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LARK-WASP GUIDED MISSILE SEMINAR

JULY 1947

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NRL REPORT NO. R-318

LARK-WASP GUIDED MISSILE SEMINAR

JULY 1947

Arthur S. Locke

Approved by:

Dr. R. M. Page, Superintendent, Radio Division III

Problem Nos. 36R05-16,
36R05-05 and 36R05-29

October 22, 1947

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CONTENTS

ABSTRACT

An interim report is made of the progress of developing the Wasp beam riding system of guidance for the Lark missile. An interim report is made of the progress of the initial study phase of the Skylark program. The progress of the Hornet system of command guidance is reported.

An outline of a talk entitled "Comparative Summary of Certain Guided Missile Trajectories", two papers entitled "A Proposed Terminal Guidance System for Skylark" and "Control Line Noise Dispersion Investigations" are included as appendices to this report.

INTRODUCTION

PURPOSE OF PROBLEM A-156R-C, LARK MISSILE CONTROL

The primary purpose of Problem A-156R-C, assigned by BuAer, is: "to modify the SP shipborne radar and, with a radar beam control receiver, afford radar beam control of the Lark missile".

The Lark is a subsonic missile operating at approximately 0.85 Mach number. Two versions are under development: KAQ-1 Lark, designed and manufactured by the Fairchild Pilotless Plane Division; and KAY-1 Lark, designed and manufactured by Consolidated Vultee Aircraft Company.

The specifications for the beam rider system provide that the operating range of the system shall be at least 90,000 yards; that the control shall be operable to at least 40,000 feet altitude. The target shall be considered to be comparable to a medium bomber. The SP shipborne radar shall be modified to incorporate automatic tracking of the target and shall transmit control intelligence to the receiver in the Lark by pulse time modulation.

The receiver shall be dimensioned as required to be located in the Lark; it shall accept and interpret the information received from the radar beam so as to furnish proportional control to the missile to maintain it on the line of sight between the radar and the target.

Fifty beam riding receivers with correlated antennae and beacons will be manufactured, under Laboratory jurisdiction, for use in Lark flight research. The Naval Research Laboratory will participate in the flight research program as consultants on beam riding guidance research.

PURPOSE OF PROBLEM O(A)-126R-C, PROJECT WASP

The primary purpose of Problem O(A)-126R-C, assigned by BuOrd, is: "to develop and test a system for control of a guided missile by means of a radar beam modulated at different frequencies in different lobes".

NRL PLANS FOR DEVELOPING BEAM RIDING GUIDANCE SYSTEMS

The problem of providing beam riding control for the Lark and developing the Wasp system of guidance are precisely similar in basic principle. The NRL plan for developing a beam riding guidance system has been based upon utilization of the implementation specified for control of the Lark missile.

An SP shipborne radar, using S-band carrier frequency scanned at 24 c.p.s., has been modified to provide pulse time modulated signals to furnish the reference for the airborne receiver. The construction of the new servo systems in the SP radar mount, designed both for automatic tracking and better performance, has been completed. Provision has been made for target

acquisition by use of an optical handstand mount. The SP radar has been installed at the Chesapeake Bay Annex of the Naval Research Laboratory and will be in operation by 1 August 1947.

The SP shipborne radar, because of weight and other physical restrictions, can not be considered adaptable for field test use. A truck mounted mobile radar, the SP-1M, differing from the SP only in that the dish is six feet in diameter as compared to eight feet and that no stabilization or cross level axis is provided, is undergoing modification for field test use. The modification of the SP-1M, to improve the mount structure and to achieve servo performance comparable to the redesigned SP, is underway.

Several designs of the receiver, designated officially as AN/APW-4, have been investigated, tested and discarded. Two receivers are now being flight tested; both are superhetrodynes, differing in demodulator and other circuit details. The research work with one receiver is being concentrated on fundamental propagation problems and long term receiver research directed toward simplification of receiver details. The flight tests with the second receiver are directed toward the immediate accomplishment of a beam rider receiver for the Lark missile.

Preliminary flights have been conducted with a human pilot guiding the plane from cross pointer meters which indicate departure of the plane from the line of sight of the radar beam. Outputs from the receiver to the cross pointer meter have been modified by equalizing circuits in such manner that the cross pointer meter presents to the pilot a combination of the error between the line of sight of the radar and the plane and the first derivative of the error. This device results in the exponential reduction of error without oscillatory flight. These flights were successful.

Flight research to determine noise and dispersion are underway. In these flights, the pilot flies on the beam by use of the cross pointer meters. The outputs of the receiver are fed to an analogue computer simulating the known transmission characteristics of the autopilot and the airframe. Frequency response tests of the autopilot and the airframe have been made and reported at previous seminars. The outputs from the analogue computer are recorded; this recorded data represents angular error from the radar line of sight. The angular error recorded represents pilot error plus system noise. Pilot error is known, inasmuch as the position of the plane with respect to the radar line of sight is recorded photographically. The next phase of the noise flight research will be to incorporate range circuits in the receiver in such manner that the recorded noise is a measure of lateral rather than angular error.

The plane used for the noise and dispersion research is an SNB in which a modified P-1 autopilot has been installed. Subsequent to the noise flight tests, the receiver outputs will be fed to the autopilot and used to guide the plane automatically along the line of sight of the radar beam. Flight tests to date have been accomplished using an SP-1M radar modified for correct RF transmission only as an interim measure until the SP radar is operative. Lack of automatic tracking and satisfactory tracking servos have been a handicap in the research. Considerable difficulty has been

experienced in engaging the receiver with the correct crossover, as predicted in previous seminars.

Throughout the entire development of the beam riding control, it is planned to examine fully all parameters of each phase of the problem, building step-by-step upon known quantities and determined facts. This procedure has entailed studies beyond the original scope of the problem and has clearly illustrated the need for intense coordination of the efforts of the Laboratory with the contractors for the control equipment and the airframe of the Lark, and with the representatives of the cognizant Naval Bureaus.

A beam rider simulator, operating on a 1:1 time scale is being constructed. This is an analogue computer and will be used to examine the dynamic behavior of the airframe and control components in simulated flight, as a closed loop. The simulator may also be used as a tester for some control components. The simulator is designed for use for study of any Wasp type beam rider; it is not limited to the specific problem of control of the Lark.

Many of the problems encountered in the development of the beam ridin guidance system are of scope beyond the strict bounds of the assigned proble but so closely related to the successful conclusion of the project that independent investigations are necessary. In order to disseminate the infor mation obtained as a result of these studies, the major portion of the Lark-Wasp meetings are devoted to the presentation of technical papers or talks on the studies. The studies include: the attenuation and modulation of signals caused by the propelling flame; the effects of ground reflection on the control line; the magnitude and effects of noise; problems of launching and capture by the guiding radar beam; optimum crossover for a beam rider guidance system; servo considerations for a beam riding airplane and the missiles; tactical problems vs transmission bandwidth and many others. Work on these investigations is continuing; additional studies will be started and similarly reported as the need arises.

The beam riding guidance system is but a part of the Lark control system and its characteristics are dependent upon dynamic behavior of the control elements and the airframe. In order to maintain the close coordination necessary between the Laboratory, the contractors supplying the airframes and control components and the cognizant Naval Bureaus, these agencie have given technical papers or talks upon their problems at the Lark-Wasp Seminars. This has resulted in a clearer appreciation of the magnitude and parameters of the interrelated problems to the mutual satisfaction of the contributing groups.

PURPOSE OF PROBLEM NRL-EL7-A, THE SKYLARK PROGRAM

The purpose of Problem NRL-EL7-A, assigned by BuAer, is to develop "a preset and command mid-course guidance and passive terminal guidance for the KAQ-1 and KAQ-2 Lark Pilotless Aircraft". The Naval Research Laboratory has been requested to serve as consultant for the duration of this program.

There are no definite specifications as to the precise type of mid-course command and passive terminal guidance system. The system is to be capable of guiding the KAQ-1 and KAQ-2 Lark Pilotless Aircraft, within the maneuverability limitations of that aircraft, from launching through mid-course and terminal phases to effect a collision with an aircraft target having the following characteristics:

Radar cross section area:	Equivalent to SNB. (3 sq. meters assumed for computation)
Speed:	300 m.p.h.
Maneuverability:	3g
Maximum Altitude:	25,000 feet

NRL PLANS FOR DEVELOPING SKYLARK

By conference with BuAer and Fairchild, and in view of the short time allotted for this development, a division of the work between NRL and Fairchild, for the initial phase of the contract, was decided upon. The terminal guidance system, at the request of BuAer, was given initial priority.

Laboratory personnel will concentrate their studies upon the application of simultaneous lobe comparison systems for terminal guidance; Fairchild personnel will concentrate upon sequential lobing type terminal guidance systems. In order to evenly weight the comparison between homing systems a standard of merit was decided upon to permit a choice of system.

Upon completion of the initial study phase, scheduled for September, a decision will be reached upon the type of passive terminal guidance system to be utilized for Skylark. Laboratory breadboard models will then be initiated by both NRL and Fairchild. Detailed planning has been delayed until this decision has been made.

The Naval Research Laboratory has reoriented the work on the Hornet system of command guidance for possible application to the Skylark program. The Hornet system, as presently envisioned and previously described in past seminars, is designed to guide the missile automatically along the radar line of sight. The ground radar automatically tracks the target; the missile, using a beacon, is simultaneously gated. When the missile departs from the line of sight of the radar, the error, observed at the ground radar, automatically codes the radar pulses with intelligence to command the missile to correct the error.

A premodulator, designed to be utilized with the SP radar, located at the Chesapeake Bay Annex of the Naval Research Laboratory, is being constructed. Preliminary flight research has been started to examine many parameters of the system under controlled conditions (i.e., propagation phenomena, fading, noise effects, etc.). The Hornet receiver will then be installed in an SNB aircraft, with the receiver outputs indicating the deviation from line of sight path on a cross-pointer meter. The pilot, by use of the cross-pointer meter, will attempt to fly by command from the ground

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radar. Subsequent to these tests, the receiver will be installed in the SNB containing the modified autopilot and the plane will be flown automatically by the command link. It is planned to follow, where true comparisons exist, the test procedure outlined for the Wasp system to obtai the greatest advantage from past experience and existing implementation. Progress on the development of the Hornet system as a potential mid-course command guidance system for the Skylark will be reported in each seminar report.

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SEMINAR MEETING OF 10 JULY 1947

PLACE OF MEETING

Naval Research Laboratory, Building 27, Room 101.

ATTENDANCE

Laboratory Personnel of Radio Division III:

Dr. R. M. Page	Dr. D. C. Harkin	F. M. Gager
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A. M. King	C. M. Morrow	J. W. Titus
J. H. Campagna	W. L. Krewson	C. E. Corrum
J. E. Meade	M. S. McVay	C. R. Ahern
G. P. Walker	C. W. Stoops	R. E. Gaylord
R. R. Riley	L. F. Gilchrist	W. C. Hodgson
G. C. Collins	C. E. Francis	A. S. Locke

Visitors:

Comdr. A.C. Packard	BuAer	R. H. Jones	BuShips
Lt. Comdr. F.M. Ralston	BuAer	R. O. Mather	AAF
A. Weinstein	BuAer	Lt. Col. R.H. Pryor	APL-JHU
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L. L. Wheeler	Sperry	D. B. Houghton	Franklin Inst.
A. P. Gertz	Sperry		

REPORTS OF PROGRESS ON LARK

SP Radar System Integration: Mr. Gilchrist reported that the General Electric Company, which has furnished a quotation for redesigning the nutators of the SP and SP-1M radars, is closed for vacation for two weeks. Therefore, no action has been taken on awarding a contract to increase the squint angle of the nutators.

The final model of the AGC system for the SP and SP-1M radars is nearing completion. Tests will be conducted with this equipment in an operating radar as soon as possible.

Change of Test Locale to CBA: Mr. Gilchrist reported that the SP-1M has been operating for flight tests, but that considerable difficulty had been experienced with the nutator bearings. Failure of this component has caused the loss of several days of flight testing.

The installation of the SP radar at the Chesapeake Bay Annex is essentially complete, with the exception of the wave guide run. The wave guide is being fabricated in the NRL shop. It is estimated that the installation will be on the air and ready for debugging not later than 1 August 1947.

Simulator Details: Mr. Titus advised that the remaining mechanical components of the simulator are scheduled for delivery on 14 July 1947. The simulator will be operating with constant missile velocity as soon as the interconnecting wiring is completed. It is estimated that two to four weeks will be required for this work.

The design of an auxiliary unit to compute missile velocity as a function of thrust, altitude, angle of climb, time and drag is again underwa Work on this component was suspended in May in order to devote more effort to a study of the frequency response of the KAQ-1 airframe. It is estimated that this unit will be added to the simulator in October 1947.

Beacons for Lark: Mr. Ahern reported that measurements have been made on the receiver in the casting resin which was shown at the June 12th conference. Although complete measurements were not made due to failure of three of the tubes, it would appear that the overall sensitivity did not suffer as a result of placing the receiver in the casting resin. It was possible, however, to measure the characteristics of the video amplifier. The gain measured approximately the same and the frequency response was shif slightly downward.

Two more receivers have been constructed but can not be cast in the resin until the ingredients to make the resin are received. With the assistance of the Plastics Section, two polyvinylchloride molds have been made for use in casting the receivers.

Investigation has been started on the receiver filter cavity. Bernard Rice's Sons of New York are tooled to manufacture such a filter cavity and we are now awaiting their proposal.

Investigation of the problem of interference of the control receiver on the beacon receiver is underway. It is expected that the local oscillator power from the control receiver feeding into the beacon receiver will reduce the effective sensitivity of the beacon receiver. The investigation will attempt to determine the amount of c.w. power necessary to block the beacon receiver. This difficulty may be corrected at two points, by the filter cavity used with the beacon receiver and by the mixer design for the control receiver. The mixer used in the laboratory model of the control receiver is a modified version of the Sharpless mixer and it has been indicated that the mixer will be redesigned. The most desirable design from the standpoint of the interference or the beacon receiver would include a directional coupler method of injecting the local oscillator energy to the control receiver crystal.

The transmitter development is still being hampered by the lack of a mechanically suitable transmitter cavity and by the lack of suitable output pulse transformers. Bernard Rice's Sons are tooled to manufacture the type of cavity required and it is expected that their proposal will provide a suitable mechanical design. These cavities are for the 2C40 tube. The RCA type A-2302 tube is also under investigation; samples of this tube have been obtained from the Signal Corps with the assistance of Major Hahn. Since no suitable cavity design exists for this tube, it is expected that the tube can not be used in the first of the beacons but may be used in later ones and test cavities are being built in the shop. Power output from the laboratory models of the 2C40 transmitter are producing pulsed power outputs of 80 to 150 watts. It is expected that the A-2302 tube will give a 300 to 500 watt output.

Information has been obtained from the Signal Corps on the pulse transformer used in the APN-55 and samples of this transformer are being constructed by the NRL transformer shop.

Since the last conference, Mr. Flowers and Mr. Ahern visited the following organizations to discuss missile beacon problems and missile antenna problems: Signal Corps Electronics Laboratory, Belmar, N.J.; Watson Laboratory, Eatontown, N.J.; Electronics Associates, Long Branch, N.J.; Boston Field Station of NRL; Cambridge Field Station of Watson Laboratory; Research Laboratory of Electronics at M.I.T.; Submarine Signal Company in Boston; and Mr. Andrew Alford, Consulting Engineer in Sommerville, Mass.

A request for flight facilities has been made and it is expected that within the next two weeks, beacon tracking tests will be underway. An APN-29 Beacon will be installed in an F8F and the beacon will be tracked with an SCR-584 which has been modified for long range operation. It is hoped that a laboratory model of the Lark beacon can be flown before the series of flights is completed. The choice of the APN-29 for preliminary flights is governed by the fact that the transmitter power output and the receiver sensitivity are the same as the Lark beacon will have and these tests will also permit comparison of the different types of beacon antennas for SCR-584 tracking.

Wasp Receiver Tests: Mr. Mackey reported that a new receiver mount in two ATR half racks was being flight tested in a long range program for analysis of propagation effects. Mr. Waterman in the discussion of noise and dispersion, included as Appendix 1 to this report, presents additional flight test information.

Wasp Receiver Production Design: Mr. Locke advised that several potential manufacturers of the Lark receiver had been contacted; had revie the wiring diagrams and preliminary specifications; and had expressed will ness to bid on the work. Upon receipt of satisfactory test data from aut matic beam riding flights the final design and specifications will be released for bids.

Investigations of the Flight Control Assembly: Mr. Locke reported that an investigation was going forward on evolving the most effective mea of modifying the production design of the FCA to accept the outputs of the beam riding receiver. A new flight control assembly has been received. quency response tests on this equipment, which have been delayed pending receipt of the new assembly, will begin immediately.

Propagation Research Through Propellant Flame: Mr. Gager reported that the recent field trip to Reaction Motors, Dover, N.J., took place 23 through 30 June 1947. Extensive data were taken in the following measure programs:

(1) S-band propagation studies through Lark flames, with single motor and two motor operation, including vertical and horizontal polarization and frequency (2700-3000 mc) as variables. Only in one instance was this work a repeat of field measurements made in March 1947.

(2) S-band transverse flame propagation studies, with single motor and two motor operation, including vertical and horizontal polarization as variables.

(3) S-band incidental flame modulation measurements on Lark motors along line-of-sight, refraction and reflection paths. This work was a repeat of work done in March 1947, but with a different mixture ratio for the Lark motors.

(4) Antenna VSWR measurements, S-band, as a function of spacing between antenna and the 400 lbs acid-aniline Lark motor.

(5) Exploratory X-band and K-band transverse and down-flame propagation measurements, both vertical and horizontal polarization, on a 1500 lb. oxygen-alcohol motor.

(6) Exploratory X-band transverse and down-flame propagation measurements, both vertical and horizontal polarization, on the 400 lb. Lark acid-aniline motor.

(7) Photo analysis of acid-aniline (Lark) flame and oxygen-alcohol (one-eighth part of XS-1 power plant) flame for the determination of relative temperature distribution and general non-uniformity.

(8) Flame investigation, in the frequency range 2700-3100 mc, of the acid-aniline (400 lb. Lark motor) as an inherent electro-magnetic noise source.

(9) Magnetic field measurements on a 1500 lb. oxygen-alcohol flame.

(10) Temperature measurements of both oxygen-alcohol and acid-aniline motors by personnel from the Optics Division, NRL.

Much of the data is now in the process of analysis and it is not possible to quantify many of the findings at this reporting data. However, it can be said that the additional S-band propagation data supports the findings of our previous field trip. The formal propagation report, now in preparation, is overdue largely because of the necessary preparations for the subject field trip.

Lark Airframe Response: Mr. Titus reported that a study of the effect of varying flight and aerodynamic parameters upon the frequency response of an airframe is continuing.

KAQ-1 Flight Tests: Mr. Perrine reported on the KAQ-1 Lark flight tests made during the past month.

Flight No. 27, KAQ-1 No. 14, was made at Inyokern, California on 20 June 1947, to test the operation of the reworked angle of attack system. Oscillations in pitch had been predicted to be approximately plus or minus three degrees. The duration of the unpowered flight was nine seconds and appears to have been successful. This was the first successful flight using the angle of attack control system.

Flight No. 28, KAQ-1 No. 33, was made at Inyokern, California on 27 June 1947, to test the radio control. The missile responded to climb, dive, climb, level off, dive, climb, dive successive command signals. The duration of the powered flight was 73 seconds at which time it was demolished by radio command. This was the first wholly successful radio controlled flight.

Two dummy KAQ-1's were successfully launched from the zero length launcher at NAMTC, Pt. Mugu, California on 17 and 18 June 1947. A launching angle of thirty degrees was used in both tests.

KAY-1 Flight Tests: Lt. Comdr. F. M. Ralston reported on the KAY-1 Lark flight tests made during the past month.

Flight No.18, KAY-1 No. 25, was launched from the ramp at Inyoke on 13 June 1947. The purpose of this flight was to test the roll contr system at high subsonic reach numbers. Launching and separation were normal with power plant operation satisfactory. The aircraft roll stab zed for approximately fifteen seconds, then began a clockwise roll and cont ed rolling until impact. The failure was believed to be caused by a mecha al defect in the roll control system. The duration of the flight was 22.7 seconds.

Flight No. 19, KAY-1 No. 21, was launched from the ramp at Inyoke on 27 June 1947. The configuration for the flight included the roll co ol system, the power plant, with the FCA programmed by radio link to contr the horizontal wing between plus five degrees and minus two degrees. T empennage was fixed at one-half degree. The motor operation launching separation were satisfactory. The aircraft rolled slowly upon separati and did not stabilize. The duration of the flight was 8.7 seconds.

REPORTS OF PROGRESS ON SKYLARK

Fairchild Skylark Studies: Mr. Perrine reported that the major portion of the time to date had been spent in establishing an organization to accomplish the work of the Skylark program. Kinematic studies of the missile are now available. The Fairchild organization is devoting its prime attention to the study of sequentially scanned homing systems. A schedule for both the study and development phases of the work has been prepared.

NRL Skylark Studies: Mr. McVay reported that preliminary studies indicate some advantages to the use of simultaneous lobe comparison homing systems in the final stages when a maneuvering target is being attacked. In such a case, error information is desired at a rapid rate, and a continuous supply of information has considerable advantage.

NRL studies are being concentrated on simultaneous lobe comparison homing systems. The TAB and Meteor systems, of NRL and MIT respectively, will be compared as prime examples of simultaneous lobing.

Considerable weight is being attached to the availability of systems equipment and to the possibility of obtaining a useable system in the short time available. The adaptability of each system to supply the data required for maintaining a constant true bearing course will be considered.

Hornet Guidance System: Mr. McVay reported that five flights have been made; considerable time has been lost because of bad flying conditions and mechanical and electrical difficulties in the plane used for flight testing. The flights have included tests on the receiver only; the receiver is operating satisfactorily. Preparations are now being made to fly the complete system.

DISCUSSION

Dr. D. C. Harkin, Mathematical Consultant, introduced and prefaced a joint talk given by Messrs. C. L. Key, C. H. Dodge, and C. E. Corum of the Mathematical Consultants Group, Radio Division III. Mr. Corum gave a talk entitled, "Comparative Summary of Certain Guided Missile Trajectories". An outline of this talk forms Appendix 1 of this report. Messrs. Key and Dodge presented a paper entitled, "A Proposed Terminal Guidance System for Skylark", which forms Appendix 2 of this report. Mr. Waterman, Head of the Equipment Research Section, presented a talk entitled, "Control Line Noise Dispersion Investigations". A copy of this talk is attached as Appendix 3 of this report.

SEMINAR MEETINGS

Guided Missile Seminars discussing the Lark, Wasp, and Skylark problems are scheduled for the second Thursday of each month at 1:30 P.M. in Room 101, Building 27, Naval Research Laboratory

C. E. Corum
Lark Seminar
10 July 1947

APPENDIX 1

COMPARATIVE SUMMARY OF CERTAIN GUIDED MISSILE TRAJECTORIES

A. Introduction

1. These remarks consist in the main of facts abstracted from various full-length reports dealing with the different types of guided missile trajectories. We have simply attempted to collect the basic facts about ideal behavior of missiles of different types.

2. Methods of control for long-range missiles are not under consideration; e.g., minimum fuel courses and celestial navigation.

3. The courses considered herein are:

a. Pursuit courses, pure and deviated
b. Line of sight (beam rider) courses
c. Proportional navigation

4. Messrs. Key and Dodge will subsequently discuss constant true bearing.

B. Pursuit Courses

1. Pure pursuit courses

a. Definition: The missile heading is always in the direction of the instantaneous target position.

b. The explicit solution of the differential equation has been given only for two cases,

1. Straight line constant speed target path
2. Circular constant speed target path

c. The differential equation for the pursuit course in the case of a target following a straight-line path at constant speed is

$$-x\frac{d^2y}{dx^2} = n\sqrt{1+\left(\frac{dy}{dx}\right)^2} \quad \text{where} \quad n = \frac{V_T}{V_M}$$

Here x and y are rectangular coordinates,

V_T = target speed,

V_M = missile speed.

The solution is

$$2(y - y_0) = \begin{cases} \dfrac{C^{-1}x^{-n+1}}{-n+1} - \dfrac{C\,x^{n+1}}{n+1} & \text{for } n \neq 1 \\ C^{-1}\ln x - \tfrac{1}{2}C\,x^2 & \text{for } n = 1 \end{cases}$$

Here C is a constant of integration,

y_o = initial value of y.

For the turning rate, we have

$$\lim_{t \to t_h} \frac{d\phi}{dt} = \begin{cases} 0 & \text{for } p < 2 \\ -4 \dfrac{V_T \tan^2 \frac{\phi_o}{2}}{r_o \sin \phi_o} & \text{for } p = 2 \\ -\infty & \text{for } p > 2 \end{cases} \qquad \left(p = \frac{V_M}{V_T}\right)$$

Here t_h = time of hit

$\frac{d\phi}{dt}$ = turning rate

ϕ = angle between tangent to curve and x-axis

r_o = initial distance from missile to target

d. Reference: Gino Loria: Spezielle algebraische und transzendente ebene Kurven (1902), pp. 607-614.

e. The turning rate approaches infinity for V_M/V_T greater than 2 as the missile nears the target (the most disadvantageous time for high turning rate). High rates of turn occur along the trajectory for smaller V_M/V_T. (See Newell, Guided Missile Kinematics, NRL Report R-2538).

2. Deviated pursuit courses

a. Definition: The missile points ahead of the instantaneous target position by a fixed angle.

b. If the fixed angle is properly chosen, then, for constant velocity target and constant speed missile, the missile trajectory is a straight line.

c. Error in selecting fixed angle or deviation of target from straight line or of target or missile from constant speed results in non-rectilinear trajectories involving high rates of turn.

d. Reference: Mathematical Analysis of Ordinary and Deviated Pursuit Curves, Project RM-6, prepared for BuAer by Tufts College Mathematics Research Project.

C. Line of Sight or Beam Rider Course

1. Definition: Missile is always on the straight line from the launching point to the target.

2. Many workers (e.g., Newell) have derived the differential equation of the beam rider for constant speed missile and constant velocity target. This equation is

$$\left(\frac{dr}{d\theta}\right)^2 + r^2 = k^2 \csc^4\theta \text{ , where } k = \frac{V_M}{V_T} \cdot R$$

Here r and θ are conventional polar coordinates; R = minimum pass distan from origin to target.

3. Dr. D. C. Harkin has developed a series solution for this differen equation. (See the forthcoming article Harmonic Analysis of Beam Rider Tur Rates, by C. L. Key, Jr., and C. E. Corum).

4. The analytical expression for the turning rate is

$$\frac{d\phi}{dt} = 2\frac{V_T}{R}\sin^2\theta\left[1 + \frac{r\cot\theta}{\sqrt{k^2\csc^4\theta - r^2}}\right],$$

which becomes infinite only if the denominator equals zero. This ultimatel implies that $\sin\theta = V_M/V_T$; this can not hold for $\frac{V_M}{V_T} > 1$.

5. The range of control is limited by noise.

D. Proportional navigation (or partial navigation)

1. Definition: The angle of inclination of the tangent to the missile path varies at a rate which is a constant multiple of the rate of change of bearing from missile to target; i.e., $\frac{dA}{dt} = \lambda\frac{d\phi}{dt}$.

2. The acceleration depends on V_M/V_T and λ, the navigation constant. The maximum acceleration does not necessarily occur at the end of the cours Computations of accelerations for several different cases may be found in ADR Report T-17 - Proportional Navigation, Its Use in Pilotless Aircraft, b Lancaster and Shornick.

3. Infinite acceleration is called for if a critical initial angle between the target path and the line from launching point to target at the ti of launching is exceeded.

4. For λ greater than or equal to 4, the acceleration is always finit for V_M/V_T greater than or equal to 1.

5. For more detailed information, see the ADR Report cited above, sinc courses are radically different for different values of λ and V_M/V_T.

6. For constant speed missile and constant velocity target, a straight line missile trajectory ensues if the missile is initially launched in the direction of the predicted impact point. This is the same as the constant true bearing course (discussed later by Key and Dodge) and deviated pursuit course for the same conditions.

7. Most analyses of proportional navigation courses have been made for constant velocity target with missile initially launched in the direction of the present position of the target. This means a high initial rate of turn. A possible remedy is to direct the missile initially toward the interception point ("future position" in fire control parlance).

8. High values of λ could cause instability. However, in the practical case this would undoubtedly be taken care of by varying λ.

9. Assuming fixed initial launching angle, fixed target course and fixed speeds of missile and target, the following statements may be made:

a. For $\lambda = 1$, a pure or deviated pursuit course is obtained, depending on whether or not the initial lead angle is zero.

b. For λ greater than 1, courses are obtained which are intermediate between pure or deviated pursuit and constant true bearing.

c. For λ infinite, a constant true bearing course is obtained.

[redacted]

Carroll L. Key, Jr.
Charles H. Dodge
Lark Seminar
10 July 1947

APPENDIX 2

A PROPOSED TERMINAL GUIDANCE SYSTEM FOR "SKYLARK"

Dr. L. J. Chu of Massachusetts Institute of Technology, has established that the ideal missile trajectory is the constant true bearing course.* He has shown that the area to which the missile can fly decreases approximately as the fourth power of the range to the target; hence, it is important to keep missile axis pointed toward the predicted point of collision. With this course, there is the greatest probability of scoring a hit on the target.

Investigation of the properties of the constant true bearing course leads to certain interesting conclusions. Let us investigate the rates of turn required, if we let

$$V_M/V_T = q \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where V_M is missile velocity and V_T is target velocity.

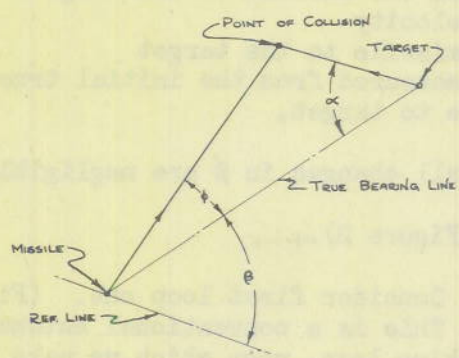


Fig. 1

Since $V_T \sin \alpha = V_M \sin \phi \quad \ldots \quad (2)$

$$\sin \phi = \frac{1}{q} \sin \alpha \quad \ldots\ldots \quad (3)$$

and

$$\cos \phi = \sqrt{1 - \frac{\sin^2 \alpha}{q^2}} \quad \ldots \quad (4)$$

Taking the derivative of equation (3)

$$\cos \phi \frac{d\phi}{dt} = \frac{1}{q} \cos \alpha \frac{d\alpha}{dt} \quad \ldots (5)$$

$$\frac{d\phi}{d\alpha} = \frac{\cos \alpha}{q \cos \phi} = \frac{\cos \alpha}{\sqrt{q^2 - \sin^2 \alpha}} \quad . \quad (6)$$

but $V_M \, d\phi = a_m$, the acceleration of the missile and $V_T \, d\alpha = a_t$, the acceleration of the target.

$$\frac{a_m}{a_t} = \frac{q \cos \alpha}{\sqrt{(q^2 - \sin^2 \alpha)}} \quad \ldots\ldots\ldots\ldots \quad (7)$$

It is apparent that maximum value of the right-hand side of the equation is 1, when $\alpha = 0$; and when $\alpha = 90^\circ$ the right-hand side of the equation is 0.

It is therefore evident that the maximum acceleration required of the missile is that of the target.

NOTE*: Meteor Report No. 3, "The Seeker Problem of Guided Missiles", by Dr. L. J. Chu.

For other types of courses, such as the proportional navigation course, or the pursuit courses, the demand is higher.

In fact, if a computer were to be employed, the ideal computer would be one which would cause the missile to fly a constant true bearing course.

We have attempted to set up a control system which will approach the ideal course. A rough design of such a system was taken to Mr. Peter Waterman for more exact design data. He suggested that we determine the effect of missile heading on the true bearing line, as this is the way in which errors in true bearing from the missile to the target must be corrected. This data was necessary to determine feedback path characteristics before the complete system could be set up. From the geometry of the situation, we determined that a change in missile heading from the correct heading causes a rate of change of bearing, the actual expression being approximately:

$$\Delta\phi = \frac{d\theta}{dt} \cdot N \cdot \frac{1}{R} \cdot \cos\phi$$

where

$\Delta\phi$ = the change in missile heading from the intersection heading
θ = the true bearing from the missile to the target
N = a constant due to velocity
R = the range from the missile to the target
ϕ = missile heading as measured from the initial true bearing from missile to target.

Second order effects enter in, but for small changes in ϕ are negligible.

Now to detail the complete system (Figure 2).

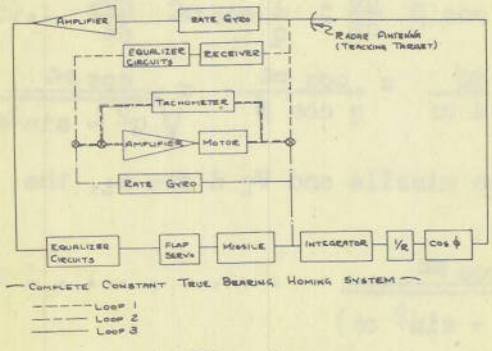


Fig. 2

Consider first loop one. (Figure 3). This is a conventional automatic tracking loop, upon which we make no specifications except that it be as good as possible. A passive loop (Transmitter at the launching sight) would probably be the best system because of simplicity and weight considerations. This loop will of necessity be one with a narrow bandpass; the actual design will be determined by groups whose specialty is in this line.

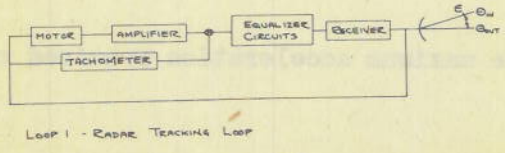
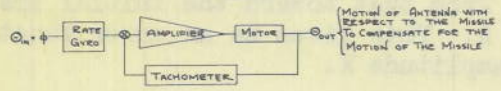


Fig. 3

Loop two is one which isolates missile turn from true antenna bearing. (Figure 4). The necessity for this circuit is almost self evident, because without it a positive change in missile heading would move the antenna in the same direction and give a positive true bearing error signal which would be

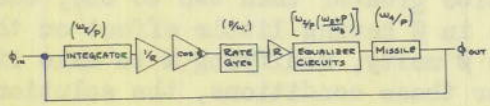
Fig. 4



LOOP 2 – THE ISOLATION LOOP

corrected very slowly by the automatic tracking circuit (loop one). This positive error signal would then be amplified through loop three in a positive direction, and make the system unstable. For the complete system to have any chance of being stable, loop two must have a much wider bandpass than that of the tracking radar, and be very tight. Fortunately, this is easily possible with components that are now available.

Loop three is the missile action loop, and is the only one that is not entirely conventional (Figure 5). Since the missile should be able to maintain a rate of turn although the error signal might be at zero (helping to reduce following lag and reducing the effect of dead space in rate gyros), we desire that there be some integration of the error signal. In addition, we desire that the system maintain a constant error sensitivity over the entire terminal trajectory, we must insert a variable gain amplifier in the loop somewhere to cancel out the effect caused by the fact that changes in missile heading effect the rate of change of true bearing, inversely proportional to the range from the missile to the target. The gain of this amplifier can be controlled by the same voltage that control the gain of the automatic tracking receiver in loop one by using the receiver A.G.C. voltage.



LOOP 3 – MISSILE CONTROL LOOP –

Fig. 5

Loop three is composed of a rate gyro, an amplifier whose gain is directly proportional to range, an equalizing circuit that is an integrator at low frequencies, the airframe (including the autopilot), and the feedback circuit which has been previously discussed. Breaking the loop at the missile output, (the output quantity is missile heading), we can set up the servo equation; i.e.,

$$(1)\quad \frac{\phi\ \text{out}}{\phi\ \text{in}} = \frac{\mu}{1-\mu b}, \quad b = -1 = \text{feedback constant}$$

and

$$(2)\quad = \frac{\omega_5}{P} \cdot \frac{\omega_4}{P} \cdot \frac{1}{R} \cos\phi \cdot \frac{P}{\omega_1} \cdot R \cdot \frac{\omega_2}{P} \cdot \left(\frac{\omega_3 + P}{\omega_3}\right) =$$

$$M \cos\phi \left(\frac{\omega_3 + P}{P^2}\right)$$

$$\text{where } M = \frac{\omega_2 \omega_4 \omega_5}{\omega_1 \omega_3}$$

Substituting (2) in (1), we get

$$(3)\quad \phi\ \text{out} = \frac{M(\omega_3 + P)\cos\phi}{P^2 + M\cos\phi\, P + M\omega_3 \cos\phi} \cdot \phi\ \text{in}$$

We are particularly interested in studying the stability of the system and its transient response as a function of the parameters M and ω_3. As an error signal (ϕ in) we used the condition that the missile is initially heading on a bearing that is different from that toward the initial instantaneous interception point by an amount K. This gives us an error function that is a multiple of a unit step, of amplitude K.

(4) Fourier Transform of $K = \frac{K}{P}$,

substituting (4) in (3)

$$(5)\quad \phi \text{ out} = \frac{M(\omega_3 + P)\, K \cos\phi}{P\,(P^2 + M\cos\phi + M\omega_3 \cos\phi)}$$

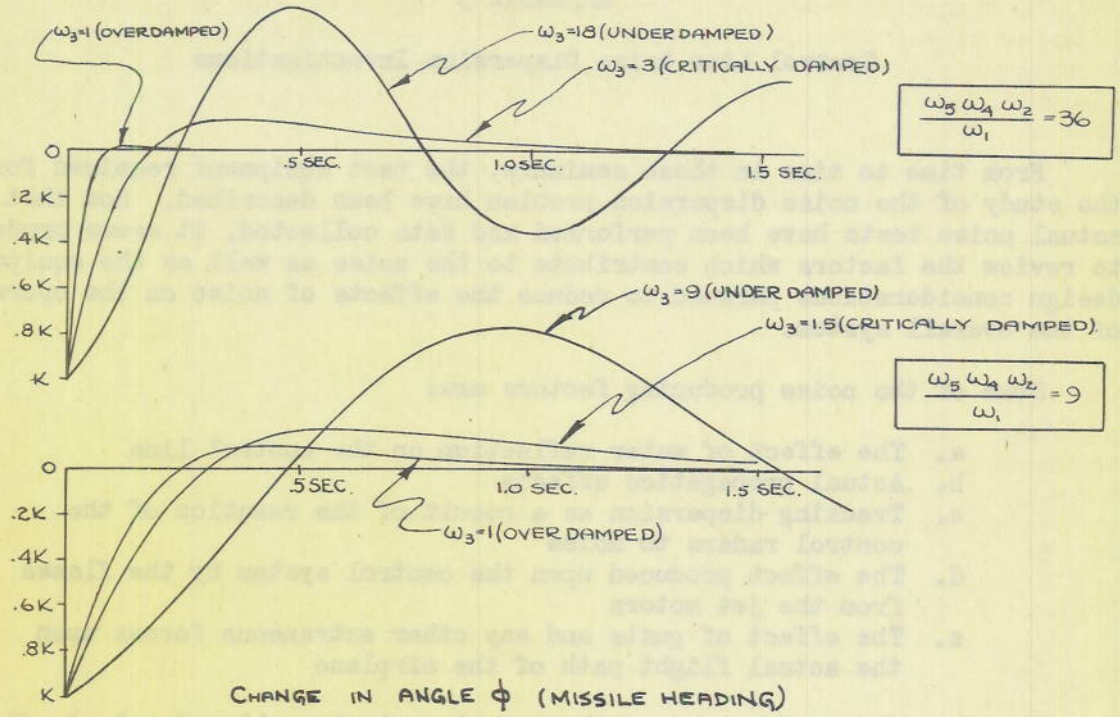
For missile to target velocity ratios greater than two to one, $\cos\phi$ is greater than .866, with small changes in ϕ having little effect on the cosine. For simplicity, we can call $\cos\phi$ unity, modifying M to make it exactly so at any particular time. Under these conditions, the solution of (5) is:

$$(6)\quad \phi \text{ out} = K - \frac{K}{2}\left[-\left(1 - \frac{1}{\sqrt{1 - \frac{4\omega_3}{M}}}\right) e^{-\frac{M}{2}\left(1 - \sqrt{1 - \frac{4\omega_3}{M}}\right)} - \left(1 + \frac{1}{\sqrt{1 - \frac{4\omega_3}{3}}}\right) e^{-\frac{M}{2}\left(1 + \sqrt{1 - \frac{4\omega_3}{M}}\right)} \right.$$

If the value of $\sqrt{1 - \frac{4\omega_3}{M}}$ is:

1. real - We have a over-damped system.
2. complex - We have a system which is under-damped.
3. imaginary - We have a system which oscillates with constant amplitude.

Plots of various transient solutions in terms of the heading of the missile are given for various values of the parameters M (gain constant) and ω_3 (integrator cut-off frequency).



CHANGE IN ANGLE ϕ (MISSILE HEADING)
FOR INPUT OF STEP FUNCTION = K

Fig. 6

Selection of the correct parameters for any specific missile is now possible.

P. Waterman
Lark Seminar
10 July 1947

APPENDIX 3

Control Line Noise Dispersion Investigations

From time to time in these seminars, the test equipment required for the study of the noise dispersion problem have been described. Now that actual noise tests have been performed and data collected, it seems prudent to review the factors which contribute to the noise as well as the equipment design considerations pursued to reduce the effects of noise on the operation of the overall system.

Some of the noise producing factors are:

a. The effect of water reflection on the control line
b. Actual propagation effects
c. Tracking dispersion as a result of the reaction of the control radars to noise
d. The effect produced upon the control system by the flames from the jet motors
e. The effect of gusts and any other extraneous forces upon the actual flight path of the airplane

To study these effects upon the actual control problem involved, first the calculation of the minimum acceptable bandwidth for the combined servo systems as derived from the tactical use for which the missile will be utilized. This study is covered in NRL Report No. 2930, by L. O. Brown, dated 26 February 1947, and has been discussed and reported in previous seminars. From the frequency spectrum analysis, the overall servo system was specified, designed, and constructed with performance characteristics outlined in Memorandum for File entitled, "Servo Considerations for SNB Beam-Riding Tests", dated 7 Nov. 1946, and a report by R. E. Gaylord, "Development of an Aircraft Control System", in Lark-Wasp Guided Missile Seminar Report dated April 1947, NRL Report No. R-3108.

A beam riding receiver was designed and constructed which would provide adequate control signals while decreasing the effects produced as a result of the various noise generating forces outlined above. Figure 1 shows a complete block diagram of the receiver.

The design of the receiver from the standpoint of noise, was largely dictated by the effects of noise produced by surface reflection of the controlling radar beam when operating the radar at low angles of elevation. When the length of the reflected path to the receiver differs from the length of the direct path to the receiver by one wave length, or a multiple of the wave length, and the reflected wave is one hundred eighty degrees out of phase with the direct wave, a signal strength null or minimum results. Figure 2 shows the distance between minimum along the axis of the beam as related to range from the radar to the receiver. Figure 3 shows the pattern of minimums existing in front of the radar.

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BLOCK DIAGRAM
OF
LARK RECEIVER

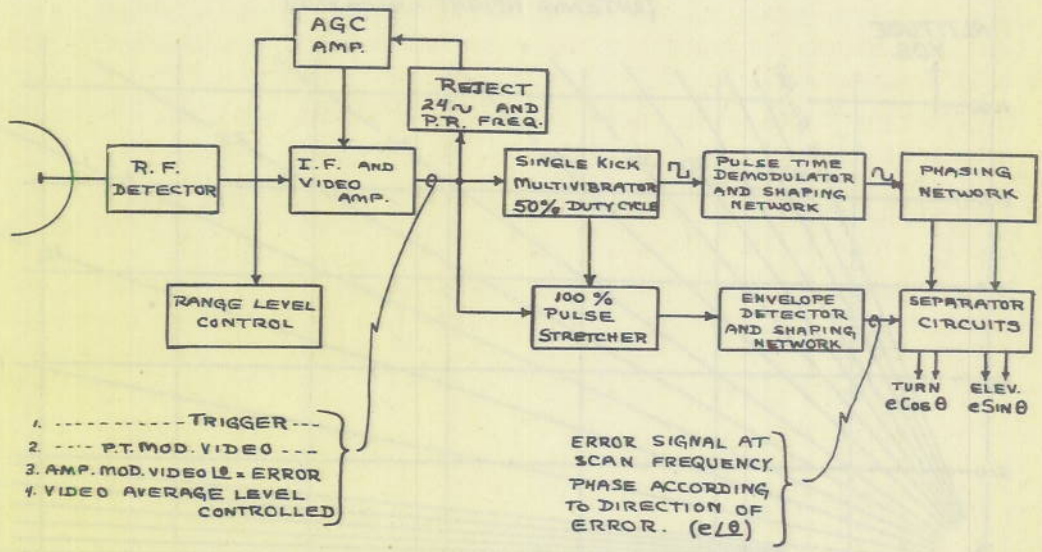
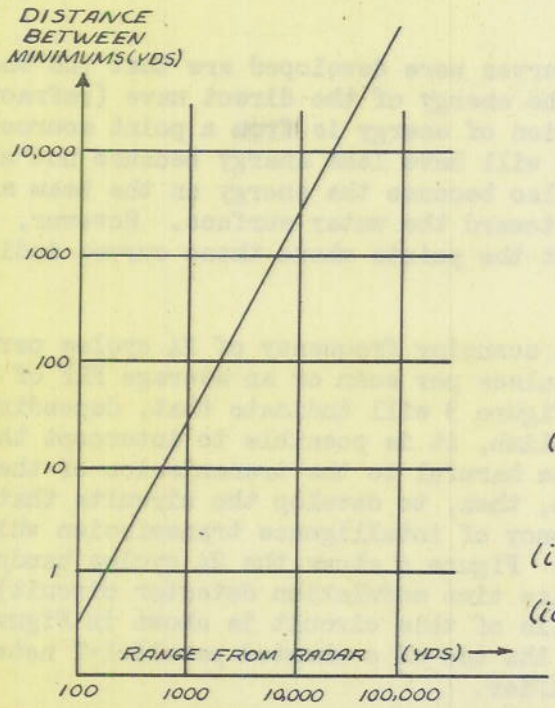
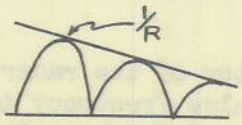


Fig. 1



DISTANCE ALONG BEAM BETWEEN MINIMUMS, CAUSED BY REFLECTED SIGNALS



(i) BETWEEN NULLS OR MINIMUMS THE SIGNAL INTENSITY VARIES AS A RECTIFIED SINE WAVE. AMPLITUDE ENVELOPE VARIES INVERSELY WITH RANGE

(ii) DISTANCE BETWEEN NULLS IS INDEPENDENT OF BEAM ELEVATION

(iii) THE RADAR IS ASSUMED TO BE A POINT SOURCE OF ENERGY PROPAGATION

Fig. 2

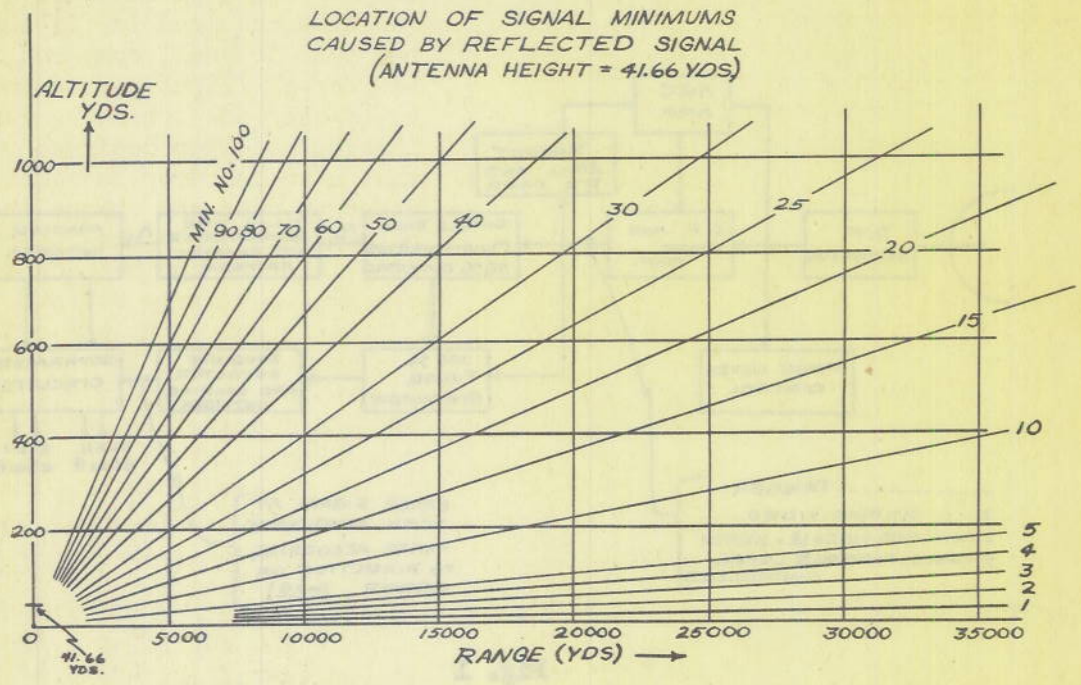


Fig. 3

The assumptions on which the curves were developed are that the energy of the reflected wave is equal to the energy of the direct wave (refraction is not considered) and the propagation of energy is from a point source. In the actual case, the reflected wave will have less energy because not all the energy will be reflected, and also because the energy on the beam axis will be greater than that directed toward the water surface. However, the signal strength will be decreased at the points where these curves indicate nulls.

The nutator of the radar has a scanning frequency of 24 cycles per second, the average pulse frequency is 24 pulses per scan or an average PRF of 576 pulses per second. Inspection of Figure 3 will indicate that, depending on missile speed, range and angle of climb, it is possible to intercept the minimums at a frequency which may be harmful to the transmission of the guiding intelligence. It becomes desirable, then, to develop the circuits that have a narrow bandwidth about the frequency of intelligence transmission which is, in this case, 24 cycles per second. Figure 4 shows the 24 cycles bandpass of the reference signal generator (pulse time modulation detector circuit). The side band transmission characteristic of this circuit is shown in Figure 5. This characteristic is obtained by the use of a shunted parallel-T network in the β path of the reference amplifier.

It is to be remembered from a talk given by Mr. Ament at an earlier meeting that around the null points are false control lines which can guide

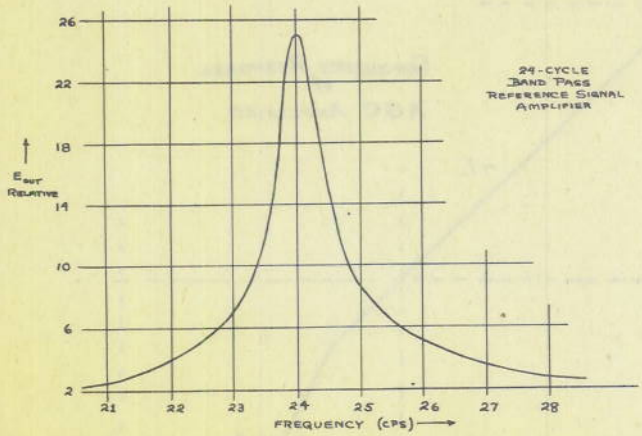


Fig. 4

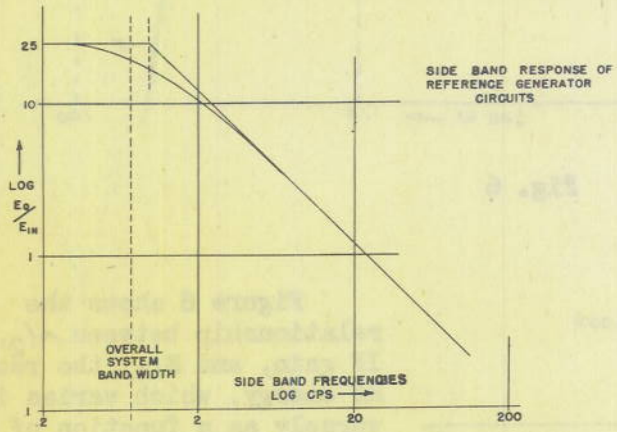


Fig. 5

the missile away from the main control line. Fortunately, the time required to fly through the null is small compared to the normal flight period between nulls over the operating ranges. Thus, a receiver designed so that a sudden drop in signal strength does not change the receiver gain for a pre-determined time interval can be made to ignore, to a large extent, the effects produced by these false control signals. In effect, this means that the receiver should be made inoperative, with the gain clamped at the normal level, during fade-out periods, so that at the end of a fade-out period, the system can continue to operate normally.

An AGC amplifier circuit for low angular frequencies of input is described in Fig. 6.

The complete AGC loop can be diagrammed as shown in Fig. 7.

IF = μ_2 (variable) E_o is vide

Video = $\mu_3 = K_3$ E_{in} is 60 mc

AGC Amp = $\mu_4 = \beta$

Writing the loop expression,

$$\frac{E_o}{E_{in}} = \frac{\mu_2 \mu_3}{1 + \mu_2 \mu_3 \beta}$$

The object of the "AGC" system is to maintain the level of $E_o = K_o$ for ranges of signal variation which the system will be subjected to. Thus solving for μ_2 as a function of E_{in}

$$\frac{K_o}{E_{in}} = \frac{\mu_2 \mu_3}{1 + \mu_2 \mu_3}$$

$$\mu_2 = \frac{K_o}{\mu_3 E_{in} - \mu_3 \beta K_o}$$

$$\mu_2 = \frac{K_o}{\mu_3} \left(\frac{1}{E_{in} - \beta K_o}\right)$$

Under steady state conditions $\beta \doteq \mu_1$

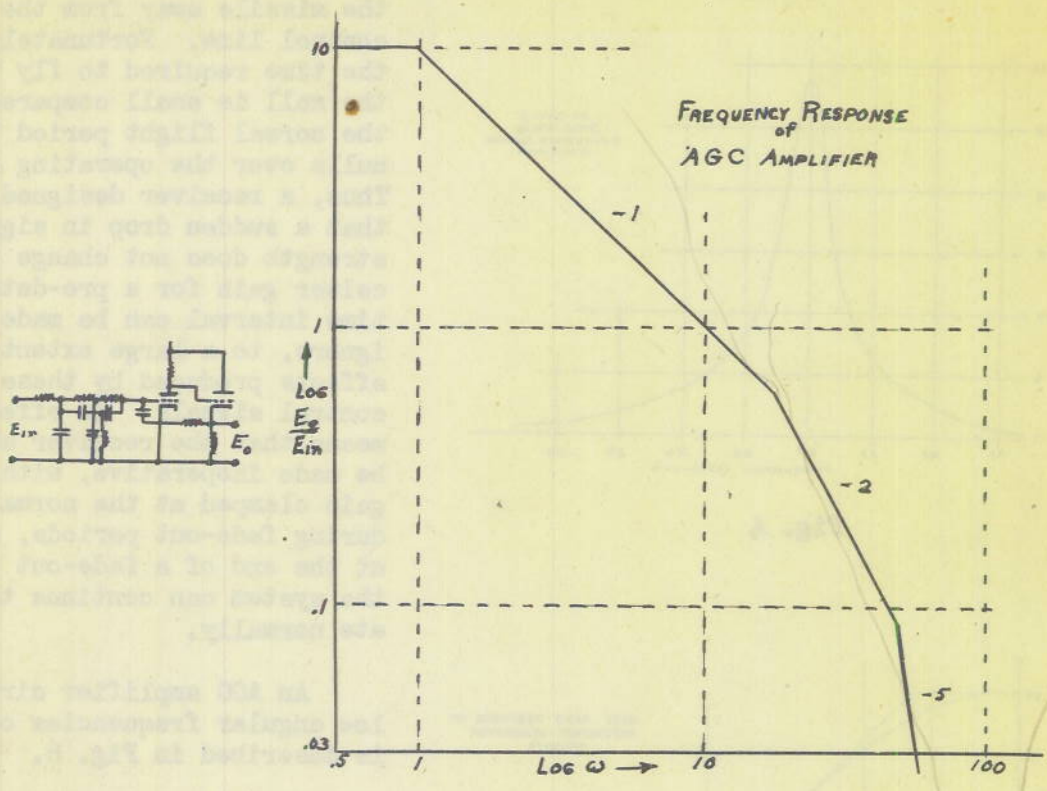


Fig. 6

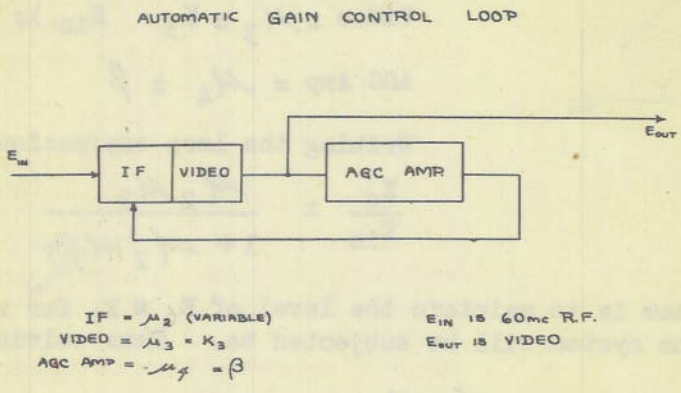


Fig. 7

Figure 8 shows the relationship between μ_2, the IF gain, and E_{in}, the received RF energy, which varies inversely as a function of range, placing a limit of approximately 100 miles on the receiver.

The AC response of the receiver AGC system can be approximated as follows:

The low angular frequency response

$$\frac{E_o}{E_{in}} = \frac{\mu_2 \mu_3}{1 + \mu_2 \mu_3 (\mu_4)}$$

$\mu_2 = K_2$ and E_o is AC modulation output

$\mu_3 = K_3$ E_{in} is AC modulation input.

μ_4 = AGC Amp.

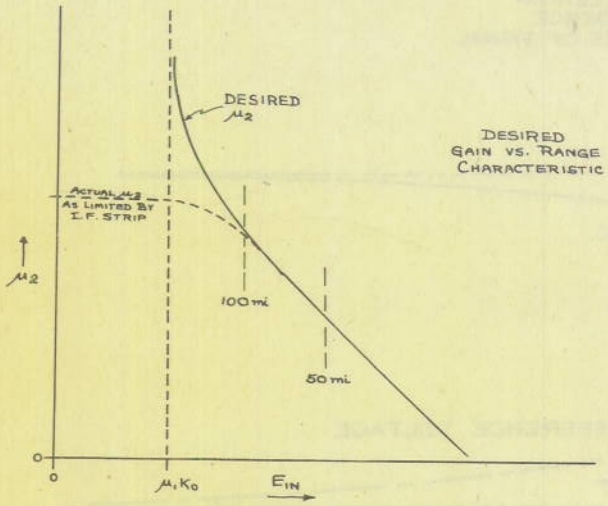


Fig. 8

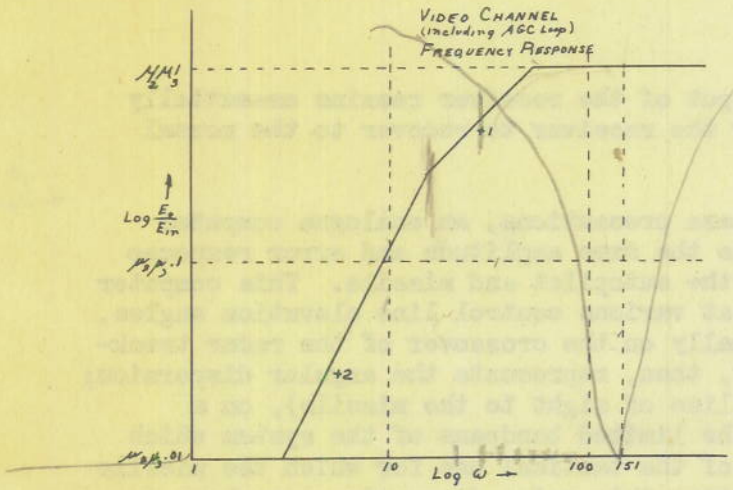


Fig. 9

For values of ω which satisfy

$$\mu_2 \mu_3 \mu_4 \gg 1$$

$$\frac{E_o}{E_{in}} \rightarrow \frac{1}{\mu_4}$$

for ω = scan frequency, $\mu_4 = 0$. Thus,

$$\frac{E_o}{E_{in}} \rightarrow \frac{\mu_2 \mu_3}{1 + \mu_2 \mu_3 (0)} \rightarrow \mu_2 \mu_3$$

μ_2 being established by the average signal level of the incoming RF and for this purpose $\mu_2 \mu_3 = K$.

Figure 9 shows the amplitude response of the AGC system plotted in a generalized manner.

In order to obtain the delay action or clamping of the receiver gain, the bias for the pulse stretche "clear out", on the receiver diagram is obtained from a portion of the pulse time modulation detector circui and has a time constant of .06 seconds or approximately 1½ scans of the tracking radar which is equivalen to 36 pulses.

<u>Approximate Time Sequence of Lark Receiver for Drop Out of Signal</u>

Figure 10 shows the combined effects on a time relation plot, illu trating what occurs when the signal drops below the clipping level of the pulse time modulation detector.

As can be seen from the time sequence diagram, the receiver gain is clamped at constant level for 36 pulses after a fade-out, then if the fade-out continues, the receiver gain will be increased slowly, so that at the end of 322 pulses, it will be 63 percent of the maximum gain of the receiver. During the scan cycle period the reference generator output remains essentially constant for the first 36 pulses of fade-out and then decays exponentially. In the ideal case, it is desirable to keep the product of these two levels constar so that when the signal again is picked up after the fade-out, the angle

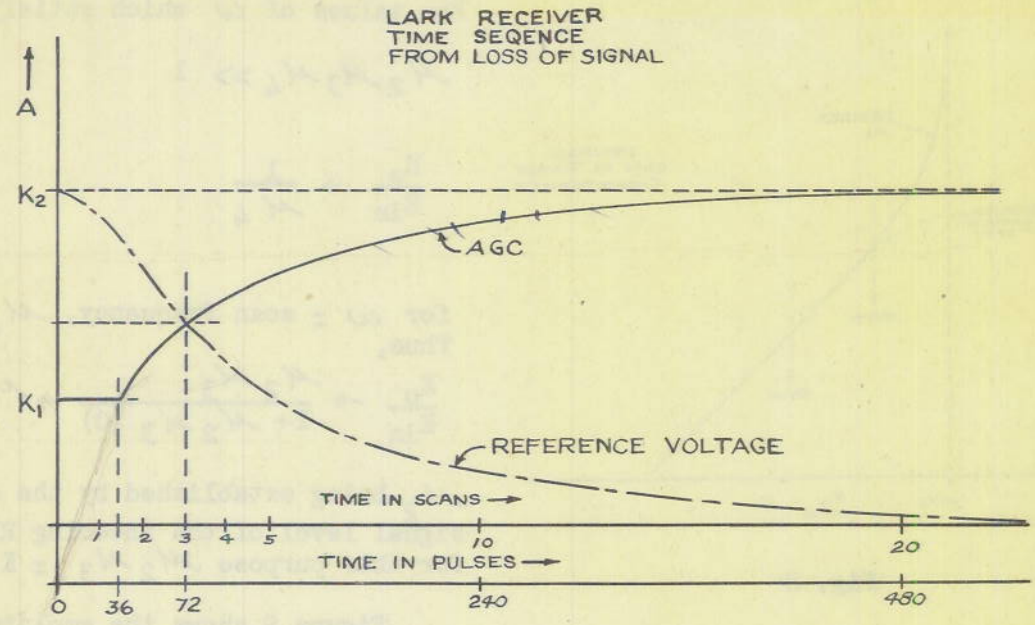


Fig. 10

sensitivity at the turn and climb output of the receiver remains essentially constant during the time required for the receiver to recover to the normal operating level.

To study the effectiveness of these precautions, an analogue computer was designed and constructed which has the same amplitude and error response characteristic of the closed loop of the autopilot and missile. This computer was flown out the radar control line at various control line elevation angles, with the receiver and plane kept manually on the crossover of the radar tracking beam. The output of the computer, then, represents the angular dispersion; (i.e., angle between control line and line of sight to the missile), on a perfect flight path, as weighted by the limited bandpass of the system which was generated as a result of a study of the tactical use for which the missile is designed. Typical curves illustrating this noise dispersion are shown in Figure 11.

Following these noise dispersion flight tests, which were made without correction for range, it is planned to conduct a series of similar tests with the analogue computer gain corrected as a function of distance from the control radar. The dispersion recorded will then be the actual lateral deviations that would be found in the missile flight path.

Flight tests have been performed utilizing cross-pointer meters corrected for the transmission characteristic through the pilot and his control, so that the meter indication represents the angular deviations from the control line as well as the rate of change of these deviations. This enables the pilot to decrease an initial error to zero exponentially rather than in an oscillatory manner.

TYPICAL
NOISE DISPERSION
TEST DATA

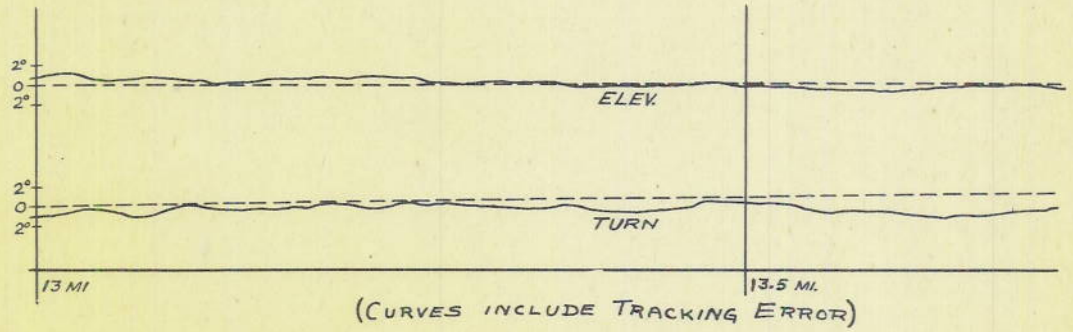


Fig. 11

It is expected that the flight test program, as outlined in Report No. R-3090, "Recommended Research Program for Development of Mid-Course Guidance System for Lark" (by A.S. Locke, dtd April 1947), will be sufficiently advanced to operate the system in complete automatic control within the next week. Performance during such tests will be discussed at the next Lark conference.

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