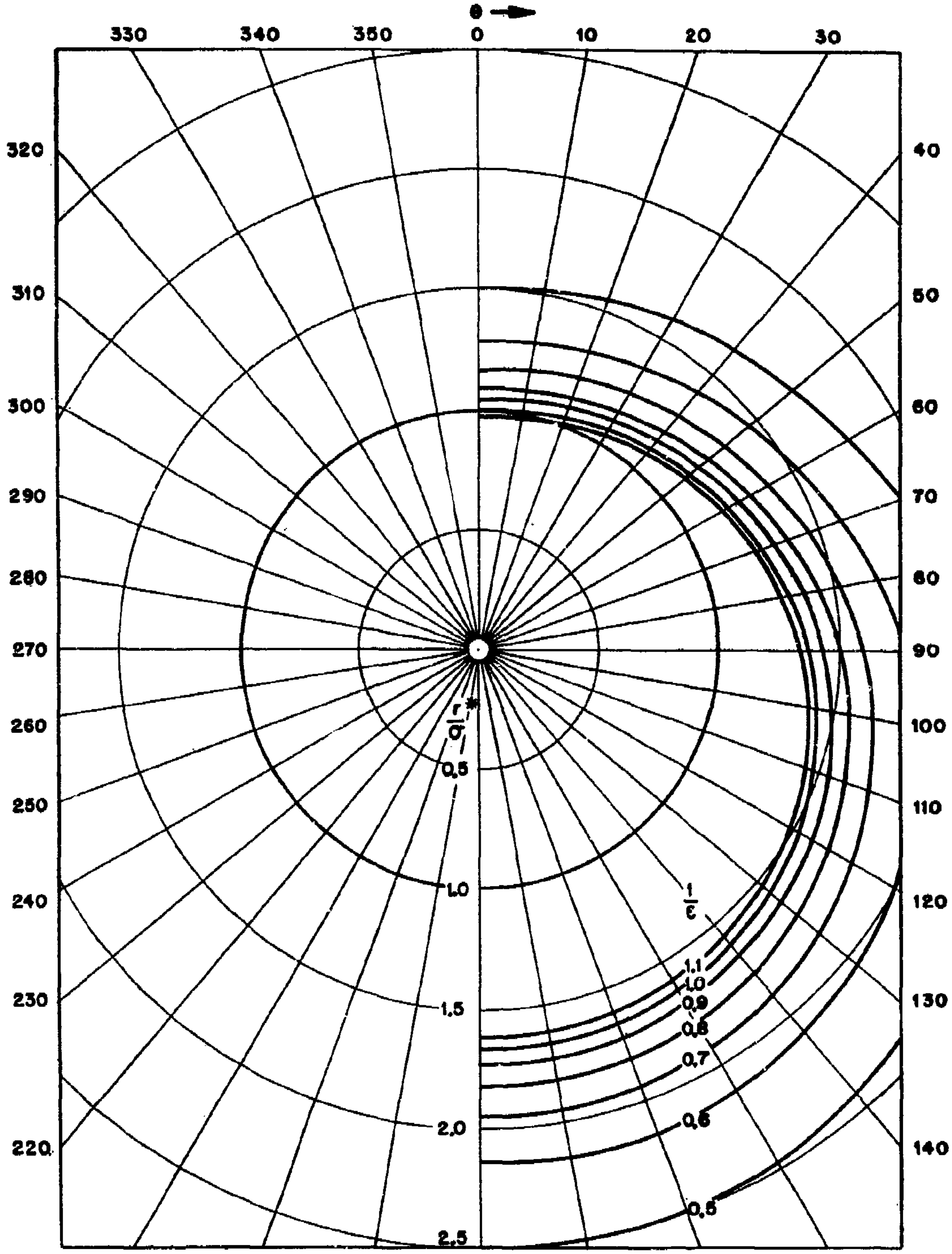


FIGURE 24. Brachydromic firing range, $\psi = 0.250$.

other hand, if an acute tail attack, either brachydromic or ballodromic, is unsuccessful, all the pursuer has to do is to zoom up, drop behind, and resume the tail chase. The tail chase remains the normal combat phase of the fixed gun interceptor going after a high-speed, high-altitude bomber flying straight.

What now if the interceptor is equipped with some flexible guns with which he can attack obliquely from some angle? Such an installation may be considered as belonging to the category of a "new weapon" but it cannot well be entirely ignored. (In fact, it is not entirely new; in World War I, the Nieuport fighter was thus equipped.) The old argument that slant fire is inaccurate because it requires compound lead correction is not wholly conclusive. If the pursuer succeeds in creeping up into some position on top or below or off to the side or at some skew corner of his victim and then flies parallel to it at the same speed, he can leisurely pour lead into it, keeping an uncorrected bead on it since the lead corrections for the two parallel motions would cancel each other. The approach phase was treated in Section A.3.1 under *Pitched Gun* (*Clinoscopodrome*), but once the interceptor approaches the terminal position angle he may throttle back and stalk his quarry.

The only obvious arguments against the effectiveness of this stalking technique are:

1. The approach into such a dangerous position would probably come from the tail through a clinoscopodromic or ballodromic pursuit during which the attacker would have been exposed to the tail defense of the bomber. The latter's job would be to prevent the pursuer from ever catching up with it. Maneuvering into a skew or top or bottom stalking position on a tomodromic interception approaching from an undefended blunt angle would require a great deal of skill and practice.

2. In firing at blunt angles the projectiles are likely to tumble, especially at the extremely high airspeeds contemplated here.

3. To aim obliquely while flying is difficult for any pilot, who, after all, has to keep one eye on where he is going, especially at high speed. The interceptor may carry a separate gunner for the oblique gun, but even so the pilot has to watch the quarry closely enough to fly parallel to him. It is a task similar to formation flying at high speed. It is reasonable to assume that this technique is therefore limited to moderate cone angles off the tail of the pursued, perhaps up to 45 degrees. Attack from the upper quadrant would be particularly difficult because of vision limitations; attack from underneath the tail would be least difficult.

In speculating about "new weapons" that may be developed to bolster the defense against faster and higher-flying bombers—aside from stepping up the firing speed of the guns—the thought of immunizing the interceptor personnel against higher acceleration stresses, rather than avoiding them, is worth following through. By seating the pilot in a crouched position with the body bent forward and the face forward, the limit of resistance to impairment of vision may be extended $2g$, from $6g$ to $8g$ for 2 seconds or from $5g$ to $7g$ for somewhat longer periods. On the other hand, a reclining position, with the head back and as low as possible, compatible with a clear view through the gunsight, and with the feet raised to pedal extensions and legs suitably supported, may be even more effective in reducing the total head of blood and yet be more comfortable and helpful in attaining the steadiness required in aiming, though special gunsights may have to be devised for this technique. Liquid pressure suits may eventually be perfected to raise the acceleration tolerance. However, similar concessions to the protection of the personnel might also be considered for the bomber to raise its maneuvering limitations, insofar as they may be governed by physiological rather than structural or stall limits.

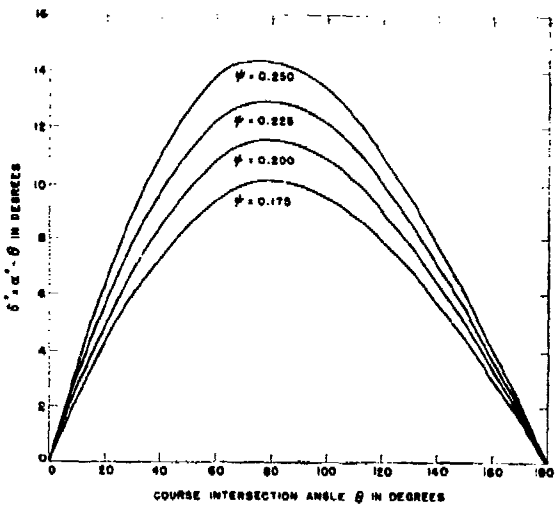


FIGURE 25. Lead angle for brachydromic interception.

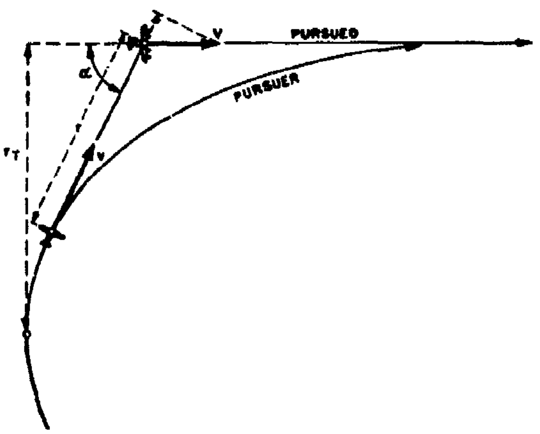
A.4 MATHEMATICAL DERIVATIONS

A.4.1 Scopodromic Pursuit Curve in the Pursued's Polar Coordinates

ANALYSIS

Radial speed component:

$$\frac{dr}{dt} = V \cos \alpha - v.$$



V = true airspeed of pursued
v = true airspeed of pursuer
$\epsilon = v/V$ = speed ratio
α = azimuth of pursuer off pursued's tail
r = range
r_T = range in cross-path position
0 = refers to any initial position

FIGURE 26. Diagram of scopodromic pursuit.

Azimuthal speed component:

$$\frac{d\alpha}{dt} = -\frac{V \sin \alpha}{r}.$$

Quotient of above:

$$\frac{dr}{d\alpha} = -\frac{V \cos \alpha - v}{V \sin \alpha} \cdot r.$$

Rearrange and substitute $\epsilon = v/V$:

$$\frac{dr}{r} = \left(\frac{\epsilon}{\sin \alpha} - \cot \alpha\right) d\alpha.$$

Transform:

$$d \ln r = d\left(\epsilon \ln \tan \frac{\alpha}{2}\right) - d \ln \sin \alpha.$$

Integrate:

$$\ln r = \ln \tan^{\epsilon} \frac{\alpha}{2} - \ln \sin \alpha + C.$$

Antilog:

$$r = c \cdot \frac{\tan^{\epsilon} \frac{\alpha}{2}}{\sin \alpha}.$$

Same for initial position:

$$r_0 = c \cdot \frac{\tan^{\epsilon} \frac{\alpha_0}{2}}{\sin \alpha_0}.$$

Quotient:

$$\frac{r}{r_0} = \left(\frac{\tan \frac{\alpha}{2}}{\tan \frac{\alpha_0}{2}}\right)^{\epsilon} \cdot \frac{\sin \alpha_0}{\sin \alpha}$$

and for $r_0 = r_T$, $\alpha_0 = 90$ degrees:

$$r = r_T \frac{\tan^{\epsilon} \frac{\alpha}{2}}{\sin \alpha}. \qquad \text{Q. E. D.}$$

A.4.2

Peak Load Factor in a Scopodromic Curve

ANALYSIS

$$\frac{d(n_q g)}{d\alpha} = 0$$

for $n_q g = \dfrac{vV}{r_T} \cdot \dfrac{\sin^2\alpha}{\tan^{\epsilon} \frac{\alpha}{2}} = \dfrac{vV}{r_T} \cdot \sin^2\alpha \left(\dfrac{1 + \cos \alpha}{1 - \cos \alpha}\right)^{\epsilon/2}$

and $\alpha = \alpha_c$.

For a quotient, the derivative vanishes when the product of its numerator by the derivative of the denominator equals the product of the denominator by the derivative of the numerator; that is,

$$\frac{\sin^2 \alpha_c d\left(\tan^{\epsilon} \frac{\alpha}{2}\right)}{d\alpha} = \frac{\tan^{\epsilon} \frac{\alpha_c}{2}\, d(\sin^2 \alpha)}{d\alpha}$$

Thus,

$$\frac{\sin^2 \alpha_c \cdot \epsilon \cdot \tan^{\epsilon - 1} \frac{\alpha}{2}}{2 \cos^2 \frac{\alpha_c}{2}} = \tan^{\epsilon} \frac{\alpha_c}{2} \cdot 2 \sin \alpha_c \cos \alpha_c$$

Everything cancels except

$$\frac{\epsilon}{2} = \cos \alpha_c \qquad \text{Q.E.D.}$$

Thus, $\cos^2 \alpha_c = \dfrac{\epsilon^2}{4}$

and $\sin^2 \alpha_c = 1 - \dfrac{\epsilon^2}{4}$

Hence,

$$\sin^2 \alpha_c \left(\frac{1 + \cos \alpha_c}{1 - \cos \alpha_c}\right)^{\epsilon/2} = \left(1 - \frac{\epsilon^2}{4}\right) \cdot \left(\frac{1 + \frac{\epsilon}{2}}{1 - \frac{\epsilon}{2}}\right)^{\epsilon/2}$$

$$= \left(1 + \frac{\epsilon}{2}\right) \left(1 - \frac{\epsilon}{2}\right) \left(1 + \frac{\epsilon}{2}\right)^{\epsilon/2} \cdot \left(1 - \frac{\epsilon}{2}\right)^{-\epsilon/2}$$

$$= \left(1 + \frac{\epsilon}{2}\right)^{1+\epsilon/2} \cdot \left(1 - \frac{\epsilon}{2}\right)^{1-\epsilon/2}$$

Q.E.D.

Equation (6a) can be transformed to read

$$r_e = r_T\left(1 - \frac{\epsilon}{2}\right)^{(\epsilon-1)/2}(1 + \epsilon)^{-\epsilon}$$

A.4.3 Least Load Factor Peak in Scopodromic Pursuit

The maximum centripetal acceleration is

$$n_{y\max} = \frac{vV}{r_T g}\cdot\left(1 + \frac{\epsilon}{2}\right)^{1+\epsilon/2}\cdot\left(1 - \frac{\epsilon}{2}\right)^{1-\epsilon/2}$$

and for v = constant, $V = v/\epsilon$, the above becomes a minimum for

$$\frac{d}{d\epsilon}\cdot\left[\frac{\left(1 + \frac{\epsilon}{2}\right)^{1+\epsilon/2}\cdot\left(1 - \frac{\epsilon}{2}\right)^{1-\epsilon/2}}{\epsilon}\right] = 0$$

Let $\left(1 + \frac{\epsilon}{2}\right)^{1+\epsilon/2} = A$ and $\left(1 - \frac{\epsilon}{2}\right)^{1-\epsilon/2} = B$

and $\frac{dA}{d\epsilon} = A'$ and $\frac{dB}{d\epsilon} = B$

Then:

$$(BA' + AB')\epsilon - AB = 0$$

Here, however

$$A' = \tfrac{1}{2}A \ln\left(1 + \frac{\epsilon}{2}\right)$$

and

$$B' = \tfrac{1}{2}B \ln\left(1 - \frac{\epsilon}{2}\right)$$

so that

$$\epsilon\left[\tfrac{1}{2}BA \ln\left(1 + \frac{\epsilon}{2}\right) - \tfrac{1}{2}AB\cdot\ln\left(1 - \frac{\epsilon}{2}\right)\right] = AB,$$

where AB cancels, and by combining the logs,

$$\frac{\epsilon}{2}\cdot\ln\frac{1 + \frac{\epsilon}{2}}{1 - \frac{\epsilon}{2}} = 1$$

The order of magnitude of its solution is readily found by expansion and with

$$x = \cos^2\alpha_c = \left(\frac{\epsilon}{2}\right)^2$$

$$2x^2\cdot\left(1 + \frac{x^2}{3} + \frac{x^4}{5} + \frac{x^6}{7} + \cdots\right) = 1$$

and the actual value by a little trial and error. It furnishes $\epsilon/2 = \cos\alpha_c = 0.65$, $\alpha_c = 49$ degrees, and $\epsilon = 1.3$; $1/\epsilon = 0.77$. That the extreme value is a minimum and not a maximum is readily seen, when the second derivative is inspected, namely,

$$\frac{\epsilon}{2}\cdot\frac{1 - \frac{\epsilon}{2}}{1 + \frac{\epsilon}{2}}\cdot\frac{\frac{1}{2}\left(1 - \frac{\epsilon}{2}\right) + \frac{1}{2}\left(1 + \frac{\epsilon}{2}\right)}{\left(1 - \frac{\epsilon}{2}\right)^2}$$

$$= \frac{\epsilon}{2}\cdot\frac{1}{1 - \left(\frac{\epsilon}{2}\right)^2}$$

This is indeed positive (which is the condition for the presence of a minimum) for all values of $\epsilon < 2$. (Of course, for larger speed ratio no load factor peak is reached during the approach phase, as the load factor would keep on increasing until the pursuer has caught up with his victim; no α_c can have a cosine greater than 1.)

A.4.4 Time of Scopodromic Approach

From Section A.4.1, the reciprocal of the azimuthal speed component is

$$\frac{dt}{d\alpha} = -\frac{r}{V\sin\alpha}$$

and from equation (1), a second form of

$$r = \frac{r_T}{\sin\alpha}\cdot\left(\frac{1 - \cos\alpha}{1 + \cos\alpha}\right)^{\epsilon/2}$$

When combined, they result in

$$\frac{dt}{d\alpha} = -\frac{r_T}{V\sin^2\alpha}\cdot\left(\frac{1 - \cos\alpha}{1 + \cos\alpha}\right)^{\epsilon/2}$$

Now, since $\sin^2\alpha = 1 - \cos^2\alpha = (1 - \cos\alpha)(1 + \cos\alpha)$

$$\frac{dt}{d\alpha} = -\frac{r_T}{V}\cdot\frac{(1 - \cos\alpha)^{\epsilon/2-1}}{(1 + \cos\alpha)^{\epsilon/2+1}}$$

This is integrated by the substitution

$$\tan\frac{\alpha}{2} = x$$

which makes $1 - \cos\alpha = \frac{2x^2}{1 + x^2}$

and $1 + \cos\alpha = \frac{2}{1 + x^2}$

and $d\alpha = \frac{2dx}{1 + x^2}$

With these substitutions the integral becomes

$$t = -\frac{r_T}{2V}\cdot\int_0^x (x^{\epsilon-2} + x^\epsilon)dx$$

which is

$$t = -\frac{r_T}{2V}\cdot\left[\frac{x^{\epsilon-1}}{\epsilon-1}+\frac{x^{\epsilon+1}}{\epsilon+1}\right]_0^x$$

$$= \frac{r_T}{2V}\left[\frac{\tan^{\epsilon-1}\frac{\alpha}{2}}{\epsilon-1}+\frac{\tan^{\epsilon+1}\frac{\alpha}{2}}{\epsilon+1}\right]_\alpha^0 \qquad \text{Q.E.D.}$$

A.4.5 Deceleration Due to Inertia Load

NOMENCLATURE

$v_{(L/D)_{max}}$ is the airspeed of best glide angle.

$\phi = v/v_{(L/D)_{max}}$ is the ratio of the actual speed to that of the best glide angle.

$e\mathcal{R}$ = effective aspect ratio.

$C_i = \dfrac{C^2_L}{\pi e\mathcal{R}}$ is the induced drag coefficient.

C_0 is the parasite drag coefficient.

ANALYSIS

At any speed the drag coefficient is made up of

$$C_D = C_0 + \frac{C^2_L}{\pi e\mathcal{R}}$$

At best glide angle (indicated by *) it is:

$$C^*_D = C_0 + \frac{C^*_L}{\pi e\mathcal{R}}$$

but here[a]

$$C_0 = C^*_i = \frac{C^{*2}_L}{\pi e\mathcal{R}}$$

[a] Proof for the fact that, at the best glide angle, induced and parasite drag are equal:

$$C_D = C_0 - \frac{C^2_L}{\pi e\mathcal{R}}$$

where $e\mathcal{R}$ is the effective aspect ratio.

Thus, $$\frac{C_D}{C_L} = \frac{C_0}{C_L} + \frac{C_L}{\pi e\mathcal{R}}$$

The derivative of this with respect to C_L, must vanish:

$$\frac{d\frac{C_D}{C_L}}{dC_L} = -\frac{C_0}{C^2_L} + \frac{1}{\pi e\mathcal{R}} = 0$$

for least $\dfrac{C_D}{C_L}$

namely, at $$\frac{C_0}{C^2_L} = \frac{1}{\pi e\mathcal{R}}$$

Hence, $$C_0 = \frac{C^2_L}{\pi e\mathcal{R}} = C_i$$

Hence, after substitution and cancellation of $\pi e\mathcal{R}$,

$$\frac{C_D}{C^*_D} = \frac{C^{*2}_L - C^2_L}{2C^{*2}_L}$$

Now, in order to carry the same weight,

$$C_L = \frac{C^*_L}{\phi^2}$$

Thus,

$$C_D = C^*_D\cdot\tfrac{1}{2}(1+\phi^{-4}) = C_0(1+\phi^{-4})$$

Now in the presence of a load factor n, the induced drag increases from $C_i = C_0/\phi^4$ to n^2C_0/ϕ^4. The difference in drag coefficient then becomes $\Delta C_D = \Delta C_i = C_0(n^2-1)/\phi^4$ and its ratio to the steady-flight drag C_D becomes

$$\frac{\Delta C_D}{C_D} = \frac{n^2-1}{1+\phi^4}$$

With S = wing area and q = velocity head, the weight carried at high speed is

$$Mg = C_LSq$$

so the deceleration of the same mass M due to excess drag is

$$-\dot v = \Delta C_D\cdot\frac{Sq}{M} = \frac{\Delta C_D}{C_L}\cdot g$$

$$= \frac{\Delta C_D}{C_D}\left(\frac{C_D}{C_L}\right)_\phi\cdot g$$

$$= g\left(\frac{D}{L}\right)_\phi\cdot\frac{n^2-1}{\phi^4+1} \qquad \text{Q.E.D.}$$

Figure 27 illustrates a clinoscopodromic approach.

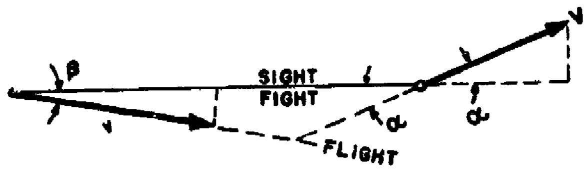


FIGURE 27. Diagram of clinoscopodromic approach.

A.4.6 Clinoscopodromic Approach

ANALYSIS

Radial speed component:

$$\frac{dr}{dt} = V\cos\alpha - v\cos\beta$$

Azimuthal velocity:

$$\frac{d\alpha}{dt} = -\frac{V\sin\alpha - v\sin\beta}{r}$$

Quotient of above, with $v = \epsilon V$

$$\frac{dr}{d\alpha} = \frac{\epsilon \cos \beta - \cos \alpha}{\epsilon \sin \beta + \sin \alpha} \cdot r$$

whence equation (11), which is (with $dr/r = d \ln r$)

$$d \ln r = \frac{\epsilon \cos \beta - \cos \alpha}{\epsilon \sin \beta + \sin \alpha} \cdot d\alpha$$

To integrate, since ϵ and β are constant, split

$$\ln r = \epsilon \cos \beta \int \frac{d\alpha}{\epsilon \sin \beta + \sin \alpha} - \int \frac{\cos \alpha \, d\alpha}{\epsilon \sin \beta + \sin \alpha} + C$$

The last of these integrals is simply

$$\ln (\epsilon \sin \beta + \sin \alpha)$$

The first one (according to *Manual of Mathematics and Mechanics* by Clements & Wilson, integral 205 *b*) is

$$\frac{2}{\sqrt{1 - \epsilon^2 \sin^2 \beta}} \cdot \tanh^{-1} \cdot \left[\sqrt{\frac{1 - \epsilon^2 \sin^2 \beta}{1 + \epsilon \sin \beta}} \cdot \tan \left(\frac{\alpha}{2} - \frac{\pi}{4} \right) \right]$$

With $a = 1 + \epsilon \sin \beta$, and $b = 1 - \epsilon \sin \beta$, this is abbreviated to:

$$\frac{2}{\sqrt{ab}} \cdot \tanh^{-1} \left[\sqrt{\frac{b}{a}} \cdot \tan \left(\frac{\alpha}{2} - \frac{\pi}{4} \right) \right]$$

However, for the sake of getting rid of the other logarithms it is preferable to express the $\tanh^{-1}$ by a logarithm also, according to $\tanh^{-1} z = \frac{1}{2} \ln (1 + z)/(1 - z)$, where the [ ] expression above plays the role of z.

Thus,

$$\ln r = \frac{\epsilon \cos \beta}{\sqrt{ab}} \cdot \ln \frac{1 + z}{1 - z} - \ln (\epsilon \sin \beta + \sin \alpha) + C$$

and for $\alpha = 90$ degrees, where $\tan (\alpha/2 - \pi/4) = 0$ so that $z = 0$,

$$\ln r_T = -\ln (\epsilon \sin \beta + 1) + C$$

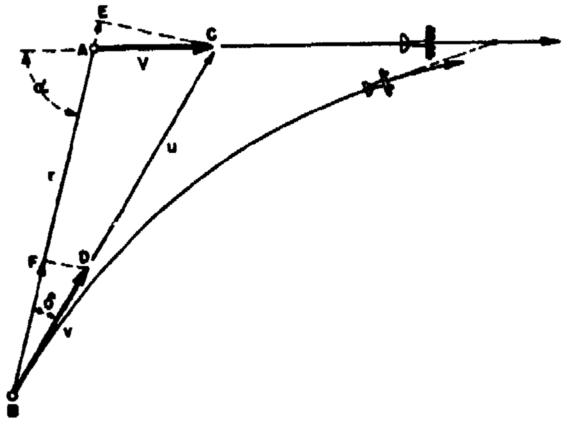
The difference of the two is free from C; its antilog is:

$$\frac{r}{r_T} = \frac{\epsilon \sin \beta + 1}{\epsilon \sin \beta + \sin \alpha} \cdot \left[\frac{1 + z}{1 - z} \right]^{\frac{(\epsilon \cos \beta)}{\sqrt{ab}}}$$

which turns into equation (12) by substituting for $1 + \epsilon \sin \beta$ and for z.

A.4.7 Ballodromic Approach

Figure 28 illustrates a ballodromic approach.



u = muzzle velocity (average)
v = pursuer's true airspeed
V = pursued's true airspeed
$\epsilon = v/V$
$\psi = V/(u + v)$
r = range
α = azimuth
δ = lead angle

FIGURE 28. Diagram of ballodromic approach.

ANALYSIS

According to the law of sines in the interception speed triangle ABC:

$$\frac{\sin \delta}{\sin \alpha} = \frac{V}{u + v} = \psi$$

Speed of range change $AE - BF$,

$$\frac{dr}{dt} = V \cos \alpha - v \cos \delta$$

Rate of azimuth change $(FD - EC)/AB$,

$$\frac{d\alpha}{dt} = \frac{-V \sin \alpha + v \sin \delta}{r}$$

Their quotient is

$$\frac{dr}{d\alpha} = -\frac{V \cos \alpha - v \cos \delta}{V \sin \alpha - v \sin \delta} \cdot r = -\frac{\cos \alpha - \epsilon \cos \delta}{\sin \alpha - \epsilon \sin \delta} \cdot r$$

or

$$\frac{dr}{r} = -\frac{\cos \alpha - \epsilon \cos \delta}{\sin \alpha - \epsilon \sin \delta} \cdot d\alpha$$

Substitute for δ

$$\frac{dr}{r} = \frac{\epsilon \sqrt{1 - \phi^2 \sin^2 \alpha} - \cos \alpha}{\sin \alpha (1 - \epsilon^{\psi})} \cdot d\alpha = \frac{\epsilon \sqrt{\csc^2 \alpha - \psi^2} - \cot \alpha}{1 - \epsilon \psi} \cdot d\alpha$$

Hence

$$\ln r = \frac{1}{1-\epsilon\psi}\left[\epsilon\psi \int \sqrt{\frac{1}{\psi^2 \sin^2\alpha} - 1} \cdot d\alpha - \int \cot\alpha \, d\alpha = \frac{\epsilon\psi I_1 - I_2}{1-\epsilon\psi}\right]$$

The second integral is simply $I_2 = \ln \sin\alpha + C_2$. The first one is solved by the substitution°

$$z = \frac{\psi \cos\alpha}{\sqrt{1-\psi^2 \sin^2\alpha}} = \frac{\psi\cos\alpha}{\cos\delta} = \frac{EA}{EB}$$

and since $\sin\delta = \psi \sin\alpha$

the differential is

$$d\alpha = -\frac{\sqrt{1-\psi^2}}{(1-z^2)\sqrt{\psi^2 - z^2}}$$

so that the first integral, I_1, is transformed into

$$I_1 = (\psi^2 - 1)\int \frac{dz}{(\psi^2 - z^2)(1-z^2)}$$

This is split into a product of linear denominators by

$$\frac{A}{\psi + z} + \frac{B}{\psi - z} + \frac{C}{1+z} + \frac{D}{1-z} = \frac{1}{(\psi^2 - z^2)(1-z^2)}$$

and solved by successively eliminating all but one term after another by successively allowing $z = -\psi, \psi, -1, 1$, which furnishes $A = B = \frac{1}{2}\psi(1-\psi^2)$ and $C = D = \frac{1}{2}(\psi^2 - 1)$. With these constants the solution becomes

$$I_1 = \frac{1}{2}\ln\left[\left(\frac{\psi - z}{\psi + z}\right)^{1/\psi} \cdot \frac{1+z}{1-z}\right]$$

When this is introduced into the original problem

$$\ln\frac{r}{r_T} = \frac{1}{(1-\epsilon\psi)}\left[\ln\left(\frac{\psi - z}{\psi + z}\right)^{\epsilon/2}\left(\frac{1+z}{1-z}\right)^{\epsilon\psi/2} - \ln\sin\alpha\right]$$

For $\alpha = 90$ degrees, where $z = 0$ the range is $r = r_T$. Thus,

$$r = r_T\left[\left(\frac{\psi - z}{\psi + z}\right)^{\epsilon/2} \cdot \left(\frac{1+z}{1-z}\right)^{\epsilon\psi/2} \cdot \frac{1}{\sin\alpha}\right]^{1/(1-\epsilon\psi)}$$

Resubstitution for z now furnishes equation (16).

Q.E.D.

° In view of the complete equivalence of the respective azimuths α and δ of one ship against the other, it is logical to seek a solution of the part of the integral which involves the lead angle by referring the geometry not to the coordinate system of either ship but to the only system that is equivalent to both, namely, their instantaneous line of sight. The projections on it of target speed and bullet speed bear the ratio $z = \psi\cos\alpha/\cos\delta$ and by virtue of the "refraction" law, $\sin\delta = \psi\sin\alpha$, governing the relation between the two angles, this is also the ratio of the two azimuth tangents, viz., $z = \tan\delta/\tan\alpha$.

The calculation being somewhat cumbersome, it may be of interest to note that approximations will serve to speed up the computation where second-order terms can be neglected. Inasmuch as ψ is of the order of 20 to 25 per cent, its second-order terms are practically negligible, especially in view of other errors or inaccuracies of assumptions, notably the disregard of the variation of the angle of attack of the aircraft with varying load factor. Therefore, a first-order expansion approximation is useful to gain an insight into the influence of ballodromic leading, for any special case; that is to say,

$$\frac{dr}{r} \backsimeq \frac{\epsilon\csc\alpha - \cot\alpha}{1-\epsilon\psi} \cdot d\alpha$$

which can be directly integrated to give

$$r \backsimeq r_T\left[\frac{\tan^\epsilon \frac{\alpha}{2}}{\sin\alpha}\right]^{1/(1-\epsilon\psi)} = r_T\left[\frac{(1-\cos\alpha)^{\epsilon-1}}{(1+\cos\alpha)^{\epsilon+1}}\right]^{1/[2(1-\epsilon\psi)]}$$

which significantly turns into the scopodromic formulas (2) when ψ is neglected.

To visualize the significance of the exponent, it is well to remember that it is half of $1/(1-\epsilon\psi) = 1 - v/u$, in which v/u is the ratio of the pursuer's own airspeed to his own gun's average effective muzzle velocity.

For the last phase of the stern chase, when the higher-order terms of α also can be neglected, the approximate range equation boils down to

$$\frac{r}{r_0} = \left(\frac{\alpha}{\alpha_0}\right)^{(\epsilon-1)/(1-\epsilon\psi)} = \left(\frac{\alpha}{\alpha_0}\right)^{(1+v/u)(1-V/v)}$$

which again agrees with the scopodromic case, equation (3), as soon as ψ is disregarded.

For the calculation of load factors, take $d\alpha/dt$ from the third equation of this section.

For $d\delta/dt$ observe that:

$$\frac{d\delta}{dt} = \frac{d\delta}{d\alpha}\cdot\frac{d\alpha}{dt}$$

and since $\sin\delta = \psi\sin\alpha$

$$\cos\delta\,\frac{d\delta}{d\alpha} = \psi\cos\alpha$$

hence

$$\frac{d\delta}{d\alpha} = \psi\frac{\cos\alpha}{\cos\delta}$$

Thus, $$\frac{d\alpha}{dt} - \frac{d\delta}{dt} = \frac{V}{r}\cdot(1-\epsilon\psi)\sin\alpha\left(1 - \psi\frac{\cos\alpha}{\cos\delta}\right)$$

To determine the time elapsed, the reciprocal of the apparent azimuthal angular velocity, $dt/d\alpha = r/V \sin\alpha(1-\epsilon\psi)$, is plotted against α, and the graph is integrated by planimeter, which yields the time elapsed. This was done for $\epsilon = 10/9$ and two values of $\psi = 0.183$ and 0.225.

A.4.8 Influence of Angle of Attack

The influence of angle of attack is shown in Figure 29.

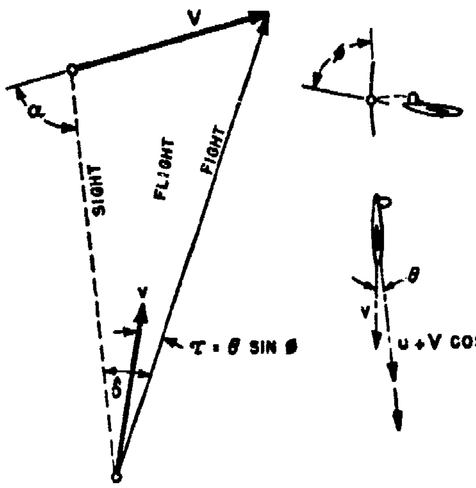


FIGURE 29. Diagram of angle of attack. (For $\alpha = 90$ degrees, $\sin \delta = \psi$; thus, for $\psi = 0.225$, $\delta = 13$ degrees.)

In computing the progress of the approach step by step, the following procedure was adopted.

From an initial position chosen far enough away so that the influence of the angle of attack is negligible, determine a first approximation of n from the ballodromic load factor from equation (17). Thence, compute $\theta = i(n - 1)$. For a practical example the aerodynamic coefficient i may be assumed $1\frac{1}{2}$ degrees. Now lay off the line of flight at a course $\alpha - \delta + \tau$ ($\tau = \theta \sin \phi$) and progress at the rate v for a step of $\frac{1}{2}$ sec. The new position furnishes new values of α and r and $\Delta\alpha/\Delta t$ from which a new banking angle is computed according to

$$\tan \phi = \frac{V^2\epsilon}{gr}\left[\epsilon \sin (\delta - \tau) - \sin \alpha\right]$$

whereupon the process is repeated.

During the subsequent scopodromic approaches, the azimuth α decreases, thus shifting the peak of the frequency curve more toward the acute angles. Each point of the frequency curve is shifted from the initial azimuth α_0 to a new azimuth α_1 corresponding to the same scopodrome, which is defined by a certain value of r_T satisfying both α_0 and r_0. The value of the ordinate, however, undergoes a change from the original value of p_{α_0} to p_{α_1} because the same number of attacks now cover a different range $d\alpha$, such that $p_0 d\alpha_0 = p_1 d\alpha_1$; hence $p_1 = p_0 d\alpha_0/d\alpha_1$. The corresponding "breadth" $d\alpha_0$ and $d\alpha_1$ are bordered by two scopodromes of slightly different parameters r_T. Therefore the variation $d\alpha_0/d\alpha_1$ must be expressed by the ratio of $d\alpha_0/df(r_T)$ and $d\alpha_1/df(r_T)$.

The parameter r_T is defined according to equation (1) by any set of corresponding values of r and α, namely,

$$r_T = \frac{r \sin \alpha}{\tan^\epsilon \dfrac{\alpha}{2}}$$

Its derivative with respect to the azimuth is

$$\frac{dr_T}{d\alpha} = r \cdot \frac{\cos \alpha - \epsilon}{\tan^\epsilon \dfrac{\alpha}{2}} = r_T \cdot \frac{\cos \alpha - \epsilon}{\sin \alpha}$$

Hence,

$$\frac{d\alpha}{d \ln r_T} = \frac{\sin \alpha}{\cos \alpha - \epsilon}$$

The ratio of the two corresponding derivatives thus becomes:

$$\frac{d\alpha_0}{d\alpha_1} = \frac{\epsilon - \cos \alpha_1}{\epsilon - \cos \alpha_0} \cdot \frac{\sin \alpha_0}{\sin \alpha_1}$$

and with this

$$p_1 = p_0 \cdot \frac{\epsilon - \cos \alpha_1}{\epsilon - \cos \alpha_0} \cdot \frac{\sin \alpha_0}{\sin \alpha_1}$$

In other words

$$p \cdot \frac{\sin \alpha}{\epsilon - \cos \alpha} = \text{constant}$$

In order to determine the variation of p at the theoretical limits of $\alpha = 0$ and 180 degrees, note that p_1/p_0 approaches α_0/α_1 for $\alpha \to 0$ and $(180 - \alpha_0)/(180 - \alpha_1)$ for $\alpha \to 180$. Now the first-order terms of the series expansion of $r = r_T \tan^\epsilon \frac{1}{2}\alpha / \sin \alpha$ are $r_T \alpha^{\epsilon-1}/2^\epsilon$ and $r_T 2^\epsilon/(180 - \alpha)^{\epsilon+1}$, respectively. The ratios of the corresponding limit angles thus become tied up with the ratio of the initial and subsequent range by

$$\frac{\alpha_0}{\alpha_1} = \left(\frac{r_0}{r_1}\right)^{1/(\epsilon-1)} \quad \text{and} \quad \frac{180 - \alpha_0}{180 - \alpha_1} = \left(\frac{r}{r_0}\right)^{1/(\epsilon+1)}$$

for $\alpha \to 0$ and 180 degrees, respectively. In view of this, the limit probability ratios become:

$$p_1 = p_0 \left(\frac{r_0}{r_1}\right)^{1/(\epsilon-1)} \quad \text{and} \quad p_1 = \left(p_0 \frac{r_1}{r_0}\right)^{1/(\epsilon+1)}$$

respectively.

Note that for speed ratio $\epsilon = 10/9$ the increase of the limit probability at tail azimuth $\alpha_1 = 0$ is afflicted with an exponent 9 and quickly assumes astronomical proportions. The probability of receiving fire from any finite azimuthal sector, though less spectacular, also crowds most markedly toward $\alpha = 0$.

A.5 COMBAT MANEUVERING TECHNIQUES

The point has been made that the chances of an interceptor's destroying a straight-flying, ultra-high-speed, high-altitude bomber from any quarter but an acute cone around the tail are remote and that it would therefore appear justified and economical to provide the bomber with defense for the tail cone only.

What now if the enemy became wise to such limited defense and if he developed the technique and practice of slant (brachydromic) attack to the point of a menace? The bomber might then be forced to change his tactics, abandon the straight-course flight plan and dodge the interceptor.

It is at once obvious that a drastic change of altitude would avail the bomber nothing, as the bomber and interceptor would suffer similar performance changes. Any loss of altitude would only aggravate the danger of later interception by other fighters. The following study will therefore first be directed to the effect of veering maneuvers in a horizontal plane. We shall consider three distinct types of maneuvers: luring the interceptor into the tail cone (see Section A.5.1), foiling the interceptor's attack by spoiling his aim or lead (see Section A.5.2) and heading toward the interceptor to deprive him of maneuvering time (see Section A.5.3).

A.5.1 Veering Away to Force Tail Combat

The most obvious maneuver to thwart an attack from an undefended angle is to veer away from the interceptor. This automatically brings the interceptor into the tail cone where strong defense is assumed available. Any attempt on the part of the interceptor to avoid the tail-cone defense zone would of necessity spoil his aim, increase his range, and practically ruin his chances.

Aerodynamic Ballistic Advantage

If the interceptor's forward guns are of the same fire power, caliber, and muzzle velocity as the tail defense guns of the bomber, then the bomber is at a great advantage over the interceptor, for the following reasons: (1) The bomber's tail guns being flexible (though within limits), the bomber pilot need not aim the entire airplane whereas the fighter pilot must do just that; at high speed this is much more difficult than at conventional speed because of the high accelerations or inertia forces accompanying every control movement. (2) The bomber's rearward fire is more accurate and the projectile has greater impact energy left because of the lesser trajectory drop and lesser air resistance as the projectile speed against air is $u - V$ for the rearward fire versus $u + v$ for forward fire; the ratio of these bullet speeds is almost 1 : 2 so that the air resistance of the attacker's bullets is several times that of the bomber's. This is important because at the larger ranges at which combat will probably have to begin at the higher flight speed, trajectory drop is quite pronounced. As an example, the deflection of a .50-in. bullet is tabulated in Table 12 as computed by extrapolation from Aberdeen Proving Grounds Ballistic Research Laboratory Report No. 117 for various ranges and for u_0 = 2,700 fps initial muzzle velocity and for firing backwards from a bomber flying 450 mph and forward from an interceptor flying at 500 mph.

TABLE 12. .50-in. bullet deflection and drop.

u_0 = 2,700 fps initial muzzle velocity
V = 450 mph bomber firing rearward
v = 500 mph fighter firing forward
h = 40,000 ft altitude

Range (yards)	Deflection		Trajectory drop*		Energy ratio
	Fighter forward (mils)	Bomber rearward (mils)	Fighter forward (feet)	Bomber rearward (feet)	Bomber : Fighter
600	4.6	4.1	8.35	7.4	1.124
800	6.4	5.7	15.3	13.6	1.159
1,000	8.3	7.3	24.8	22.0	1.202
1,200	10.3	9.0	37.2	32.5	1.251
1,400	12.4	10.95	52.0	46.0	1.318
1,600	14.7	12.9	70.4	61.8	1.370

*Computed as a first approximation by extrapolation from Aberdeen Proving Ground Ballistic Laboratory Report No. 117, assuming resistance to vary approximately proportional to air density and square of bullet flight speed.

Figure 30 is a graph of these values versus range. At lower altitudes the difference is even much more pronounced because of the greater air density.

Similar tables can be constructed for 20- and 37-mm caliber if trajectory data are made available.

Disparity of Arms

If the interceptor carries guns of larger caliber and /or much greater muzzle velocity than the bomber, then this may offset the interceptor's handicap. The bomber pilot will then have to resort to other tactics to shake off the attacker. He can still veer away from him as long as he is out of the attacker's range in order to gain time, especially if the speed differential is small. However, it will be essential for the bomber's commander to know the armament and performance characteristics of the attacker. The bomber commander may even decide to enter a mock dogfight and emerge from it into tail combat at a short enough range to bring his own tail defense armament into most effective action.

A.5.2 Dogfight

If the bomber wishes to avoid tail combat, he can accept a dogfight before the attacker has approached to within his firing range.

Attempts to express the phoronomy of such a dogfight in analytical terms indicate that the results are too complicated and cumbersome to evaluate load factors and lead angles. Even in the simple idealized case of the bomber flying in a steady circle and the pursuer following in a scopodromic spiral, the equations describing the pursuer's path are rather unmanageable. However, some insight into the effect of various maneuvers can be gained by graphical construction of the pursuer's path.

Acceleration Handicap of Pursuer

It is immediately apparent that if the pursuer continues at full power scopodromically, ballodromically, or somewhere in between after the bomber has turned toward his side in front of the pursuer, then the pursuer's path tightens up and reaches a much higher load factor than the steadily turning bomber.

If the pursuer is unable to stand more than a certain load factor in combat, say 4 or 5, then he has to relinquish his quarry and let it pass.

The success of an escape turn on the part of the bomber depends a lot on the ratio of the turning radius to the range at which the turn is begun. If the radius is large compared to the initial range, then the chase might develop into an advantage for the pursuer who would essentially trail the bomber, just slightly cutting short to properly lead the target. Thus the pursuer would catch up eventually and his load factor would be but slightly higher than that suffered by the bomber – in fact, little more than in proportion to the square of his speed advantage.

If, however, the turning radius is commensurable to the initial range, i.e., if the bomber does not let the attacker approach closer than a couple of thousand yards, then the attack can possibly be outmaneuvered by turning toward the attacker. If this maneuver is judiciously executed, it can be made to lead to a close-range encounter passage in which, it is true, the attacker has an exceedingly brief chance of a burst, but under exceedingly unfavorable aiming conditions. Immediately afterwards, however, the bomber's tail defense has a chance of hitting the pursuer under much better aiming conditions, safe from return fire. The next phase following the encounter offers the bomber a gain of range before the pursuer can turn around and resume the chase. The bomber may so maneuver that the pursuer blacks out in the chase or, if the bomber does not want to pass a given certain load factor, he loses his pursuer before he arrives at firing range. This sort of maneuver effectively shakes the pursuer off while the bomber passes ahead of him. If the pursuer attempts an S turn after passage, then the bomber will straighten out its course when in opposite position and put so much distance between himself and the pursuer that the engagement is broken off.

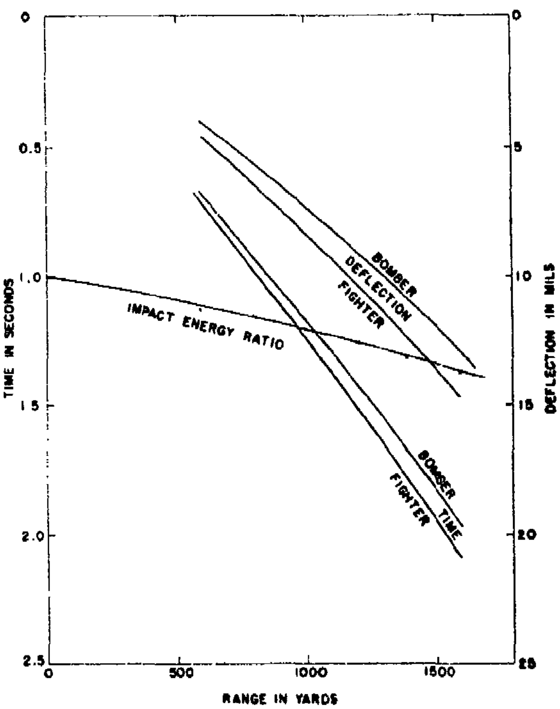


Figure 30. Impact energy ratio and bullet flight time.

Tracking in Circular Flight

The pursuer may, of course, prefer to follow the pursued in his track rather than cut short across the turn and avoid the higher load factor in the later phases. He would then simply creep up behind him though it would take a little longer. However, this is easier said than done. For one thing, the flight path does not usually remain visible, and when it does leave a condensation track, it is preferable not to fly through it. Secondly, when tracking along a curved path, the aim is very far off, unless a very large gun elevation is available. Obviously, tracking 1,000 yd behind on a 1,000-yd radius places the target 30 degrees off the pursuer's flight-path tangent, to which a lead correction still has to be added.

Initiative of Escape

Once the bomber has taken the initiative and started to turn in the direction to force the higher load factor upon the pursuer, the sense of turn in the dogfight must not be changed because the first one to make an S turn suffers a tactical disadvantage, except when the bomber decides to accept tail combat in a flight direction favorable to him with regard to the sun, clouds, or reinforcements.

A.5.3 Head-on Parry

If the interceptor is detected while still in a forward quadrant, then the bomber may choose to head directly for the attacker. Even though the latter may not be flying at top speed, the range will now diminish so fast (say at 400 to 450 yd per sec) that only one to two seconds are available for combat.

Snag Dodge

The bomber allows the attacker to come on to within about 2,000 yd, or almost within long-range firing distance, and then veers out of his way to spoil his aim. An effective escape maneuver now consists in an S snag so close to the enemy that he has no time to turn after the bomber and cannot turn sharply enough to lead properly. Then the bomber gets away before the pursuer can complete a 180-degree turn. The chances of a destructive hit in such a delayed veering maneuver from a head-on encounter are very slim indeed.

The interceptor may choose to attack ballodromically during the encounter but he will get only a few rounds in and these under very unfavorable lead conditions, practically at "cross paths," which means about 20-degree lead. (At 600 yd, this is 6 to 8 bomber's lengths.) During or immediately after the frustrated close-range passage, the bomber reverses his banking angle and returns to his original course heading. While the pursuer completes his more than 180-degree turn, he loses about 3,000 yd in distance before he can resume the tail chase which will bring him within a few degrees of the bomber's tail by the time (almost 2 minutes) he may again arrive within firing range, unless he has lost his quarry in the melee.

Head-on Passage

On the other hand, the interceptor may choose a second alternative, namely, that of foregoing all chance to hit or fire at the bomber during the first encounter, and passing the bomber's course ahead of him merely in order to lose less distance for a subsequent tail attack. This, however, the bomber can foil by starting to trail the interceptor. The trick here will be to avoid being dragged away from the original objective or lured into the fire of other fighters.

A.5.4 Vertical Escape Maneuvers

The question may be raised if vertical escape maneuvers or their combination with horizontal ones have merits for the bomber.

Not in Tail Chase

In the tail chase the answer apparently is no. Most likely, the pursuer would suffer the lesser load factor and he would be in a favorable position whenever the bomber levels off.

Looping

Only if the bomber were to start looping just before the pursuer has arrived at his maximum firing range would the attack be foiled. However, the pursuer could probably follow suit and be right on the bomber's tail after the loop is completed or when the bomber rolls out at the top of the loop. To continue looping would theoretically be a possible defense tactic but it is hardly practical and would only serve to let other fighters catch up and join the chase.

Zooming Up Behind

The pursuer, however, may benefit from vertical maneuvers. For instance, if in catching up fast he fails to bring his quarry down, he may instead of veering out of the way, zoom up behind him to kill speed only to utilize the potential energy thus gained in diving after the quarry in a subsequent attack. However, the only effect of such a maneuver as compared with merely throttling would seem to be the interruption of fire which may be desirable while changing ammunition drums or clearing jams. Otherwise, between a fixed gun pursuer and a limitedly flexible tail gun of the bomber, the advantage would usually be on the side of the latter.

Descent for Lower-Altitude Bombing

The bomber may be tempted or forced to descend to lower altitudes to fulfill his mission when poor visibility obscures the target at great height. During the descent itself he does not necessarily enhance his risk because in the descent he picks up extra speed. The proximity of the compressibility limits his gain, just as it does to the interceptor who may be trailing him down. The interceptor may perhaps gain a little more if it has thinner wings but this advantage may be balanced by the fact that the interceptor is probably already designed to have its best performance at a lesser lift coefficient than the bomber so that the same speed-up would increase its drag more. At the higher descent speeds, load factors in any curved pursuit increase with the square of the true speed so that the hazards of angular fire are still further reduced until the advantage is absorbed by the greater air density.

The time the bomber has to stay at lower altitudes can be very brief. The descent can be made very flat and may take 50 miles, certainly enough to correct for a reasonable navigation error. After delivery of the bombs, the bomber's climbing speed is increased and he may still have excess kinetic energy to retrieve several thousand feet before being slowed down to the steady climb rate. During the remainder of the climb to the stratosphere he would have little to fear from those interceptors that might be taking off to go after him. Only in case other interceptors have been hovering above and dive after him would he be at a speed disadvantage. However, he could have known of their presence if he was equipped with sufficiently long-range detecting apparatus and could have decided to stay up until he might have shaken off or outlasted the interceptors or chosen an alternative target for which he would not have to descend.

A.5.5 Recapitulation

To summarize the results of the maneuvering study thus far, it may be said:

The best plan undoubtedly is to provide the bomber with sufficiently powerful tail armament so that it can accept a tail chase on better than equal terms with whatever interceptor is fast enough to catch up with him before running out of fuel. Better than equal terms does not necessarily mean more powerful weapons because of the aerodynamical bullet speed advantage for the rear fire, as has been explained in Section A.5.1 under *Aerodynamic Ballistic Advantage.*

At a speed differential of only 50 mph (or 25 mph) it takes the tail chaser fully 5 minutes (or 10 minutes) to creep up from 7,000 yds into firing range.

Any attack from a forward quarter can be turned into an almost head-on encounter and foiled short of firing range.

The bomber can so maneuver that any attack will eventually wind up as a tail chase and that the attacker will drop behind whenever he tries any other trick. The bomber cannot be sure of shaking a tail chaser off permanently, but he can probably turn any angular attack into a tail combat whenever he wants to.

The bomber can accept a dogfight and may outlast the interceptor.

A.5.6 Maneuvers with Slant Gun

The most effective countermeasure to improve the interceptor's chances in a dogfight near the load factor limits would appear to be its provision with some elevated guns. This will permit the interceptor to fire across a chord of the dogfight circle without running into excessive load factors—without, in fact, having to cut too much across the victim's path. In such a sharp turn, both ships are steeply banked so that the gun elevation becomes essentially an azimuth correction. The slight lateral correction, consisting of the gun elevation times the sine of the banking angle, can be compensated by the pursuer circling slightly lower than the pursued and by trajectory drop. Visibility for aiming such a gun elevated at, say, 15 degrees can be easily provided for the pilot. This arrangement will also come in very handy in a stalking straight attack from below the tail without dogfighting. However, such an elevated gun requires means for proper lead correction for the own-speed vector, and it does not by any means assure superiority of the pursuer against a bomber equipped with tail guns covering similar cone angles and similar lead correction devices.

The consequences of the presence of a slant gun on the interceptor have already been mentioned. If a high-speed fighter version of the high-speed bomber prototype were eventually developed, it might to good advantage also be equipped with a slant gun of moderate caliber or one that can be elevated in turns.

A.6 MULTIPLE INTERCEPTION

The question now arises whether concerted pursuit by several interceptors having fixed guns may become unduly dangerous to a lone bomber.

A.6.1 Multiple Brachydromic Approach

If an interceptor squadron flying in close formation tries to attack the fast bomber in brachydromic approach from some odd angle, the individual interceptors would be forced to peel off as the rear ones would have to head more ahead of the bomber. Therefore, if all the interceptors were to participate in the fire their formation would become loosened up. As for the bomber's defense, the situation hardly differs from the brachydromic attack by a single interceptor because the individual fighters come into range one by one and all from the same quarter, almost from the same angle.

A.6.2 Multiple Tail Chase

If several interceptors were to come up from the rear and tried to place themselves simultaneously around the tail—say one to the right, another to the left, one above and another below—and if they were now to press into firing range together or in such rapid syncopation that the bomber's defense gunnery could not cope with all of them, then the bomber might veer slightly to the side of the nearest attacker just before he comes into firing range. This maneuver brings all the attackers into the same quarter, and they would lose a lot of time if they rearranged themselves.

A.6.3 Multiple Ballodromic Approach

In ballodromic approach a squadron of interceptors would be more handicapped by high load factors, aggravated by the requirements of maintaining formation, than a single interceptor. Otherwise the situation for the bomber's defense winds up in a tail chase or can be turned into a tail chase prematurely whenever the bomber veers to run away.

A.6.4 Multiple Clinoballodrome

A situation annoying to the bomber can possibly arise from simultaneous attack by two pursuers approaching ballodromically, but one in or above and the other below the bomber's level. Of course, they would quickly get into each other's way if both were equipped with fixed-level guns only. However, if at least the lower one is equipped with an elevated gun, they can attack simultaneously without interference. The bomber might then try to turn in order to hamper the two closely flying attackers by high load factors. Such a tactical turn may be especially indicated where the two attackers make it a habit to fly in a staggered formation, the one above slightly ahead of the lower one, leaving the burden of avoiding interference to the lower one who has the better visibility. In the escape turn, the upper forward one becomes the inner one and gets into the firing line of the rear lower one, which has to take the outer line, and there is not much the latter can do about it but cease firing.

A.6.5 Simultaneous Interception

Now what if several interceptors were to make concerted attacks from entirely different sides and angles timed to arrive simultaneously? Such tactics are highly improbable. It would seem almost impossible to spot the bomber so accurately, to disseminate the information to all concerned, and to work out and transmit a timed multiple interception plan to the several fighter units, all of which were moving at a rapid pace while these preparations were taking place. Then they would have to approach from stations several miles apart in space. The least error in their calculations or any deliberate course change on the part of the bomber would completely upset the schedule. It seems certain that most of the interceptors, insofar as they do not miss the engagement altogether, would wind up in a tail chase. The small speed differential would make it difficult and tedious for them to sneak up at once.

A.6.6 Multiple Frontal Attack

Multiple frontal attack is dismissed as impractical because of lack of maneuvering room and time.

A.7 MASS RAID TACTICS

Navigating a fleet of bombers together toward a common objective or toward different objectives may offer each bomber some measure of protection.

A.7.1 Decoy Action

To what extent such protection may be secured by decoy action, drawing the interceptors to a feint and away from the real raid, is a matter of strategy which is considered outside the scope of the present study, except insofar as it may have a bearing on the armament requirements for the bomber. If some of the decoy bombers were equipped with extra armament instead of full bomb loads, a bluff might be perpetrated which might discourage the enemy from attacking the real bombers from undefended angles or ranges. Such extra armament should then be so designed that it is not easily distinguishable and that the standard and specially armed aircraft cannot be told apart in the air.

A.7.2 Lateral Attack

In a mass formation raid by a fleet of fast high bombers, dodging of interception would be impractical. The chances for slant attack by interception appear somewhat enhanced because, if the interceptor aims to intercept one airplane, he may miss it but catch another, but the interceptor would also risk drawing fire from several of the bombers.

The vulnerability of a mass formation could undoubtedly be reduced by providing special armament and/or armor for the airplanes assigned the extreme positions in the formation at the expense of their bomb load. This has the design disadvantage of a duplicity of type and the tactical disadvantage of more replacement parts and limitations of the tactical disposition of the units. However, if mass formation raids are contemplated, it may be well worth while to create not only the full-load bomber but also a protective fighter having the same performance and range with reduced or even with no bomb loads.

The fighter version would have some forward-firing guns, possibly capable of elevation, and possibly armor for the occupants. The elevated guns need not be continuously movable in elevation. It may suffice to provide two elevation positions: for instance, (1) parallel to the high-speed flight path and (2) at 10 or 15 degrees elevation therefrom.

In view of the probability of most interceptions' winding up in a tail chase, the bombers—or at least those assigned the rear positions in the formations—might deserve rear armor.

A.7.3 Formation Shape

The shape of the mass formation has an influence upon the mutual assistance between units. At high speed, considerations of the prevalence of tail attack may call for different formation shapes than at speeds at which the interceptors can attack from all quarters.

Lone stragglers behind would have to rely on their own fire power to ward off pursuit.

A compact phalanx with many bombers abreast along the trailing edge of the formation has the obvious advantage of drawing any tail attacker into the defense fire of the adjacent bombers at good azimuths and almost at the same range with almost no lead correction requirements.

A dense packing of bombers in several tiers above each other (three-dimensional formation), all terminating in one huge vertical trailing plane, would further enhance mutual assistance against the tail chase into which any persistent interception must develop.

Single leaders or navigators ahead of the main phalanx may not be particularly endangered, provided some of the bombers in the front line of the main formation are equipped with a forward-firing gun.

If some such forward-firing guns are distributed throughout the formation, it might serve to discourage any interceptors from trying to break into the formation from above or below in case any of them have enough extra ceiling or climb (or rocket boost).

A.7.4 Formation Density

The safest density of the formation will probably depend not only on the degree of mass formation training attainable under combat conditions but also very much upon the concentration of interceptors loosed against a mass raid.

Obviously, any three-dimensional pattern with several bombers in tiers above each other would have to open up upon arrival at the objective in order to avoid hitting the lower ships with bombs from the upper ones. The technique of this maneuver would hardly differ much from that of similar situations of bombers at lesser speeds, so that no new problem seems to arise from a boost of airspeed or altitude.

If the rear bombers are to derive tactical aid from the firing power of their formation neighbors, then their spacing must remain dense enough; it should be but a fraction of the dangerous firing range. For example, assuming the bomber's tail armament covers a cone of 30 degrees semiapex angle (i.e., 30 degrees off the fuselage axis), a spacing of more than 200 yd would render the bomber powerless to assist his neighbor when the pursuer approaches within 350 yd.

A very much more scattered formation, with several hundreds or thousands of yards spacing between bombers, would cover a huge area. For instance, 400 bombers in a single-layer square lattice of 2,000 yd spacing would cover 500 square miles of surface. This would be highly confusing to any ground organization trying to dispatch interceptors. However, once the interceptor squadron encounters any part of the raiding force, a man-to-man duel is likely to result, with no further immediate advantage to the bomber; on the contrary, in order to prevent disorganization of the raid schedule, the individual bomber will refrain from escape maneuvers and stay on his job.

Mass raids in waves of bomber groups, in dense formation of each group, timed to arrive at the interception gateways at intervals intended to exhaust the interceptor force will probably have even greater merits at ultra-high speeds than they have at current moderate speeds. If they are timed to arrive at intervals equivalent to the interceptors' flight duration, then all the fighters sent up to intercept the first wave will be out of fuel and out of commission for the next alarm. Furthermore, while they land they are making so many airports less available for take-off of the next lot. It may even be a good trick to disperse the first wave into several spaced groups 50 or 100 miles apart in order to arouse interceptors from many places so as to disorganize many stations when the next, more concentrated wave comes through. Strategic choice of targets for various waves may aid in creating further confusion of ground defense measures. The opportunities for such long-range strategy increase rapidly with the speed and range of the craft as distances shrink and decoy and evasion detours become more feasible. They force the defender to spread his interception out thinner. Similarly, the long-range and high-speed bombers cooperating in a mass raid can be directed to disperse and feign repulsion—only to reunite, after the fuel supply of the interceptors has been exhausted, to complete the bombing raid and return to their bases.

A.3 PRELIMINARY CONSIDERATIONS OF EFFECTIVENESS OF FIRE

The previous chapters of this investigation contain a great deal of evidence of the overwhelming preponderance of tail combat phases to be expected when an ultra-high and fast bomber is to be intercepted by fighters having but a small speed advantage. In a qualitative way it appears obvious that any defensive devices that impair the bomber's performance may work to its own disadvantage, rather than to its safety. The performance is impaired by the weight of armor and armament and, even more, by the drag of protruding parts, which increases rapidly with the degree of angular gun coverage. A quantitative treatment would require expression of the performance loss in terms of armament coverage. In view of the multiplicity of means (guns of various caliber, fixed mounts, eyeballs, and turrets), this is hardly feasible. However, it is obvious that armament covering a limited tail cone and one or two fixed, essentially forward directions can be accommodated at an almost negligible drag and an easily tolerable weight penalty, whereas full coverage of all angles would entail either many guns involving a very heavy weight penalty or turrets involving a prohibitive drag penalty.

A.3.1 Limitations of Probability Calculation

If it were possible to show that the chances of being hit from certain angles are entirely negligible, then defense against attack from these angles would be wasteful on any count. If it were possible by rigorous methods to arrive at a quantitative probability distribution of hits from various angles in space, then the decision of armament limitations of the bombers could be put on a scientific basis. The following study does not pretend to accomplish all this, but merely to analyze the factors governing the chances of hits in interception and to substantiate the inference that ultra-high performance is more valuable to the bomber than defense against ineffective combat phases.

A.3.2 Relevant Influences

The probability of a hit in interception from any particular angle off the tail of the bomber depends on many factors, such as:

1. The speed of the bomber at the high altitude of the raid and his initial maneuvers.
2. The speed of the interceptor, both in the climb and in high-altitude level flight, and the speed losses due to maneuvering.
3. The probability of any one initial position at the instant when the interceptor detects, identifies, and picks his quarry.
4. The mechanism of direction or the technique of the chase up to arrival at firing range.
5. The load factors that the interceptor can or will tolerate.
6. The maximum and minimum firing range.
7. The technique of the chase while in firing range.
8. The influence of the chase maneuver (range, banking, and acceleration) upon the interceptor's aim.
9. The perfection of the interceptor's aiming devices, especially its correction for phoronomic influences.
10. The number and distribution of guns on the interceptor, their caliber, and firing speed.
11. The interceptor's firing tactics (burst density versus range, azimuth, bank, etc.)
12. The influence of range on scatter and penetration.
13. The size and pattern of vital areas on the bomber and the influence of azimuth thereon.
14. The chances of the interceptor to approach to any particular proximity and azimuth without being warded off by the bomber's defense or by the fire from other bombers in the same formation.
15. The influence of cooperation between several fighters attacking the same bomber upon items 4, 7, 11, and 14.
16. The effect of the bomber's escape maneuvers upon items 4, 5, 7, 8, 11, 13, 14, and 15.

A.3.3 Assumptions

It is at once apparent that the variety and multiplicity of these influences alone constitute too complex an aggregate to cover completely. Only by the most radical process of elimination of variables and selecting "representative" examples shall we be able to reduce the problem to a useful digest. If this is attempted here at all, it is done with a keen realization of the fact that different assumptions will lead to different results, but it is contended that the examples selected are representative in that they indicate a significant trend.

1. Let us assume (a) the bomber's speed $v = 450$ mph at 40,000 ft and (b) that it is not diminished in combat and that he continues in straight level flight.
2. Let us assume (a) the interceptor's speed $V = 500$ mph at 40,000 ft and (b) that it is not appreci-

ably diminished in combat. (Taking this speed loss into account will favor tail combat phases.)

3. Let us arbitrarily assume that the range at which the interceptor detects and selects his victim is a definite value, say 5 miles or 8,800 yd. If the interceptor pilot's knowledge of the whereabouts of the bomber before he detects and identifies it on his own detector is but approximate or inaccurate, he may patrol an assigned area at random course. However, this assumption might introduce a systematic error because the chances are that the pilot does have a fair idea of the bomber's whereabouts and he already heads for him. The azimuth at which he is most likely to come upon his quarry will therefore depend upon the interception strategy. Not knowing whether this will be in the nature of a patrol barrier or of a long-range forward lunge or a mass melee after the invader has penetrated deeply into the territory, we may defend a random-course-at-detection assumption as representing a sort of grand average of various such strategies.

With this assumption—namely, all initial course angles θ_0 of the interceptor equally likely—the probability for the bomber to be detected from any particular azimuth α_0 is then

$$p_{\alpha_0} = \frac{1}{2\pi}\oint_{\phi=-\pi/2}^{\phi=\pi/2} \cos\phi \, d\theta_0$$

with

$$\phi_0 = \tan^{-1}\frac{\sin\theta_0}{\dfrac{1}{\epsilon} - \cos\theta_0} - \alpha_0 \qquad (31)^{p}$$

This integral has been computed for $1/\epsilon = 0.9$ for azimuth steps of 10 degrees and the resulting probability distribution plotted against azimuth α_0 in Figure 31.

4. It may be expected that, after detection and identification of the quarry, the pursuit takes a course somewhere between the scopodromic and ballodromic concept. (Let us disregard the alternative of brachydromic interception since it may be contended that its probability is very much smaller because of the greater skill required for its execution, in the very much shorter combat duration and its considerably lesser fire concentration.) In fact, the scopodromic technique is but a special case of ballodromic, namely, with $\psi = 0$.

In reality the interceptor will at first have to stick close to the scopodrome until he gets close enough to determine the relative motion of the quarry accurately. During the passage through the region of high load factor, even if he wanted to open fire already, he would have to allow for his high angle of attack, which puts him between the scopodrome and the theoretical (path-fixed gun) ballodrome. Later, he approaches the latter more closely, but then they differ but little, and the azimuth will have shrunk to very acute values.

The probability of arriving at various firing ranges at various azimuths can be computed by transferring the initial probabilities along or between the scopodromic and ballodromic curves of Figures 2 and 11.[q] Figure 31 shows examples of the effect of scopodromic approaches from 5 miles detection range.

5. When arriving at firing range, however, the approach may be thwarted or hampered by high load factors. The tolerable load factor depends on the time of exposure. For simplicity's sake, let us assume that a load factor of $5g$ is the limit for the interceptor and that if his path would tend to lead to higher loads, he would ease up and drop into the sector between $4g$ and $5g$ (more crowded toward $5g$). The result of this restriction is also shown in Figure 31 in dotted lines. In reality, at least the later phases of the attack must be more nearly ballodromic in order to hit. The transition means a temporary increase of load factor followed by some relief.

6. The probability of receiving effective fire from any particular azimuth depends very much on the firing range of the interceptor. The critical azimuth at which the maximum load factor is attained is of the order of 56 to 58 degrees and the critical range at this azimuth for $5g$ is 550 yd (with $u = 2{,}200$ fps muzzle velocity) and 690 yd (with $u = 2{,}875$ fps). If the firing range begins at but little less than this, then the combat azimuth region is very narrow; as larger firing ranges than the critical are considered, the region of combat azimuths expands rapidly.

As to the minimum range at which the engagement is considered decided or broken off, let us arbitrarily assume it to be 150 yd. Changing this ± 50 yd would not affect the result very much.

7. Let us assume now that during combat the quasi-ballodromic chase continues, and the pursuer keeps creeping up without throttling until he arrives at a certain minimum range where he breaks off the engagement to avoid collision. (This assumption is rather arbitrary. It tends to enhance the probability of hits from close range and acute azimuth near the tail. Any departure of the interceptor from these tactics will affect the conclusions. If he throttles down to the same speed as his quarry, he can extend the duration of any range convenient to him at will, but this will only crowd the probabilities of hits more closely around the tail $\alpha = 0$.)

8. The accuracy of aiming the airplane by the gunsight at a distant target undoubtedly depends some-

[p] For derivation see Section A.8.6.

[q] The calculation is explained in Section A.8.6 for scopodromic approach.

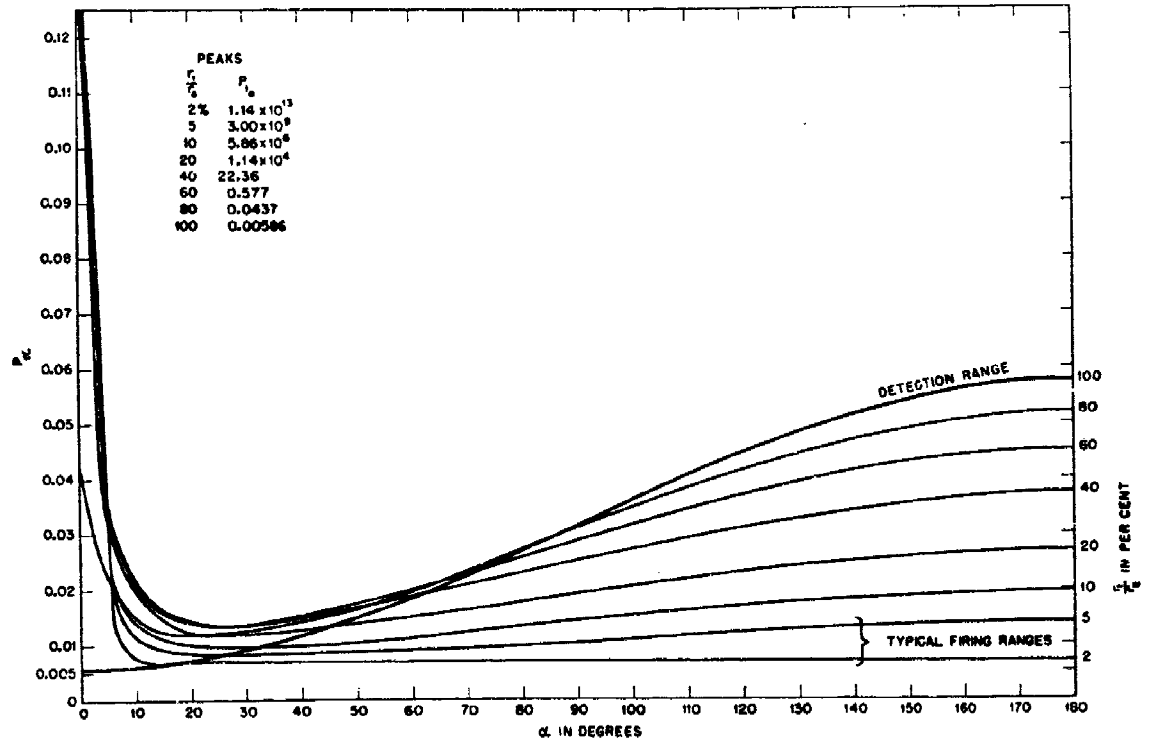


FIGURE 31. Azimuthal distribution of encounter probability at any range r_1 in terms of the detection range r_0.

what on the size of the target as it stands out against its background, but sufficient information is not available to express this influence in mathematical terms. Therefore it will have to be left implied in a generous assumption of the influence of range upon scatter to be introduced separately.

A transient surge of acceleration (load factor) has a very pronounced influence on aiming accuracy insofar as it impairs the steadiness of the pilot-gunner's head position and his precise coordination. It must broaden the scatter pattern in the direction of the resultant inertia force, perhaps somewhat in proportion to the excess of the load factor over unity.

The banked attitude of the airplane causes the trajectory correction of a conventional fixed gunsight to be in the wrong plane. The error due to this influence would tend to increase approximately in proportion to the square of the range and the sine of the banking angle. Not enough information is on hand to assign a definite value to the proportionality factor. As a compromise it may perhaps be arbitrarily assumed that the last two errors combined will tend to double the scatter pattern at $3g$ and treble it at $5g$.

9. If the gunsight of the interceptor is fixed so that he has to make allowance for leading his target by estimate and keep his crosshair way ahead of the target, large errors will be introduced whenever a large lead angle is required. However, even where the sight is equipped with a lead corrector to bring the crosshair back on the target, the range and turning rate or the target speed and aspect have to be first determined and then cammed into the sight. At best this introduces guessing errors which increase with range and with the sine of the azimuth. Again it is difficult to assign definite probability values to these errors beyond stating that they cause the average scatter area to increase with α. Practical experience may eventually be accumulated and applied to arrive at a more rational choice for this coefficient. Reference si made to item 13.

10. The number and the firing speed of the guns determine the density of the fire but they will have no influence upon the relative probability of hits being attained from any one quarter, although they do have an influence upon the seriousness of transient combat phases, such as those discussed in the section on brachydromic passage.

11. While the desire to conserve ammunition will prompt the interceptor to hold his fire as long as the defense of the bomber permits him, it may be assumed, (a) for simplicity's sake and (b) in order to stay on the conservative side for the bomber, that

the firing is done continuously (or at regular uniform burst intervals) from a certain long firing range r_e to a certain short firing range r_s. In reality, the tendency to fire more or longer bursts at shorter range would favor the acute tail azimuths.

12. To arrive at any definite probability values, the primary scatter function which is characteristic for the gun and its installation would have to be known for various conditions.

13. The size of the vital area is assumed to be approximately 700 sq ft, which comprises either the central part of the fuselage in lateral aspect or the four engines and the fuel tanks in rear aspect. Neglecting the variation of the vital area with azimuth helps a great deal to simplify the problem. This simplification is, however, rather arbitrary, especially if it also neglects the difference in compactness of the vital area. In rear aspect the height of the vital area is smaller and its span larger than in lateral aspect. This works in a way to compensate for the variation of errors in trajectory drop—errors which are most serious at the longer ranges which are more likely to be associated with large azimuths. It is proposed, for simplicity's sake until more accurate knowledge is gained, to offset this aspect influence against the influence of imperfect leading described in paragraph 9.

14. For the present purpose, let us disregard the possible influence of defense fire from the bombers upon the attacker. One may later attempt to appraise the relative chances of the two craft.

15. Let us merely assume that cooperation between interceptors concertedly attacking a single bomber is effective in diverting the latter's fire so that assumption (14) is justified.

16. Let us assume the bomber refrains from executing any escape maneuvers and keeps on flying straight, relying solely on his own speed to let all attacks eventually develop into tail chases.

A.8.4 Examples

Under these numerous and drastic assumptions, the relative probability of a hit in a vital area from any azimuth can be evaluated theoretically by computation and shown graphically.

It is certain, however, that under any of the assumptions proposed, by far the most of the serious fire will come from acute azimuth angles near the tail.

A.8.5 Interpretation

The likelihood of the interceptor's approaching to a range of effective fire at acute azimuth in pursuit of a bomber flying straight will depend on the relative chances of the attacker and the attacked to put each other out of combat during the earlier phases of the approach. At any given azimuth, these chances are governed by the influences of range, target aspect, lead required, azimuth, bank and load factor, the ballistic air velocity on bullet impact, and armor. It may be justified to make the same assumptions as outlined in Section A.8.2 except that the interceptor is likely to be a smaller target, say 400 to 500 sq ft. But this may be approximately offset by the fact that a flexible gun of the bomber can fire at appreciable azimuth, with negative lead correction fully corrected for by a simple mechanically compensated sight like the French Alkan sight; this correction is accurate enough for the assumed bomber's high speed V, whereas the additional forward lead to be guessed to allow for the pursuer's cross-field velocity component is only a negligible fraction of that required by the interceptor's gun. As to the ballistic advantage of the bomber, let us assume that it is a stand-off against the interceptor's protected fuel tanks.

The decisive difference between the two craft then remains the presence of the load factor on the pursuer and its absence on the bomber. A quantitative appraisal of relative chances of the two combatants therefore depends largely on the assumption made in item 8 and on their relative fire power (number of guns in action).

A.8.6 Probability of any Azimuthal Position

The probability of arriving at a definite fixed detection range r_0 at any particular detection azimuth α_0 is assumed to be proportional to the cosine of the angle ϕ at which the relative flight vector of the pursuer intersects the range vector. If all course angles θ_0 of the pursuer are equally likely, the probability per unit sector is $p_{\alpha_0} = 1/2\pi \int \cos\phi \, d\theta_0$; but of these only the positive values of $\cos\phi$ are to be taken as representing approaches. The negative values would represent recession from closer range, i.e., stepping out of the detection range circle rather than into it; they must be disregarded. The integral of all probabilities for all α_0 is therefore less than unity, meaning that many courses θ_0 are misses. (See Figure 32.)

To express ϕ in terms of θ_0, observe on the speed vector diagram that $V \stackrel{\wedge}{-} v = W$ is the relative speed vector of the two craft making an angle ω with pursued's path.

In the vector triangle the law of sines says

$$\epsilon \sin(\omega + \theta_0) = \sin\omega$$

from which

$$\tan\omega = \frac{\sin\theta_0}{\left(\frac{1}{\epsilon} - \cos\theta_0\right)}$$

and $\phi = 180 - \omega - \alpha_0$.

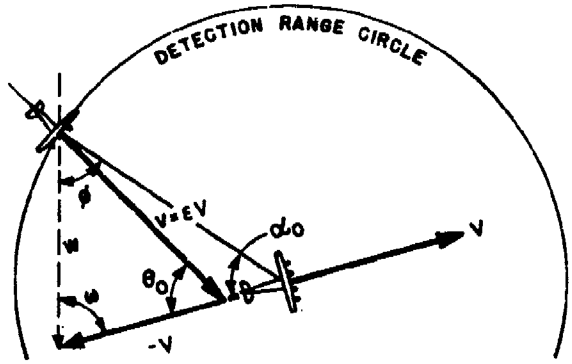


FIGURE 32. Speed vector diagram.

In this way values of $\cos \phi$ were computed for 10-degree steps of course angle θ_0, plotted against θ_0 for each α_0; their positive parts were then planimetered. The result of this procedure is the master graph in Figure 31 labeled "detection range."

A.9 MOCK INTERCEPTION TO SCALE

Interception of aircraft at ultra-high speed and altitude involves techniques which differ from those applicable to conventional interception practice in many respects. It is therefore appropriate to study the new techniques not only theoretically but also practically as far as possible in advance in order to be prepared to use the new craft to full advantage as soon as it becomes available. Any extrapolation from lower-speed to higher-speed operation must be governed by certain scale rules lest it be misleading. By observation of proper scale rules, however, it should be possible to gain some insight into the practicality or difficulty of some of the maneuvers theoretically studied, into the practical validity of some of the assumptions made in the theoretical studies, and into the chances of interception combat in the various maneuvers investigated.

A.9.1 Scale Rules

As a general rule, in order to maintain geometrical similarity of the relative motion between the mock maneuver and its prototype, the ratio between the true airspeeds of the two craft must remain unchanged and the speed advantage of the pursuer must be the same percentage of his true speed in both cases. However, this will not always allow the load factor (acceleration) to remain the same in corresponding phases of those maneuvers which involve turning in any plane; only in straight-flight interception like the brachydromic passage do no load factor problems arise.

A.9.2 Instrumentation

Aircraft to be used for mock-interception studies or practice should be equipped with accelerometers, gun cameras, gunsights, and airspeed meters on the dials of which the true airspeeds desired to be held are suitably marked with proper density correction for the altitude at which the maneuvers are to be executed. On the bomber, if the defense is to be simulated by a gun turret or flexible tail gun, some means should be provided to record the gun excursion, or at least its azimuth, on the gun camera film or on some separate recorder adapted to be synchronized or otherwise tied in with the gun camera.

In planning the various maneuvers Figure 33 will be helpful. It shows the turning times for the completion of a 180-degree nonskid horizontal turn at various constant speeds and properly banked so as to attain and hold certain g values on the accelerometer.

It should be remembered that all course changes in mock maneuvers must be executed with reference to true compass points and not with reference to landmarks because otherwise wind might distort the maneuvers appreciably.

A.9.3 Stretched Time Scale

If, in simulating any curved approach at reduced speed scale, the distances between the two craft at various maneuver phases of the mock combat are

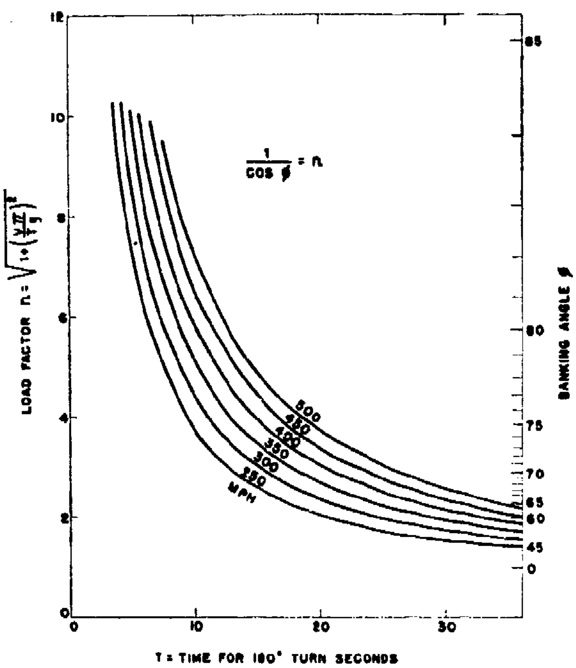


FIGURE 33. Turning times for completion of horizontal turns.

correctly reproduced, the problems of target recognition, range determination, and aiming accuracy may appear in "full size" but the time available for the planning and execution of the maneuver is stretched in inverse proportion to the speed reduction, and the severity and precision of the accompanying banking operation are much reduced, according to Figure 33.

For instance, in practicing scopodromic or ballodromic approaches of various parameters, i.e., from various abeam distances r_T and also from various initial azimuths α_0 while at a given initial range r_0, say at speeds v = 333 mph pursuit vs 300 mph bomber, to simulate 500 and 450 mph respectively, at a speed scale of 2:3, each mock maneuver will take $^3/_2$ as long as the real one, and a load factor corresponding to $3.42g$ will represent $5g$ in the real case.[r]

A.9.4 Reduced Range Scale

It would also be interesting to study or interpret such maneuvers on the basis of time available rather than of correct distance. This simply amounts to interpreting a mock approach to represent a real one from $^2/_3$ the distance at every azimuth. Then the target will appear $^3/_2$ times too large at every phase but the load factors (g) and the banking are correctly represented, and a vivid picture of the difficulty of performing the maneuver and aiming during the banked phases is conveyed.

A.9.5 Practice Maneuver Pattern for Curved Approach

In executing specified mock approaches from definite ranges, it may be difficult to determine these ranges in flight. Post mortem evaluation can probably be reconstructed from the gun camera records. Besides, the following procedure may be helpful in planning the mock flights somewhat as depicted in Figure 34.

First fly the two craft in close formation at a certain (say 0 degrees) compass course to check their airspeed meters against each other. Then agree by radio on the speeds to be maintained during maneuvers. Upon a definite signal the pursuer turns 90 degrees off the course (say to the right, course 90 degrees). The bomber flies straight on for a prearranged number of seconds (say 30) and then completes a 180 degree right turn carefully to maintain a definite average load factor (say 2.5) during the turn in order to complete it in a definite time (say 17 sec). He then proceeds straight and level at the same original altitude and speed in the opposite direction (course 180 degrees). The pursuer also turns at the same rate, either after the same lapse of time since the break-away or after a shorter or longer period according to a prearranged schedule; he turns in the opposite sense (say to the left) to maintain symmetry. He may not have to complete a 180-degree turn but picks up his target, boosts his speed to the desired speed advantage, and heads for his quarry. If

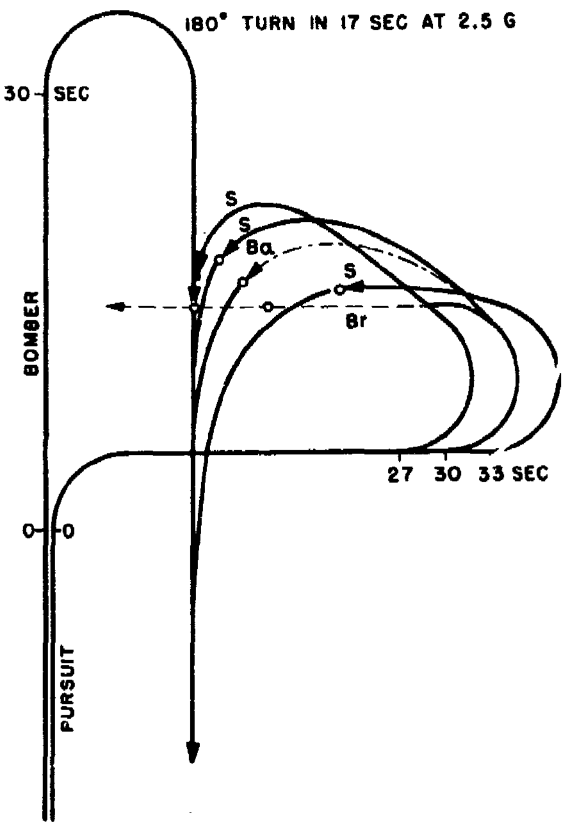


FIGURE 34. Practice maneuvers (S = scopodromic, Ba = ballodromic, Br = brachydromic).

he turned simultaneously with the bomber, then he can sweep into a scopodrome after completing but 135 degrees of a turn (to course 315 degrees), and he will begin the approach at 135 degrees bomber's azimuth. The later the pursuer turns, the greater is the parameter r_T of the ensuing pursuit curve. If the pursuer waits to begin the turn after twice the time the bomber flew away before he started his, then the distance traveled straight by the pursuer is approximately r_T. The bomber will be found dead ahead on course 270 degrees, and the scopodrome will be large, winding up in a tail chase before entering firing range.

[r] Load factors in horizontal turns are not exactly proportional to the speed ratio $v_1 : v_2$ but

$$n_1 : n_2 = \sqrt{(R^2g^2 + v_1^4) : (R^2g^2 + v_2^4)}$$

where R is the turning radius.

The sooner the pursuer turns, the sharper and the more vicious the critical phase of the approach maneuvers becomes.

It must be noted that the banking maneuver differs in character for different speed ratios. If the pursuer has an ample speed advantage, then the phase of steepest banking occurs very late, while already close to the quarry's tail. If he flies twice as fast as the bomber, the pursuer has to bank more and more as he approaches collision. However, if the speed advantage is but a small fraction of either craft's speed, then the pursuer has to "unbank" again, viz., begin leveling off at a certain position in the chase. As the speed advantage diminishes, the critical phase of steepest banking approaches the position where the pursuer passes 60 degrees off the pursued's tail. For a speed ratio 10:9 this critical azimuth is about 56 degrees. As soon as the pursuer passes this azimuth, he has to give counter aileron and begin to unbank, even faster than at the rate he banked before. Otherwise he overshoots.

A.9.6 Practice Maneuver Pattern for Straight Passage

In simulating brachydromic passages, again either the ranges can be considered full scale and the time stretched as in a slow motion picture or else the time lapse can be reproduced correctly by reference to proportionally closer range phases. In practicing brachydromic passages, the trick for the pursuer to learn consists of the following maneuver. Aim ahead of the bomber so that the latter appears at an angle off your bow slightly less than that at which you would estimate your ship appears off his bow; if you find the course where this "lead" or relative crab angle does not change while you fly straight, it will lead to collision (for safety's sake the pursuer may fly at a slightly higher level than the bomber); during the approach, correct your course slightly, so that the target seems to creep up slowly to smaller and smaller lead angles and finally passes dead ahead at short range, all while both ships fly straight.

As an aid in executing practice maneuvers of this sort, the two cooperating pilots may again start out flying in formation; then on a signal the pursuit breaks out at right angles and they both fly straight for a predetermined number of seconds (or until they signal each other by radio). Now both make a 180-degree turn in opposite sense and so that they head for interception near the original parting point, as depicted in Figure 34. Thus, only slight course correction (toward the bomber) will be necessary for the interceptor to properly "miss" the bomber and to let him fly past ahead, while getting in a "burst" during the passage.

A.9.7 Escape Turns

Maneuvers involving escape turns on the part of the bomber may be practiced either under exactly the same time stretch and acceleration-reduction consideration or else under the same range scale equals speed-scale condition as outlined in Section A.9.4.

Appendix B

LATERAL STABILITY OF HOMING GLIDE BOMBS WITH APPLICATION TO NAVY SWOD MARK 7 AND MARK 9

B.1 LATERAL STABILITY EQUATIONS

The motion of a glider in flight is determined by two factors: the aerodynamic forces and moments due to the reaction of the air on various parts of the glider, and the forces and moments due to gravity. The resultant of the gravitational forces may be represented by a force equal to the weight of the glider acting vertically downward through the center of gravity. The resultant of the aerodynamic reaction is conveniently represented by three mutually perpendicular forces acting through the center of gravity and three moments acting about these three mutually perpendicular axes which meet at the center of gravity. In general, a glider has a plane of symmetry which in normal steady flight includes the direction of motion. For convenience, we will choose axes as follows: the X-axis is taken in the plane of symmetry in the direction of the relative wind during the steady-flight condition, the Y-axis perpendicular to the plane of symmetry, and the Z-axis in the plane of symmetry and perpendicular to the X-axis. Rotation about the X-, Y-, and Z-axes are denoted by the angles ϕ, θ, and ψ respectively, and angular rates of rotation about these axes by p, q, and r.

We may ordinarily consider the motion of a glider as divided into two independent types of motion. One type, called longitudinal motion, includes motion that does not displace the plane of symmetry of the airplane, and the stability of motion in this plane is termed longitudinal stability.[1] The other type of motion, called lateral motion, includes all components that do displace the plane of symmetry, and the stability of this motion is termed lateral stability. The longitudinal stability of homing glide bombs is discussed in detail in reference (1), and will not be considered further here. The present discussion of lateral stability refers principally to gliders in which the aileron is the only lateral control surface, although the discussion of stability with fixed control surfaces applies equally well to gliders equipped with both rudder and ailerons.

The stability characteristics of a glider are studied from the standpoint of the motion obtained from small displacements from a state of equilibrium. Under equilibrium conditions the glider flies in a straight line at constant speed with the plane of symmetry vertical—wings level. The resultant air reaction lies in the plane of symmetry and passes through the center of gravity. Let us define the following quantities:

γ = angle between flight path and horizontal
ϕ = angle of roll
ψ = angle of yaw
δ = angular displacement of ailerons
W = weight of glider
m = W/g, mass of glider
V = velocity along X-axis
v = velocity in Y-direction (sideslip velocity)
ρ = air density
S = wing area
b = wing span
Y = force along Y-axis (lateral force)
L = moment about X-axis (rolling moment)
N = moment about Z-axis (yawing moment)
$p = \dfrac{d\phi}{dt}$ = rate of roll
$r = \dfrac{d\psi}{dt}$ = rate of yaw
A = moment of inertia of glider about X-axis
C = moment of inertia of glider about Z-axis.

Let us also define the following coefficients:

$$\left.\begin{aligned} C_L &= \frac{\text{Lift}}{\frac{1}{2}\rho SV^2} & C_D &= \frac{\text{Drag}}{\frac{1}{2}\rho SV^2} \\ C_l &= \frac{L}{\frac{1}{2}\rho SV^2 b} & C_n &= \frac{N}{\frac{1}{2}\rho SV^2 b} \\ C_y &= \frac{Y}{\frac{1}{2}\rho SV^2} & \beta &= \frac{v}{V} \end{aligned}\right\} \quad (1)$$

At equilibrium, the quantities $L, N, Y, p, r, \phi, \psi$, and v are all equal to zero.

Let us now assume a small displacement from equilibrium and determine the equations which govern the motion. In order to reduce the complexity of the problem to enable a solution to be obtained without a prohibitive amount of calculation, the following assumptions are made:

1. Forces and moments on lifting surfaces are assumed proportional to the square of the airspeed.
2. Forces are unaffected by angular velocities and angular accelerations, and moments by angular accelerations.
3. The glider is assumed symmetrical, and thus lateral motions and longitudinal motions are assumed to be independent.

4. The combined effect of two or more forces or moments is assumed proportional to the algebraic sum of the separate components.

5. The changes in aerodynamic forces and moments due to a deviation are assumed proportional to the deviation.

6. Secondary effects involving the product of two small quantities are neglected.

7. The principal axes of inertia of the glider are assumed coincident with the reference axes.

The lateral equations of motion are given by:

$$m\frac{dv}{dt} + mV\frac{d\psi}{dt} = \frac{\partial Y}{\partial v}v + mg\sin\phi\cos\gamma + mg\sin\psi\sin\gamma \quad (2)$$

$$A\frac{d^2\phi}{dt^2} = \frac{\partial L}{\partial v}v + \frac{\partial L}{\partial p}p + \frac{\partial L}{\partial r}r + \frac{\partial L}{\partial \delta}\delta \quad (3)$$

$$C\frac{d^2\psi}{dt^2} = \frac{\partial N}{\partial v}v + \frac{\partial N}{\partial p}p + \frac{\partial N}{\partial r}r + \frac{\partial N}{\partial \delta}\delta \quad (4)$$

Let us define the following quantities:

$$\left.\begin{array}{ll} L_p = \dfrac{1}{A}\dfrac{\partial L}{\partial p} & N_p = \dfrac{1}{C}\dfrac{\partial N}{\partial p} \\ L_r = \dfrac{1}{A}\dfrac{\partial L}{\partial r} & N_r = \dfrac{1}{C}\dfrac{\partial N}{\partial r} \\ L_v = \dfrac{1}{A}\dfrac{\partial L}{\partial v} & N_v = \dfrac{1}{C}\dfrac{\partial N}{\partial v} \\ L_\delta = \dfrac{1}{A}\dfrac{\partial L}{\partial \delta} & N_\delta = \dfrac{1}{C}\dfrac{\partial N}{\partial \delta} \\ \multicolumn{2}{c}{Y_v = \dfrac{1}{m}\dfrac{\partial Y}{\partial v}} \end{array}\right\} \quad (5)$$

Remembering that ϕ and ψ are assumed to be small quantities, equations (2), (3), and (4) become:

$$\frac{dv}{dt} = -V\frac{d\psi}{dt} + Y_v v + (g\cos\gamma)\phi + (g\sin\gamma)\psi \quad (6)$$

$$\frac{d^2\phi}{dt^2} = L_v v + L_p\frac{d\phi}{dt} + L_r\frac{d\psi}{dt} + L_\delta\delta \quad (7)$$

$$\frac{d^2\psi}{dt^2} = N_v v + N_p\frac{d\phi}{dt} + N_r\frac{d\psi}{dt} + N_\delta\delta \quad (8)$$

Let us assume that v, ϕ, ψ, and δ vary with time according to laws of the form:

$$\begin{array}{ll} v = v_0\epsilon^{\lambda t} & \phi = \phi_0\epsilon^{\lambda t} \\ \psi = \psi_0\epsilon^{\lambda t} & \delta = \delta_0\epsilon^{\lambda t} \end{array} \quad (9)$$

and determine what values of λ will satisfy the above equations. The stability of the various motions will be determined by the nature of the values of λ that satisfy these equations. If λ is positive, small displacements in these quantities will continuously increase with time, and the motion will be unstable. If λ is negative, small displacements will decrease with the time, and the motion will be stable. If λ is complex, the motions will be oscillatory, with increasing or decreasing amplitude depending upon whether the real part of λ is positive or negative.

If we substitute the values of v, ϕ, ψ, and δ given by equation (9) into equations (6), (7), and (8), we obtain:

$$(\lambda - Y_v)v - (g\cos\gamma)\phi + (\lambda V - g\sin\gamma)\psi = 0 \quad (10)$$

$$-L_v v + (\lambda^2 - \lambda L_p)\phi - \lambda L_r\psi - L_\delta\delta = 0 \quad (11)$$

$$-N_v v - \lambda N_p\phi + (\lambda^2 - \lambda N_r)\psi - N_\delta\delta = 0 \quad (12)$$

Here we have three equations involving four variables, since so far we have made no mention of the variation of δ with the time.

B.2 STABILITY WITH FIXED CONTROL SURFACES

If we assume fixed control surfaces, we set δ equal to zero, and we have three equations in three variables. To determine what values of λ satisfy the above equations, it is necessary to determine only what values of λ make the following determinant vanish.

$$\begin{vmatrix} \lambda - Y_v & -g\cos\gamma & \lambda V - g\sin\gamma \\ -L_v & \lambda^2 - \lambda L_p & -\lambda L_r \\ -N_v & -\lambda N_p & \lambda^2 - \lambda N_r \end{vmatrix} = 0 \quad (13)$$

Solving the above determinant, we obtain the following equation for λ:

$$\begin{aligned} &\lambda^5 + (-N_r - L_p - Y_v)\lambda^4 \\ &+ (L_pN_r - L_rN_p + L_pY_v + N_rY_v + VN_v)\lambda^3 \\ &+ (-L_pN_rY_v + L_rN_pY_v - L_vg\cos\gamma - N_vg\sin\gamma \\ &+ VL_vN_p - VL_pN_v)\lambda^2 + (L_vN_rg\cos\gamma \\ &- L_rN_vg\cos\gamma - L_vN_pg\sin\gamma \\ &+ L_pN_vg\sin\gamma)\lambda = 0 \end{aligned} \quad (14)$$

This equation may be written in the form:

$$A\lambda^5 + B\lambda^4 + C\lambda^3 + D\lambda^2 + E\lambda + F = 0 \quad (15)$$

where

$$\left.\begin{aligned} A &= 1 \\ B &= -L_p - N_r - Y_v \\ C &= L_pN_r - L_rN_p + Y_v(L_p + N_r) + VN_v \\ D &= (L_rN_p - L_pN_r)Y_v - L_vg\cos\gamma \\ &\quad - N_vg\sin\gamma + V(L_vN_p - L_pN_v) \\ E &= (L_vN_r - L_rN_v)g\cos\gamma + (L_pN_v \\ &\quad - L_vN_p)g\sin\gamma \\ F &= 0 \end{aligned}\right\} \quad (16)$$

The determination of the values of λ which satisfy equation (15) depends in general upon the solution of a fifth-degree equation. Since in this case, one root is zero, it reduces to a fourth-degree equation. The values of the above quantities for a conventional type glider are such that the roots of equation (15) are one pair of conjugate complex roots, two negative roots, and, of course, one zero root. In general, the real parts of all the roots will be negative, corresponding to a stable condition, if all coefficients are positive and Rouths' discriminant $(BCD - D^2 - B^2E)$ is positive.

Let us now investigate which are the important terms in the equation in λ and thus show how the nature of the solutions depends upon the values of the aerodynamic coefficients involved. In C, the quantity VN_v is large compared with the other terms present, and in D, the quantity $V(L_rN_p - L_pN_r)$ is large compared with other terms. Let us, then, for the present, neglect the other quantities involved in these terms, and let C and D be given as follows:

$$C = VN_v \qquad D = V(L_rN_p - L_pN_r) \tag{17}$$

In general, C and D will be large compared with B and E. Let us assume then that we may approximately reduce equation (15) to the following form:

$$\left[\lambda^2 + \left(B - \frac{D}{C}\right)\lambda + C\right]\left[\lambda + \frac{E}{D}\right]\left[\lambda + \frac{D}{C}\right]\lambda = 0 \tag{18}$$

Multiplying, we obtain:

$$\lambda^5 + \left(B + \frac{E}{D}\right)\lambda^4 + \left[C + \frac{D}{C}\left(B - \frac{D}{C}\right) + \frac{BE}{D}\right]\lambda^3 + \left\{D + \frac{E}{D}\left[C + \frac{D}{C}\left(B - \frac{D}{C}\right)\right]\right\}\lambda^2 + E\lambda = 0 \tag{19}$$

Thus, in order that equation (15) may be approximately represented by an equation of form (18), the following relations must hold:

$$B \gg \frac{E}{D} \quad C \gg \frac{D}{C}\left(B - \frac{D}{C}\right) + \frac{BE}{D} \quad D \gg \frac{EC}{D} \tag{20}$$

In general, the values of the aerodynamic coefficients for normal flight conditions of aircraft type missiles are such that these conditions are satisfied. Inserting the values of B, C, D, and E in equation (18) and assuming the approximate values of C and D given by equation (17), we obtain:

$$\left[\lambda^2 + \left(-N_r - Y_v - \frac{L_vN_p}{N_v}\right)\lambda + VN_v\right]\cdot\left[\lambda + \left(\frac{L_vN_r - L_rN_v}{L_vN_p - L_pN_v}\right)\frac{g}{V}\cos\gamma - \frac{g}{V}\sin\gamma\right]\cdot\left[\lambda - L_p + \frac{L_vN_p}{N_v}\right]\lambda = 0 \tag{21}$$

With these approximations, λ is given by:

$$\left.\begin{aligned}
\lambda_1 &= L_p - \frac{L_vN_p}{N_v}\\
\lambda_2 &= -\frac{g\cos\gamma}{V}\left(\frac{L_vN_r - L_rN_v}{L_vN_p - L_pN_v}\right) + \frac{g\sin\gamma}{V}\\
\lambda_{3,4} &= \tfrac{1}{2}\left(N_r + Y_v + \frac{L_vN_p}{N_v}\right)\\
&\quad \pm i\sqrt{VN_v - \tfrac{1}{4}\left(N_r + Y_v + \frac{L_vN_p}{N_v}\right)^2}\\
\lambda_5 &= 0
\end{aligned}\right\} \tag{22}$$

Thus, v, ϕ, and ψ can be represented by equations of the form

$$\begin{aligned}
v, \phi, \psi &= C_1 \exp\left[L_p - \frac{L_vN_p}{N_v}\right]\\
&+ C_2 \exp\left[-\frac{g\cos\gamma}{V}\left(\frac{L_vN_r - L_rN_v}{L_vN_p - L_pN_v}\right) + \frac{g\sin\gamma}{V}\right]\\
&+ C_3 \exp\left[\tfrac{1}{2}\left(N_r + Y_v + \frac{L_vN_p}{N_v}\right)\right]\cdot\\
&\qquad \cos\left[\sqrt{VN_v - \tfrac{1}{4}\left(N_r + Y_v + \frac{L_vN_p}{N_v}\right)^2} + C_4\right]\\
&+ C_5
\end{aligned} \tag{23}$$

where C_1, C_2, C_3, C_4, and C_5 are arbitrary constants which have values depending upon which of the quantities v, ϕ, and ψ is being represented and the particular boundary conditions for that quantity and where $\exp R = \epsilon^R$.

In general, the first term in equation (23) represents a rapid subsidence, whose rate is a function mainly of L_p, the roll damping term. This is the most important term in roll motion.

The second term is a slow subsidence or divergence, whose rate depends primarily upon the magnitude of L_vN_r compared with L_rN_v, and upon the glide angle γ. This term determines the spiral stability characteristics of the glider; if the exponent is negative, the glider is spirally stable; if positive, spirally unstable. In general, L_vN_r is larger than L_rN_v, and spiral stability is obtained, although the stability is always small. As seen from the second term of equation (23), spiral stability is increased greatly at steep angles of descent ($\sin\gamma \to -1$).

The third term represents an oscillation whose period is determined largely by the term VN_v, and is given approximately by $T = 2\pi/\sqrt{VN_v}$. As is to be expected, this period depends mainly on N_v, the yawing moment due to sideslip, and the damping depends mainly on the term N_r, the yawing moment due to rate of yaw. These are the main terms in the yaw motion. The constant C_5 occurs because of the fact that in a nonhoming missile, the zero point for measuring angle of yaw is arbitrary; there is no preferred direction in space.

B.3 STABILITY OF SWOD MARK 12 AND MARK 13 AIR STABILIZERS

The following is a table of values of the lateral coefficients applicable to the SWOD gliders:

	Mark 12	Mark 13
W (lbs)	900	1500
S (sq ft)	18.3	24.4
b (ft)	8.4	10
A (lb sec² ft)	23	45
C (lb sec² ft)	75	200

$$\frac{\partial C_l}{\partial\left(\frac{pb}{2V}\right)} = -0.3$$

$$\frac{\partial C_l}{\partial\left(\frac{rb}{2V}\right)} = 0.2C_L$$

$$\frac{\partial C_l}{\partial\beta} = -0.17$$

$$\frac{\partial C_n}{\partial\left(\frac{pb}{2V}\right)} = -0.03C_L$$

$$\frac{\partial C_n}{\partial\left(\frac{rb}{2V}\right)} = -0.2$$

$$\frac{\partial C_n}{\partial\beta} = 0.17$$

$$\frac{\partial C_y}{\partial\beta} = -0.6$$

The values of W, S, b, A, and C are measured values determined at the National Bureau of Standards. The values of $\partial C_l/\partial\beta$, $\partial C_n/\partial\beta$, $\partial C_y/\partial\beta$ given in the table were obtained from a wind-tunnel test at the California Institute of Technology of an early model glider somewhat similar to the Mark 12 glider[2]. However, since there are some marked differences between this model and the present Mark 12 and Mark 13 gliders, these values should be considered as only approximate. Page 20, Table 3, of reference (2), gives the following values:

$$\frac{\partial C_l}{\partial\psi} = 0.003 \qquad \frac{\partial C_n}{\partial\psi} = -0.003 \tag{24}$$

and from Figure 12 of reference (2),

$$\frac{\partial C_c}{\partial\psi} = 0.010$$

where C_c is the crosswind force coefficient, which for small angles of yaw may be considered equal to C_y, the lateral force coefficient. The values of the damping terms

$$\frac{\partial C_l}{\partial\left(\frac{pb}{2V}\right)},\ \frac{\partial C_l}{\partial\left(\frac{rb}{2V}\right)},\ \frac{\partial C_n}{\partial\left(\frac{pb}{2V}\right)},\ \text{and}\ \frac{\partial C_n}{\partial\left(\frac{rb}{2V}\right)}$$

are estimated by the methods described in references (3) and (4) and should be considered as only very approximate.

Let us substitute the above values into the stability equations for a typical condition of flight of Mark 13, with fixed controls in pitch. Assume $C_L = 0.3$, which corresponds approximately to an average position of the elevons of 10 degrees up from neutral. At equilibrium this gives a velocity of flight at sea level of $V = 415$ fps.

Under this condition of flight, the following quantities have the values listed below:

$$\left.\begin{aligned}
V &= 415\ \text{fps}\\
\gamma &= -12.5\ \text{degrees}\\
L_p &= \frac{\partial C_l}{\partial\left(\frac{pb}{2V}\right)}\cdot\frac{\frac{1}{4}\rho SVb^2}{A} = -4.0\ \text{sec}^{-1}\\
L_r &= \frac{\partial C_l}{\partial\left(\frac{rb}{2V}\right)}\cdot\frac{\frac{1}{4}\rho SVb^2}{A} = +0.8\ \text{sec}^{-1}\\
L_v &= \frac{\partial C_l}{\partial\beta}\cdot\frac{\frac{1}{2}\rho SVb}{A} = -0.5\ \text{ft}^{-1}\ \text{sec}^{-1}\\
N_p &= \frac{\partial C_n}{\partial\left(\frac{pb}{2V}\right)}\cdot\frac{\frac{1}{4}\rho SVb^2}{C} = -0.03\ \text{sec}^{-1}\\
N_r &= \frac{\partial C_n}{\partial\left(\frac{rb}{2V}\right)}\cdot\frac{\frac{1}{4}\rho SVb^2}{C} = -0.6\ \text{sec}^{-1}\\
N_v &= \frac{\partial C_n}{\partial\beta}\cdot\frac{\frac{1}{2}\rho SVb}{C} = +0.1\ \text{ft}^{-1}\ \text{sec}^{-1}\\
Y_v &= \frac{\partial C_y}{\partial\beta}\cdot\frac{\frac{1}{2}\rho SV}{m} = -0.15\ \text{sec}^{-1}
\end{aligned}\right\} \tag{25}$$

Let us now substitute these values into equations (16), and thus determine the coefficients in equation (15) for λ. We thus obtain the following equations for λ:

$$\lambda^5 + 4.75\lambda^4 + 44.6\lambda^3 + 189.0\lambda^2 + 9.81\lambda = 0 \tag{26}$$

$$\begin{aligned}
\lambda_1 &= -4.35 & \lambda_2 &= -0.053\\
\lambda_{3,4} &= -0.172 \pm 6.55i & \lambda_5 &= 0
\end{aligned} \tag{27}$$

λ_1 represents a rapid subsidence which corresponds to the high damping in roll. λ_2 is a slow subsidence determining the combined roll and yaw spiral motion. λ_3 and λ_4 are a pair of conjugate complex roots which represent a damped oscillation in yaw.

If we put the values of the constants in equation (25) in the simplified expressions given by equation (21), we obtain:

$$(\lambda + 4.15)(\lambda + 0.057)(\lambda^2 + 0.6\lambda + 41.5) = 0 \quad (28)$$

$$\lambda_1 = -4.15, \quad \lambda_2 = -0.057$$
$$\lambda_{3,4} = -0.30 \pm 6.44i \quad (29)$$

These values are a fairly good approximation to those given by equation (27), except for the damping of the yaw oscillation.

B.4 LATERAL CONTROL SYSTEM[3,4] OF SWOD MARK 7 AND MARK 9

In the case of homing gliders, that is, the case where the control surfaces are moved in such a way as to direct the glider toward a target, the manner in which the control surfaces are caused to move in response to the homing signals depends upon the characteristics of the particular servomechanism used. It is not possible to compute the effect of a general functional relation and to consider all possible specific relations which have been used as a basis for servomechanisms. We will consider here only the case of the lateral control system used in SWOD Mark 7 and Mark 9.[5,6] The complete theory, taking into account the off-on link between the gyro and the servo, time lags in the servo, time lags in the homing control, and the complete set of lateral stability equations, would be a very unwieldy calculation, and it is thought that by treating these various factors separately as to their effects, the discussion may be made clearer.

Lateral stabilization is obtained through the turn gyro, which is essentially a rate gyro equipped with electromagnet coils and electrical contacts. The electromagnets are connected to apply torques to the gimbal frame which are proportional to the error angle in yaw as obtained by the homing device. The electrical contacts are arranged on opposite sides of the gimbal frame so that one contact or the other is closed, depending upon the sign of the sum of the torque applied by the electromagnets and the torque due to precession of the gyro wheel. Closing of a contact causes the servo to move the ailerons. The gyro is mounted in the glider at an angle so as to be sensitive to both roll and yaw.

It was assumed in the derivation of the equations of motion that the principal axes of inertia of the glider were coincident with the reference axes. In general, this is not true, for in the case of SWOD Mark 7 and Mark 9, the roll axis under normal equilibrium flight conditions is inclined to the direction of the relative wind by about 3 degrees. This difference has only a very small effect on the stability calculations for free flight, but must be taken into account in the case of homing flight.

Since the flight path is on the average toward the target on a true homing course, the error angle as measured by the homing device will differ from the error angle referred to coordinates where the X-axis is in the direction of the axis of roll by an amount given for small angles by the following equation:

$$\psi' = \psi - \beta\phi \quad (30)$$

where ψ' is the error determined by the homing device, ψ is the error angle, referred to coordinates with X-axis along the roll axis, β is the angle between the roll axis and a line from the glider to the target, and ϕ is the angle of bank.

Let α represent the angle the axis of the gyro makes with the axis of roll. Let c represent the rate of yaw in degrees per second that produces the same torque on the gimbal frame as an angular error of one degree. The particular contact on the gyro which is closed depends on the sign of the quantity ω defined by

$$\omega = \frac{d\psi}{dt} + \tan\alpha\,\frac{d\phi}{dt} + c(\psi - \beta\phi) \quad (31)$$

When ω is positive, that contact on the gyro will be closed that causes the servo-control unit to move the ailerons differentially at a constant speed to produce a rolling moment to the left; when ω is negative, the other contact will be closed, causing the ailerons to move at constant speed to give a rolling moment to the right. Thus the movement of the ailerons is always in such a direction as to reduce the value of ω to zero. A hunting motion is set up, the gyro contacts alternately closing and the ailerons moving alternately for right and left differential.

If we neglect this hunting motion, and assume that ω is, on the average, zero, we have

$$\frac{d\psi}{dt} + \frac{d\phi}{dt}\tan\alpha + c\psi - \beta c\phi = 0 \quad (32)$$

If we neglect the sideslip motion of the glider and assume, for the moment, that equilibrium of forces always exists along the lateral axis, equation (6) reduces to:

$$0 = -V\frac{d\psi}{dt} + (g\cos\gamma)\phi + (g\sin\gamma)\psi \quad (33)$$

In general, γ is sufficiently small so that the term involving $\sin\gamma$ may be neglected in equation (33) and $\cos\gamma$ set equal to unity. Equation (33) thus becomes:

$$\frac{d\psi}{dt} = \frac{g}{V}\phi \quad (34)$$

Substituting equation (33) and its time derivative in equation (32), we obtain:

$$\frac{d^2\psi}{dt^2} + \frac{d\psi}{dt}\frac{1}{\tan\alpha}\left(\frac{g\cos\gamma}{V} - \frac{g\sin\gamma\tan\alpha}{V} - \beta c\right) + \frac{(1+\beta\tan\gamma)cg\cos\gamma}{V\tan\alpha}\psi = 0 \quad (35)$$

If we use the simplified equation (34), which neglects terms in $\sin\gamma$ and $\tan\gamma$, and assume $\cos\gamma$ equal to unity, we obtain:

$$\frac{d^2\psi}{dt^2} + \frac{d\psi}{dt}\left(\frac{g}{V\tan\alpha} - \frac{\beta c}{\tan\alpha}\right) + \frac{cg\psi}{V\tan\alpha} = 0 \quad (36)$$

This equation has the following approximate solution:

$$\psi = \psi_0 \left\{\exp\left[-\frac{t}{2\tan\alpha}\left(\frac{g}{V} - \beta c\right)\right]\right\} \cdot \cos\left(\sqrt{\frac{cg}{V\tan\alpha}} + \sigma\right) \quad (37)$$

This equation represents a damped oscillation in yaw.

It is seen that the damping is influenced considerably by the value of βc. The effect of this quantity, in general, is to reduce the damping. If the line from the glider to the target is below the roll axis (β positive), the damping of the oscillation is decreased; if it is above the roll axis, the damping is increased. As has already been noted, the average value of β for SWOD Mark 9 is about 3 degrees. β occurs in the damping term multiplied by c, the ratio of the rate of turn of the gyro to the error angle. The effect of β on the damping is thus emphasized by a large value of c. In the case of high sensitivity homing information—that is, a large signal for a small error angle—the damping may become negative, the oscillations become undamped and increase in amplitude to a limit where the homing information saturates on each oscillation, and these assumed equations no longer hold.

Let us assume typical values of the constants in this equation. Let $\alpha = 20$ degrees, $\beta = 0.05$, $c = 0.5$, and $V = 415$ fps. We obtain:

$$\psi = \psi_0 \exp(-0.103t)\cos(0.326t + \sigma) \quad (38)$$

This shows that an oscillation in yaw should occur with a period of about 19 seconds and damping to $1/\epsilon$ of its initial value in about 10 seconds.

Although this simplified theory predicts quite closely the period of the oscillation in yaw actually obtained in flight, the predicted damping is not obtained, and sustained hunting of about this period and of an amplitude of about 4 degrees is obtained. In order to increase this damping in yaw sufficiently, a bias gyro has been added to the control systems of SWOD Mark 7 and Mark 9. This gyro[5] is similar to the turn gyro except that it does not contain the electromagnets, but only contacts, one or the other of which closes, depending upon the sense of the rate of turn. Its design and operation are described in detail in reference (5). This gyro is mounted in the glider along the average roll axis so that it will be sensitive chiefly to the yawing motion of the glider. Rolling motion will affect it slightly, because the axis of roll does not remain fixed for all conditions of flight.

The bias gyro is connected in the circuit of the turn gyro so that when the rate of yaw of the glider is to the right, the right coil in the turn gyro is shunted by a resistor, and when the rate of yaw is to the left, the left coil in the turn gyro is shunted. The effect of the shunting current in the coils is shown in Figure 11 of reference (5). It is seen that a bias is given to the signals put into the electromagnets in such a direction as to oppose the yawing motion of the glider and thus increases the damping of the yaw oscillations. Experimentally, it has been found necessary to use this bias gyro to obtain sufficient damping in yaw.

Figure 1 shows a typical flight of SWOD Mark 9. The curve labeled "Apparent Angular Horizontal Motion of Reflector" shows that an oscillation in yaw of period of about 20 seconds is evident, but it is of very small amplitude.

Obviously the reason the damping predicted by the simplified theory is not obtained is due to the approximations made, which, in effect, neglect the effects of sideslip velocity, the time lags present in the homing signals, and the roll hunting motion involving time lags in the gyro and servo system.

Let us now consider the effect of time lag in the homing intelligence. The homing intelligence has a time lag which is equivalent to that produced in an RC circuit of time constant of approximately 0.3 second. If we assume that the homing information has a lag corresponding to an RC circuit, equation (32) becomes

$$\frac{d\psi}{dt} + \frac{d\phi}{dt}\tan\alpha + c\exp - \frac{t}{RC}\int\frac{(\psi - \beta c)}{RC} \exp\frac{t}{RC}\,dt = 0 \quad (39)$$

Combining this equation with equation (34), we obtain:

$$\frac{d^3\psi}{dt^3} + \left(\frac{g}{V\tan\alpha} + \frac{1}{RC}\right)\frac{d^2\psi}{dt^2} + \left(\frac{g}{VRC\tan\alpha} - \frac{\beta c}{RC\tan\alpha}\right)\frac{d\psi}{dt} + \frac{cg\psi}{VRC\tan\alpha} = 0 \quad (40)$$

If RC is zero, this reduces, of course, to equation (36).

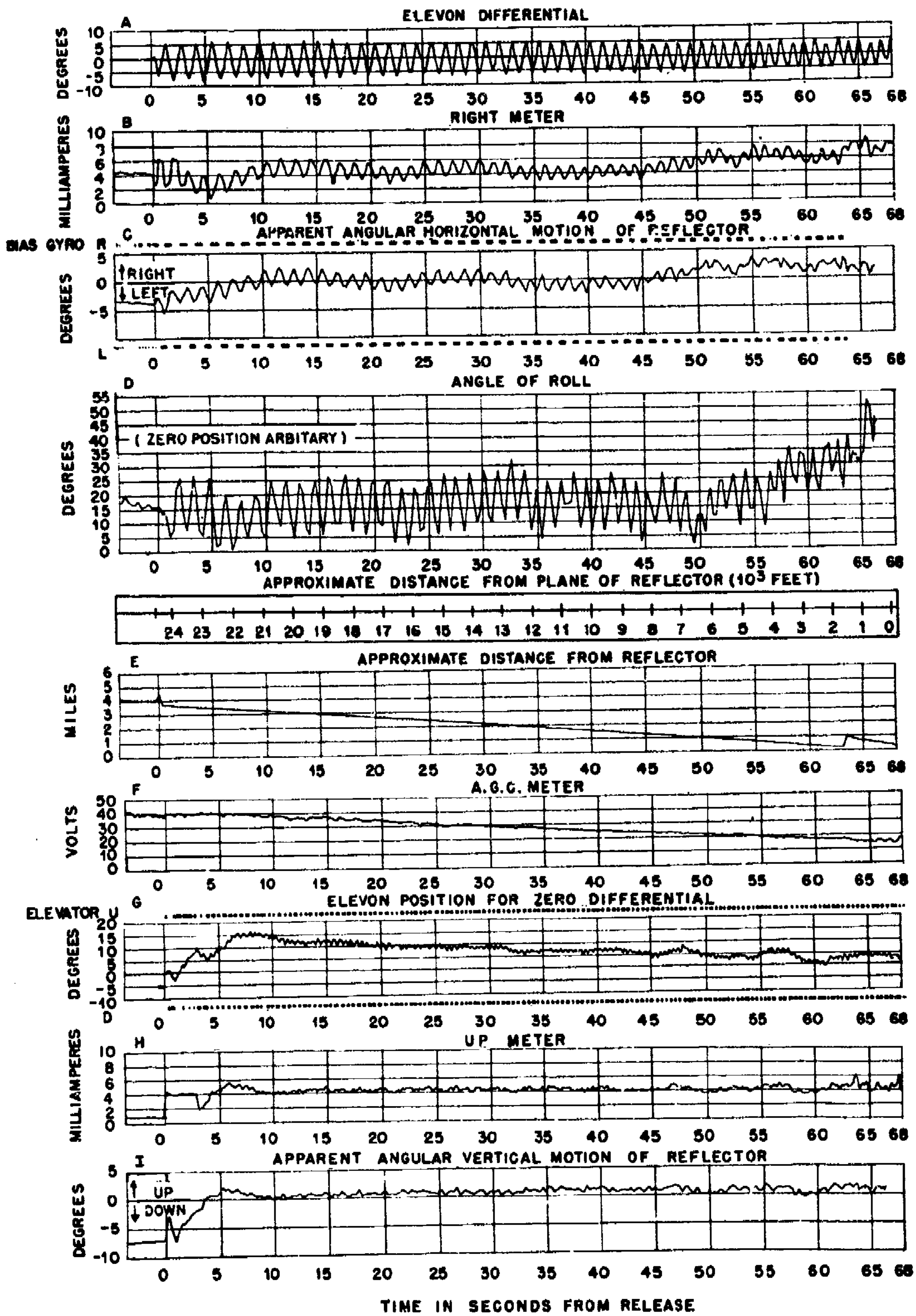


FIGURE 1. Typical flight of SWOD Mark 9.

If we substitute the values of β, c, α, and V used in equation (38), and in addition let $RC = 0.3$, equation (40) becomes:

$$\frac{d^3\psi}{dt^3} + 3.55\frac{d^2\psi}{dt^2} + 0.687\frac{d\psi}{dt} + 0.355\psi = 0 \quad (41)$$

Solving, we obtain:

$$\psi = \psi_1 \exp - 3.38t + \psi_2 \exp - 0.086t \cos (0.324t + \sigma) \quad (42)$$

It is seen that the period of the oscillations is virtually unchanged, but that the damping is decreased about 20 per cent. Sideslip effects and the hunting in roll with its various time lags involved are still neglected.

To investigate the effect of sideslip velocity, let us consider the general stability equations, with an ideal servomechanism, where the differential of the ailerons δ, instead of increasing or decreasing at a constant rate depending upon the sign of ω, will actually be proportional to ω. Thus let us write

$$\delta = -K\omega = -K\left(\frac{d\psi}{dt} + \frac{d\phi}{dt}\tan\alpha + c\psi - \beta c\phi\right) \quad (43)$$

If we assume δ is given by an expression of the type $\delta = \delta_1 \exp(\lambda t)$, we may write equation (43) as follows:

$$\delta + K(\lambda \tan \alpha - \beta c) + K(\lambda + c)\psi = 0 \quad (44)$$

If this equation is combined with equations (10), (11), and (12), the values of λ which satisfy the four equations are those that make the following determinant vanish.

$$\begin{vmatrix} \lambda - Y_v & -g\cos\gamma & \lambda V - g\sin\gamma & 0 \\ -L_v & \lambda^2 - \lambda L_p & -\lambda L_r & -L\delta \\ -N_v & -\lambda N_p & \lambda^2 - \lambda N_r & -N\delta \\ 0 & K(\lambda\tan\alpha - \beta c) & K(\lambda + c) & 1 \end{vmatrix} = 0 \quad (45)$$

When the above determinant is solved, an equation of the fifth degree in λ with 55 terms is obtained. This may be written in the form given by equation (15) with coefficients given in the following table:

$$A = 1$$

$$B = -N_r - L_p - Y_v + K[N_\delta + L_\delta \tan\alpha]$$

$$\begin{aligned} C = {} & L_pN_r - L_rN_p + Y_v(L_p + N_r) + VN_v \\ & + KL_\delta[-N_r\tan\alpha - \beta c + N_p - Y_v\tan\alpha] \\ & + KN_\delta[L_r\tan\alpha - L_p + c - Y_v] \end{aligned}$$

$$\begin{aligned} D = {} & Y_v(-L_pN_r + L_rN_p) - L_vg\cos\gamma \\ & - N_vg\sin\gamma + V(L_vN_p - L_pN_v) \\ & + KL_\delta[\beta cN_r + cN_p + N_rY_v\tan\alpha + \beta cY_v \\ & - N_pY_v + VN_v\tan\alpha] + KN_\delta[-\beta cL_r \\ & - cL_p - L_rY_v\tan\alpha + L_pY_v - cY_v \\ & - VL_v\tan\alpha] \end{aligned}$$

$$\begin{aligned} E = {} & (L_vN_r - L_rN_v)g\cos\gamma + (-L_vN_p \\ & + L_pN_v)g\sin\gamma + KL_\delta[-\beta cN_rY_v - cN_pY_v \\ & + N_vg\cos\gamma - \beta cVN_v - (N_v\tan\alpha)g\sin\gamma] \\ & + KN_\delta[\beta cL_rY_v + cL_pY_v - L_vg\cos\gamma \\ & + \beta cVL_v + (L_v\tan\alpha)g\sin\gamma] \end{aligned}$$

$$\begin{aligned} F = {} & KL_\delta[cN_vg\cos\gamma + \beta cN_vg\sin\gamma] \\ & + KN_\delta[-cL_vg\cos\gamma - \beta cL_vg\sin\gamma] \end{aligned} \quad (46)$$

Let us now substitute values for the coefficients in this equation for the typical flight conditions given by equation (25). We need values for the additional quantities L_δ, N_δ, K, α, and β. From wind-tunnel tests[2] we may take $\partial C_e/\partial\delta = 0.072$, which gives $L_\delta = 80$. We will assume for this flight condition that no yaw moments are produced by the ailerons; that is, $N_\delta = 0$. Let $K = 5$, $\alpha = 20$ degrees, and $\beta = 0.05$, which are typical values. The equation for λ becomes:

$$\lambda^5 + 150.4\lambda^4 + 138.1\lambda^3 + 6{,}229\lambda^2 + 953\lambda + 622 = 0 \quad (47)$$

This equation has the following approximate roots:

$$\begin{aligned} \lambda_1 &= -149.8, \\ \lambda_{2,3} &= -0.225 \pm 6.43i, \\ \lambda_{4,5} &= -0.0765 \pm 0.316i \end{aligned} \quad (48)$$

Comparing this result with the free-flight results, equation (27), we see that instead of two subsidences, a damped oscillation, and a zero root, we now have a very rapid subsidence and two damped oscillations. The roots λ_2 and λ_3 represent a natural yaw oscillation which is similar to that for the free-flight condition and whose period and damping are mainly a function of the aerodynamic constants. The roots λ_4 and λ_5 represent a damped oscillation whose period and damping depend primarily upon the constants α and c assumed for the ideal servo system. The period of this oscillation is about the same and the damping somewhat less than that obtained from equation (38), in which sideslip velocity was neglected. While the effect of sideslip is sometimes taken into account by introducing an "aerodynamic lag" in the simplified equation, it is important to note that there is no evidence of a true aerodynamic lag when the complete equations of motion are used.

By examination of the solutions of equations (36), (40), or (45), it is seen that the damping in yaw should increase as α decreases. If we let $\alpha = 0$ in equation (36), we obtain:

$$\frac{d\psi}{dt} + \frac{c\psi}{1 - \frac{\beta cV}{g}} = 0 \quad (49)$$

Solving for ψ, we obtain:

$$\psi = \psi_0 \exp\left(-\frac{ct}{1 - \frac{\beta cV}{g}}\right) \quad (50)$$

This equation shows that the yaw oscillation should reduce to a subsidence when $\alpha = 0$. However, if we let $\alpha = 0$ in equation (46), which takes into account sideslip velocity effects, we obtain the following equation for λ:

$$\lambda^5 + 4.75\lambda^4 + 22.6\lambda^3 + 173.7\lambda^2 + 851\lambda + 622 = 0 \quad (51)$$

which has the following roots:

$$\begin{aligned} \lambda_1 &= -0.871 \\ \lambda_{2,3} &= -4.08 \pm 2.49i \\ \lambda_{4,5} &= +2.14 \pm 5.16i \end{aligned} \quad (52)$$

We obtain the rapid subsidence and the damped natural yaw oscillation as in the case $\alpha = 20$ degrees, but now λ_4 and λ_5 represent a rapidly divergent oscillation, and thus an unstable condition results. At some small value of α, the real parts of the roots λ_4 and λ_5 change from negative to positive, changing the oscillation from a damped one to a divergent one.

B.5 ROLL STABILIZATION SYSTEM

In order to study the effects of the roll hunting motion on the lateral stability, a more detailed discussion of the roll stabilization system will be given, taking into account the off-on character of the link between the gyros and the servo clutches, and the time lag in the response of the servo. Let us assume that the glider is flying straight and level, that the hunting motion in roll has reached a steady-state condition, and that the motion is periodic. If the effects of rolling moment due to rate of yaw and rolling moments due to sideslip velocity are regulated, equation (7) for the motion in roll becomes:

$$\frac{d^2\phi}{dt^2} = L_p\frac{d\phi}{dt} + L_\delta\delta \quad (53)$$

At time t equals zero, let the rate of roll p equal p_1, the angle of bank ϕ equal ϕ_1, and the rolling acceleration produced by the ailerons equal $L_\delta(d\delta/dt)t_1$. Let us define K as equal to $L_\delta(d\delta/dt$, and thus K becomes the acceleration in roll produced by the amount of differential on the ailerons developed by the servo in moving the ailerons at constant speed $d\delta/dt$ for one second.

At the instant $t = 0$, the ailerons start to move differentially with a constant speed and in such a direction as to reduce the rolling acceleration. At time $t = t_1$, it is easily seen that the rolling acceleration will become zero, and at $t = 2t_1$, it will become equal in magnitude and opposite in sign to its value at $t = 0$. At $t = 2t_1$, it is assumed that the direction of motion of the ailerons reverses, so that at time $t = 3t_1$, the rolling acceleration is again reduced to zero, and at $t = 4t_1$, it is equal to its value at $t = 0$. Thus a periodic hunting in the aileron motion is obtained of saw-toothed waveform, and with a period $4t_1$. The aileron differential δ as a function of the time is shown in Figure 2.

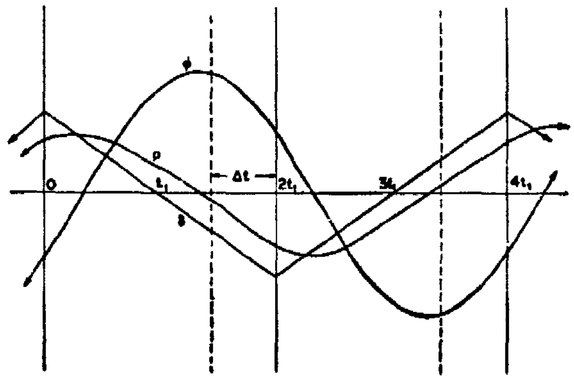


FIGURE 2. Aileron differential δ as function of time.

We may express the motion in roll between $t = 0$ and $t = 2t_1$ by the equation:

$$\frac{d^2\phi}{dt^2} = L_p\frac{d\phi}{dt} + Kt_1 - Kt \quad (54)$$

Solving this differential equation for p and ϕ, including the initial conditions that $p = p_1$, and $\phi = \phi_1$, at $t = 0$, we obtain:

$$p = -\frac{K}{L_p}\left\{t_1\left[1 - \exp(L_pt) - \right] - t - \frac{1}{L_p}\left[1 - \exp(L_pt)\right]\right\} + p_1\exp(L_pt) \quad (55)$$

$$\phi = -\frac{K}{L_p}\left\{t_1t + \frac{t_1}{L_p}\left[1 - \exp(L_pt)\right] - \frac{t^2}{2} - \frac{t}{L_p} - \frac{1}{L_p^2}\left[1 - \exp(L_pt)\right]\right\} - \frac{p_1}{L_p}\left[1 - \exp(L_pt)\right] + \phi_1 \quad (56)$$

At $t = 2t_1$, let $p = p_2$, and $\phi = \phi_2$. Then p_2 and ϕ_2 will be given by the following equations:

$$p_2 = \frac{K}{L_p}\left[t_1 + \frac{1}{L_p}\frac{1 - \exp(2L_pt_1)}{1 + \exp(2L_pt_1)}\right] \quad (57)$$

$$\phi_2 = \frac{K}{L_p^2}\left[t_1 + \frac{1}{L_p}\frac{1 - \exp(2L_pt_1)}{1 + \exp(2L_pt_1)}\right] \quad (58)$$

Since we have assumed a steady-state condition, the values of p and ϕ at $t = 2t_1$ must be equal in magnitude and opposite in sign to their values at

$t = 0$. Putting $p_1 = -p_3$ and $\phi_1 = -\phi_3$, we obtain the following equations for p and ϕ:

$$p = -\frac{K}{L_p}\left[t_1 - t - \frac{1}{L_p}\cdot\frac{1 + \exp(2L_pt_1) - 2\exp(L_pt)}{1 + \exp(2L_pt)}\right] \quad (59)$$

$$\phi = \frac{K}{L_p^2}\left[t(1 - L_pt_1) + \frac{L_pt^2}{2} - t_1 + \frac{1}{L_p}\cdot\frac{1 + \exp(2L_pt_1) - 2\exp(L_pt)}{1 + \exp(2L_pt_1)}\right] \quad (60)$$

Let us assume that there is a time lag Δt between the time the angular velocity to which the gyro is sensitive $(d\psi/dt + d\phi/dt \tan \alpha)$ is reduced to zero and the time the ailerons reverse their motion. This time lag includes the time it takes for the gyro contacts to reverse and the servo clutches to engage and reverse the direction of motion of the ailerons. If reversal of the aileron motion takes place at $t = 2t_1$, the angular velocity to which the gyro is sensitive must reduce to zero at time $t = 2t_1 - \Delta t$. Let the values of p and ϕ at this time be denoted by p_3 and ϕ_3, which are given by the following equations:

$$p_3 = -\frac{K}{L_p}\left\{-t_1 + \Delta t - \frac{1}{L_p}\left[\frac{1 - 2\exp \overline{L_p(2t_1 - t)} + \exp(2L_pt_1)}{1 + \exp(2L_pt_1)}\right]\right\} \quad (61)$$

$$\phi_3 = \frac{K}{L_p^2}\left\{t_1(1 - L_pt) - \Delta t + L_p\frac{(\Delta t)^2}{2} + \frac{1}{L_p}\left[\frac{1 - 2\exp \overline{L_p(2t_1 - t)} + \exp(2L_pt_1)}{1 + \exp(2L_pt_1)}\right]\right\} \quad (62)$$

Since, at time $t = 2t_1 - \Delta t$, the angular velocity to which the gyro is sensitive is reduced to zero, we have the following relation:

$$\frac{d\psi}{dt} + \frac{d\phi}{dt}\tan\alpha = 0 \quad \text{at} \quad t = 2t_1 - \Delta t \quad (63)$$

If again we neglect the effects of sideslip velocity, we may make use of equation (34) and thus obtain the following relation between p_3 and ϕ_3:

$$\frac{g}{V}\phi_3 + (\tan\alpha)p_3 = 0 \quad (64)$$

Because of the high damping in roll, the terms $\exp(2L_pt_1)$ and $\exp[L_p(2t_1 - \Delta t)]$ are negligible compared with unity for the observed values of t_1 and Δt, and will be neglected in what follows. Substituting equations (60) and (61) in equation (64), we obtain:

$$\frac{Kg}{VL_p^2}\left[t_1 - L_pt_1\Delta t - \Delta t + L_p\frac{(\Delta t)^2}{2} + \frac{1}{L_p}\right] - \frac{K\tan\alpha}{L_p}\left[-t_1 + \Delta t - \frac{1}{L_p}\right] = 0 \quad (65)$$

Solving for t_1, we obtain:

$$t_1 = \frac{\Delta t - \dfrac{1}{L_p} + \dfrac{g}{VL_p\tan\alpha}\left(\Delta t - L_p\dfrac{(\Delta t)^2}{2} - \dfrac{1}{L_p}\right)}{1 + \dfrac{g}{VL_p\tan\alpha}(1 - L_p\Delta t)} \quad (66)$$

It is seen from the above equation that for values of α such that $-g/(VL_p\tan\alpha) \ll 1$, the period of the roll hunt is determined chiefly by the damping acceleration in roll L_p and the time lag Δt. The amplitude of the roll hunt from equation (60) is seen to be a linear function of the period and directly proportional to the ratio of the rolling acceleration produced per second by the elevons. Thus, to keep the roll amplitude small, time lags in the gyro and servo units must be kept to a minimum, and the rate of application of restoring moment small.

As α takes on smaller and smaller values so that $-g/(VL_p\tan\alpha)$ becomes of the order of unity, the denominator in equation (66) becomes very small, increasing the period and amplitude of the roll hunting motion, until at the value of α determined by the equation

$$\frac{g}{V\tan\alpha}\left(\frac{-1}{L_p} + \Delta t\right) = 1 \quad (67)$$

the denominator of equation (66) becomes zero, and the hunting motion becomes unstable.

Let us substitute appropriate values of L_p, g, V, α, and Δt for SWOD Mark 9 and determine the resultant values of the amplitude and period of the roll motion. Let us use the values of L_p and V given by equations (25) and, in addition, set $\alpha = 20$ degrees and $\Delta t = 0.1$ second. Substituting these values into equation (66), we obtain $t_1 = 0.35$ second. Thus the roll hunting motion should have a period $T = 4t_1 = 1.4$ seconds. The amplitude will be approximately given by ϕ_3, which has a value of 0.095 radian or 5.4 degrees. These calculated values check well with experiment as is seen by referring to the curve of Figure 1, showing the angle of roll as a function of the time for a typical flight of SWOD Mark 9.

From equation (67), the smallest value of α that may be used before the motion becomes unstable is about 3.5 degrees. This equation, however, neglects rolling moments due to sideslip and to rate of yaw which, if taken into account, have the effect of increasing this minimum angle.

3.6 MODEL TESTS OF LATERAL CONTROL SYSTEM

To study the effect of time lags and speed of the servo system on the roll hunting motion, a mechanical model to represent equation (53) was constructed. A photograph of the model is shown in Figure 3. It consists of a table free to rotate about a vertical axis and carries the turn gyro used in the control system. On the same axis is a cylinder which rotates inside a concentric cylinder with a small separation. The space between the cylinders is filled with oil to produce viscous damping of the motion of the table. Since the spacing of the cylinders is small and the oil is sufficiently viscous, the damping force is quite accurately proportional to the first power of the angular velocity of the table. A cord is wound around the shaft which supports the table, and each end is connected to a spring. The other ends of the springs are connected by cords around pulleys to the servo arms. Thus, if the small spring displacement caused by the motion of the table is neglected, the torque applied to the table will be proportional to the displacement of the servo arms and to the constants of the springs. If the ratio of the torque applied per radian displacement of the servo to the moment of inertia of the table is made equal to the value of L_δ for the missile, and the ratio of the damping torque to the moment of inertia of the table is made equal to the value of L_p

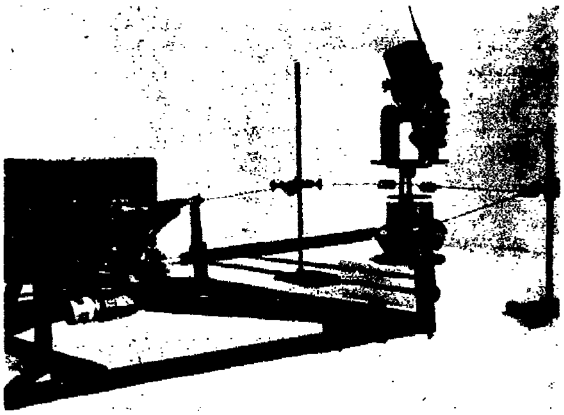


FIGURE 3. Mechanical model to represent equation

$$\frac{d^2\phi}{dt^2} = L_p\frac{d\phi}{dt} + L_\delta\delta.$$

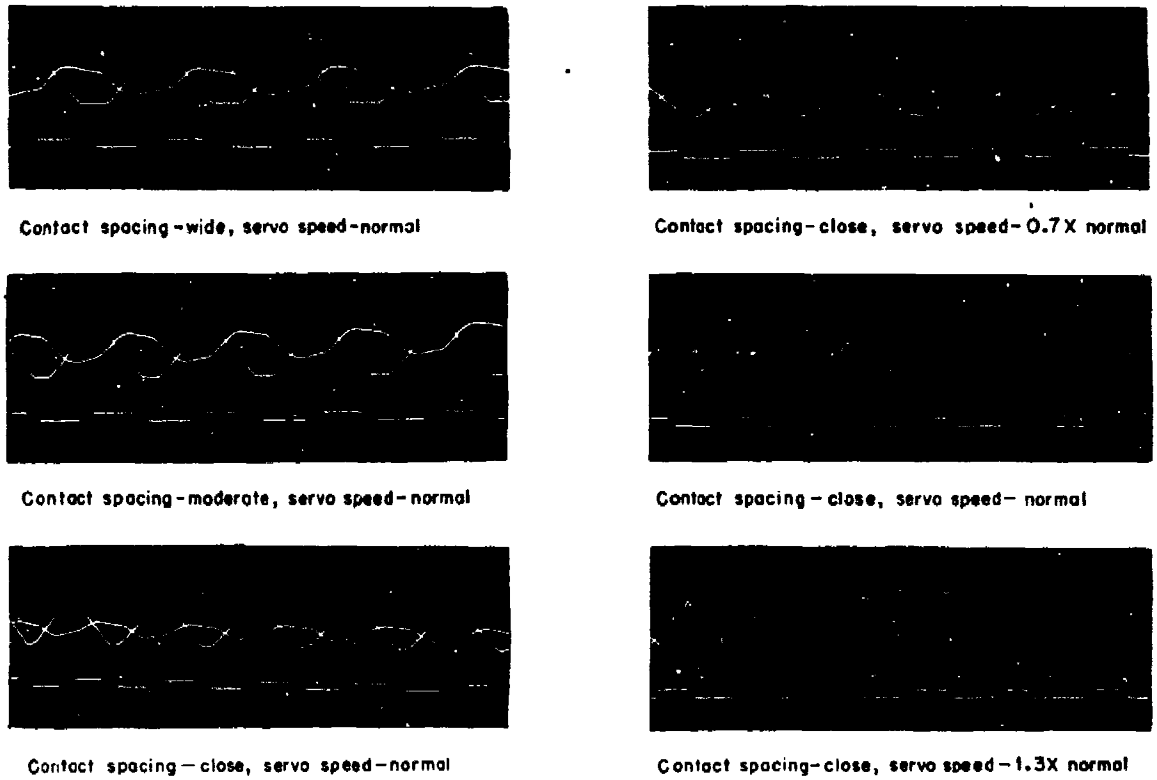


FIGURE 4. Roll simulator records showing effects of gyro contact spacing and servomotor speed on amplitude of roll hunting motion. Sawtoothed type curves represent differential motion of elevons; sinusoidal type curves, angular motion of table; and broken lines, operation of right and left servo clutches, respectively. Film speed is approximately 1 inch per second.

for the missile, the motion of the table will be governed by equation (53). If the turn gyro mounted on the table is connected to the servo, as in the missile, a hunting motion will be set up, simulating the roll hunting motion of the glider. Some records obtained with the model are shown in Figure 4; they were taken to study the effect of time lag in the system and rate of movement of ailerons on the amplitude of the roll hunt. The results are in accord with the theoretical treatment above.

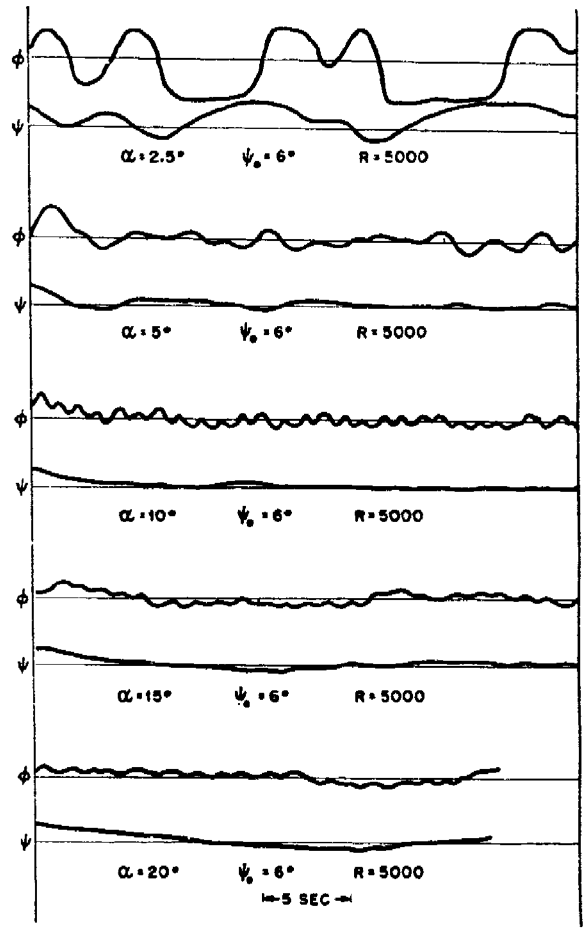


FIGURE 5. Series of runs in which angle of gyro is varied from 2.5 to 20 degrees.

The Servomechanisms Laboratory of the Massachusetts Institute of Technology, in connection with the development of an alternative control system for SWOD Mark 7 and Mark 9, constructed a device to simulate the roll and yaw motions of a glider. A platform was arranged so as to be free to rotate about a horizontal axis (representing roll motion) and to be driven in rotation about a vertical axis. A torque motor and generator were connected to the roll axis, and synchros were attached to the arms of the servo under test. Electrical circuits were arranged so that a torque was applied about the roll axis proportional to the differential displacement of the ailerons and to the rate of roll, with proper constants of proportionality so that the motion in roll would be represented by equation (53). The platform was driven in rotation about a vertical axis at an angular velocity proportional to the angular displacement about the horizontal or roll axis, and the constant adjusted so that its motion would be represented by equation (34). All effects due to sideslip and the cross derivatives L_r and N_p were neglected.

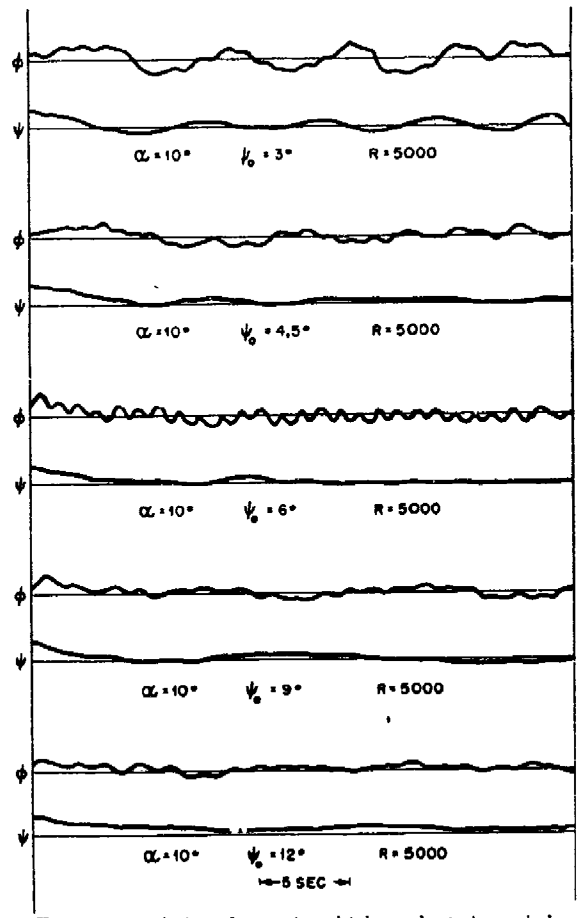


FIGURE 6. Series of runs in which angle ψ_0 is varied.

The turn and bias gyros and antenna system used in SWOD Mark 7 were mounted on the platform and a beacon for homing signals placed at a distance from the platform. The system was operated so that the lateral motions of the glider in flight would be simulated. Records obtained of the angle of bank ϕ and the angle of yaw ψ of the platform as a function of the time for various adjustments of the control system are shown in Figures 5, 6, and 7. In all records shown, the platform was initially set 5 degrees off the axis of homing. The vertical scale for ϕ is four times that for ψ.

Figure 5 shows a series of runs in which the angle of the gyro is varied from 2.5 to 20 degrees. For 2.5 degrees the motion is unstable, as predicted by the roll stabilization theory in Section B.5, the platform hitting its limit stops during the test. The value of 15 degrees, found to be most satisfactory from flight tests, is somewhat larger than the best result from the model tests, the difference being due to the terms neglected in the equation governing the model tests.

Figure 6 shows a series of runs in which the angle designated as ψ_0, the minimum error angle that produces saturation of the differential amplifier which feeds into the turn gyro coils, is varied. This, in effect, is the same as varying the value of c, the rate of yaw in degrees per second that produces the same torque on the gimbal frame of the gyro as an angular error of 1 degree. The value $\psi_0 = 6$ degrees was found most suitable from flight tests, and this value is seen to be satisfactory by this model test.

Figure 7 shows the effect of the bias gyro on the damping of the yaw oscillations. If a bias gyro is not used ($R = \infty$), sustained oscillations in yaw are obtained both in flight tests and in the model test. The most suitable value for the biasing resistor determined from both flight tests and model tests was found to be about 5,000 ohms.

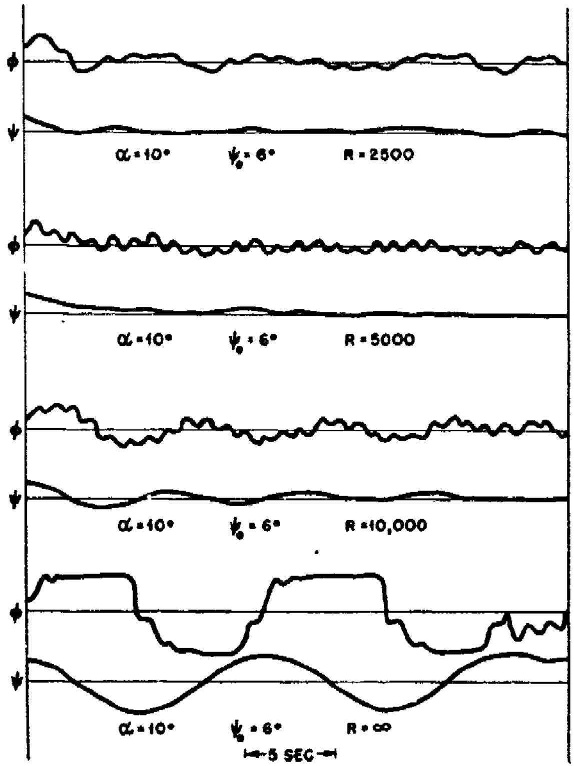


FIGURE 7. Effect of bias gyro on damping of yaw oscillations.

Appendix C

INFRARED RADIATION AND ITS APPLICATION TO HOMING MISSILES

C.1 INTRODUCTION

Target-seeking devices based upon infrared radiation are rendered unique by two factors. First, an object at any temperature different from its surroundings radiates heat differentially. Second, this differential radiation can be detected in the dark without revealing the observer, as occurs, for example, when using radar. The term "infrared" has been used to include all electromagnetic waves between a wavelength of 7,000 A ($= 0.7\mu = 7 \times 10^{-5}$ cm) and 3,000,000 A ($= 300\ \mu = 0.03$ cm). Wavelengths greater than this are most satisfactorily produced by electrical means.

In accordance with well-known laws, the total amount of energy radiated by any object varies with the fourth power of its absolute temperature, and the distribution of the radiated energy among the different frequencies changes with altered temperatures. In Figure 1 is plotted the radiant energy as a function of its wavelength for several different temperatures. This shows graphically the reason for our particular interest in using the far infrared for heat detection. It will be seen that the temperature must rise to about 500 C (932 F) before there is any appreciable radiation appearing at wavelengths visible to the eye. Nevertheless, at any temperature above absolute zero, any object is continuously radiating heat energy. Furthermore, for many military targets whose temperatures will be slightly above that of their surroundings, the peaks of the radiation curves occur within the wavelength band designated in Figure 1 as the "water vapor window." The atmosphere is transparent to radiation of these wavelengths, while on either side are large areas within which absorption by atmospheric carbon dioxide and water

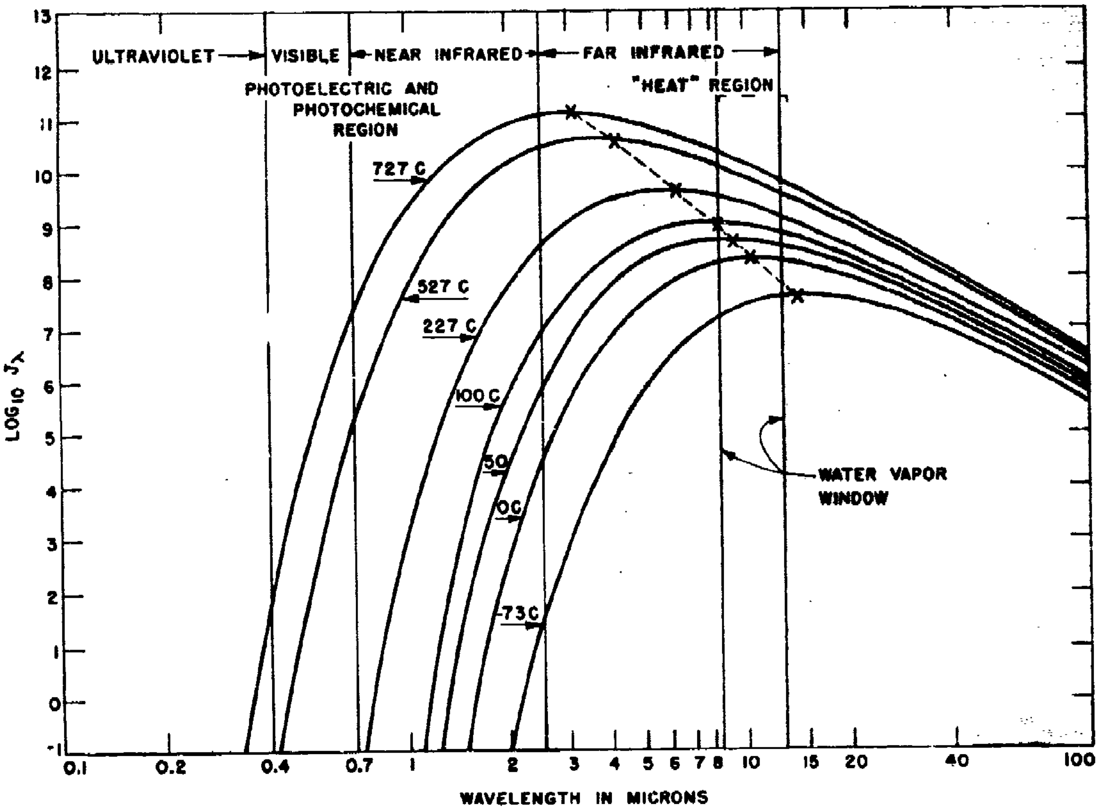


FIGURE 1. Black-body radiation.

vapor is complete. This transmitted radiant energy may be detected by appropriate devices other than the eye. The fact that such devices can be made of phenomenal sensitivity has led both scientists and gadgeteers to pursue intensive work in this field. This in turn has resulted in many hundreds of proposed, and a few successful, devices.

Devices for detecting an object by infrared radiation may be sharply classified into two groups: those utilizing the far and those dependent upon the near infrared. Partly by nature and partly by definition, the two classes have the following characteristics:

Far Infrared	Near Infrared
1. "Far infrared," as used in this report refers to heat radiations of wavelengths longer than 2.5 μ. However, because of atmospheric absorption, operations are restricted to the band between 8.5 and 13 μ.	1. "Near infrared," as used in this report, refers to the wavelength band between the visible and 2.5 μ.
2. Far infrared devices usually depend upon the heat energy radiated by *all* objects rather than upon the use of special sources. Reflection is of minor importance. Most solids and liquids radiate approximately as "black bodies" at these wavelengths, so that the contrast for any detection problem is primarily determined by temperature differences.	2. Most near infrared devices require the use of a special source of radiation directed over a path of some kind to the receiver. For detection problems, reflected radiation is frequently used. With only a few exceptions, when a natural source is hot enough to emit much energy in the near infrared, it is hot enough to emit some in the visible at the same time.
3. Most solids and liquids absorb completely all radiation not reflected at their surfaces, so that very few materials may be used as lenses and windows. Changes in direction must usually be accomplished by reflection.	3. The optical system may be handled by the same general methods as for visible light. Certain selective absorptions and reflections create some of the special uses for near infrared devices.
4. Photoelectric and photochemical receivers cannot be used. The basis of operation depends on the absorption of radiant energy as heat.	4. The most sensitive and rapid receivers in this range are photoelectric and photochemical devices.

C.2 GENERAL CONSIDERATIONS

Many of the problems met in infrared research are, of course, common to both the above categories. In this classification falls the matter of attenuation over long paths in the atmosphere. The principal constituents of the atmosphere, nitrogen and oxygen, have no absorption bands of any importance to this discussion. On the other hand, water vapor, carbon dioxide, and ozone have strong absorption bands, and various atmospheric colloidal particles—smoke, dust, clouds, etc.—cause considerable attenuation.

C.2.1 Energy Loss Due to Tiny Suspended Particles

Any solid or liquid particles in the atmosphere may attenuate incident radiation by two distinct processes. The first is by absorption of the radiant energy within the particle, which in general will result in its reradiation at a longer wavelength corresponding to the black-body temperature of the particles. The second is by a change in the direction of the incident radiation due to diffraction, reflection, and refraction, or to any one of these. Such change in direction after contact with many particles is considerable, and virtually no radiation is transmitted. Only when the particle size is small with respect to wavelength, as is the case in very faint haze, do the dispersing phenomena become substantially less effective. When the particle size is very small, attenuation may be due only to scattering. *In such cases,* as is well known, the scattering may be considerably less for the longer waves.

There are essentially two types of atmospheric particles—solids and liquids.

Smoke, Dust, etc. Solid particles are nearly opaque to visible and infrared radiation; hence, attenuation by large particles is due simply to reflection and absorption. For particles small with respect to wavelength, attenuation is chiefly by scattering. The resulting use of near infrared in aerial photography for penetration of atmospheric haze is common knowledge.

The penetration of smoke screens is another application for infrared which has received some consideration. A limited number of field and laboratory tests on smoke penetration have been made.[1] These indicate that there is good penetration by the far infrared in some cases and by the near in a very few cases, depending on the type of smoke used. In general, the size of the smoke particles tends to increase with time after original production of the smoke, so that penetration, particularly in the near infrared, decreases eventually to useless values. Attenuation by other opaque particles, such as dust, is also a matter of particle size and presents a similar special problem in each case considered.

Water Droplets. A considerable study, by both experimentation,[1,2] and theory[3] has been made of infrared fog and cloud penetration. The evidence at first seems conflicting. However, if the question of particle size is correctly understood, the results are conclusive. This quantity is difficult to measure, particularly when the density of a fog or haze is so low that the visibility may be several miles. However, transmission for several wavelength bands and the distribution of water particle sizes have been measured simultaneously in a series of experiments.[4] The longest wavelength band used included the 8.5- to 13-μ water vapor window. Something of the order of one hundred observations were made in several different natural fogs and clouds. In no instance was any difference in transmission observed between the visible and the infrared. All this information indicates conclusively that reflection, refraction, absorption, etc., are sufficient at all useful wavelengths to restrict the transmission in most fogs and clouds to ranges little, if any, greater than for visible light. Use of the infrared beyond 15 μ is not helpful, as water vapor absorbs strongly at longer wavelengths, and energy levels are low.

When the particle size is small with respect to wavelength, the problem is the same as for dust, smoke, or any other small particles. Apparently, haze and fog particles often are less than 1 μ in size when the visibilities are a mile or more. In such a haze infrared might have appreciably increased range over the visible. Some dense fogs and clouds may have a sufficiently high percentage of small droplets so that a small increase in range for the infrared might be observable through them, also, and some fogs may contain a large amount of smoke. However, it is unusual to find a cloud in which more than 50 per cent of the particles are smaller than 10 μ in diameter or a sea fog in which many are smaller than 20 μ.[4] In most clouds and fogs the infrared is attenuated as much as the visible.

Mist and raindrops (also snowflakes) are, of course, considerably larger than any of the above, and no reliable observations in the infrared indicate any improvement over visible light when such large particles *only* are in the optical path.

Certain experimental results obtained under special conditions, and some theoretical work based on rather doubtful assumptions, indicate some improvement in transmission in the infrared. This work accounts for the common misunderstanding concerning fog and cloud penetration. It is considered, however, that if the visual range is something of the order of 500 yd, the complexity of infrared apparatus needed to increase that range to 600 or even to 800 yd is not justified.[5]

C.2.2 Absorption Bands Due to Gases

Water Vapor. The absorption by water vapor has been measured in detail throughout the infrared spectrum over actual atmospheric paths.[6] Under average conditions, the total amount of water vapor, in a path a few hundred yards long near the surface of the earth, is large enough so that absorption may be considered complete *at certain wavelengths* for such or longer paths.

Carbon Dioxide. This gas is present to an extent of but 0.03 to 0.04 per cent, but this is sufficient to cause sharp absorption at several wavelengths in the infrared.[7]

Ozone. Substantial quantities of ozone in the stratosphere limit the infrared and the ultraviolet solar radiation received at the earth's surface. Below 20,000 ft, however, ozone is negligible.

Absorption by water vapor and carbon dioxide in the atmosphere generally limits the use of infrared to two broad bands in the spectrum, one extending from the visible to about 4 μ and the other from 8.5 to 13 μ. The former covers the near infrared, plus a portion of the far infrared which does not seem particularly useful for military purposes. The temperatures of sources whose radiation peaks are between 2.5 and 4 μ (see Figure 1) range from about 500 C to 1,000 C. Such sources seem to be uncommon, and where they do occur they are easily shielded. Furthermore, those in the higher part of this range radiate sufficiently in the near infrared to be detected by the more sensitive photoelectric receivers. As is indicated in Figure 1, increasing the temperature of a black body increases the intensity of radiated energy at all wavelengths at which there is any emission, not just at the wavelength of the peak.

Water vapor shows strong absorption between 13 and 20 μ, and beyond 20 μ it renders the atmosphere virtually opaque to infrared radiation. In general, therefore, the nature of the sources, existing receivers, and atmospheric absorption confine the work to the near infrared (0.7 to 2.5 μ) or to the 8.5- to 13-μ water vapor window.

As will be seen from Figure 2, this limitation is not particularly unfortunate. Here is shown the per cent transmission at various wavelengths through an atmospheric path containing water vapor and carbon dioxide. On the same wavelength scale are superposed the curves for black-body radiation at temperatures from 0 C to 100 C. It is evident that this window covers the peaks of the radiation curves for objects at common terrestrial and atmospheric temperatures. In this region, also, nonselective receivers may still be very sensitive.

For aerial photography, where atmospheric haze presents a common difficulty, near infrared suffers less attenuation than visible light. Other than this, the use of near infrared offers transmission advantages over the visible only in very special cases. Smoke-screen penetration might be an example. The 8.5- to 13-μ transparent band, however, is useful because it covers exactly the wavelengths radiated by many desirable military and naval targets under usual conditions.

C.2.3 Emission of Infrared Radiation

The most common sources of infrared radiation are solid materials which, in general, radiate as black bodies. In other words, their surfaces may be considered 100 per cent absorbing or 100 per cent emissive at any infrared wavelength. Most solids and liquids come closest to being ideal black bodies at the longer wavelengths, beyond 5 or 10 μ. Exceptions are polished metals, such as are used for reflectors. The most common sources in the near infrared are simply solid materials heated to incandescence.

Gases behave in a very different manner from solids and liquids, radiating and absorbing only in rather narrow spectral bands. It has frequently been suggested that various targets, particularly aircraft, be detected by the energy radiated by their exhaust gases. However, exhaust gases are largely water vapor and carbon dioxide, which are also common in the atmosphere. Consequently, the energy radiated at wavelengths characteristic of these gases is reabsorbed in a relatively short atmospheric path. This conclusion has been verified experimentally.

Where long-wavelength infrared is concerned, it is important to remember that almost all solid and liquid objects are radiating in a manner characteristic of their temperature. Consequently, any infrared receiver is affected by radiation from its immediate surroundings and from any other object included in its field of view, as well as from the particular source under consideration. Any heat source must be considered with relation to its background. This point is fundamental in designing infrared receivers.

C.2.4 Conclusion

Any solid body which is at a temperature higher than its surroundings (and this includes many otherwise indistinguishable military and naval targets) will emit heat radiation in the far infrared which can be detected by appropriate receivers at distances of several miles through clear or hazy air.

C.3 HEAT-DETECTION DEVICES

Reasons have already been advanced for the use of the far infrared between 8 and 13 μ (80,000 and 130,000 A, 0.0008 and 0.0013 cm) for detection of military targets. It has been shown that such varied targets as men, ships, buildings, and airfield landing ramps are continuously radiating energy which can be detected at distances up to several miles by the use of appropriate devices. The chief limitation in detection is the factor of background radiation, an object being detectable only if it stands out sufficiently against a more or less uniform heat background. This memorandum describes means for detecting such differential radiation.

C.3.1 Receivers

The utility of any device is obviously determined by the characteristics of the receiver. Any *far infrared* receiver is essentially a radiation thermometer, in which radiant energy must be absorbed by the sensitive element, producing a temperature change. Measures of merit which should be considered in comparing different receivers are: (1) sensitivity; (2) speed

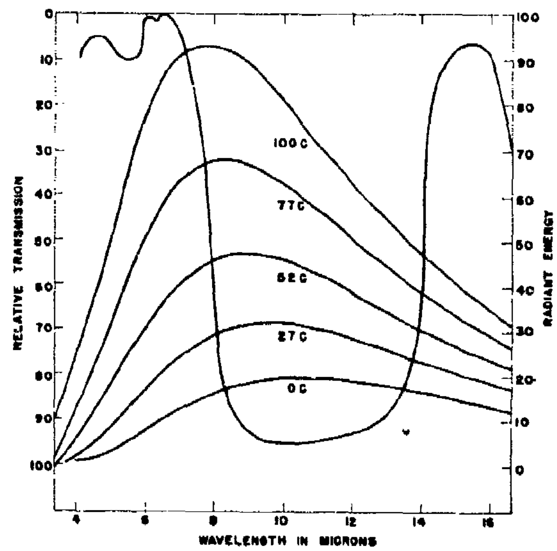


FIGURE 2. Black-body radiation and relative transmission through air containing H_2O and CO_2.

of response; (3) ruggedness; (4) adaptability to a suitable type of indicator; (5) size and shape of sensitive area; (6) freedom from vibration, from changes in ambient temperature and pressure, etc.; (7) size and weight, simplicity of essential auxiliary apparatus, etc.; (8) other special features.

Determination of relative merits of receivers, therefore, is truly valid only in terms of specific applications, but it is possible to make a few general comparisons.

The temperature change produced by the absorbed radiation may be measured conveniently by any of three well-known types of sensitive receiver.

Thermocouples. A thermocouple is a joined pair of conductors of dissimilar metals forming a closed circuit. Any difference in temperature between the two junctions will produce a measurable voltage difference, and hence, a current will flow through the circuit. Several tiny couples may be connected in series to increase the sensitivity, forming a thermopile.

Thermocouples may be made of fine wire or of thin films of metal on a nonconducting surface, such as cellophane. The speed of response is governed by the mass of material to be heated. In most cases with which we are concerned, this means that the thermal mass should be as small as possible. Thermocouples may be made of approximately the same sensitivity and ruggedness as any other device but tend to be slower in response. Suitable amplification for indication can be provided. Size and shape are less variable than is the case for bolometers and gas radiometers.[8]

Bolometers. A bolometer is a radiation receiver whose temperature change due to incident radiation is observed through some accompanying change in its electrical properties, such as resistance or dielectric constant.

Here again, the smaller the thermal mass, the more sensitive the device and the more rapid its response.[9] Bolometers have been made of thin films or strips of metal, of semiconductors with high temperature coefficients,[10] or of condensers whose dielectric constant changes with temperature.[11]

Bolometers of special construction have been made with extremely high sensitivity, high speed of response, adequate ruggedness, and freedom from unwanted disturbances. The signal from bolometers is particularly well adapted to electronic amplification.

Gas Radiometers. If radiation is admitted to a tight, gas-filled chamber in which the radiation is absorbed, the temperature, and consequently the pressure, will be raised. The pressure change may be observed optically or electrically.[12]

Such instruments may be rugged, extremely sensitive, and rapid in response, producing a signal capable of high amplification, but they are subject to greater difficulties from vibration than the other instruments.

Image-Producing Receivers. So far, the only method of producing an image or "infrared picture" has been by some scanning process, except for some instruments which are as yet in the early research stage.[13]

C.3.2 Applications of the Far Infrared

This section has been interested in the application of the far infrared to automatic control of homing missiles. Other workers have investigated possible uses in signaling and in various detection problems. Under proper conditions the latter idea shows promise.

Automatic Control. By the use of electronic amplification, the signals from infrared receivers can be used for relay operation and consequently can serve to aim or guide a vehicle toward any heat source or other thermal discontinuity in the background.

This section has concentrated its efforts in the heat field on the development of a high-angle, heat-homing bomb, designated "Felix."

This consists of a standard 1,000-lb GP demolition bomb with added false nose and tail. The nose carries the heat-detection unit with its associated amplifier, while the tail carries the means of guiding the flight. A small, parabolic mirror mounted with its axis 5 degrees off center is rotated rapidly, thereby scanning a field totaling 20 degrees in diameter. Any thermal discontinuity in the field produces an electrical pulse in the output of the nickel-strip bolometer. A commutator on the mirror drive shaft makes possible identification of the particular quadrant of the field in which the target is located. Suitable relays and servomotors operate the control surfaces of the bomb in accordance with the information received from the eye. As an antihunt device, the whole eye is linked with the rudder in such a manner that the projectile, in turning, is made to see ahead of where it is going at the moment. Only when it is pursuing a straight path does it look directly forward. A bolometer strip of blackened nickel, 0.2 μ to 3 μ thick, 0.25 mm wide, and 5 mm long, in low-pressure hydrogen, gives adequately fast response.

C.3.3 Background Radiation

It is obvious that any automatic control problem involves discrimination between the particular target and its surroundings or background. If variations in the background are of the same order of magnitude as the discontinuity presented by the target, such means of control cannot be used. It must be remembered that any single receiver has a field of view and that the field of view of such a single element determines the resolution of the whole device. Consequently, even if a particular target is very much hotter or colder than any other area in the background, if it is small with respect to the optical resolution of the receiving system, it may be impossible to distinguish it from the background. In other words, the change in radiant energy at the receiver as it sweeps across the target may still be less than changes produced by the background. Using a smaller angle of view lessens this particular difficulty but at the same time increases the difficulty of searching. A number of receivers are now capable of detecting the radiation from common military targets at distances up to several miles. When these detectors are inserted in heat-homing missiles, the necessarily widened field of view makes the target-to-background signal ratio or signal-to-noise ratio, rather than ultimate sensitivity, the limiting factor.

Studies on background radiation have been carried out extensively by Section 16.4 of NDRC and by the U. S. Navy Department. In general, natural vegetation tends to remain at the same temperature as the surrounding air, both day and night. Consequently, regions well covered with grass and trees present a fairly uniform background. By contrast, in urban areas surface temperatures vary widely: in the daytime, because of varying rates of absorption of solar energy; at night, because of varying rates of cooling and different internal heating.

The conclusion is that satisfactory heat targets are moderately rare on land. Large factory buildings or areas are acceptable when surrounded by natural vegetation, but usually not when in the midst of urban districts. The influence of camouflage on this picture might be interesting. Airport landing strips and parking ramps offer one particularly useful field for attack by heat-homing missiles. On the other hand, ships of 5,000 tons and up may be detected easily from altitudes of 10,000 ft against sea backgrounds.

C.3.4 Methods of Operating Infrared Receivers

This section will compare two rather different methods of operating long-wavelength infrared receivers for detection or control. It is obvious from the preceding section that any detection or control apparatus functions best on the differential between the target and its background, *not* on the absolute signal strength of the target. This may be accomplished in two ways:[18]

1. *Steady-state method.* Provide two receivers. One "sees" the target, the other its adjacent background, and the indicator operates on the *difference* in temperature between the two receivers.

2. *Pulse method.* Provide one receiver, which sees the target and its background alternately, and an indicator operating on the resulting *change* in temperature of the receiver.

Consider the use of radiation thermopiles for specific examples of each method. In the first, two receivers would be provided and the thermocouple junction connected so that the emf would be in one direction if one receiver was warmer than the other, and the reverse if colder. The two receivers would be mounted adjacent to each other in the focal plane of a mirror or lens so that an image of the target could be placed on one receiver and an image of the background on the other. Any resulting emf would then be amplified by some means and used to aim a detector or operate a control.

In the second method, a single receiver would be placed in the focal plane of the optical system and one set of thermopile junctions connected to this receiver, the other set to a large thermal mass at ambient temperature. In such a system, under most conditions, there would be a difference between receiver and ambient temperature, and a resulting emf, but the coupling to the amplifier should be made so that only changes in emf would cause signals. Some sort of scanning would be provided to produce a change in emf when the image of the target crossed the receiver.

Other types of radiation receivers may also be used in both ways, and thermopiles may perhaps be used more effectively in some variation of the above, but here we are comparing only the two methods. The first permits radiation from the target to remain on the receiver for a comparatively long period of time so that, in general, radiation equilibrium may be established with the target; this is known as the steady-state method. The second, involving scanning, places only a pulse of radiant energy on the receiver and has been named the pulse method.

The chief advantage of the steady-state method is that it permits the realization of higher sensitivity simply because the longer exposure times permit the receiver to absorb more energy. The chief advantage of the pulse method is that any false signals superimposed on the system may be excluded from the amplifier, provided they have a long period compared to the rate of scanning. The most sensitive steady-state receivers devised to date have a relaxation time of 0.5 to 10 seconds; i.e., that amount of exposure time is required to approach the steady-state condition. Many military detection and control problems, however, require that an exposure time of considerably less than 1 second produce usable signals. Also, sensitivity is greatest for an optical system which just covers the receiver with an image of the target; but again, speed of operation requires a considerably greater field of view. These two factors make it difficult for the steady-state method to be fully effective.

The pulse method, on the contrary, must be based on the use of a fast-response receiver. Where a relaxation time t of 1 second might be satisfactory for a steady-state receiver, from 0.1 to 0.001 second would be required for one working on the pulse method. Sensitivity is proportional to $\sqrt{t}$, other factors being properly matched. The steady-state method would, then, be three to thirty times more sensitive than the pulse method, because of this effect. However, the scanning procedure used in the pulse method permits a smaller instantaneous field of view, which gives a comparative gain in sensitivity if the total field of view swept out by the scanning equals the stationary field of the steady-state receiver. The ratio between the two instantaneous fields might also be three to thirty times, so that these two factors offset each other. It is concluded, then, that the maximum sensitivities which can be achieved by the two methods are not widely different for most military applications. There will, of course, be exceptions.

The greatest advantage of the pulse system has not yet been considered; namely, its elimination of slow "drift" effects. All slow changes in the receiving network of a steady-state system appear as signals. In the pulse system, however, only changes which occur at the scanning frequency come through as signals. The causes of false signals which may occur in the two systems will now be considered.

In steady-state systems two receivers and their circuits are compared, so that any difference along the network causes an apparent change in the matching. Such changes might be caused by thermal emf's at points other than at the thermocouple junctions, or resistance changes if we have a bridge circuit, or other effects of changing temperature and pressure, which will vary in each case with the particular type of receiver and circuit. Also, if the radiation receivers are not perfectly matched with respect to the thermal mass, their temperatures will change at different rates as the ambient temperature changes or as they may shift from a condition of radiation balance with a very cold field of view to radiation balance with a field considerably warmer.

To overcome these difficulties, the circuit must be very carefully designed and matched electrically, the entire circuit well insulated thermally and possibly held at constant temperature by a thermostat. Even so, all steady-state systems must be furnished with some balancing adjustment. This adjustment can be either manual or automatic; if automatic, it can be arranged to change the balance at such a rate as to overcome changes which occur at a sufficiently slow rate. The system then begins to approach the pulse method, but in a rather complex manner.

In the pulse method, slow changes have no effect unless they are so large as to affect the sensitivity by severely unbalancing a bridge circuit, overloading a transformer with direct current, blocking the amplifier, or some similar effect. There is, however, a difficulty to which the steady-state system is not subject at all: the circuit is commonly tuned to the scanning frequency, or at least responds to signals occurring at that frequency, and in that case some false signals are bound to be generated by the scanning itself. For example, microphonics resulting from mechanical unbalance might be synchronous with the scanning frequency. Various other kinds of noise due to the scanning may occur.

It is essential to consider all the facts mentioned above in designing an infrared detector or control apparatus. In general, for an application which permits fairly slow operation, such as searching for ships from a shore station, the steady-state method may be used if the apparatus can be kept in balance. For applications involving very rapid response, as is the case with most airborne equipment, the pulse method appears more promising.

C.3.5 Infrared Receiver Development

This report covers the receiver development which has taken place under Section 5.5 of NDRC toward two objectives. The first was to develop a receiver particularly adaptable to flight conditions, including flight in a target-seeking bomb. This requires extreme portability, rapid response, large angle of view, freedom from microphonics and from drift of "zero setting," and operation throughout rapid changes in ambient temperature and pressure. It was felt that these requirements could best be met by a simple metallic bolometer in a d-c bridge circuit with some sort of scanning to furnish a-c pulses for electronic amplification. Work has also been done with thin thermopiles produced by evaporation.

The second objective was to develop receivers with similar characteristics but with considerably higher sensitivity than anything previously available. A very promising possibility was found in the thermistor bolometer initiated by the Bell Telephone Laboratories and further developed under the supervision of Section 16.4 of NDRC.

Metallic Bolometers

The Hammond Platinum Bolometer. Starting in January 1941, Laurens Hammond, of Chicago, cooperated in the development of an infrared device for locating surface vessels from aircraft. As primary receiver, Hammond used a thin platinum-strip bolometer. When two platinum strips about $1\,\mu$ thick, connected in adjacent arms of an a-c bridge, were used, moderate sensitivity was obtained. Later in 1941, it was decided that the use of a d-c bridge circuit was much more satisfactory for an instrument requiring extreme portability. When the circular scanning system already mentioned was used, any thermal discontinuity in the field created an electrical pulse in the bridge circuit. By this means an a-c amplifier could be used with the d-c bridge circuit.

As this work progressed, it became apparent that both higher sensitivity and faster response would be essential.

Improved Metallic Bolometers. Under Contract OEMsr-60, Harvard University[10] has been able to improve greatly the design of metallic bolometers requiring rapid response. It was shown that a small thermal mass is essential to good sensitivity. Other considerations in the same study indicate that the shorter the relaxation time of the bolometer, the greater the sensitivity. Designed on the basis of the factors discussed above, bolometers have been made with relaxation times as short as 0.002 second. Substitution of the thin nickel strips for platinum, and mounting them in an atmosphere of hydrogen under a pressure of 5 mm has resulted in bolometers with sensitivity enough to detect a minimum signal of 10^{-8} watt per sq cm when used with the scanning system employed for Felix.

Much acrimonious dispute has raged over the relative utility of these different types of receiver. As has been pointed out, the absolute sensitivity is not the only criterion. If there were no other limitations, we could amplify the receiver voltage indefinitely, and hence, we could detect indefinitely small quantities of heat. However, it is well known that a certain random noise voltage will be developed across the grid of the first tube in the amplifier. If the voltage across the bolometer strip is much less than this, it will be swamped by this noise. Noise voltage may be due to (1) fluctuations arising in the amplifier, (2) thermal noise in the bolometer bridge—so-called "Johnson noise," (3) "current" or contact noise and (4) microphonics, if any. By proper design it is possible to minimize, but never to eliminate, this irregular voltage variation. In addition, of course, for homing devices the thermal noise due to response to the background is high. Subsequent amplification applies both to target-signal voltage and to noise voltage, so that the limiting factor in determining useful sensitivity is the ratio of signal voltage to noise voltage. For control purposes, this ratio must be of the order of three to one or larger, or erratic operation may ensue.

C.3.6 Infrared Optics

Scanning Systems. For automatic control of a missile, a circular scanning pattern seems necessary, rather than the simplest form of back-and-forth line scanning. Most of the work of this group has been carried out with a system which scans by rotating a parabolic mirror off axis. The alignment is such that the axis of rotation passes through the optical axis at the focal point of the parabola. This means that an image at the center of the receiver is always in sharp focus. Such a system can be arranged to scan a circular area and, by means of a commutator, to indicate in what sector of the field of view any particular heat source lies.

Transparent Materials. The classic material for far infrared optical parts has been rock salt. The only limitations in its use are the difficulty of obtaining it in large pieces, and its solubility in water. Waterproof coatings have been necessary to combat the latter. For Felix, however, it has been found that sheet silver chloride possesses many advantages. Experiments indicate that silver chloride sheets can be cut and pressed into the desired shapes for windows which are thin enough so that rapid changes in ambient temperature do not produce fogging, strong enough to resist wind velocity of the magnitude to be expected, and yet transparent enough to transmit at least 80 per cent of the incident energy in the 8.5- to 13-μ band.

C.3.7 Infrared Electronics

Almost all infrared devices considered by this section have involved electronic amplification. As has been pointed out, most of the work has been with resistance bolometers placed in some sort of bridge circuit. This leads immediately to two quite different means of amplification, both of which have been extensively developed. The first involves the use of an a-c bridge current and an amplifier tuned to the same frequency. The second uses a d-c bridge current with an amplifier less sharply tuned to amplify pulses of unbalance of the bridge.

A-C Bridge System. This system has been used almost entirely for the thermistor bolometer and is under development.

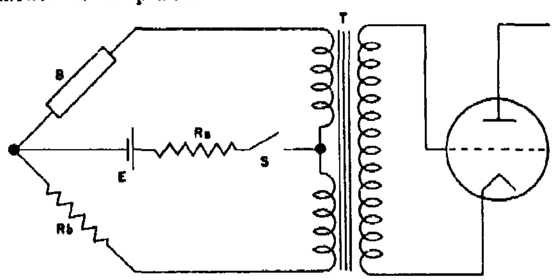


FIGURE 3. Input circuit.

D-C Bridge System. A major difficulty in the design of an amplifier for the d-c bolometer excitation system is the building of a low-frequency amplifier which will give a sufficiently good ratio of signal to noise and which at the same time does not produce too much phase shift with variations in scanning frequency. It may be impossible to obtain as high over-all sensitivity by this method as is possible with an a-c bridge system, but there are other advantages for a rugged field instrument. These advantages have been brought out. A large part of this work has been done in designing such an amplifier for use with the

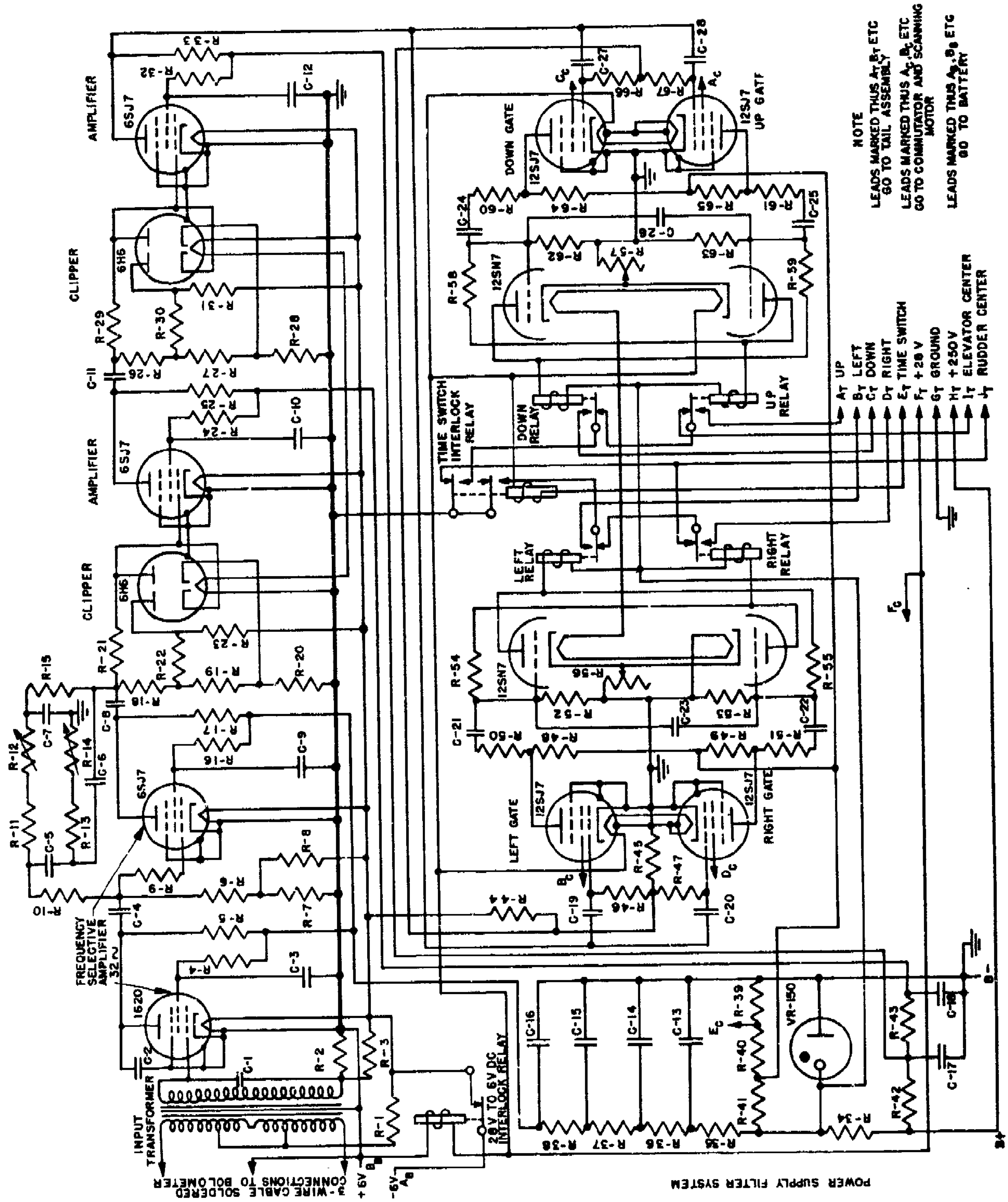


FIGURE 4. Wiring diagram of electronic unit.

low-resistance metallic bolometer. Because of its low resistance, the bolometer is coupled to the amplifier by means of an input transformer. The most efficient input circuit seems to be that shown in Figure 3, which is the result of a careful theoretical analysis of the network. The amplifier has been particularly designed for control relay operation so that it is quite different from one which might be evolved for a different purpose. (See Figure 4.)

C.4 CONCLUSIONS

In brief, then, Section 5.5 of NDRC has demonstrated that many military and naval targets are continuously radiating large quantities of energy within the wavelength band from 8.5 to 13 μ to which the lower atmosphere is transparent. These wavelengths, far beyond the visible, will pass through most ordinary military smoke screens, and, of course, are as easily received by night as by day. The use of easily produced metallic bolometers has demonstrated that receiving devices can be operated rapidly enough by this far infrared radiation to control homing missiles. With the aid of a scanning device utilizing a rotating mirror, heat targets can be distinguished from altitudes up to 10,000 ft.

The heat-homing missile, Felix, has been designed to operate in this range. Tests currently under way will show whether its reliability in the field will correspond to its laboratory indications.

GLOSSARY

AAF. Army Air Forces.

AFC. Automatic flight control.

AGC. Automatic gain control.

ALTITUDE SIGNAL. The radar signal returned to an airborne radar set by the ground or sea surface directly beneath the aircraft.

ANGLE OF ATTACK. The angle between a reference line fixed with respect to an airframe and the apparent flow line of the air through which it flies.

ARROW STABILITY. The partial derivatives of yawing and pitching moments with respect to angles of attack in yaw and pitch.

ASG. A specific airborne radar search set.

ASPECT RATIO. The ratio of span to mean chord of an airfoil; therefore, in wingless missiles such as Azon and Razon, the ratio of the bomb diameter to its mean length.

AXIS OF SCAN. In a scanning system, the axis about which information as to the target location is collected and with reference to which target displacement is measured.

AZON. A visually directed remotely controlled bomb radio controlled in AZimuth ONly. The AAF nomenclature for the 1,000-lb version is V B-1; for the 2,000-lb version, it is V B-2.

BACK COUPLING. A mechanical feedback link which displaces the scanning system through an angle which is a function of the rudder and/or elevator displacement.

BALLODROMIC. Heading to hit; leading (from *ballein*, to hurl, to hit; *dromos*, course).

BAT. A glide bomb of controlled flight steered by full-span trailing-edge wing flaps and a fixed empennage structure. Guidance is accomplished by a radar transmitter and receiver on the missile. The bomb is steered to fly toward the direction from which the distinctive reflection is received.

BEAM-RECEPTOR CHARACTER. The characteristic of an antenna array which gives it a maximum sensitivity in a single direction, with continuously decreasing sensitivity with angular departures from this direction.

BORE-SIGHTED. Aligned. The phrase is borrowed from gunnery usage where it means aligning the sight of a piece with its bore. In the present volume, it refers to the alignment of the axis of scan (*supra*) of the intelligence device of a missile with some appropriate reference axis such as the tangent to the flight path.

BORE-SIGHT ERROR. Error in alignment of the axis of scan of the intelligence device of a missile. *See* Bore-Sighted.

BRACHYDROMIC. Heading short; slanting to pass through the wake (from *brachys*, short; *dromos*, course).

CANARD TYPE OF HEAD CONTROLS. Aerodynamic control surfaces placed at the nose of the fuselage of an airframe as contrasted with the conventional aircraft empennage.

CARDAN-MOUNTED. Gimbal-mounted.

CASSEGRAIN MIRROR. A plane mirror mounted between the surface of a spherical (or parabolic) mirror and its focus. The purpose is to project the image formed by the out of the incident rays. Named after Cassegrain the astronomer, who invented it.

CHORD. The dimension of an airfoil perpendicular to its span. The name derives from the chordal character of such a dimension with respect to the curved surfaces of the airfoil.

CIRCLE OF CONFUSION. The smallest circle which can be resolved by an optical system.

CLAMP CIRCUIT. A bias-control circuit for the output stage of a video amplifier.

CLINODROMIC. Heading at a constant lead angle (from *klinein*, to lean or to incline; *dromos*, course).

CLINOSCOPIC. Looking aslant, specifically sighting to lead a target (from *klinein*, to lean, to incline; *skopos*, target, aim).

COMPLIANCE. The reciprocal of stiffness.

COMPRESSIBILITY BURBLE DRAG. The large and sudden increase in parasitic drag believed to be experienced by an airfoil as it passes through the velocity of sound.

CONTROL-PLANE. *adj.* The qualifying term which describes the transmitting antenna on an aircraft which radiates the control signal by which a guided bomb is steered.

CRAB. An attachment to the Norden bombsight which superposes on the field of view of its telescope an image of a falling bomb at its predicted point of impact.

CRAB ANGLE. The angle between the direction in which an aircraft is heading and its true course.

CROSS-PATH RANGE. The direct range from a pursuing aircraft to its quarry when the former is flying a true pursuit curve.

DARK TIME. The time interval or portion of a time cycle when a photosensitive device (e.g., a phototube) is dark.

DEAD BAND. The region near zero where an instrument sensitive to positive or negative values of a quantity gives no response.

DEAD REGION. Dead band.

DEPRESSION ANGLE. The angle measured downward from the horizontal to the axis of an airborne radar beam directed at a target. This is the complement of the incidence angle of the beam at the target plane.

DOVE EYE. The thermosensitive element used to control the heat-homing missile, Dove.

DRAG-WEIGHT RATIO. The ratio of drag of an airframe to its total weight.

EARS. Wind vanes mounted in the wind stream surrounding a missile and used to align a homing device (or television image) axis with the line of flight.

ELEVONS. Wing flaps combining the functions of ELEVators and ailerONS.

EMR. Electro Mechanical Research, Inc.

Felix. A heat-homing missile developed by the Massachusetts Institute of Technology.

Flow Spoiler Type. A type of airframe control in which the smooth flow around an airfoil is interrupted or "spoiled" or so disturbed as to destroy in part the lift.

Free Gyro. A gyroscope mounted in two (or more) gimbal rings so that its spin axis is free to maintain a fixed orientation in space.

Frequency Pulling. The tendency of a modulation stage to change the frequency of a direct-coupled master oscillator.

Gating. The act of making a radar receiver operative for short intervals periodically spaced so that in effect a "gate" is opened for wanted signals and closed to others.

Glide Bomb. A winged missile powered by gravity. The wing loading is so high that it is incapable of flight at the speeds of conventional bombardment aircraft. Such a missile must, therefore, be carried rather than be towed.

Glide-Path Angle. The angle, measured from the horizontal, of inclination of the tangent to the glide path.

Glide-Path Ratio. The ratio of lift to drag. This is the cotangent of the glide-path angle.

Glider (Bomb). A winged missile powered by gravity. The wing loading is sufficiently low so that it is capable of flight at the speeds of conventional bombardment aircraft. Such a missile may, therefore, be towed rather than be carried.

GP Bomb. General purpose bomb.

GSAP (Camera). Gun-sight aiming-point camera. An automatic motion picture camera put in operation by the pressure on machine-gun trigger. It was developed and used by the Services to record precision of aim in fixed-mount gunnery.

Head-End Tuner. In a radio receiver of the superheterodyne type, one or more tuned radio-frequency stages in advance of the first detector.

Helicodromic. Heading along bent skew spiral.

Hinge Moment. The moment tending to restore a control surface which has been displaced from a position of equilibrium

Homing Intelligence. A signal received in a missile from its target which can be made to cause the missile to fly toward or to "home on" the target.

Hunting. An oscillation about a mean or intended value as: a course, a desired frequency, a control-surface deflection, etc.

Interlacing. A technique in television scanning wherein, if the lines are sequentially numbered, all the odd-numbered lines are scanned first following which all the even-numbered lines are scanned.

Interrupter Controls. *See* "Flow Spoiler Type."

Intervalometer. An instrument associated with the bombsight which measures the time interval between the release of several bombs dropped in train.

Isobars. Curves of constant acceleration loading of a pursuing aircraft flying a true pursuit curve.

Jag. A device attached to the Norden bombsight which biases the synchronism adjustment of the sight to provide partial correction for systematic variation in time of fall of a Razon caused by application of control.

Ladder Filter. A chain of T or π filters.

Latitude. The range in brightness of a scene over which fidelity of response of a television pickup tube (or photographic emulsion) is maintained.

Lead Prediction. The act of directing a missile (or projectile) ahead of a moving target—leading in aim—to a predicted collision point.

Leakance. A reciprocal of resistance. Conductance.

Leveling Circuit. An r-c filter circuit used to level out fluctuations of a bias voltage.

Lubber Mark. A mark on the casing of a compass which gives the heading of an aircraft or vessel carrying the compass.

Mach Number. The ratio of the velocity of an aircraft to the velocity of sound at the location of the aircraft.

Mimo. The Miniature IMage Orthicon, a television pickup tube.

Mimo-Plane. The television receiving antenna located on the aircraft controlling Roc by means of television.

Mimo-Roc. The television transmitting antenna on the Roc missile.

MIT. Massachusetts Institute of Technology.

Mosaic Cathode. The photo cathode in the iconoscope characterized by being made up of discrete particles like a mosaic.

Multipaths. The several paths by which, due to reflections, a radiated signal, particularly a television signal, may reach the receiving antenna from the transmitter.

NACA. National Advisory Committee for Aeronautics.

NBS. National Bureau of Standards.

Nodding Motion. A method of inclining a homing receiver so that it can "look chordally at" the target across the trajectory during the early phases of the flight of a homing missile when the attitude of the missile is relatively horizontal.

Orchard Heater. An oil-fired heater used to ward off frost in citrus orchards.

Parabolic Thinking. Nodding motion.

Pelican. A radar-homing glide bomb equipped with a radar receiver and which automatically homes on radar reflections from an airborne radar set mounted in the aircraft which releases the missile. It is also characterized by full-span, trailing-edge wing flaps and a fixed empennage structure so that it flies with substantially constant angle of attack.

Phantasmagoria. A simulated guided-missile system by which one or more of the motions of the missile may be dynamically studied at a reduced scale in space and an expanded scale in time.

Phoronomy. Science of relative motion of moving bodies with respect to each other.

PHUGOID. A path of flight; specifically, the path of a glider having longitudinal stability and having its control surfaces fixed.

PICK-OFF. A means of having a sensitive instrument, as for example a gyroscope, actuate a control system or an element thereof.

PITCH. *v.* To rotate, usually through a small angle, about a horizontal axis called the pitch axis, which is perpendicular to the longitudinal axis of an aircraft or ship. *n.* The act of pitching. *adj.* Of, or pertaining to, a pitching motion.

PITCH GYRO. A gyroscope so mounted in an aircraft as to be sensitive to pitch.

PITCH-INPUT LINK. A link in a servomechanism or simulator whereby the motion of pitch is inserted into the system for control or study.

PRESENTATION TUBE. A cathode-ray tube for the presentation of a signal such as a radar signal or a television picture.

PROPORTIONAL CONTROL. Control in which the action to correct an error is made proportional to that error.

PROXIMITY PARAMETER. A parameter which expresses the distance between an aircraft, flying a pursuit course, and its quarry when the pursuer passes abeam of the quarry.

PULL-OUT. The act of changing from a power dive to level (or climbing) flight.

RADAR DISH. The dish-shaped reflector behind a radar antenna.

RADAR WIDTH. In a radar homing set, the range of error within which the response is proportional to the error in heading.

RANGE-TRACKING ELEMENT. An element in a radar set which measures range and its time derivative. By means of the latter, a range gate is actuated at the predicted instant of signal reception.

RAPID INCIDENCE ADJUSTMENT. A short-period highly damped oscillation of an aircraft about its pitch axis following a sudden change in altitude.

RASTER. A system of luminescent lines traced on the phosphor of a cathode-ray tube by motion of the cathode-ray beam. The changes of brightness in the lines produce a picture as a television picture or a radar map. This word is of German origin and is used in particular in television. In the present volume, its use is limited to a system of parallel lines for the production of a television picture.

RATE GYRO. A gyroscope with a single gimbal mounting such that angular rates of rotation about an axis perpendicular to the axis of the gimbal mounting produce measurable precessional forces.

RAZON. A high-angle radio-controlled bomb visually guided in Range and AZimuth ONly.

RCA. Radio Corporation of America.

REDUNDANCE. The property of an equation which permits a plurality of solutions; therefore, in a mechanical system describable by such an equation, the property which permits a plurality of modes of action.

RHB. Radar homing bomb; specifically, one in which the radar transmitter is not located in the missile, e.g., Pelican.

RINGING. Sustained oscillation which occurs in a high-gain amplifier inadequately stabilized.

ROC. A medium angle controlled missile characterized by (1) four symmetrical wings with full-span wing flaps and four fixed fins or, (2) a single cylindrical wing capable of being rocked about the yaw and pitch axes and a fixed cylindrical empennage.

ROLL. *v.* To rotate, usually through a small angle, about an axis substantially collinear with the longitudinal axis of an aircraft, or ship. *n.* The act of rolling. *adj.* Of, or pertaining to, rolling motion.

RUN-OUT TIME. The time of travel, from neutral to full extension, of the control surfaces of an airframe.

SAILPLANE. A glider capable of soaring.

SAP BOMB. Semi-armor-piercing bomb.

SATURATION ANGLE. Radar width.

SCOPODROMIC. Heading as looking; homing (from *skopos*, target, aim; *dromos*, course).

SERVO-LINK. A mechanical power amplifier by which signals at a low power level are made to operate control surfaces requiring relatively large power inputs; e.g., a relay and motor-driven actuator.

SERVOMECHANISM. The feedback loop of a servo system exclusive of the missile itself.

SERVO SYSTEM. A closed feedback loop comprising the intelligence device, automatic pilot if any, the amplifying link, and the missile itself.

SHADING. The appearance of dark areas in a received television picture which sometimes cover the entire screen.

SINK. A point or element in a system where energy is dissipated or otherwise removed from the system.

SLANT RANGE. The range to the target along a line of sight.

SPOILER. A surface which is projected into the wind stream surrounding an airfoil and "spoils" or interrupts the air flow reducing the lift.

SQUIB. An electrically ignited charge of explosive contained in a cylinder used to actuate a process remotely, e.g., to release a parachute.

SRB. Send-Receive Bomb, a radar homing bomb in which the transmitter as well as the receiver is carried in the missile, e.g., Bat.

SYNCHRO. A dynamo electric machine having a polyphone stator and a single-phase rotor.

TEARING. The destruction of a received television picture due to interference or malefaction characterized by the appearance of tearing.

TIME OFF. The time interval during which an intermittently energized control element is de-energized.

TIME ON. The time interval during which an intermittently energized control element is energized.

Tomodromic. Heading to cut; intersecting (from *tomos*, a cutting; *dromos*, course).

Track in Range. To adjust the gate in a radar set so that it opens at the correct instant to accept the signal from a target of changing range from the radar.

Trail Angle. The angle between a line joining the point of impact of a bomb and the releasing aircraft at the instant of impact, and the vertical, the aircraft having performed level unaccelerated flight from the point of release.

Transfer Function. The function relating the output of a closed-cycle servo system to its error.

Trembling. Shaking, vibrating, oscillating.

Tumble. The act performed by a 2-frame free gyroscope when both frames become co-planar. Under these circumstances, the gyro wheel rotates about a diameter as well as about its polar axis. Control is lost.

Umbilical Switch. A switch located in the cable connecting a missile with the aircraft during carriage. This switch is actuated upon release of the missile and the pulling out of the cable.

"Venetian Blind" Structure. A form of electron multiplier structure in the image orthicon pickup tube; so-called on account of its cross-sectional resemblance to a Venetian blind.

Water-Vapor Window. The region in the electromagnetic spectrum between 8.5- and 13-μ wavelength radiations where water vapor is transparent.

Weathercock Stability. The partial derivatives of yawing and pitching moments with respect to angles of attack in yaw and pitch.

Wing-Incidence Angle. The angle between the airstream incident at the leading edge of a wing and the direction which such an airstream would have were it to produce zero lifts.

Yaw. *v.* To rotate, usually through a small angle, about an axis perpendicular to the pitch and roll axes of an aircraft or ship. For an aircraft in normal level flight, the yaw axis is vertical; in a missile, however, it adopts an inclination as the missile noses over on its trajectory. With a high-angle bomb dropped from great height, for example, the yaw axis is nearly horizontal at impact. *n.* the act of yawing. *adj.* Of, or pertaining to, yawing motion.

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Contract Number	*Name and Address of Contractor*	*Subject*
Transfer of funds	National Bureau of Standards Washington, D. C.	Glide bomb
NDCrc-96	Hazeltine Electronics Corporation Washington, D. C.	Television
NDCrc-173	Radio Corporation of America New York, New York	Television, gliders, aerial torpedo
NDCrc-180	The Massachusetts Institute of Technology Cambridge, Massachusetts	Heat control
NDCrc-183	Gulf Research and Development Company Pittsburgh, Pennsylvania	Bombs
NDCrc-188	The Massachusetts Institute of Technology Cambridge, Massachusetts	Bombs
OEMsr-141	Radio Corporation of America New York, New York	Glide-bomb controls
OEMsr-171	Radio Corporation of America New York, New York	Television
OEMsr-187	Remington Rand, Inc. New York, New York	Television apparatus
OEMsr-240	The Massachusetts Institute of Technology Cambridge, Massachusetts	Engineering, bombs
OEMsr-278	Purdue University Lafayette, Indiana	Radio control for model airplanes
OEMsr-286	Hazeltine Electronics Corporation Washington, D. C.	Television
OEMsr-298	Radio Corporation of America New York, New York	Television equipment
OEMsr-327	Douglas Aircraft Company Santa Monica, California	Dive bomb
OEMsr-441	Radio Corporation of America New York, New York	Television
OEMsr-476	Vidal Corporation Camden, New Jersey	Gliders
OEMsr-513	Radio Corporation of America New York, New York	Television
OEMsr-514	Radio Corporation of America New York, New York	Television
OEMsr-515	Radio Corporation of America New York, New York	Television
OEMsr-615	Radio Corporation of America New York, New York	Television
OEMsr-620	Farnsworth Television and Radio Corporation Fort Wayne, Indiana	Television equipment
OEMsr-694	Hammond Research Corporation Gloucester, Massachusetts	Radio control link
OEMsr-727	Dalmo-Victor Company San Carlos, California	Electromechanical coupling devices
OEMsr-921	Electro-Mechanical Research, Inc. Houston, Texas	Scanning, stabilization, and bolometers
OEMsr-978	Eastman Kodak Company Rochester, New York	Data recording cameras

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1002	Bendix Aviation Corporation Detroit, Michigan	Amplifier, Roc
OEMsr-1013	The Massachusetts Institute of Technology Cambridge, Massachusetts	Stabilization, servomechanism
OEMsr-1068	General Mills, Inc. Minneapolis, Minnesota	Organic homing device
OEMsr-1081	Union Switch and Signal Company Pittsburgh, Pennsylvania	1,000-lb Azon
OEMsr-1093	Farnsworth Television and Radio Corporation Fort Wayne, Indiana	Television camera
OEMsr-1159	Philco Corporation Philadelphia, Pennsylvania	Television radio link
OEMsr-1172	General Electric Company Schenectady, New York	Television radio link
OEMsr-1180	Timm Aircraft Corporation Van Nuys, California	Production design, gliders
OEMsr-1182	Fairchild Camera and Instrument Company Jamaica, New York	Scanning system
OEMsr-1191	Columbia Broadcasting System New York, New York	Comparison of television cameras
OEMsr-1195	Harvey Radio Laboratories, Inc. Cambridge, Massachusetts	Radio link and Razon simulator
OEMsr-1258	Remington Rand, Inc. New York, New York	Heat homing bomb, Felix production
OEMsr-1274	Norton Company Worcester, Massachusetts	Heat homing bomb, Felix production
OEMsr-1285	Union Switch and Signal Company Pittsburgh, Pennsylvania	2,000-lb Azon
OEMsr-1287	Fairchild Camera and Instrument Corporation Jamaica, New York	Felix scanning head
OEMsr-1301	General Instrument Corporation Elizabeth, New Jersey	Special amplifier, Felix
OEMsr-1314	Philco Corporation Philadelphia, Pennsylvania	Razon receiver
OEMsr-1317	Polaroid Corporation Cambridge, Massachusetts	Scanning device
OEMsr-1348	General Electric Company Schenectady, New York	Thermal elements
OEMsr-1402	Remington Rand, Inc. New York, New York	Felix production design
OEMsr-1415	Union Switch and Signal Company Pittsburgh, Pennsylvania	1,000-lb Razon
OEMsr-1445	Bendix Aviation Corporation Detroit, Michigan	Roc amplifier
OEMsr-1451	Remington Rand, Inc. New York, New York	Felix production
OEMsr-1454	L. N. Schwien Engineering Company Los Angeles, California	Control and test instruments
OEMsr-1493	Specialties Manufacturing Company, Inc. Syosset, New York	Electronic simulator

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Numbers	*Subject*
	Army
AC-1	Improvement of precision in bombing, bombing through overcast.
AC-36	Controlled trajectory bombs.
AC-41	Radio control of model aircraft.
AC-42	Development of a radar system and equipment for controlling target-seeking bombs.
AC-51	Development of radar system and auxiliary equipment for controlling target-seeking bombs.
OD-98	Investigation and development of rocket target.*
SC-26	Control equipment for glide bombs.
SC-49	Moth.
	Navy
NA-109	Radio controlled aircraft.
NA-116	Two-inch dissector tube.
NA-162	Standardization of output requirements of electronic homing devices.
NA-183	Sonic control of guided missiles.*
NA-190	Mimo (miniature Image Orthicon) tube.
NA-228	Investigation of X and S band antenna patterns for guided missile applications.
NA-238	Development of a flight table.
NO-40	Controlled trajectory bombs.
NO-115	Radar homing bomb.
NO-169	Guided missiles—Project Bat.
NO-174	Bat.
NO-235	Development of a homing missile in the microwave radar region.
NO-257	Dove.
NS-132	Television cameras.
NS-136	Counter-measures against guided missiles.
NS-281	Use of the Image Orthicon against camouflage and through haze.

*These projects were never implemented by the Division.

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