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Radar AND COMMUNICATIONS

A REPORT PREPARED FOR THE AAF SCIENTIFIC ADVISORY GROUP

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The AAF Scientific Advisory Group was activated late in 1944 by General of the Army H. H. Arnold. He secured the services of Dr. Theodore von Karman, renowned scientist and consultant in aeronautics, who agreed to organize and direct the group.

Dr. von Karman gathered about him a group of American scientists from every field of research having a bearing on air power. These men then analyzed important developments in the basic sciences, both here and abroad, and attempted to evaluate the effects of their application to air power.

This volume is one of a group of reports made to the Army Air Forces by the Scientific Advisory Group.

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TABLE OF CONTENTS

Part I. The Use of Radar in Air Force Operations

Part II. Radar, a Discussion of Future Trends of Interest to the Army Air Forces.

Part III. Aircraft Radio Communication Equipment

PART I

THE USE OF RADAR IN AIR FORCE OPERATIONS

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PART I

THE USE OF RADAR IN AIR FORCE OPERATIONS

INTRODUCTION

The last four years of war and of war-stimulated research have resulted in the development of equipment and techniques in the radar and electronics field which offer possibilities of profoundly affecting the whole concept of future air force operations. These devices have already passed the laboratory stage, and nearly a billion dollars' worth of radar equipment is now in actual combat use in the Army, the Navy, and the Army Air Forces. Thus, the fundamental ideas in the field have been thoroughly proven and are definitely "here to stay."

In spite of the rapid progress made in a relatively short time, the technique in the field is still in its infancy. Enormous possibilities lie ahead, and additional research both on the technical and on the operational side, will pay huge dividends in more effective military air force operations.

At the same time, the rapid introduction of new and miraculous devices has led to the feeling among the uninitiated that anything is possible by the use of electronics. It is, therefore, of greatest importance to understand thoroughly the limitations as well as the possibilities of radio, radar, and electronic equipments in order to avoid raising impossible hopes and in order to eliminate unnecessary and ill-conceived research and development programs.

Fundamentally radar is a device which enormously extends the range, power, capabilities and accuracy of human vision. For example:

1. The human eye cannot see in darkness or through fog, clouds, and rain. Radar is not at all limited by darkness or by fog, and to only a slight extent by heavy clouds and rain.

2. The human eye determines only roughly and with difficulty the distance to an object which it sees. Radar determines the distance rapidly, accurately, and continuously.

3. The human eye can pick up or see objects such as airplanes only at distances of a few miles. Suitable radar can see airplanes up to distances of 200 miles.

4. The human eye, aided by optical instruments, can get accurate data on bearing, elevation, and range of only one distant object at a time, and considerable time is required for such determinations. Radar can determine and display these data within

a few seconds for all objects in [redacted] us area, in the best cases up to a radius of 200 miles.

These features of radar open up many possibilities, such as all-weather day and night air operations, an increase in accuracy and versatility of bombing, gunfire, and navigations, the control from the ground or from the air of major air force operations, provision of information and controls to relieve the overburdened pilot both in navigation and in combat, and the accurate remote control of pilotless aircraft.

To realize all of the operational possibilities of radar devices, however, careful attention must be given both to the design of new aircraft, to allow incorporation and proper location of the necessary electronic equipment, and also to the planning of tactics and operations in such a way as to make fullest and most effective use of the possibilities of radar.

Furthermore, it must be realized that radar is not a facility or attachment which will occasionally be used under bad conditions. Rather, the air force of the future will be operated so that radar is the primary facility, and visual methods will be only occasionally used. Bad weather or darkness are normally prevalent from 60 to 90% of the time, and predictions of good weather at remote points often fail of realization from 25 to 50% of the time. Hence, in an all-weather air force, radar must be the universally used tool for bombing, gunfire, navigation, landing, and control. The whole structure of the air force, the planning of its operations, its training program, and its organization must be based on this premise. The development and perfection of radar and the techniques for using it effectively are as important as the development of the jet-propelled plane.

The present report outlines very briefly some of the present and future possibilities of radar and related techniques in various types of air operations.

ALL WEATHER FLYING

The ability to achieve air force operations under all conditions of darkness and weather may contribute more than any other single factor to increasing its military effectiveness. Hence, any research program designed to overcome the limitations to flight at night and in bad weather will pay big dividends. The use of pilotless aircraft of various types will, of course, be an aid to providing an all-weather air force. The essential problems, however, are similar, whether the airborne vehicle is manned by a pilot or not.

There are many elements which contribute to the all-weather air force. Among them are:

1. The design of aircraft; their stability, maneuverability, landing and take-off speeds, flying speed, rate of climb, maximum altitude, etc. (These factors at least will determine how difficult it is to overcome weather limitations.)

2. The design of suitable airfield facilities, such as runways, lights, control facilities, fog clearance equipment, radio beams, radio ranges, and radio communication facilities.

3. Aircraft flight instruments and controls, allowing more accurate and more automatic control and operation of the aircraft in conditions of bad visibility.

4. The solution of the icing problem, which is second only to the problem of blind landing in its serious interference with all-weather operations.

5. Radar aids to overcome the limitations of visibility.

The present section will confine its attention to the last named item above, and will take up only the flying aspects. The navigation, bombing, gunfire control, and other aspects will be treated in succeeding sections.

In blind flying, radar aids will be of greatest importance in the problem of traffic control in or near an airport, and in the problem of landing an aircraft under conditions of bad or zero visibility.

BLIND LANDING

The purpose of blind landing facilities is to allow an aircraft to come down on a runway as accurately, as safely, and as rapidly under conditions of zero visibility as under conditions of unlimited visibility. This requires the establishment in the vicinity of the runway of a system of coordinates in space so that the pilot may determine his distance from the proper landing path and the action which he must take to approach and remain on it. This system of coordinates can be provided in various ways, but the only methods independent of weather will be radio methods.

Two somewhat different methods have been developed for establishing the necessary coordinate system. These are:

1. The "glide-path-localizer" system, whereby radio beams are laid down in space, one in a vertical plane to give the pilot proper line of approach to the runway, the "localizer," the other in a plane tilted slightly from the horizontal to give him the proper glide path; ILS

2. The precision radar system, wherein the exact position of the airplane is determined by radar by an observer on the ground, who can then pass the information to the pilot and give him instructions for landing. GCA

The glide-path-localizer system requires for each landing path two radio transmitter systems. These conceivably could by mobile systems which are moved from one position to another on the landing field, as wind conditions change, or they could be fixed transmitters which, in a complete setup, would require a pair of transmitters at each end of each runway. The localizer transmitter antenna is designed to give two radio beams which have equal intensity only in a vertical plane which contains the center line of the runway. These beams provide the pilot a "right," "left," or "on course" signal, depending on his position. Thus, his approach to the runway follows somewhat the same principle as the approach to an ordinary radio-homing beacon, the difference being that the localizer must be much more precise and must give suitable signals when the plane is only a few feet from the proper landing path.

The glide-path radio transmitter also transmits two radio beams which are roughly horizontal and intersect along a plane which is tilted at an angle to the horizontal equal to the desired glide angle, for example, from 2-1/2° to 4°, and which contacts the runway at the approach end. A pilot flying down the landing path will then get one signal if he is above the proper glide path, another signal if he is below, and a suitable null signal when he is on the path.

Since the pilot must be able to receive and interpret both the localizer and glide-path signals simultaneously, the simplest method of presentation to the pilot is by means of a cross-pointer meter, one pointer indicating whether he is to fly up or down, the other indicating whether he is to fly right or left to approach the landing line. Alternatively the signals may operate directly into the automatic pilot, making the landing process completely automatic, at least to the touchdown point. The glide-path signal, of course, should vanish at the touchdown point, but the localizer signal should continue so that the plane can still taxi down the runway.

While a glide-path-localizer system of the above type has been visualized for a number of years, the engineering problems are considerable, and no completely satisfactory system has yet been engineered. The one now going into use, the SCS-51, is having some success in the field, but it is recognized by all to be only a first approach to the problem. The difficulties with this particular system are that the radio frequency used is sufficiently low (the wavelength long) that the problems of sighting, of ground reflections, and other related difficulties become serious. In this system, in fact, the glide-path transmitter uses ground reflection to create the desired antenna pattern. Hence, if the ground in the vicinity of the airport is not flat for a considerable distance from the transmitter, the glide path will not be smooth and will show bumps or other discontinuities.

A much-improved system, using microwave transmitters, has been under development for some time at the Sperry Gyroscope Company. This system, because of the short wavelength, avoids most of the troubles due to ground reflections. On the other hand, the techniques for using microwave frequencies for such an equipment are still under development, and there are still engineering difficulties to be solved. Nevertheless it seems clear that the ultimate glide-path-localizer system must be on microwaves (5 cm or less) in order to gain the necessary precision and freedom from difficulties due to ground reflections. In addition, the microwave system makes possible the use of much smaller antennas, both on the ground and in the aircraft. Further developments of the microwave glide-path-localizer equipment should be pushed as rapidly as possible in order to solve the remaining engineering difficulties.

The glide-path-localizer system for providing the necessary coordinates for a suitable landing path has the following advantages:

1. Many aircraft can use the facility independently, without interference.

2. No radio communication with the plane is required during the landing other than the normal communications required in ordinary visual landings.

3. The system can be permanently on the air without attention, so that it can be used at any time by any plane coming into the airfield.

4. A continuous-wave system uses up less of the radio spectrum than a pulsed-radar system, so more channels are available for use by neighboring airfields.

The difficulties of the system are:

1. Every plane must be provided with the necessary receiving equipment whose weight, however, need not exceed 30 lb.

2. There is no mechanism inherent in the system for the control of large traffic and avoiding collisions.

The precision radar system, known as GCA (Ground Control of Approach), consists in reality of three radar sets. The first is for general surveillance of the traffic in the vicinity of an airport and is used for controlling airplanes as they come into the vicinity of the airport. A second radar system is a precision system which gives accurate information, when the airplane is near the landing path, on its distance to the right or left of the exact path. The third radar system is a precision system which gives the position of the aircraft above or below the glide path.

The precise information as to the airplane's departure from the glide path in bearing and in height is presented in a simplified form to a ground controller, who gives oral instructions by radio to the pilot on how to fly in to a landing. For this reason the system is sometimes referred to as the "talk-down" system; however, the ground controller could equally well transmit the information over the radio channel in such a form as to go on a pilot's instrument or, indeed, to go into the automatic pilot. The system differs from the glide-path-localizer system in that the control is in the hands of a ground observer rather than the pilot.

In its present form the GCA system is known as the AN/MPN-1. The three radar sets are housed in a single truck, which houses also the necessary operators and controllers. The truck is located just off the runway, near the approach end, but can readily be moved from one location to another to take care of different runways.

The advantages of this radar landing system are:

1. It requires no equipment or antennas in the aircraft other than normal radio communication equipment.

2. It supplies complete information as to the positions of other planes in the area, so that it can be used for traffic control and avoiding collisions.

3. It requires almost no training for a pilot to follow the oral directions and make a satisfactory approach.

4. It removes a considerable burden from the tired pilot after a long mission.

The disadvantages are:

1. In the case of heavy traffic a considerable load will be put on the radio communication channels.

2. Existing radio channels are rendered unusuable by static in bad weather.

3. There are problems of identifying the plane which the radar "sees" to insure that it is the same plane with which radio communication has been established.

These disadvantages are not inherent, however, and can be removed by further development of techniques.

TRAFFIC CONTROL

The control of heavy traffic near an airfield is one of the most difficult and important problems in all-weather flying. Assuming that some blind-landing path has been established, as discussed above, the elements required in the traffic control problem are:

1. A method of providing continuous accurate information on the position of every plane within a radius, say, of 50 miles of the airfield.

2. A recognition method to distinguish one plane from another.

3. Reliable radio communication, unaffected by atmospheric noise, and with enough channels to handle communications to several planes at once.

4. Equipment in the aircraft to determine his location with respect to the field, to obstructions or landmarks, and to detect the presence of other planes nearby (desirable but not always essential for military aircraft, such as fighters).

5. A suitable organization and set of procedures for making best use of equipment and techniques available under the greatest variety of conditions.

Items (1) and (4) are already available in existing ground and airborne radar equipments, although further development of existing ground radar of the V-Beam type to satisfy item (1) is of importance. Item (2) relates to the whole radar identification problem, which is treated in a separate section, and is probably the most difficult problem of all. Item (3), radio communication, is also treated separately, for the problem of noise-free communication in all weather comes up everywhere. The development of the organization and procedures mentioned in item (5) could be accomplished by a suitable experimental program aimed at the evaluation and intergration of various equipment and techniques.

The V-Beam technique mentioned above is that used in the radar set AN/CPS-6. This equipment makes use of two fan-shaped radar beams, one in a vertical plane and the other at 45°. These two beams sweep around together through 360° in bearing. The vertical beam serves to give complete information as to the position in plan of all aircraft in the vicinity, and, combined with the slant beam, gives information on the height of the aircraft. This equipment was not designed for airport traffic control, and a number of refinements in it would be required to adapt it ideally to the traffic-control function. A device for the elimination of fixed-target echoes and a reduction in size and weight by going to a higher frequency, and an improvement in precision are desirable. A suitable equipment of this sort would replace the general surveillance set now used in the GCA equipment, and would provide the necessary first prerequisite for airport traffic control.

Since the traffic density will be greatest along the landing path itself, a precision radar for monitoring the path will also be required.

FUTURE POSSIBILITIES

Although there is room for great technical development of the radio and radar aids to landing and traffic control mentioned above, one of the chief problems is the development of a system in which all conceivable aids will be properly integrated and used together. This can only come as a result of extensive experience and a comprehensive program of trials.

There will be, in fact, several future systems for different types of airports. Thus, a permanent commercial air base, a large air-transport command base, a bombing command base, and temporary advanced airfields, accommodating principally fighters and fighter bombers, all present a different problem.

With a large, permanent air base one might visualize a traffic-control radar of the V-Beam type to be used for general handling of traffic within, say, 50 miles of the field. A localizer-glide-path system, or group of systems, would be available for setting up coordinates of the landing path, and all planes coming into the field suitably equipped would land by automatic instruments. A precision radar system would also be available for monitoring the landing path, avoiding collisions, and for assisting in landing planes not equipped with glide-path-localizer equipment, or in which the equipment is not in operation.

At forward air bases mobile GCA equipment of improved types would probably offer a suitable solution to the whole problem. As the airfield developed and came to be more permanent or to handle more traffic, additional equipment could be installed, bringing it up eventually to the status of a permanent field.

In addition, it is evident that most medium and large planes will require an airborne radar as an aid to navigation to the airfield, for seeing the lay of the land near the field, detecting obstacles, and other aircraft. Modern airborne radar can even see the runways on a field, and this facility will aid the pilot greatly in any landing in bad visibility. Fortunately many, if not most, of the larger planes, will carry such radar anyway for bombing, sea search, navigation, and other purposes. Further improvement in airborne radar for all these purposes is of great importance.

NAVIGATION

The central problem of air navigation is to determine quickly and accurately the geographical position of an aircraft. The problem presents itself in many forms, with a variety of requirements on the accuracy and speed of solution, simplicity of apparatus, traffic capacity, security, and other characteristics of the navigational system. It is convenient, in discussing the application of radar and related radio techniques to the problem, to separate methods requiring no ground stations or ground markers of any sort from systems which make use of ground stations. The latter class can be further subdivided into systems whose range is essentially limited by the optical horizon and systems capable, at least in principle, of coverage well beyond the horizon. The last distinction is a fundamental one from a technical point of view; from an operational point of view, the distinction between short- and long-range systems is equally important but less sharply defined.

NAVIGATION BY RADAR

Navigation by radar vision has already come to play an important role in air force operations. It has been made possible by the development of microwave radar, which permits the use of narrow beams, by means of which a more or less recognizable map of the surrounding country is continuously provided to the navigator. In its earliest and crudest form (H2S), little more than cities, towns, and coastlines could be distinguished; cities were identified by their spacial relation to one another and to some extent by the character of the echo appearing on the indicator screen. As shorter wavelengths become available and the techniques of presentation improved, the similarity between the countryside and its radar map increased. This improvement can be expected to continue. X-band (3.2-cm) radar now in production (APQ-7) provides resolving power of the order of 0.5°, and shorter wavelengths with which the same resolving power can be obtained with smaller antennas, are just beginning to be exploited. Resolution of this order allows the navigator to identify many features of the landscape, rivers, streams, bridges, rail lines, etc., and thus, by reference to an ordinary map, to obtain his position, even in strange country. Besides this information, which is always available, heavy storm clouds make themselves evident on the radar screen, warning the navigator of conditions ahead.

The radar information can also be used in connection with flight instruments of the air-position-indicator type. The radar, since it provides a view of the ground, enables ground speed and drift to be determined, and affords occasional fixes in ground coordinates. These data can be combined with true air speed and heading, and integrated. The entire system is then a ground position indicator which gives a continuous direct indication of the instantaneous position of the aircraft in ground coordinates. The inherent accuracy of this indication, in the form of the instrument now under development (APA-44), is of the order of 1% of the distance traveled since the last fix.

Over the sea, of course, radar contact flying, like visual contact flying, is restricted to areas within sight of identifiable land. Radar, however, sees land much further than the eye, ranges of from 50 to 100 miles being not uncommon. This greatly relaxes the requirements on dead-reckoning navigation. For example, in a 1000-mile flight to a distant island, a 4% dead-reckoning error would not prevent making a radar landfall.

The problem of ground speed and drift determination by radar over the sea (by means other than radar buoys) has not yet been solved, but recent developments in overland drift determination arouse hope of progress in this direction.

SHORT RANGE GROUND STATION SYSTEMS

Perhaps the simplest ground station system is the radar beacon, which extends the possibilities of direct radar navigation by providing a strong, readily identifiable, artificial echo. Microwave beacons are normally seen to line-of-sight ranges. On the radar set the distance to the beacon is determined with the inherent range accuracy of the set, and the bearing of the beacon relative to the aircraft is indicated as accurately as the width of the radar beam allows. A single beacon station on the ground thus provides a nagivational fix to any suitably equipped aircraft within the horizon. The value of radar beacons has been widely demonstrated, and the number of uses to which they can be put continually increases. The radar beacons will unquestionably play an important part in future air navigation, both for military and civilian traffic. In this connection, however, one inherent limitation of beacon systems should be mentioned. The number of radar sets which can use a single beacon at one time is limited; each interrogation of the beacon calls for an individual reply. The possibility of "overinterrogation" of the beacon, in dense traffic, will be a matter of concern in some applications.

Much greater precision can be obtained by measuring simultaneously the distance of the plane from each of two ground beacons, thus locating the plane at the intersection of two circles. This is the basis of the British "H" system, its microwave equivalent, "Micro-H," and Shoran. Generally speaking, interest in these systems has centered in their application to blind bombing, and to other special problems of navigation, such as dropping of paratroops or supplies at assigned points. The fact that micro-H navigation requires essentially only an ordinary radar set in the aircraft, however, suggests that its field use may expand in the future as microwave radar becomes more nearly a standard item of aircraft equipment.

The inverse of the H-system (Oboe) places in the aircraft a beacon, which is interrogated by each of two ground stations. This is a highly specialized system, not at all adaptable to ground navigation, and it is, therefore, discussed in the section on bombing.

The methods we are discussing here are sometimes called "telemetric" methods since they are based on accurate measurements of distances. We have now to consider another important member of this class, the hyperbolic method. This requires, in its simplest form, two pairs of ground stations (one station may be common to each pair) which emit synchronized pulses. In the aircraft these pulses are received and the time difference between the arrival of the pulses from the members of a pair is measured. This locates the aircraft on a hyperbolic line of position and two such lines (one from each pair) give a fix.

The great advantage of the hyperbolic-grid system is that the plane carries only a receiver; the traffic capacity of the system is unlimited.

The British "Gee" system is an example of a hyperbolic system of rather short range.

LONG RANGE GROUND STATION SYSTEMS

The distance to which the systems discussed above are effective is limited to the range over which stable radio transmission, at the high frequencies there used, prevails. For this reason the long-range navigational systems work on relatively low radio frequencies.

We shall not discuss the older radio-beam systems, nor the various direction-finding systems, as the characteristics and limitations of these are well known. One beam or radio beacon system, the modern German "Sonne" system, should perhaps be mentioned, as it is perhaps the most elegant example of its class. Sonne allows an observer to determine his bearing relative to a land station with an accuracy of the order of 1°. Two stations thus provide a fix. The range of the Sonne system is some 1000 to 2000 miles.

In general, the determination of bearing by means of directional antenna patterns, at the low frequencies, does not lead to a very accurate determination of position at long ranges. In this the telemetric methods are superior, the notable example being the Loran system, which is now in wide use. (Loran coverage now extends over one-fourth of the area of the globe.)

Loran is a hyperbolic-grid system operating, in its standard form, at about 2 megacycles. The range over water is of the order of 700 nautical miles by day, and 1400 miles by night, and the errors in fix vary from .1 mile to 10 miles, depending on the geometry of the lines of position. SS Loran, now in use over Europe, employs widely spaced pairs, synchronized by sky-wave transmission. SS Loran is capable of providing accuracy of the order of from 1 to 2 miles over an area of 1,000,000 square miles, but can be used only at night.

At lower frequencies still, transmission conditions are more favorable. The low-frequency Loran system now under development is expected to have a range of 1200 miles by day and perhaps 2000 by night, and to permit lines of position to be determined to 1 or 2 miles at 1000 miles. Accuracy such as this would probably suffice for all general long-range navigation problems, both civilian and military. There is, however, one aspect of future Loran development which is of particular importance in connection with long-range guided missiles or long-range bombers. There appears to be some possibility of increasing the accuracy of position determination by an order of magnitude through a new technique of pulse comparison. This development is still in the laboratory stage.

Clearly, no single system will provide the complete answer to the navigation problem for military aircraft. The requirements are various; aircraft and air tactics are continually changing. It is also clear, however, that radar and radio techniques are available in rich variety, and we may expect the vigorous application of these techniques to all air navigation problems in the future.

THE CONTROL OF AIR OPERATIONS

This subject includes military functions involving radar surveillance of movements of friendly and enemy aircraft, and the guidance of our own planes on their missions.

The first serious use made of radar was to watch over the Luftwaffe and to warn of its approach to England. Such early-warning radar was put into operation at the time of the Munich agreement. These "C.H." stations, together with a later and improved type "C.H.L.," enabled the RAF to conserve its strength against the numerically superior Germans in the Battle of Britain. The distance from which aircraft could be spotted by the early C.H. stations was 150 miles, and was limited by the height at which they flew. However, the very long wavelength upon which they operated (10 m) made direction measurement a tedious and approximate business. It also allowed very low-flying aircraft to escape detection entirely, for it is impossible to keep a long-wave beam pointed along the ground unless the station is situated up high, as on a mountain; and there are no mountains in the south of England.

The introduction in June, 1940, of the C.H.L. equipment overcame these difficulties to some extent. Its shorter wavelength (1-1/2 m) allowed the construction of an antenna which could be rotated in azimuth; thereby direction finding was made more exact. These stations could moreover spot low-flying aircraft when mounted at heights easily obtainable in England. (Indeed, the "L" in the code designation C. H. L. stands for "Low.") A great improvement in operator's facilities was also effected, for these sets introduced the plan position indicator, a big step forward in the radar art.

In this country, the prewar efforts of our Signal Corps produced the early-warning radar models SCR-270 and SCR-271. Operating on a wavelength of 3 m, these equipments were able to detect small aircraft as far away as 120 miles. In some respects this equipment was superior to the C.H. and C.H.L., although in the matter of operator facilities and comforts it left something to be desired. An SCR-270 was installed at Pearl Harbor previous to 7 December 1941 and plotted the first Japanese raid. Later on, and especially at Guadalcanal, this equipment gave a very good account of itself.

Mention should also be made of the splendid equipment produced in Canada and in Australia, and New Zealand. The Australians, in particular, during the early, difficult days of the Japanese war, produced their LW/AW or Lightweight Aircraft Warning set. This equipment weighed about 5,000 lb and required a supporting military establishment of 45 men. Upwards of 100 of these were installed in outlying air strips. These were transported entirely by air, the entire operation requiring nine C-47's. Many times the same nine aircraft were enabled to take off in time to escape Jap strafers by the very equipment they had delivered.

The easiest index of progress in the radar art is: How short a wavelength can one use? Judged by this criterion, the Germans, in the early period (1939-41), led the world by producing gear operating at 50-cm wavelength. Apparently their High Command underestimated radar's importance, however, and subsequent development was retarded; nor did they realize its offensive possibilities. The results have been disastrous to Germany, for British radar helped turn back their bombers, whereas their radar defenses were later saturated by the RAF, which, in addition, employed radar bombsights. The Germans made frantic efforts to duplicate captured Allied gear.

Japanese radar apparently stems from equipment captured in the Phillipines and in Singapore (U.S. Army SCR-270 and SCR-268; British GL Mk. II and SLC). Although their Navy possessed microwave equipment of Japanese design, their radar development is generally considered to be three years behind ours.

In the military use of such equipment the importance of knowing the height as well as the position of aircraft is obvious. Now the procedure for finding height by long- and medium-wave stations, such as SCR-270 and C.H.L., depends upon a painstaking calibration involving many test flights, and this is readily seen to be a disadvantage. Moreover, the direction of the aircraft is not given with real precision. The wide beam causes a single airplane echo to be so fuzzy as to overlap that of any other plane within 10 or 15 miles. The great advantage of microwave equipment is that it overcomes these difficulties. A further advantage is that low-flying aircraft are easily detected, the only requirement being that they be above the optical horizon.

PRESENT STATUS

The development, here and in England, of the microwave technique has so increased the use of radar that a continued historical account would be much too long. In this section, therefore, we shall briefly summarize the various functions of control radar, assuming in each case that the most modern equipment is used.

Control of Night Fighters.

The task is to detect enemy bombers as far away as possible (200 miles) and to place a night fighter on a practical closing course with each bomber. The task is complicated by the fact that the enemy carries tail-warning radar, necessitating broadside attacks. The RAF have gotten scores of 20% pretty consistently using Mosquitoes against German aircraft. This operation requires great skill and cooperation between the pilot and ground controller in order that the two aircraft, original several hundred miles apart, shall be brought into correct relationship for a "kill."

Control of Day Fighters.

This type of operation, when used defensively, has already been alluded to in connection with the Battle of Britain. Its chief aim is to conserve fighter strength by minimizing the fruitless patrolling of peaceful areas. The idea is to send up squadrons directly at enemy formations, or to direct friendly planes already in the air toward a scene of activity. Although this was originally a defensive operation, it has been made to pay off offensively as well. Our aircraft were enabled to dive out of the sun or from cloud cover upon German craft over a considerable region of western Germany. Statistics show a very marked increase in both the total number of kills and in the kills per loss ratio.

Fighter Escort Rendezvous.

The effective range of Eighth Fighter Command planes has been increased by precisely-kept rendezvous with the bombers. This is made possible by directions from the fighter-control stations.

Air-Sea Rescue.

Since track is kept of all airplanes and, in particular, of returning bombers, it is possible to send rescue craft to the location of ditched airplanes. In addition, many damaged aircraft which would otherwise have been lost, are guided to friendly airstrips.

Meteorology.

Heavy storms and thunderheads appear on the screen as recognizable patterns. Aircraft may therefore be guided around or through such storms. In places without enemy activity, like the Panama Canal Zone, this is one of the chief uses of ground radar.

All the above operations may be carried out by means of the MEW (Microwave Early Warning type AN/CPS-1) radar. This is a scanning type of radar; that is, it sends out a long finger of radiation which slowly rotates like the beam of an airport searchlight beacon. The azimuth angle and range of objects spotted by this beam are "plotted" to scale as bright spots on the face of a cathode-ray tube. A map may be drawn on the face of the cathode-ray tube, and there will then appear on this map a bright spot for every airplane (or group of airplanes if they are close to one another) within range.

It is characteristic of such equipment that more than one indicator tube may be provided. The entire picture need not be presented upon each of these; instead, a different, magnified section may be shown on each tube. The value of this will be appreciated when it is realized that one MEW set covers an area of 120,000 square miles. One man would indeed be kept busy following all the aircraft detected.

The MEW equipment does not tell the height of aircraft, and for this purpose a British set, the A.M.E.S. Type 15, is provided. The finger of radiation of "beam" of the A.M.E.S.-15 bobs up and down like a seesaw. In consequence of this motion, it is able to indicate angle of elevation as well as the range of aircraft. A new equipment, called V-Beam (AN/CPS-6), combines the functions of both MEW and A.M.E.S.-15.

Ground-Controlled Bombing.

An important function of an air force is to support the ground troops by bombing, rocket fire, and strafing. Since the targets are protected by intense automatic weapons fire, it is desirable for the pilot to find the targets quickly; but this is rendered difficult by their small size and by camouflage. For this job the airplane must be precisely directed to a spot on the ground which is not visible on the radar screen. A device of very high precision is therefore required, and this has been found in an adaptation of the SCR-584 equipment, originally designed to control heavy antiaircraft artillery.

The means of indication is not primarily a cathode-ray tube in this equipment. Instead, a pencil is made to move over a large scale map, drawing a plot of the aircraft track. the operator simply advises the pilot to go right or left so as to pass over the target and gives him warning of his distance from it. The SCR-584 has been particularly successful in denying the use of frontline roads to the enemy. Single fighters are simply kept flying up and down important highways 24 hours a day. At night other aircraft drop flares from a higher altitude to illuminate the road.

At the present time fighters and medium bombers are the types most in need of ground control; however, a very special equipment was used by the RAF Bomber Command during 1943 and 1944 in its heavy attacks upon the Ruhr. This equipment, whose code name is "Oboe," will now be described.

Oboe equipment requires two ground stations separated from 50 to 200 miles. Each of these stations measures the distance from itself to the controlled aircraft. These two distances and the distance separating the two stations determine a triangle and hence locate the position of the aircraft. In order to make the operation more certain, a signal repeater or beacon is carried by the airplane.

To approach the target the aircraft is required to fly a circular course whose center is at one of the ground stations. The deviation of the plane from the prescribed course is precisely measurable (±10 yards) at the ground station, and an A-N signal is automatically retransmitted to the pilot. While this is going on, the second station simply waits until the aircraft is a certain distance from it and then gives the drop signal. Thus the bomb-dropping point is defined by the intersection of two circles, one of which is centered about each of the ground stations.

The Oboe procedure is far more complicated than the above would indicate. The station sites must be surveyed to the utmost attainable precision. The pilots and navigators must be able to fly a very difficult course at high altitude. The control apparatus is complicated by corrections for the ellipticity of the earth, wind speed, bomb ballistics, etc. Finally, but one plane can be controlled at a time. In spite of these apparent drawbacks, the RAF Pathfinder Force was able effectively to flare-mark targets in the Rhineland for over a year. The main force bombers bombed the radar positioned flares, and these were replaced every three or four minutes in order to control the bomb pattern. A microwave version of this equipment was used; however, there are now superior systems available giving the same precision and greater traffic-handling capacity.

FUTURE DEVELOPMENT

The future development of control radar falls into two categories; radar for the defense of this country and radar for attack. It is probably not necessary to say much more about the defensive possibilities of ground-control radar. The problem of the future is chiefly an economic one; to install sufficient stations to surround the country completely is possible and necessary. Since these stations will be easily integrated into the air-lines navigational net, the investment will be of great peacetime value.

Indeed we may except to see a band of MEW stations, consisting of at least two rows spaced 200 miles apart, the stations of each row also being about 200 miles distant, one from the other; it will completely cover the country. In addition, there will certainly be an MEW or V-Beam station at every major airport and at points every hundred miles or so between airports. The part played by these stations in peacetime will be:

1. Customs surveillance to prevent smuggling.
2. Survey of the airlines, including a course plot for every airplane flown, in order that the position of aircraft making forced landings be accurately established.
3. Detection of unexpected storms on the airways and the guidance of aircraft through or around storms.
4. Emergency navigation aid for lost aircraft.
5. Policing of the airways, keeping noncommercial aircraft out, preventing collisions, and directing the aerial police force.

These will be the peacetime uses of the MEW network; in war it will be our protection against sneak attacks, and against air raids of all descriptions. For this purpose radars of the MEW or V-Beam type can be developed easily to whatever degree is necessary to cope with higher-flying and faster aircraft of the future.

The possibilities of control radar for offensive warfare have an even more direct bearing upon aircraft design. The use of ground-based control radar requires the air force's commanding officer and his staff to remain on the ground at present, and moreover, the range of operation is limited by the earth's curvature to about 300 miles.

On the other hand, once they have taken off, there is today no unified command of our strategic bombers at all, unless radar is used. Anyone who has observed formations being made by the Eighth Air Force bombers subsequent to take-off, must realize that each wing is a separate entity in the air. Furthermore, even this small number of airplanes is only kept under control with difficulty. The trouble is that no one can command without knowledge, and this is unobtainable in the air. Consequently, the plan of attack is extremely inflexible. As a result, no maneuvers are possible to avoid unsuspected enemy defenses; no possibility exists of changing the attack best to fight the enemy.

Suppose, however, that each group commander could see the positions, on a screen, of his own group; that each wing commander could similarly see on a screen each of his group commander's aircraft, and similarly for division and air force commanders. At the same time, the enemy air positions would be easily visible. It would then make sense for the commanding general to fly, for he would have sufficient information with which to make decisions. Moreover, his information would be hot and accurate. No one need tell him anything; instead, he would see the force as it might be spread over thousands of square miles.

The essential apparatus for the first such general staff plane is available in the AEW (Airborne Early Warning) apparatus, which can see all aircraft in the area of over 30,000 square miles. Suitable radar beacons to act as flags on the various command aircraft are also available.

The utility of such a scheme may prove sufficiently great that special long-range aircraft will be designed for the purpose. Note that the use of such aircraft is not predicated upon the continued employment of long-range heavy bombers; they will be needed as long as we send any airplanes to attack by any means, and as long as the enemy sends other aircraft to meet them.

AIRBORNE RADAR FOR ATTACK ON SURFACE TARGETS

Radar may be carried by aircraft as an aid in the attack of surface targets whether on land or sea. It is useful not only as a means of seeing through cloud and darkness, but also by virtue of its ability to measure distance and to perceive objects at great distances. Radar sights are available at present for firing all the major weapons of an aircraft: guns, cannon, rockets, torpedoes, and bombs. Radar bombsights fall into several classes according to the tactics required and the nature of the target. Possibly the most important of these, and one whose description can be made most general, is the type used for long-range overland bombing from high altitude.

AVAILABLE! BUT THEY DON'T WORK! NO!

RADAR FOR HIGH ALTITUDE BOMBING OVER LAND

The method of operation of this apparatus follows. A beam of radiation, very narrow in the plan view but broad as seen from the side, is sent out from the bottom of the fuselage. The ground is thereby illuminated along a straight narrow path, starting from beneath the plane and extending to a maximum range of perhaps 50 to 100 miles. This beam can be rotated in azimuth (or in the plan view), and this is done rapidly and at a constant rate. Thus the surface of the earth is angularly scanned, and by pulsing this transmitted energy, it is scanned in range as well. Naturally the signals reflected back from various objects on the earth's surface after detection and amplification are best displayed by the Plan Position type of indicator (PPI); water appears black, whereas all land gives a medium bright signal, and built-up regions return a very strong signal. This latter effect is caused by the many flat surfaces and corners in a mass of building reflecting the beam like facets on a diamond. Indeed, cities, as seen on the PPI screen, sparkle like a mass of jewels set in a luminescent map. Land-water boundaries, shorelines, and beaches appear sharply drawn on the radar screen, shown in their natural proportions and easily recognizable.

It is also possible to generate an artificial signal which can be made to appear on the screen, if so desired, in the form of a cross. Moreover, the device which generates this signal may be connected to the telescope of the optical bombsight. If this is done, the cross will appear to cover the image on the PPI screen of whatever object on the ground at which the telescope is pointing. One may therefore adjust the bombsight computer (and consequently steer the airplane) either by looking through the telescope or by looking at the PPI tube.

The equipment described above represents a gradual development from what was originally ASV apparatus used to hunt subs. At the present time the difference between blind-bombing equipment and ASV or "Sea-Search" equipment is that the latter emphasizes sensitivity to objects normally hard to detect, whereas bombsights emphasize precision and ability to show detail. The difference is anlogous to that met in photography, where fine-grained emulsions are slow or insensitive, whereas the most sensitive emulsions are coarse grained and do not reproduce fine details. The underlying causes are of course, entirely different, and this analogy should not be used as a basis for reasoning about radar.

A large variety of radars of this general type is in production. Some are designed for high-precision bombing, such as AN/APQ-7 and AN/APQ-34; others are good for medium-precision, high-altitude bombing as well as the ASV function, such as AN/APS-15 and AN/APQ-13; still others are suitable only for low-altitude bombing and ASV use, such as SCR-717. A particular gear, the AN/APS-10, has been designed chiefly to make available to transport aircraft the navigational data referred to above. It is a lightwieght set of medium sensitivity and medium precision. In addition, the Navy has its own complete line of these equipments. Installed weights vary: 150 lb for AN/APS-10; 500 lb for SCR-717; and 1100 lb for AN/APQ-7. Power required varies from 0.4 kva single phase 115 v, 400 c and 0.05 kw, 27 v DC for the AN/APS-10, to 2.3 kva single phase 115 v, 400 c and 0.4 kw, 27 v DC for AN/APQ-7, being roughly proportional to weight.

FUTURE DEVELOPMENT OF HIGH ALTITUDE BOMBSIGHTS

The invention and future development of expendable pilotless bombers, such as V-1, Willie Orphan, etc., and of guided bombs, such as Azon and Razon, make it difficult to discuss the future of bomb-aiming equipment in general. In this section, therefore, we shall restrict ourselves to devices useful in bombers which carry men and are not expendable. The future development of the apparatus previously described will be conditioned by the type of aircraft it is intended for, and conversely, will also affect the design of the aircraft, for there are certain fundamental limitations imposed by ballistics, aerodynamics, and electronics. We know, for instance, that if bombers are to travel much faster and higher than at present, then the bombs will be dropped while the aircraft is a correspondingly greater distance ahead of the target.

This fact is illustrated by the following table which shows the approximate forward throw of an average heavy bomb for three airplanes.

Airplane	*Altitude*	*Ground Speed*	*Forward Throw of Bomb (measured along the earth's surface)*
B-24	20,000 ft	300 mph	2.3 miles
Me-262	40,000 ft	600 mph	6.5 miles
XB-?	80,000 ft	1200 mph	17.0 miles

In addition, here is some information of interest concerning optical bombsights: The time generally allowed for aiming the Norden bombsight when high precision is desired is about one minute; this means that the target is normally first seen in the telescope about 5 miles in advance of the dropping point or 7.3 miles from the plane itself, according to the top line of the table. A similar aiming allowance of one minute applied to the third plane gives us a figure of 37 miles as the distance at which the target must first be distinguished. There are only a few places on earth where the atmosphere is so clear that one can use a telescope at such distances, and most of these are not worth bombing.

Precision requires a corresponding increase in maximum seeing range even for the radar. This is not impossible to achieve, especially if the airplane flies at greater altitudes; however, it is also very necessary not to lose the fineness of detail at the dropping point. The latter requirement, in the light of present knowledge, will almost certainly require the antenna structure to be larger. Thus, if a four-foot antenna is satisfactory at 400 mph, roughly an eight-foot one will be required at 800 mph, and so on. This may mean that very small, fast, human-piloted airplanes are impractical as long-range, high-altitude bombers, because no bombsight can be fitted.

There is one possible way out of this dilemma, for radar, by viture of its map-drawing ability, makes possible offset bombing. That is, one aims at one object in order to hit another, whose geographical position is known with respect to it. Thus the aiming point might be taken in advance of the dropping point by 15 miles for the case of the 1200-mph airplane in the table above. Then a bombsight suitable for the B-24 would also display sufficiently fine detail for the fast airplane. The catch is that a compass accurate to about one-tenth of a degree would be required for precision offset bombing; by way of comparison, the newest Gyrosyn and Fluxgate compasses are good to ± 1.5°. Granted the improved compass, a bombsight computer exists in the AN/APA-44 which is very suitable for offset bombing, even under these more stringent conditions of the future.

Alternatively, if the very fast small aircraft is to be used at distances not greater than the horizon (about 250 miles for an airplane 30,000 ft high) from friendly territory, satisfaction can be guaranteed. Any method proposed for controlling a pilotless airplane will also control one with a man in it. In addition to such methods, there exists a satisfactory device in the SCR-297 of Shoran equipment.

An aircraft employing Shoran measures its range from two fixed points on the ground. These ground points are suitably delineated by radar signal-repeating stations or beacons. As is the case when Oboe equipment is used, the airplane may be located by a range triangulation process. With Shoran, however, the aircraft is not controlled from the ground and several aircraft may therefore utilize the beacons at once. Shoran, installed in a limited number of aircraft, has given very good results in Italy. It is possible to combine this style of equipment with the PPI type previously described. This has been done, and it is in use at present in B-17 and B-24 airplanes of the Eighth Air Force. It is called "Micro-H."

The problem of bombing land targets by means of radar from low altitudes has not received much study to date. Methods dependent upon ground stations such as Shoran are satisfactory as far as precision is concerned, but their use severely limits the range of operations. Self-contained equipment of the PPI type probably can be developed to the extent necessary if only large strategic targets are involved. With the exception of bridges, radar attacks on small tactical targets deep in enemy territory will continue to be difficult.

RADAR FOR BOMBING SHIPS

The problem of bombing ships from high altitudes is simpler in that much less detail need be presented on the radar screen. However, ships cannot be bombed successfully from high altitudes unless they are stationary or moving in a straight line, because the large time of fall of the bomb otherwise allows the ship to evade it. This might be remedied by the use of the Razon or Pelican types of bomb. No radar exists at present for directing the Razon bomb. Whether such a radar should be built may depend upon the importance attached to bombing isolated targets such as ships from high altitude, as well as on its technical possibility.

Ships have been bombed by radar for the past two years from low altitude using SCR-717B radar and the AN/APQ-5 attachment. Great precision has been obtained and this could be increased by the employment of the AN/APA-5 attachment. The limitations which apply to high-altitude bombing over land do not at all apply in this case. These aircraft may be as small and as fast, and may travel as far from base as is possible, as far as radar is concerned.

To summarize, we might take all the adjectives which describe a bombing operation and discuss the various combinations of the various qualities from the radar point of view. Such qualities are: low- or high-level attack, slow or fast attack, near or far from base, water or land target, strategic or tactical target, large or small airplane, and so on. This, however, would be out of place in a preliminary survey. It is obvious that which of the above alternatives is more desirable depends on technical factors, other than electronic; emphasis will also be given to the technical developments of the enemy, such as his fighter and antiaircraft development. Possibly the most important datum in question is the sort of war we expect to fight in the future. It would seem that a war fought against a small country would not be "total;" that is, all our industry and man-power would not be utilized. Under such conditions we might expect to work with competent and highly trained personnel, a small budget, and ineffective enemy opposition. This set of circumstances may turn out to be ideal for the use of very large aircraft equipped with complicated apparatus of high precision, capable of placing small numbers of bombs in the right places, the aircraft themselves forming part of a permanent establishment. Radar for such a purpose would be very different from that employed in a "total war." The latter, in which we have a conflict between industrial rather than purely military establishments, may of necessity be fought with large masses of relatively simple equipment. It may be that long-range guided missiles will turn out to be most important in such a case.

ROCKET AND CANNON FIRE

To date, the firing of fixed cannon (75 mm and 105 mm) and of rockets from aircraft has been successful only in daytime operations. The use of radar range finders, together with optical sights, has ~~marvelously~~ improved the accuracy of both types of fire against surface vessels and bridges, the increase in accuracy in the case of the 75-mm cannon being a factor of four or five at an "open-fire" range greatly in excess of that previously used. The AN/APA-30 attachment is suitable for supplying the correct superelevation to an optical sight from a search radar. The AN/APG-13 is a self-contained radar range finder weighing about 100 lb installed; it supplies about the same information as does AN/APA-30. Although these equipments are useful only by day, the problem of firing against ships and bridges by night is by no means insuperable, the chief difficulty being the fixed nature of the cannon or launching devices. This makes it necessary to know the relative velocity of the air and the target, as well as the target bearing, the latter being easily obtained at present by most airborne radars.

The problem of ground strafing, whether by machine gun, cannon or rocket, is receiving some study. The chief complication arises from the smallness of the target and the resultant difficulty of resolving its echo from those of surrounding objects. An ingenious solution is promsed by the "Vulture" project. In this device again, only range data are given to the gunsight, the problem being to set the radar range finder upon the same target at which the pilot is aiming. This is achieved by an application of the conical scanning principle, which furnishes a method of obtaining pseudoresolution, useful under certain restricted circumstances. It may be that the development of extremely high resolution, short-range radars is possible, having beam widths on the order of 0.1° and pulse lengths of 0.01 microsec. Such devices should give fairly good pictures of the ground, useful for strafing.

A separate attack is being made upon the problem of detecting moving vehicles. These, by virtue of the Doppler effect, send back a distinctive fluttering echo, and some attempt is being made to utilize this effect. Indeed it may be possible to show the moving targets on an airborne PPI tube to the exclusion of all else. This would be an extension of the MTI (Moving Target Indicator) apparatus now under development for ground-control radar.

AERIAL WARFARE

FIGHTERS

"Night fighting" is the classic example of the use of radar in plane-to-plane combat. This general term has a restricted meaning, namely, the attack on night bombers by specially equipped fighter planes. The special equipment of the fighter usually included and AI (Aircraft Interception) radar set, such as SCR-720, an IFF interrogator, and a voice radio. Because such aircraft are incapable of carrying more than a few hundred pounds of electronic equipment, the distance at which they are able to detect enemy bombers is limited to a few miles.

P61 carried a 9000# radar thing. + was no damn good!

Like the majority of radar equipments, AI apparatus is characterized by its narrow, finger-like beam of pulsed radiation. The use which is made of the beam and the resultant signals, however, is sufficiently different from the usual radar to make a description worth while. The SCR-720 set provides the pilot with a special indicator, which endeavors to show him something much like what he would see if he were looking through his windshield in daylight. To this end, the signal of the target airplane appears as a dot on an otherwise neutral background. As the target is approached, the dot is made to grow "wings," that is, it is distorted to appear roughly larger, as the target would, if visible. This action is calibrated, so that when the wings reach a certain size the pilot will know that he is within firing range. If it is permissible, he may thereupon fire blind. The motion of the spot on the tube also follows what might be the apparent motion of the target as it would be seen framed in the windshield. That is, if it were ahead and lower, the spot would appear at the bottom center of the tube; if the target were ahead and to the right, this would be similarly indicated, and so on. The center of the indicator tube is accurately lined up with the guns' cross-over point, and is, indeed, the "gunsight." Because the apparatus is installed in the noses of aircraft, it cannot see behind. Although this is not a handicap to night fighting, there are some aircraft for which special radar has been developed to enable them to detect tail attacks.

Night fighters almost invariably work in conjunction with a ground control station because of the limited range of their equipment. The procedure is then for the ground station to vector the night fighter (who flys entirely blind) into such a position relative to the bomber that it can be detected and "homed on" by the AI. It has always been and still is a severe restriction upon our night-fighter pilots that difficulties in recognition require a sufficiently close approach to the target to permit visual identification. To a large extent this has been due to poor IFF discipline and is being remedied. However, it will always be true, as long as recognition is based upon one single characteristic, electronic or otherwise, that the means of recognition may be disabled by accident or enemy action. Therefore we can only improve, we cannot make perfect, recognition devices by radar or any other single technique. One improvement in electronic recognition equipment might be to couple the radar and voice radio, so that the pilot interrogated could himself give the password. The possibility of making an AI radar capable of discerning such fine detail that the cathode ray tube would show a reasonably clear picture of the target might also be considered for its IFF value.

Indeed, this possibility is but one of several very different ways in which night-fighting equipment may develop. The tendencies are:

1. For the range and resolving power of ground control stations to increase, implying that no radar need eventually be carried in the aiplane, ordinary day fighters being used also at night.

2. For the range and resolving power of the airborne radar also to increase, but because of the size and weight limitations, both improvements will not be had in the same aircraft.

Thus, if range increases, one may have a free-lance night fighter which need not depend on any ground station; conversely, if in the more distant future resolution should increase to the point where recognition is possible, the range will probably not be great enough to dispense with ground control.

Much study will be required to determine what the future effect of these divergent tendencies will be. One possibility is that for defensive purposes, small radarless aircraft, like Me-163, will be used in conjunction with an extensive permanent network of long-range, high-resolution control stations. It may also be that free-lance aircraft, with powerful long-range AI sets, will be increasingly employed as intruder aircraft over enemy territory; for this purpose the IFF problem need worry only our adversaries. Still another possibility is that fighter planes, because of their speed, will need such great distances to maneuver in that radar will always be needed by the opposing pilots in order to find one another.

Thus far, we have considered what is essentially the problem of how to use the fixed-gun fighters (with guns we also include rockets if these are used from fixed mounts). For these the radar job is mostly one of homing on the enemy.

If it be assumed that the enemy jinks or has good radar-controlled defensive fire, or otherwise makes deflection shooting necessary, flexible turret guns will be required, togther with more complicated radar of the automatic-tracking or "lock-on" variety. Such equipment, capable of following the most violent maneuvers of the enemy and also of continuously aiming turret guns at him, is available in the SCR-702. This set, which was originally intended for use in the A-26 airplane, together with its associated computer, presents an attractive possibility (described more completely below).

It has become increasingly clear that even day fighters will require radar, at least for two purposes: range finding and tail warning. It has been found that the most successful day-fighter pilots are those who can judge the range to the enemy most accurately and who hold fire until the range has closed to an effective firing value. This range data can be supplied for the pilot simply and automatically by a lightweight radar, which can be used to light a green light when it is time to fire. New, fast planes, such as the P-80, will particularly need this facility, for the firing time in an encounter may be short indeed.

A fighter pilot suffers the great disadvantage that he cannot see behind him, especially when he is intent on the pursuit of an enemy ahead. He needs an automatic "rear-view mirror." The radar known as AN/APS-13 provides this warning when a plane comes within firing range of his tail, and ~~many~~ fighters owe their lives to this.

a [illegible]

DEFENSE OF BOMBERS

The defensive fire control for heavy bombers against both day and night fighters is a complex problem of radar, directors, turrets, and guns. In view of the present tendency to strip B-29's of all except the tail turrets, perhaps radar for the service of this plane should first be discussed. The AN/APG-15 equipment, weighing but 125 lb, is a complete radar system built into the rear gun turret. This set, operating on a wavelength of 12 cm, provides both angle and range data, enabling the turret to fire completely blind. Range is, of course, measured by timing the pulse echoes from the target; angle data is found by means of the conical scan principle, common to this equipment, the Vulture equipment for overland strafing, the SCR-584 equipment for antiaircraft fire control, and the previously mentioned SCR-702.

The fundamental idea of these devices is to send out the equivalent of four divergent beams from the radar. These four beams might, for instance, be sent out one degree to right, one degree to left, and one degree up, and one degree down with respect to the line of sight. If now the beams are all fat enough to overlap one another, it is possible for a target airplane to intersect all four of them at once. It obviously will intersect them unequally, however, unless it is exactly on the line of sight. Then, if each of these beams corresponds to a separate radar set, the four signals of the four sets will be unequal in strength and this can be read from four meters. Furthermore, by observing the four meters one could point the whole assemblage until they all read equally. One would thus have located the airplane.

The actual AN/APG-15 is much more clever than that, however, for it was an early discovery that the same result could be obtained by using only one beam. The idea is to move the beam to each of the four positions, right, up, left, down, in succession, at a rate which is fast compared to the motion of the target. A simple commutating switch then may connect the radar receiver to each of the four indicating meters in succession. The meters may be replaced by up-down and left-right servos to position automatically the antenna as in SCR-702 and SCR-584. Alternatively, some form of cathode-ray tube may be used and manual pointing employed, as with the AN/APG-15.

Bomber turret guns are equipped with rather precise lead computing sights to insure that the large deflection angles, which are becoming larger and larger as the speed of bullets remains constant while aircraft go faster, are accurately computed. It is vitally necessary to know the range of the attacking plane; optical methods, while sufficiently accurate, require more attention for their adjustment than the heat of battle allows the gunner to devote to them. Radar range finders fortunately can be made completely automatic rather simply. The AN/APG-5 and AN/APG-14 equipments are available for this purpose.

The fire-control and associated radar equipment for heavy bombers can be made indefinitely more and more complex. An analysis to determine whether one should abandon such air battleships seems in order before developing more complicated equipment, whose chief function may be only to slow down the airplane to the point where still more complexity and fire power is needed.

At the present time the glaring inadequacy in aerial warfare is the nature of the guns. The bullets travel too slow and there are not enough of them. The present radar is far better than the guns can make use of now, and there seems little point in improving it along present lines. If satisfactory controlled missiles should be developed for air-to-air fire, it will not be difficult to make suitable control radar equipment. The problem is to get the missile.

GUIDED MISSILES

We are witnessing the earliest stage in the development of guided-missile warfare, and it is already strikingly evident that the effectiveness of each new weapon of this class will depend to a very large extent on the solution of the problem of intelligence and control. On this point, the now familiar object lesson of the German V-1 is very convincing. The controls of this missile, which is, of course, not strictly a guided missile, are rudimentary, but, within their limitations, well thought out and intelligently applied. The accuracy realized was sufficient to make the weapon drastically effective, if not, as it might well have been in somewhat different circumstances, decisive. If the range and azimuth errors at the target could have been reduced by a factor of ten, however, a hundred-fold increase in density, on a single target, would have been possible. London would not have been the only target large enough at which to shoot. Had the Germans been able to guide the bombs along tortuous paths, the defense would have been more severely taxed. One cannot measure numerically the increase in over-all effectiveness which would have resulted from these improvements. Undoubtedly new countermeasures would have been called forth in time. The picture suggested, nevertheless, is one of a radically altered military situation.

The modification required in the weapon consists in the addition of two elements to the system: first, means for determining continuously and accurately the location of the buzz bomb; and second, a secure communication link for the transmission of steering orders to the missile. As we shall see, existing radar and radar techniques are capable of providing these facilities, and more. The important point here, however, is that an advance solely in the art of control can create an essentially new weapon.

In what follows, the intelligence and control problem will be viewed rather broadly. The role which radar and related radio methods may be expected to play in the solution of the problem will be outlined, and the mutual influence of future radar and missile developments will be suggested.

For this purpose it seems best to avoid the obvious classifications of missiles into categories according to methods of propulsion, or nature of launcher and target, or aerodynamic properties, and to concentrate on the essential features of the intelligence and control problem. These are (1) location of the missile, (2) location of the target, (3) transfer of intelligence to and from the missile, and (4) the problem of the servoloop.

LOCATION OF THE MISSILE

The instantaneous position of the missile can be determined from a controlling base (which need not be the launching base), or it can be obtained at the missile itself, and either relayed to the controlling base or used directly on the missile to control its course.

Microwave radar provides one method of locating the missile from the base. Accurate determination of range is inherent in the method; accurate azimuth determination (with present techniques, to roughly one mil) is obtained by lobe-switching methods familiar in fire-control radar. Accurate altitude, or elevation angle measurements can only be made when the elevation angle is greater than a few degrees. This would be the case for high-trajectory rockets (V-2), or antiaircraft missiles, but not for low-altitude, long-range missiles.

The radar method is extended and improved through the use of responder beacons. A radar beacon on the missile provides a strong, reliable signal at long range, permits the elimination of extraneous echoes, and can provide positive identification of the missile.

Another method which could be used is the Oboe system, described more fully in "The Control of Air Operations," page 11. Two ground stations interrogate a beacon on the missile, thus measuring its range from two points. The method is very accurate; it is somewhat less flexible than the direct radar method, and is, of course, applicable only where fixed control bases, themselves accurately located with respect to one another, can be provided. The method does not give height information.

A fundamental limitation to both methods, in fact to any method using high-frequency radio waves, is that the missile cannot be followed over the horizon. Here we begin to see how inextricably the development of control methods and the development of the controlled vehicle are tied together. A vehicle which can fly no higher than, say, 10,000 ft can be seen, from the ground, no further than 140 miles. Clearly it would be foolish to expend a large effort in improving the range of the vehicle without a parallel development of some other means of location and control. Without the latter, one would tend to favor high-altitude missiles for long-range bombing.

The line-of-sight range limit can be circumvented by providing one or more airborne "relay stations" (a method already developed for Oboe), by putting the controlling radar itself in an aircraft, or by shifting the location problem to the vehicle itself, which brings us the second case mentioned in the beginning of this section.

The determination, at the missile, of the missile's position, either in fixed coordinates or relative to the target, is essentially a navigation problem. It is interesting to examine the navigation methods outlined in "Navigation," page 8 with this new application in mind.

Direct-radar navigation seems to require human intelligence. The radar maps would have to be transmitted back to the base for interpretation. This would require a high-frequency link which would be technically possible within horizon range. A somewhat similar method involves the use of a television system, replacing the eyes of the absent pilot and providing more accurate map, but only in clear weather.

A very simple method is provided by a narrow radio beam, laid down along the desired course. This is accurate only at short ranges; a variant of this method has been seriously considered for control of antiaircraft projectiles.

The telemetric methods (H, Shoran) lend themselves to automatic operation, and allow the missile to navigate as an independent entity. This last point has an important bearing on the traffic capacity of the system. Loran, in its present form, does not provide high accuracy (although it would compare favorably with the German V-1) but it does reach to very great ranges. Moreover, future improvements in Loran methods may provide very much improved accuracy. Should this possibility be realized, it might have a profound effect on the development of long-range propulsion methods.

LOCATION OF THE TARGET

The location of fixed targets is, of course, a matter of reconnaissance and accurate mapping. A new problem arises when the attack is directed against a moving target, such as a ship or aircraft. The target locator, be it radar, television camera or any other device, then becomes a part of the guided missile system, and its characteristics influence the apparatus and the tactics.

If the locator is itself on the missile, the operation is normally one of homing. Many varieties of homing missile have been devised, usually for rather specialized applications. Radar homing may be useful against isolated targets, ships or aircraft, but land targets cannot be singled out and identified automatically, Heat homing is limited to special types of targets.

It may be technically possible to combine long-range guidance with a homing operation at the last stage of the attack. A tactical situation in which this operation would be profitable is not easy to visualize, however. Knowledge of the presence and disposition of such distant targets is not likely to be available unless means for striking from shorter range are also available.

TRANSFER OF INTELLIGENCE TO AND FROM THE MISSILE

Missiles which do not operate as independent units require a radio link with the controlling base. Over this link are passed, from base to missile, control signals which tell the missile what to do. The reverse path may be required for reporting back from the missile its position, altitude, speed, heading, or other pertinent data.

Reliability and security from enemy jamming are essential requirements of such a link. It will require constantly renewed effort to meet the latter requirement, as our own methods and those of the enemy are refined and improved. With the development of microwave techniques, however, the task of the jammer has become more forbidding. Moreover, the relatively simple intelligence which such a link is usually required to transmit can be coded in a variety of ways, providing a "lock" type of security.

The transmission of more elaborate information, such as a radar map or a television picture, requires wide communication channels at high frequencies. The fundamental problems are not new.

An important aspect of the communication problem is the requirement, in most applications, of high traffic capacity; that is, the ability to receive information from and control several missiles simultaneously but independently. This, like the jamming problem, calls for coding methods, multichannel operation, and other technical tricks; it also calls for careful study of the tactical operation and the functioning of the whole organization involved in the dispatch of the missiles.

THE SERVOLOOP

The combination of all the elements of intelligence and control in the form of a complete system leads to a dynamic problem in which it is not possible to treat any single element by itself. The guided missile, with its locator and controls, forms a closed servoloop in which information is obtained, used to actuate controls which alter the course, which, in turn, changes the information, etc. This loop contains mechanical, electrical, and, in some cases, human links. The dynamics of its operation, for instance, its stability, are determined in a complicated way by the individual elements. The aerodynamic properties of the missile, for example, cannot be ignored in designing the communicating link. If the target is moving, it also enters the problem, its maneuverability is an important parameter of the dynamic system.

The successful development of guided-missile methods will require careful analysis of the whole system.

GENERAL CONSIDERATIONS

The development of radar and other detection and navigation devices has provided a wealth of technical means for locating and guiding missiles. The application, even of existing techniques, to guided missiles, however, brings in new and important problems because of the large scale on which guided-missile warfare must be planned. Measured on this scale, present production of radar equipment is far from mass production. The design of the equipment is such that it is doubtful whether the industrial resources of the country could provide mass production. It will be necessary to develop radar components which are to present radar equipment as the V-1 engine is to a standard aircraft engine, if such production is to be potentially available.

GENERAL TECHNIQUES

IDENTIFICATION

In a large number of situations where radar is used, the problem arises of identification of the targets detected. It is true that this problem does not arise in cases where radar is used for bombing land targets, for navigation, or for certain other special purposes. In most cases, however, it is of great importance to have some method of determining the identity of targets. In some cases all that is desired is a sure method of identifying friend or foe (IFF). In other cases a method of recognizing individual friendly craft is desired.

At first the problem appears to have a ready solution: to have each friendly aircraft or ship carry a beacon which will give a characteristic reply when challenged by a radar signal. The reply will have a general "code of the day" used by all friendly aircraft or ships (to distinguish against enemy craft) plus a personal recognition signal for each individual craft. The difficulties in such a system are so great, however, that no completely satisfactory one has ever been designed, or even visualized. A universal system may, indeed, be quite impossible, or any attainable one may be so complex as to render it impractical.

The difficulties in the system may be visualized by listing the over-all requirements and limitations which a universal system must meet:

1. It must respond to every airborne, ground, or ship radar in use. Since the frequencies of such radar sets vary from 100 to 30,000 megacycles (with a likelihood of still higher frequencies coming in the future), it appears at once impossible to satisfy this condition.

2. The identification beacon must reply in such a way that it can be seen and the code identified on any radar set for which identification is necessary. This, again, meets the same difficulty as in (1) above, in regard to frequency of reply.

3. The identifying signal must be such that even where very large traffic is concerned, the signal can readily be associated with the corresponding radar echo. In other words, the "resolution" of the identification must be equal to that of the radar.

4. While elaborate codes are needed for individual identification, the coded signals must be presented on the radar indicator, and the code from one reply must not obscure other signals or other replies.

5. The system must be secure against use by the enemy, either through the enemy's challenging the beacons and homing on them, or using them for early warning, or by the enemy's reproducing equipment and thereby radiating signals which would designate him as friendly.

6. It is desirable to have the identification system also usable as a beacon system, since beacons for various purposes on the ground, in ships, and in aircraft are

of great importance in specific locations, in providing precise information on navigation or bombing, in homing on friendly ships, aircraft, or ground stations, and for other purposes.

The technical difficulties are such that there appears no immediate hope of meeting all of these six requirements. The Mark V IFF system, now under development at the Naval Research Laboratory, is designed to meet as many of these as possible within the limitations of the techniques available at the time the system was laid out in 1942. In this system the difficulties of replying to all frequencies is avoided by having a special frequency band set aside for all IFF interrogation and response. A number of individual channels within this IFF band are provided for various purposes. It is probable that only a "separate-band" system of this sort is feasible. This means, of course, that every radar must be equipped with a special transmitter, the "interrogator," operating in the IFF frequency band, and a special receiver, the "responsor" to receive the replies. The frequency chosen for the Mark V system is too low to give the necessary resolution required in modern radars without excessively large IFF antennas. It would be possible to develop a new IFF system, using frequencies in the X-band (3 cm), which would be superior in many respects to the present Mark V, which operates at about 30 cm. Considerable development of techniques would be required, nevertheless, to bring such a system to the point where it could be introduced into service.

Such a high-frequency system, however, while useful, will not satisfy all the requirements of a universal identification, recognition, and beacon system. It will, therefore, be necessary to develop other equipment to assist in solving the problem. All possible supplementary identification, recognition, and beacon systems will probably have to be used in special circumstances, and those already known and others not yet suggested should be investigated and developed. Additional techniques useful for these purposes are the following:

1. Maintenance at a search radar station of continuous tracks on all aircraft, which are compared with full data on dispatch of all aircraft in the vicinity. Complete information on traffic is one of the best insurances that strange or unfriendly aircraft will be recognized.

2. The use of a variety of responder beacons for various special purposes; for example, special beacons in the airplanes which are to be controlled by a particular type of radar set; special ground beacons for homing; beacons on ships for guiding aircraft; shore-marker beacons for use by ship fire-control radar, etc. While it is undesirable to multiply the variety of special beacons, it seems essential to use many of them to accomplish all the possible desirable purposes.

3. The use of propeller-modulation frequencies as an aid in identification of aircraft. Under suitable conditions such modulation frequencies can be detected and measured on suitably equipped radar sets. (This is of no use in jet-propelled planes, of course.)

4. The use of techniques for direction finding on the aircraft or ship radar and communication frequencies as an aid in matching the position of a particular aircraft with a particular radar signal.

5. Requesting an aircraft with whom a controller is in radio communication to make particular turns or maneuvers in order that the radar signal can be associated with the aircraft.

6. The ejection by an aircraft, when instructed, of material which will give recognizable radar signals; for example, aluminum "chaff" or "window" material.

7. The use at short range of visual or infrared light signals.

8. Special attachments on the normal IFF equipment or particular modifications thereof to adapt it in special circumstances to new services.

COMMUNICATIONS

The necessity for reliable, noise-free radio communication channels which operate under all conditions of weather has been repeatedly mentioned in connection with the use of radar. Since it has become clear that radar allows a more adequate control of all sorts of air force operations than has heretofore been possible, it is evident that the possibilities can only be realized when an adequate radio communication system has been put into use by the air force. The requirements of such a satisfactory radio communication system are briefly:

1. It must operate, or at least have certain channels which operate, under all conditions of weather and atmospheric static. (This is possible if one uses frequencies upward of 1000 megacycles.)

2. The airborne antennas must be sufficiently small and suitably designed for the highest speed aircraft of the future.

3. The airborne components should be small in size and weight and consume the minimum of electric power.

4. A large number of channels, preferably selected by push-button control, must be available to avoid congestion.

5. Oral communication should be replaced by fast and partially automatic teletype where feasible.

6. Facilities should be incorporated in equipment to be used in or over enemy territory which will prevent the enemy from making use of the tradio transmissions or decoding them.

7. Transmissions must be difficult for the enemy to jam.

8. Selective directional communication from ground to a single plane should be possible.

Three different functions of radio communication must be distinguished, each of which will probably require a separate frequency band:

1. Long-range communication, that is, beyond line of sight;
2. Medium-range communication, within line of sight, up to 200 miles;
3. Very short-range communication, up to 20 miles (such as between planes in a formation).

Propagation conditions require that communication of the first type be at relatively low frequency, and will thus always be susceptible to atmospheric static. This can be minimized only by going to higher power transmitters.

Medium-range, line-of-sight communication should be at the highest frequency possible consistent with technical requirements of power available and techniques developed. Almost complete freedom from atmospheric noise can be achieved above 1000 megacycles (30 cm), and the evidence suggests that a satisfactory communication system could now be developed at a frequency of about 4000 megacycles (8 cm). Existing techniques can provide adequate power at this frequency, antenna structures are small and efficient, but some development in the frequency stability would be required.

There are two types of service which need to be considered in medium-range, air-ground communication: The "broadcast" type, where a ground station wishes to communicate simultaneously with many aircraft; and the "private line" type, where the ground station wishes to select a particular plane and talk continuously to it alone for a period. The latter service is not yet available in any system, and it is urgently needed in ground control of aircraft in night fighting, air-ground tactical cooperation, traffic control near an airport, and many other cases. With microwave techniques now being developed and with highly directional antennas, this type of service is now in sight.

For very short-range communication, such as that between planes in a formation, a very desirable feature would be to have the range of transmission limited so that it cannot be detected by the enemy at distances appreciably greater, say, than 25 miles or less. It now appears possible to achieve this result by using frequencies of the order of 60,000 megacycles (5 mm). Radio waves of this frequency are rapidly absorbed by the oxygen in the atmosphere, and this absorption is of such a nature that the energy becomes undetectable rather quickly beyond the given range. This range can, in fact, be adjusted by altering the frequency, since the absorption of oxygen changes as rapidly as a function of frequency in this range. Thus, it would be possible with a given transmitter power to adjust the frequency for a detection range of 3, 5, or 20 miles. With such a system the planes of a formation could communicate with each other at will with the certainty that their transmissions would be unheard beyond the preset range. Hence, they would not be warning the enemy of their approach, nor would the enemy be able to listen in and interpret their communications.

The above discussion shows the importance of investigating microwave techniques for plane-to-plane and plane-to-ground communications. These techniques will also find important application in ground-to-ground communications used for liaison, orders, intelligence, transmission of radar data, etc. In cases where laying of ground wires or setting up normal radio stations is difficult on a rapidly moving front, microwave communication links may be used as a substitute where line-of-sight propagation is involved. Such a system, the AN/TRC-6, a 6-cm communication and relay system, is now being introduced, and a great expansion of its application and use can be anticipated.

In addition to and in conjunction with microwave techniques, there are considerable possibilities in the application of pulse techniques to communication problems. In existing communication equipment a continuous carrier wave is modulated, either by amplitude or frequency modulation, to carry the intelligence signal. In a pulsed system the transmitter is modulated with a series of pulses, and the intelligence is carried by altering timing, phase, or the width of the pulses. Such a system has many advantages from the security point of view since special techniques in the receiver are required to decode the message. In addition, the pulse signals are difficult to jam by ordinary C-W jamming transmissions, and hence added security is gained. Several types of pulse systems have been tried out, some of which give the possibility of eight or ten communication channels on a single radio frequency. Such a system is also attractive from the point of view of use with automatic transmitting or recording equipment.

It is, therefore, evident that new techniques, when further developed, will allow radio communication service meeting all the requirements stated above.

RADIO COUNTERMEASURES

The subject of radio and radar countermeasures is a complex but important one. As much attention may be given to the "war of the ether" as to the war of ammunition." It is of great importance to deny the enemy, to the maximum extent possible, the use of the ether for his radio, radar, and control functions. It is of equal importance to the enemy to deny ourselves of this facility, and therefore great attention must be given to equipment which is as free as possible from enemy interference.

In principle it can be said that any radio or radar equipment can be at least partially jammed by the enemy (or the enemy's equipment jammed by ourselves), given sufficient knowledge of the equipment, sufficient weight and complexity in the jamming equipment, and sufficient power. It is useless, therefore, to talk about radio and radar equipment which is "jam proof." On the other hand, it is perfectly feasible to design radio and radar equipment which is so difficult to jam that the cost is prohibitive. There are thus two distinct and important problems in the countermeasure field:

1. To produce maximum interference with the enemy's radio and radar transmission at minimum cost (jamming);

2. To design our own radio and radar equipment such that the cost of interference by the enemy becomes prohibitive (antijamming).

JAMMING

The problem of jamming enemy transmissions divides itself into three parts: (1) Intelligence, that is, securing the maximum possible information on the exact frequencies used by the enemy for different types of equipment or service, and the nature and characteristics of the equipments themselves; (2) Detection, that is, the use of search radio receivers to explore the spectrum known to be in use by the enemy to determine what equipment is actually in use in an area, the exact frequency on which it operates, and the nature of its transmissions; (3) Jamming, that is, the use of techniques which will cause the maximum interference with the enemy's service.

1. *Intelligence.*

Intelligence is of the greatest importance. As the enemy develops more sophisticated techniques, it becomes more and more necessary to learn about them as rapidly as possible; otherwise jamming equipment of our own may be quite useless, or a great deal of energy and equipment will be required to insure against all possibilities. It is of utmost urgent importance to have adequate intelligence communicated promptly to those in charge of the development of countermeasure equipment. In order that the equipment may be designed most effectively to do the job in hand, the intelligence program should involve:

a. Special instructions to all intelligence officers to secure maximum amount of information and documents on enemy radio and radar techniques;

b. Prompt and thorough examination by specialists of all captured enemy radio and radar equipment, and the forwarding of such equipment intact to the cognizant laboratories;

c. Thorough examination by specialists of all reports coming in to various offices which will yield further information on enemy radio and radar transmission.

2. *Detection.*

The problem of detecting and analyzing enemy radio and radar transmissions is a large, difficult, and important one. A thorough analysis of the characteristics of a given radar signal can only be analyzed with rather complete equipment, capable of determining not only the frequency, but the pulse repetition rate, the pulse shape and size, power level, and other features. This means that special equipment of a variety of sorts, capable of searching the entire radio spectrum and analyzing unambiguously all transmissions detected, must be placed in quantities in forward areas during wartime. Special airplanes must be equipped to make extensive patrols over and near enemy territory for the specific purpose of gathering information on enemy radio and radar and transmitting it to the countermeasure experts. Special ground watch stations and stations on ships must also be fully equipped for analyzing enemy radiations from ground, ship, and airborne transmitters. In a global war a world-wide listening and analysis chain must be set up with special facilities in all combat theaters and a capable technical coordinating agency in the air force headquarters.

3. *Jamming.*

There are several general methods for rendering enemy radar less useful:

a. Electrical jamming, such as transmission of radio signals at the frequency of the enemy equipment so strong and of such a nature so as to mask completely the intelligence received;

b. Confusion jamming, such as the use of material which gives radar echoes (such as strips of metallized foil, known as "chaff" or "window," reflectors on parachutes or balloons, etc.) to "infect" an area with so many signals as to mask the real ones;

c. Deception tactics, such as employment of single planes equipped with special devices to give radar signals which appear to be due to large formations;

d. Saturation tactics, such as employment of so many aircraft coming in so many directions at once, with or without the use of window and electrical jamming, so as to make it impossible for radar operators to keep track of what is going on;

e. Avoidance, such as taking advantage of the fact that every radar has "blind spots," i.e., it cannot see over the horizon or down low, especially over land behind mountains, etc.

In simple cases where a specific enemy equipment, operating on a specific frequency with well-known characteristics, is being widely used, the electrical jamming of it may be a relatively simple matter. For example, in the early days of the use of the German "Wurtzburg" chain of stations for antiaircraft gun control and night fighter interception control, simple jamming transmitters carried by a certain fraction of the Allied air formations over German territory caused a large reduction in the usefulness of the enemy stations. In other cases, however, where the enemy is using a wide variety of equipment, scattered throughout a wide band of frequencies and equipped with special antijamming features, the electrical jamming of the enemy's radar may be far too costly to contemplate. In such cases one must resort to all possible confusion, deception, and avoiding tactics.

In any case, the air forces must have developed and manufactured in small quantities a wide variety of jamming transmitters suitable for various frequency bands and various power levels, some designed to go in aircraft and others in ships or ground stations, in order that, very promptly when new enemy transmissions are detected, the equipment can be put into action to jam them. This involves a large and expensive development and manufacturing program, with the chance that less than 10% of the equipment manufactured will actually be used. It is an essential program, nevertheless; otherwise there will be many months' delay between the detection of new enemy radio transmissions and the time in which equipment will be on hand to jam them. There are situations in which this delay might be disastrous. These limitations of such equipment must also be clearly understood since it is never possible to put enemy equipment completely out of action by jamming. The jamming can only be an aid to our own freedom of action, but never a complete guarantee under all conditions.

Fast action is one of the most important features of an adequate countermeasure program. If only a few hours or, at most, a few days elapse between the enemy's use of a new radio technique and the appearance of damaging jamming signals or techniques, the discouraging effects on the enemy using new equipment will be greatly enhanced. If the enemy can count on several months of trouble-free operation before jamming or confusion appears, the introduction of the new equipment will be very much to his advantage.

ANTIJAMMING

The steps which need to be taken to make our radar equipment more costly to jam are:

1. Narrower beam width; since this concentrates the power available and therefore requires a most powerful jamming signal, it makes the jamming signal effective only over a narrower angular range, and it reduces confusion caused by use of window and saturation tactics.
2. Higher power, since this forces the use of correspondingly higher power by the jamming transmitter.
3. The operation of different sets of the same type at different frequencies, since this requires a multiplicity of jamming transmitters to cover the different sets at different frequencies.
4. The ability to tune a set rapidly to new frequencies, thus keeping out of the frequency channel on which jamming signals are observed.

5. The use of receivers which do not easily "saturate."

6. Proper sighting to minimize blind spots.

All modern American radar has been highly developed in these various respects, some of it to the point where forbidding amounts of power over wide ranges of frequencies would be required for effective jamming. Still further progress in this direction will certainly come in the future, if development is continued, through the use of shorter wavelengths (higher frequencies), larger and more efficient antennas, higher power per unit of weight, and improved receiver circuits.

The jamming of airborne radar on the part of the enemy is an extraordinarily costly and difficult job. An airplane moves rapidly from one place to another and quickly gets out of range of particular jamming equipment. The jamming of airborne bombing equipment, for example, even over a single important target, might well require scores of high-power jamming transmitters scattered throughout the whole area in the vicinity of the target. The effect of such transmitters would be primarily to allow the detection of the target at a much greater range than without the transmitters. The chief problem in airborne radar, therefore, is the protection of night fighter equipment against jamming by the target aircraft.

The jamming of ground stations presents a different problem. In this case the station is fixed, which means that the jamming transmitter must be brought in the vicinity of it, usually by aircraft. The limitations of size and weight of equipment transportable by aircraft makes the jamming of high-power, narrow-beam ground stations particularly difficult. In general, the jamming transmitter can jam a radar station only in to a certain range. Within this minimum range the jamming is ineffective. This requires the aircraft to have both high power and to come in close to the jamming station. In either case this presents danger, since the jamming plane can be singled out and action taken by fighters against it.

SUMMARY

While considerable further analysis of the countermeasure problem would be possible, it can be said in summary:

1. A considerable effort is worth while in the development of jamming and confusion methods to reduce the effectiveness of enemy radar and radio. It cannot be expected, however, that such countermeasures will be always or continuously effective, and their limitations must be understood. At the same time, when employed tactically in a proper way to give the maximum element of surprise in cases where important operations are involved, appreciable confusion can be expected.

2. Further development of techniques for making our own radar less susceptible to jamming must also be developed. It can be anticipated that many types of our radar will not be jammed at all, while other types will possibly suffer to some extent under particular circumstances.

3. The whole problem of jamming and antijamming is one which depends on skill in tactical employment as well as in technical use of the equipment. Flexibility in the equipment and in the use of it can both overcome much of the enemy's jamming attempts as well as make our own jamming attempts more effective. Thus, highly skilled operational and technical people throughout the air force and in the headquarters, supplied with the most highly developed equipment, are essential to the carrying out of the radio war.

PART II

RADAR

A Discussion of Future Trends
of Interest to the Army Air Forces

By

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PART II

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PULSED RADAR

INTRODUCTION

Radar locates distant objects by illuminating them with radio waves and detecting a return signal, or echo. The direction of the echoing object is known more or less precisely if the transmitted energy or the sensitivity of the receiver to incoming energy, usually both, is confined to a small region in angle by the use of directive antennas. The fact that a measurable time interval elapses between the transmission of the radio energy and the reception of the corresponding return signal permits the distance or range to the object to be measured, and allows echoes from many objects at various ranges to be sorted out.

It is not easy to define radar in more specific terms without excluding, at one point or another, devices which are based on the above principles but which operate in a manner characteristically their own. For example, the distinction between "pulsed radar" in which short pulses of high intensity are transmitted, and "CW radar" which uses a modulated continuous wave of relatively low power, must be drawn at a rather early stage. The remarks which follow are made with pulsed radar in mind, primarily, a special section being devoted to the problems and possibilities of the CW methods. It is our purpose here to discuss the basic art of pulsed radar, without respect to particular devices for particular military problems, in order to suggest the present and future possibilities as well as the important limitations in the development of this art. We shall do this by considering in turn three important properties of a radar set, its range, its resolving power and its rate of coverage or scanning rate. Certain other topics which cannot be omitted from any assessment of the future possibilities of radar will be taken up separately, under "Target Properties," and "Propagation."

The essential parts of a pulsed-radar system appear in Fig. 1. We have first the primary power supply whose function is prosaic but whose characteristics may impose critical limitations on the other equipment. The transmitter consists of a high-power oscillator and the modulator, or pulser, which drives it. The transmitting tube emits, in short pulses of high intensity, electromagnetic waves which are radiated from the antenna. This radiated energy in the form of a train of waves of length equal to the duration of the pulse times the velocity of light, is confined

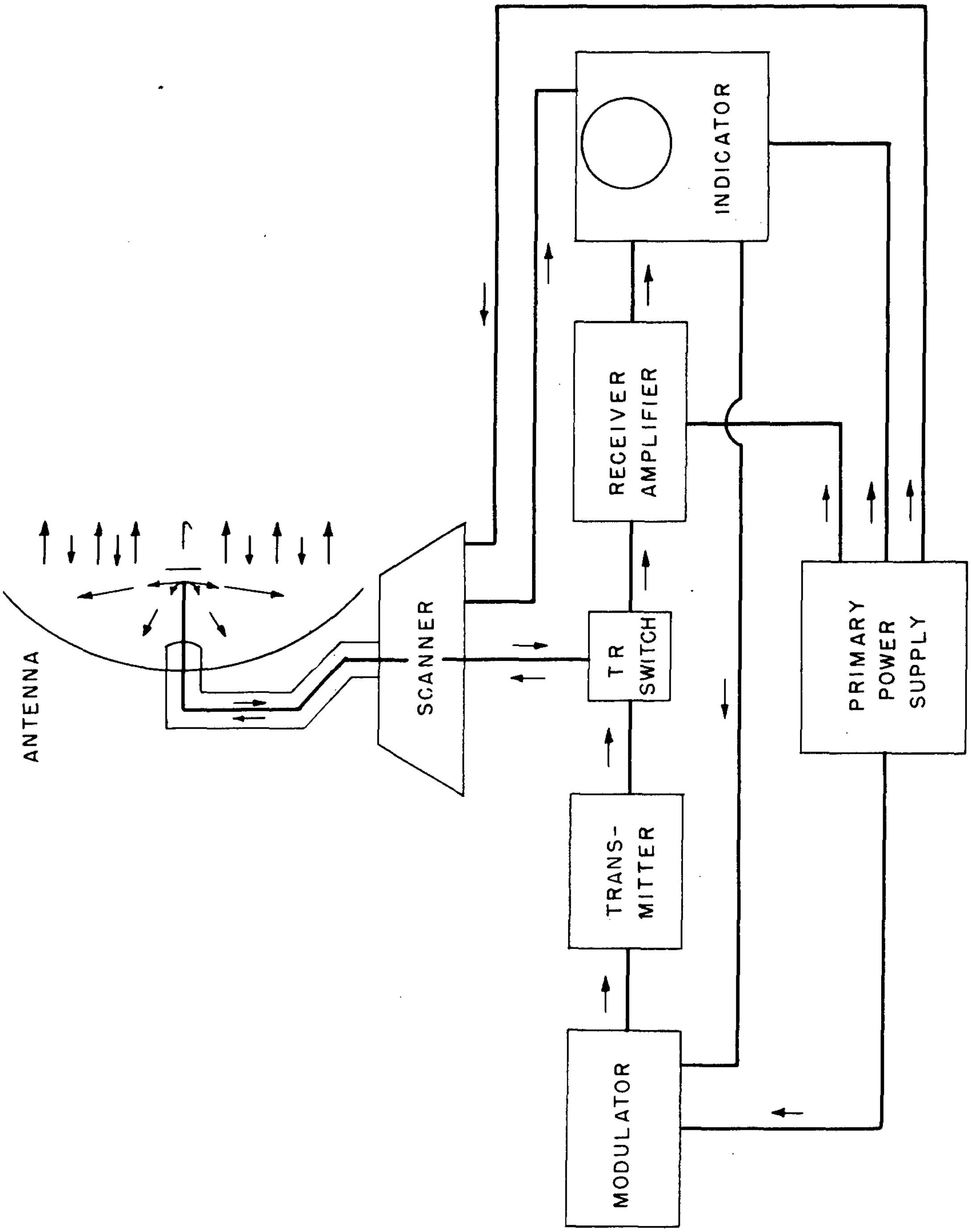
ANTENNA
SCANNER
TR SWITCH
TRANS-MITTER
MODULATOR
RECEIVER AMPLIFIER
INDICATOR
PRIMARY POWER SUPPLY

Figure 1

within a beam by the directional property of the antenna. One can think of a packet, or bundle, of waves of constant thickness in the direction of travel, but continually spreading in directions at right angles to the direction of travel. Any part of this energy which is reflected from an object within the beam spreads out again, more or less in all directions, and a very small fraction of it travels back and is received by the antenna. This signal, or echo, is amplified in the receiver and presented somehow on an indicator. It is not necessary, of course, that the receiving and transmitting antennas be one and the same, but they usually are. The difficulties of duplex operation (common transmitting and receiving antenna) which beset the early days of radar have very largely been solved and are therefore of no particular interest here. We include under "indicator" the time-measuring circuits on which we depend for range measurement. The scanner includes the mechanical and electrical devices for moving the antenna and providing, to the indicator, information of its instantaneous position.

RANGE

An important characteristic of a radar system is its range, the maximum distance at which targets of a given type can be more or less reliably detected. The factors which influence the range include most of the component parts of the radar system, not excepting the observer, as well as certain characteristics of the target and of the transmission path.

Ordinarily, the range limit is set by the requirement that the return signal be distinguishable against the inevitable background of receiver noise. The factors which control this limit are now well understood. The problem has been so thoroughly studied, in fact, that one can predict with considerable accuracy the performance of a radar set against a given target, when the characteristics of the individual components of the set have been specified. One can, moreover, be sure that no trick has been overlooked which, at little cost or sacrifice, would effect a remarkable increase in range. That is to say, the limitations to radar range are of a fundamental nature, and are not to be avoided by mere ingenuity. We shall discuss these factors collectively and individually below.

In the case of a "free-space" transmission path, which implies a direct line of sight between radar and target and the absence of any alternate transmission path via a reflecting surface, the power received in the radar echo varies as the inverse fourth power of the distance to the target. More strictly, we should also have postulated a target small compared to the cross section of the radar beam, and a transparent, i.e., nonabsorbing, atmosphere. The latter condition is normally fulfilled in the microwave region except for wavelengths less than about 2 cm. This familiar inverse-fourth-power law sets the high price which must be paid for increased range. Under other conditions of propagation which will be discussed later, such as propagation over the horizon, in the neighborhood of a reflecting surface, or through an absorbing atmosphere, the signal falls off even more rapidly than $1/R^4$ and the price is thus still higher.

The received radio-frequency signal power can be increased: (1) by increasing the transmitted power; (2) by enlarging the antenna, thus increasing the concentration of incident power on the target (by making a more directive beam) and affording at the same time a large effective receiving area for the returning echo; (3) by using a shorter wavelength, thus getting increased directivity without increasing the antenna size, and hence, if other factors remain the same, a stronger signal.

If the radar receiver were perfect, the background of random noise power against which the signal would have to compete, after amplification of both noise and signal, would be determined solely by the bandwidth of the receiver and the absolute temperature* of the system. (The input noise power would be given in fact by $kT\Delta f$ where k is a universal constant, Boltzmann's constant, and Δf is the receiver bandwidth.) It is customary to describe the actual receiver by a number called the over-all noise figure, N, which measures how many times worse it is than an ideal receiver at room temperature. Anything which can be done to improve the noise figure of receivers will bring an increase in range.

In addition to these factors, the manner in which the signal is finally presented to the observer, be it a human or an electrical observer, the length of time during which echoes continue to be received from the same target, and many other related scanning and presentation factors influence the maximum range. Lumping all such factors under a single symbol, S, with the warning that S is not independent of the other quantities appearing in the formula, we can summarize the above relations precisely by writing:

$$R_{max} \text{ prop to } \sqrt[4]{\frac{P_t \cdot G^2\lambda^2\sigma}{N \cdot \Delta f \cdot S}} \tag{1}$$

where:

P_t = peak transmitted power

G = antenna gain (we assume the same antenna is used for transmitting and receiving)

λ = wavelength

σ = scattering cross section of the target

N = noise figure of receiver (a number greater than 1)

Δf = bandwidth of the receiver

S = scanning and presentation loss factor.

The reason for suppressing the factor of absolute temperature, which enters in determining the noise power in the hypothetical ideal receiver, is that part of the noise in all existing radar receivers is of different origin and would not be reduced by cooling the whole receiver. However, even this noise shares with thermal noise the property of being proportional to bandwidth; hence, we leave Δf in explicitly.

It has been shown often and conclusively that for a given pulse length, τ, the optimum bandwidth for detecting weak signals is of the order of $1/\tau$. It is instructive to replace Δf in the formula (1) by $1/\tau$, giving:

$$R_{max} \sim \sqrt[4]{\frac{P_t \cdot \tau \cdot G^2\lambda^2 \sigma}{N \cdot S}} \tag{2}$$

The product, $P_t \cdot \tau$ in (2) is simply the total energy radiated in one pulse.

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* The question of what temperature it is which sets the limit for an ideally perfect radar receiver is a rather subtle one, but one to which a definite answer can be given. Suffice it to say here that in the most favorable case imaginable the random noise power arises from the thermal radiation received by the antenna itself, which in turn depends on the temperature of all absorbing matter within the boundaries of the radar beam.

Another useful form of the relation can be obtained by expressing the gain of the antenna in terms of its frontal area, A, and the wavelength. Apart from numerical constants, $G \sim A/\lambda^2$ and (2) assumes the form:

$$R_{\max} \sim \sqrt[4]{\frac{P_t \cdot \tau A^2 \sigma}{N \cdot S \cdot \lambda^2}}, \tag{3}$$

confirming our earlier remark that decreasing the wavelength without reducing the size of the antenna increases the range, other things being equal.

From the above relations some factors have been omitted which cannot be neglected by the designer of the radar set. For example, loss of power in r-f transmission lines entails some loss in range. Although in the past, improvement in the microwave art has markedly improved performance, there is not much room for further improvement in this respect. If r-f line losses were to be eliminated completely, the range of most modern radar sets would be increased only from 10 to 20%. Any substantial increase in radar range must be sought elsewhere. We must examine in detail the factors in (3).

Transmitter Power and Energy per Pulse.

P_t and τ are characteristics of the radar transmitter, i.e., high-power pulsed oscillator and the modulator which drives it. Figures 2 and 3 display the history of pulsed-magnetron development, in respect to peak-power output and efficiency, at three microwave frequencies, S-band, X-band, and K-band. The history begins with the British multicavity magnetron. There is necessarily a good deal of arbitrariness in the curves, and only the general trend is significant. Not every upward step in output power was due to an improvement in the transmitting tube itself. The increase from 10 to 50 kw in S-band was brought about by the development of higher-power pulsers. At the present time it is probably the tube itself which imposes the essential limitation, although it must be expected that further advances in high-power transmitters will call for corresponding developments in pulsing techniques.

It is important to realize that the curves of Fig. 2 lie above one another in order of increasing wavelength not because development was begun earlier on S- than on X-band and earlier on X- than on K-band, but because magnetrons of this type are subject to inherent limitations which depend on the wavelength. These arise because the physical size of the elements of the tube must be reduced just as the wavelength is reduced. Thus the cathode of the K-band magnetron must be much smaller than that of the S-band magnetron, making it more difficult to provide the same current, etc. It can be shown on rather general grounds that the power output of magnetrons of the same type but different frequency should vary approximately as λ^2. Very roughly this relation has prevailed for some time between S- and X-bands and X- and K-bands. It is interesting to include this relation in formula (3) in which case λ no longer appears explicitly in the $R_{\max}$ relation.

The efficiency likewise is necessarily lower for tubes working at a shorter wavelength. In any case, it is clear that we cannot hope for much increase in power output solely through improved efficiency.

It is unlikely that the advantage in power enjoyed by the longer wavelength tubes will be eliminated by further development. The art of "scaling" (developing a tube similar in all respects to another but operating at a new wavelength) is well

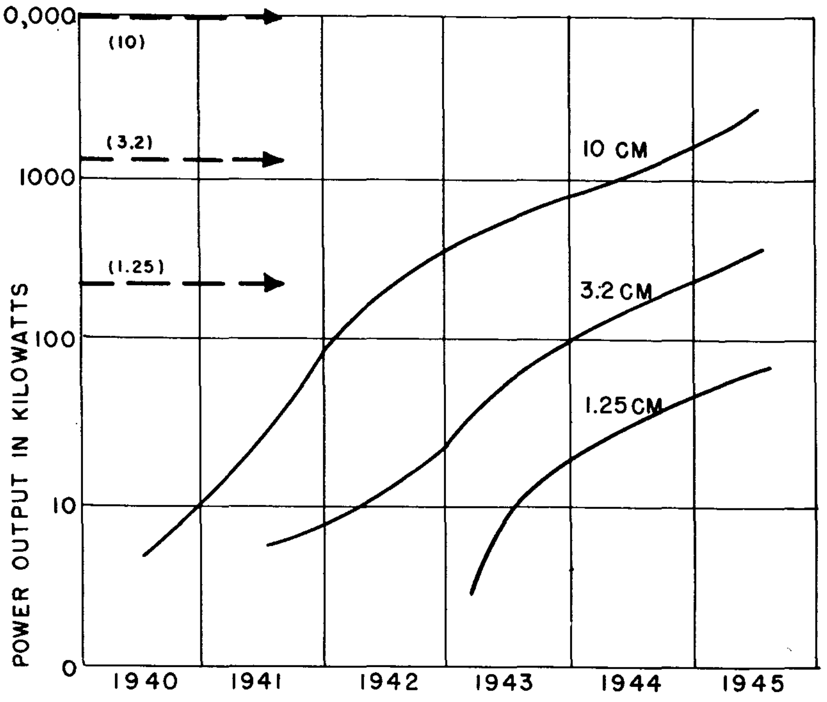


Figure 2

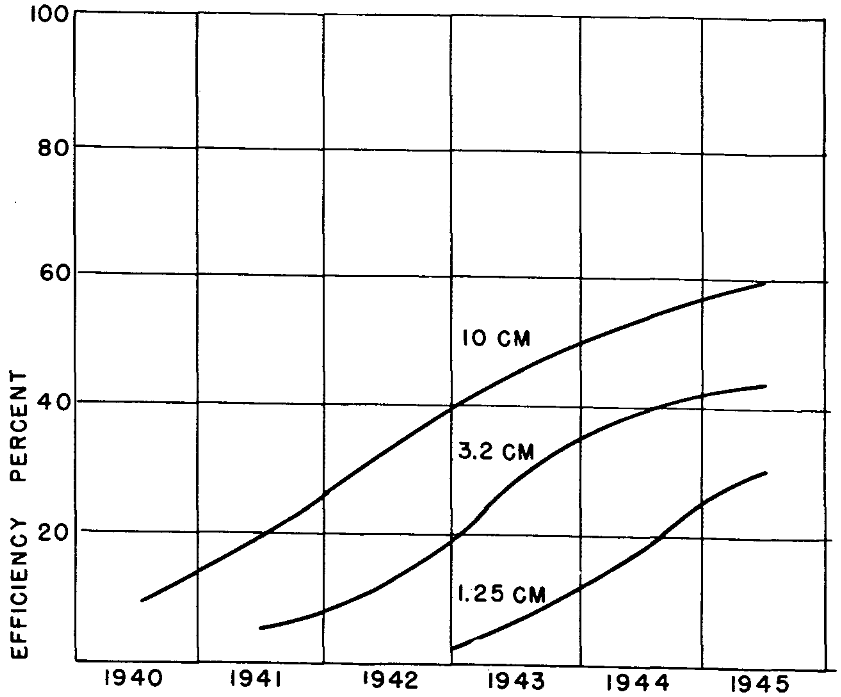


Figure 3

understood and works both ways; if a one-megawatt K-band tube were developed, the advance thus made would permit the development of a still higher-power X-band tube.

Another limitation which works in much the same way is the capacity of wave guides and transmission lines to transmit power without electric breakdown. The limits for transmission in standard guides filled with air at atmospheric pressure are marked by the dotted lines in Fig. 2. The limiting power is lower for the shorter wavelengths essentially because the guides are smaller. One notes that powers not much below the dotted lines are available in each band. One should not regard this as a serious limitation, however. Ways to handle higher power, when it is available, will certainly be found. In fact some are already known.

With the output power limited for one reason or another, we may still seek to increase the total energy per pulse by increasing the pulse duration, with a resulting increase in range, according to formula (3). A long pulse is not wholly a blessing in many applications. A narrower bandwidth, with poorer range resolution, is automatically demanded, and, what is often more serious, unwanted echoes from extended targets ("clutter"), such as the sea or rain clouds, are increased relative to single target echoes. Therefore, it has sometimes been the practice to employ long pulses for searching at maximum range, switching to shorter pulses when observation at closer ranges is required. At S-band, pulses as long as 10 microsec have been used, although 5 microsec pulses are now more usual in long-pulse applications, at S as well as at X. Much longer pulses can be and have been used at lower frequencies. In the design of transmitters, pulse length and peak power are not unrelated. Lengthening the pulse entails some reduction in peak power, though not so much as to nullify the expected increase in total energy per pulse.

Whatever advantage the long pulse offers can be realized only if the transmitter frequency is maintained precisely constant during the pulse. This is often so severe a requirement that it cannot be met with existing techniques. For this reason, as well as for others, the development of electronic frequency control for high-power magnetrons should be strongly encouraged.

One cannot, at present, foresee a likely competitor for the magnetron as a source of pulsed high power at microwave frequencies. One hesitates to predict what further advances in power will be forthcoming, in view of, on the one hand, the startling increase of roughly 1000-fold in S-band peak power within the last four years, and on the other hand, of the rather fundamental limitations which seem to be not far off. Certainly the development of higher-power pulsed sources should be encouraged and supported. The importance of high power, in military radar, lies not only in increased range but in reduced vulnerability to jamming. It does not appear likely that nonmilitary applications of microwaves will put such a premium on high power, and therefore the support by military agencies of high-power developments is indicated.

Antenna Gain.

The gain of an antenna measures its directivity, being specifically the ratio of the intensity at some point along the axis of the beam, to the intensity which would have been measured at that point had the antenna radiated the same total amount of power uniformly in every direction. The gain is also connected in a fundamental way with the effective receiving area of the antenna, upon which depends the fraction of the power, scattered by the target, which the antenna receives. This receiver area is, in fact, always precisely equal to $G\lambda^2/4\pi$ where G is the gain and λ the wavelength. A broad beam (low gain), no matter how achieved, implies a small effective receiving area and conversely. On the other hand, another quite general principle tells us that high gain cannot be had at a given wavelength except at the expense of increased antenna size.

Often the most practical way to effect a desired increase in the range of a radar set is to build a larger antenna. Increasing the frontal area of the antenna by a factor of two increases the received signal power by a factor of four. This is not the only change; with the narrower beam which the larger antenna sends out, scanning losses are somewhat increased. On the other hand, the improved angular resolution is usually an advantage.

Ground-based radar systems are usually best able to capitalize on the advantages of large antennas. Development in this direction has certainly not reached its limit. The size of airborne antennas is limited by the fact that they have to be carried by airplanes. Increase in antenna gain here poses a problem which has to be attacked by the aircraft designer and the antenna designer working together. Moreover, for many of the search and mapping functions of airborne radar, it is required that the beam be broad in one direction. This limits the rate of increase of gain with antenna size.

It must be noted that the limitations on antenna gain, once the size of the antenna is specified, are at present just the fundamental ones discussed above; antenna designers have already approached very near to the theoretical limits imposed by the wavelength and the dimensions of the antenna.

Use of a shorter wavelength permits increased antenna gain, but because of the many other factors which inevitably change also, this is rarely the way to increase the range. Exceptions to this will be taken later.

Receiver Performance.

The development of microwave radar has been marked by an improvement in receiver noise figures as vast (and therefore as effective in improving range performance) as the striking increase in transmitter power shown in Fig. 2. We must now ask how much further we can go in this direction before the theoretical limit is reached. In modern microwave receivers at 10 and 3 cm, noise factors of about 10 have been achieved. A perfect receiver would be only 10 times better than this, corresponding to an increase in range by about 1.8 times. Actually an improvement by a factor of 2, rather than 10, over the best present performance seems a more realistic hope for the next few years. It is doubtful whether one should confidently expect further improvement in receiver noise figures from peacetime developments. Such improvements must be bought at the expense of painstaking and costly tube design, not economically justified by the moderate gain in performance. At the same time, it may be doubted whether such improvement from the military standpoint is as important as work directed toward insuring that the performance of receivers in the field is universally and reliably nearly as good as that obtainable in a single laboratory set. This is a problem of tube and crystal standardization and quality control.

Scanning Loss.

The role which the indicator plays in determining range performance is a complicated one. Broadly speaking, no tricks can be played to obtain a large increase in range while meeting all other requirements of scanning speed, etc. However, many small improvements can be had through proper design based on an understanding of the factors involved.

A related subject, which should be mentioned, is improvement in range through integration of information from many pulses. It has often been suggested that if many pulses can be directed against the same target, it should be possible to detect the target even though each individual return echo were too weak to be detected by itself. This is indeed the case and there are many examples of such integration devices. Perhaps the most important is the eye itself, which, in viewing a simple range-time-base indicator ("A-scope"), automatically averages many sweeps with a substantial increase in effective sensitivity. However, now that the integration problem is well understood, it can be seen that the glowing predictions of many early proponents of special devices of this sort cannot be realized, for fundamental reasons. The laws which control the gain achieved are definite, and the price paid for the gain is always slower scanning speed or longer observation time.

The advantages to be gained when such storage and integration methods are used to distinguish a wanted signal from other echoes, rather than from noise, is an entirely different matter, and will be considered in another section.

RESOLVING POWER

Angular Resolution.

The ability of a radar system to distinguish a target from a neighboring target at the same range depends on the narrowness of the radar beam. This in turn is limited by the wavelength and the size of the antenna, according to a basic relation which can be expressed approximately by writing.

$$\theta = \frac{\lambda}{d} \tag{4}$$

Here θ is the width of the beam in radians between points of half intensity, and d is the dimension of the antenna perpendicular (usually) to the line of sight. The broadening of the beam arises from diffraction. Thus high angular resolution is inevitably associated with a large antenna, or a short wavelength, or both. To give an example, with an antenna 10 ft long, at a wavelength of 1.25 cm, it is not difficult to form a beam which at large distances from the antenna is about $1/4^\circ$ wide. It is not possible to do much better than this except with a larger antenna, or a shorter wavelength.

It is clear that in the development of higher-resolution radar, for detailed mapping, etc., both lines of fundamental development (shorter wavelengths and larger antenna systems) must be pursued. Each is beset with challenging difficulties. We mention in passing that the development of very high resolution implies a parallel develop-

development of indicator techniques if the full advantages of narrow beams are to be realized.

High angular accuracy, as opposed to angular resolution is obtained by methods of lobe comparison, in which a single isolated target, illuminated by a relatively broad beam, is nevertheless located with high angular precision, e.g., many fire-control radars such as SCR-584. There is room for significant improvement in this technique. Lobe-comparison methods now in use find the position of the target by comparing the signals received, successively, from two slightly different directions. During the time required to switch the beam from one direction to the other, fluctuations in the echo can occur for reasons quite unconnected with the angular displacement of the beam, thus falsifying the result of the comparison. It has been recognized for some time that this difficulty could be avoided if exactly simultaneous comparison were possible. Several very promising methods for simultaneous lobe comparison have recently been devised and are being developed.

Range Resolution.

Resolution in range is increased by using shorter pulses. This in turn implies wider receiver pass bands, as well as improvements in indicator techniques similar to those hinted at above. Pulses as short as .05 microsec have been used in experimental systems, corresponding to range resolution of the order of 25 ft. The generation of pulses even shorter than this should be possible. The wide receiver band appears at present the most difficult problem.

It should be noticed that in most applications range resolution of existing sets surpasses the angular resolution, in the sense that at the typical ranges involved, the pulse packet is broader than it is long. For example, if the beam width is 1° and the pulse length 1 microsec, the range resolution is about 125 ft at all ranges, while the angular resolution at 5 miles is of the order of 500 ft.

SCANNING AND COVERAGE

The process of "seeing" by radar differs from "seeing" by the eye or by the camera in one important respect, and from this difference arises not only the startling capabilities of radar but also certain basic limitations. Radar measures range directly, but not instantaneously, requiring for a range measurement the time for the passage of a pulse to and from the target. Moreover, an area or volume in space is searched by scanning the radar beam so as to cover progressively all parts of the region in question.

The consequences of this can be seen through a specific example. Suppose we wish to search the sky in all directions, out to a maximum range of 30,000 yd, by pulsed radar, using in order to meet a requirement on angular precision, a beam 2° wide in elevation and azimuth. The maximum allowable pulse repetition frequency is set by the maximum range, if we are to get unambiguous information, and is about 5400 pps. On the other hand, the hemisphere to be searched contains approximately 2700 angular elements the size of the beam; hence, at least 2700 pulse transmissions are required to search the hemisphere completely. The time for a complete search cannot therefore be less than one-half second. Note that the only physical constant we have introduced, in deriving this limiting scanning speed, is the velocity of light. For many reasons it is neither desirable nor possible to approach this limit closely.

This fundamental restriction has its origin in the fact that we must funnel all the information obtained by "dissecting" the hemisphere through a single channel. The only way to lift the restriction is to multiply the number of channels simultaneously in use. One simple way to do this is to provide two radar sets and assign to each one half of the region to be searched. More elegant methods can and will be thought of but the principle must remain the same.

It cannot be claimed, however, that, within the basic restrictions outlined above, radar-scanning problems have been solved. There is still vast room for improvement, even revolutionary improvement, in scanning devices. In particular the true electrical scanner (no moving mechanical parts) is still around the corner. It is easy, although perhaps not quite fair, to say that, in television terms, we have the rotating mirrors and the perforated disk, but not the iconoscope. It is not unlikely that the development and exploitation of electrical scanning will be closely linked to that of very wide-range electronic tuning for high- and low-power microwave oscillators.

TARGET PROPERTIES

When radio waves strike an object in space, reflected or "scattered" waves spread out from the object because the object forms a discontinuity in the otherwise homogeneous medium through which the waves are travelling. The object need have no special shape; it need not be an electrical conductor in order to reflect at least partially the incident energy. It is required only that it be electrically dissimilar to its surroundings. Without attempting to define precisely what is meant by "electrically dissimilar," we may say that in fact any ordinary solid or liquid substance is capable of reflecting radio waves. This is why it is so difficult to hide an isolated object from radar detection. An airplane constructed entirely of glass, if such were possible, would reflect less than a similar metal airplane, but not very much less. Its radar "visibility" would not be greatly reduced just as, in a searchlight beam, its visibility to the eye would not be greatly reduced.

In order to conceal an airplane from a searchlight, it would be much better to paint it blank. Is it possible to make an object black for radar? In a limited sense it is, by various methods which have been actively developed by both ourselves and the Germans. Special coatings can be made which, when applied to a large flat surface, result in nearly complete absorption of incident waves over a limited range of wavelength. Such materials serve many useful purposes. Most military radar targets, however, are not flat surfaces of large extent. For fundamental reasons an object of a complicated shape, such as an airplane, cannot be entirely blacked out for wavelengths which are not infinitesimally short compared to the dimensions of the object itself. One therefore must not expect that airplanes of the future will be totally concealed from radar by means of a special coat of paint. Nevertheless, the continued development of low-reflection coatings is a problem of unquestionable military importance.

One of the most drastic limitations to the powers of radar arises from the fact that an object, although it may reflect the incident waves, can be very thoroughly concealed by the similar echoes from neighboring objects. The wanted echo is lost in the clutter or unwanted echoes. To this fact is due the disappointingly limited usefulness thus far of radar in ground operations. In order to see how this limitation may be overcome in the future, we must look for some distinguishing features of the wanted echo on the one hand, and for ways of reducing the unwanted echoes on the other. The latter is most directly accomplished by reducing the pulse length of the radar, and reducing the beam width. This decreases the volume of the pulse packet and hence reduces the number of reflecting objects returning echoes from the same place at the same time.

The distinguishing features of an individual echo are very few. As we have said, nonmetallic objects, as well as metallic objects, reflect. A tank parked in a wood, and the trees around it produce echoes which differ, if at all, only in intensity. In certain very special cases a characteristic relation between the polarization of the incident and reflected waves may be identifiable. There is, however, one important characteristic of many military targets which strikingly distinguishes them from their surroundings, their rapid motion. It is possible to exploit this advantage by various means discussed in a later section, and to isolate the echoes from targets which are moving. The further application and improvement of these techniques is likely to prove one of the most productive lines of radar development during the next few years.

PROPAGATION

The propagation of radio waves of the high frequencies used for radar differs from low-frequency radio-wave propagation in the following ways:

(1) The Kennelly-Heaviside layer does not reflect such waves to an appreciable degree.

(2) These short-wavelength radiations do not spread far beyond the horizon by diffraction.

(3) If we exclude the lower radar frequencies (below 1000 megacycles, say), waves which strike the earth are usually scattered in a random manner, or absorbed; the rough surface of the ground does not act as a good mirror.

These effects, all natural consequences of short wavelength and high frequency, are responsible for the quasioptical nature of microwave propagation, which is loosely described by saying that microwaves travel in straight lines, as light does, and that radar cannot see beyond the horizon. The description is not entirely accurate, for there are, in turn, important differences between microwave propagation and the propagation of light. These are:

(1) Around relatively small obstacles the waves spread appreciably, by diffraction, and very small obstacles, such as droplets of water in a cloud scarcely affect their passage at all.

(2) The surface of the sea, rough though it may appear, is a good mirror for waves in this frequency range, especially when the waves strike the surface at nearly grazing incidence.

(3) Water vapor, when it is present in the atmosphere, has a strong influence on the refraction, or bending, of such waves, whereas for visible light its effect is very slight.

A detailed analysis of the consequence of these effects would require a lengthy treatise. We state here in the broadest terms a few important conclusions. The range of microwave transmission is limited for practical purposes to "line-of-sight," that is, within the horizon, except under certain atmospheric conditions, for propagation in a nearly horizontal direction near the surface of the earth. The exception is a consequence of the effect of water vapor mentioned in (3) above together with temperature variations in the atmosphere. This "anomalous propagation" is familiar to many radar operators, and is caused by a bending of the path of the waves, which in extreme cases carries the radiation far beyond the horizon. It now appears that at sufficiently high frequencies such bending is the rule rather than the exception over a large part of the ocean's surface. Over land these effects are less common, and for transmission in directions other than horizontal, are rarely of any importance. Thus, if we are concerned with radar for high-altitude bombing, the straight-line-propagation picture works quite well enough. If however, we plan to guide a long-range missile flying at low altitude over water by radar we must study thoroughly the effects of refraction and reflection.

The effects of condensed water in the atmosphere are various. Throughout the centimeter wavelength range, relatively large water drops, as in rain storms, frequently produce radar echoes. These may obscure the desired target, which is bad, or they may provide a warning of and location of a storm area, which is often useful. The exploitation of radar for weather analysis has only just begin. The possibilities, as yet largely undeveloped, can be indicated by listing the measurements which are being made or which could be made with existing techniques suitably adapted for the purpose:

(1) Location and delineation of storm areas.

(2) Determination of winds aloft.

(3) Examination of storm structure in three dimensions.

(4) Measurement of degree of turbulence in storm.

(5) Distinguishing between echoes from water drops and ice.

(6) Determination of total water vapor content of atmosphere.

In general, the shorter the wavelength the stronger the echo from small solid or liquid particles, and likewise, the greater the attenuation of energy as it passes through a cloud of such particles. Thus wavelengths below about 3 cm suffer increasingly serious attenuation in rain.

At long wavelengths the normal atmosphere itself (excluding the ionosphere) is essentially transparent. That is to say radio waves travel through the atmosphere without being absorbed. Our progress to shorter and shorter wavelengths has at last brought us to a region of the spectrum where the atmosphere is no longer wholly transparent, and an appreciation of this is of the utmost importance if we are to assess the possibilities of developments at still shorter wavelengths. Below roughly 2-cm wavelength, attenuation or absorption by constituents of the atmosphere begins to be appreciable over long transmission paths. The first offender is water vapor, which, in a region centered about 1.3-cm wavelength, causes a serious attenuation in some cases over distances as short as 10 to 20 miles. In the neighborhood of 5-mm wavelength a very drastic attenuation is observed, due to oxygen which is capable of attenuating the intensity of a signal by a factor of 100 in a distance of one mile. Slightly below 3-mm wavelength absorption by water vapor again sets in and there is good reason to believe that it remains prohibitively high at all shorter wavelengths until one passes far down into the infrared.

The inescapable inference is that a wavelength in the neighborhood of 3 mm is the shortest useful wavelength for radar. Clearly, also, a choice of a wavelength in the millimeter range for a particular application must be made with special care. The existance of these absorption bands, on the other hand, opens up certain new possibilities. One can, for example, take advantage of the oxygen absorption to provide extreme security for a short-range communication device. It would be possible to carry on voice communication between two planes two miles apart at 30,000 ft without allowing a detectable signal to reach the ground.

CW DETECTION METHODS

Detection systems based on the transmission of a continuous wave of relatively low power have been under development since the earliest days of radar. The possibility of receiving a detectable signal under such conditions is suggested if one examines the fundamental radar equation (2). Suppose that the pulse duration, τ, is increased and the peak power transmitted, P_t, decreased in like proportion. At the same time the pass band of the receiver, Δf, is to be decreased consistent with the increased pulse length. Then R_{max} remains the same. Although the intensity of the received echo is less, the background of noise power against which it must be compared is also less.

In principle this process can be carried as far as we like. It has, however, certain inevitable consequences which can be illustrated by a simple example. Let us compare a pulsed-radar set which transmits 10^5 w peak power, in pulses 1 microsec long, at the rate of 500 pulses per sec, with a CW system radiating 1 w and having a band width of 10 cps. We assume the antenna gain and the wavelength are the same for the two systems. Then a single echo from a distant target is just about detectable, in the pulsed system, when the signal which the CW system receives from the same target is also barely detectable. There are important practical differences, of course: in the pulsed system we must solve the problem of generating and transmitting very high power; in the CW system we must maintain an exceedingly accurate frequency control, and we must overcome or avoid the difficulty of detecting the very weak echo in the presence of the much stronger outgoing wave.

The important difference, however, is a fundamental one; it is connected with the amount of information which each system is capable of providing in a given time. It appears that in the CW system we have sacrificed our ability to measure directly and quickly the distance to the target. A more general, and more accurate, statement is that we obtain in 1/10 sec (which is the time required for the response of the narrow band receiver) only one piece of information, viz., that the target is or is not in the beam. In 1/500 sec, with the pulsed system, we obtain essentially 200 pieces of information, since we are able to say whether an echo did or did not occur during any one of the 1-microsec intervals contained in the 1/500 sec interval. Thus the information-gathering rate of the pulsed and CW systems are in the ratio of 100,000 to 1, which is, not accidentally, the ratio of the respective peak powers transmitted.

Actually, it is possible to measure range with a CW system of this general type, and where the amount of information required is small, the method has advantages. A notable example is the frequency-modulation altimeter, in which we are concerned with the location, in range only, of a single target, the surface of the earth. The application makes the minimum demand on the "information-rate" of the system, and at the same time, puts a premium on certain advantages of the method, among which are light weight and low minimum range. It is not surprising that this is the one CW system which has found wide military use.

It was recognized very early that CW detection is particularly well suited to take advantage of the distinguishing property of motion of a target. Indeed this ability was thought by many to offset the other disadvantages of CW methods. During the last year or two, however, we have learned how to use pulse radar for moving target detection, without sacrificing its inherent advantages, in many applications. Thus it is no longer appropriate to discuss moving target detection solely as a branch of the CW radar art; we must take a broader point of view, as we shall try to do in the following section.

MOVING TARGET DETECTION

INTRODUCTION

All moving-target detection systems are based on effects which can be traced, more or less deviously, to the familiar Doppler effect. A source emits radiation at a definite frequency, f_o, measured at the source. An observer moving with a velocity v away from the source detects radiation of frequency $f' = f_o (1 + \frac{v}{c})$ where c is the wave velocity. Further, an echo returned from a moving object to the original source differs in frequency from the original wave by an amount $\Delta f \doteq \frac{2f_o v}{c}$ or $\Delta f = \frac{2v}{\lambda}$. This shift in frequency, called the Doppler shift, is conveniently remembered as the rate at which the moving target traverses half-wavelength intervals. This suggests an alternative description of the phenomenon: The result of the target motion is that the phase of returned signal, relative to that of the transmitted signal, changes by 360° as often as the target moves one half-wavelength. At 10 cm wavelength (3000 mcps) the Doppler drift amounts to 9 cps for a target speed of 1 mph.

CW DOPPLER SYSTEMS

The most direct use of the Doppler phenomenon is met in CW radar. The signal returning from a moving target, differing slightly in frequency from the transmitted signal, is mixed with a portion of the transmitted signal, and the "beats" are detected. The Doppler frequency is thus derived directly. One then knows that there is a moving target within the beam, and one knows, not its velocity, but the radial component of its velocity. Actually the instrumentation is not as simple as might be supposed from the above description, because of a certain difficulty connected with the superhetrodyne detection of microwave signals at a very low (audio) intermediate frequency. However, a more serious difficulty arises from the "inverse-fourth-power law" to which CW radar, no less than pulse radar, is subject. Very small nearby targets return stronger signals than do very large distant targets, there being no range discrimination, the stronger signals hopelessly swamp the weaker signals. These stronger signals may come from many nearby moving objects, leaves, birds, even insects.

This shortcoming of the pure CW Doppler system is to a considerable extent circumvented in the Sperry TPS-7 system which is best described as an interrupted CW system. The transmitter is on, and receiver off, for 500 microsec and then the transmitter off and receiver on for 500 microsec. If a moving target is present, Doppler beating occurs from the time the receiver is turned on to a point determined by the range of the target. Thus, at least for nearer targets, the target response increases with range. By clever manipulation this echo pattern is made to yield a headphone signal and a pseudo-PPI. The latter is characterized by a wandering PPI trace, which settles down in range, in the presence of a moving target, with a precision which improves with target echo strength. There is confusion when more than one moving target lies in the beam at one time.

A still different approach involves frequency modulation of the transmitter and receiver (Armstrong FM radar). The transmitter radiates only during alternate modulation cycles. The deviation frequency is fixed but the modulation frequency is swept between 10,000 and 500 c. Any one value of modulation frequency admits echoes from one radar range. Thus 10,000 cps corresponds to a range of 9.3 miles and 500 cps to 186 miles. Moving targets appearing at any range are detuned from fixed targets by the Doppler frequency. By ingenious manipulation, a pseudo-PPI is derived, on which deflection modulation of the radial trace shows moving targets, with the deflection direction indicating in or out target motion.

PULSE DOPPLER SYSTEMS

That is is possible, in principle, to distinguish moving from fixed targets, in a pulsed-radar system, can be seen as follows. Suppose that the transmitted pulse could be made very accurately synchronous in phase with a stable continuous oscillator. We might then compare the received echo, as regards phase, with this same oscillator. If the echo came from a stationary target each successive phase comparison on succeeding pulses, would have the same result. Had the target moved between pulses a distance equal to a quarter wavelength, the relative phase of echo and reference oscillator would be found to change by 180° from one pulse to the next. In general any radial motion will be betrayed by some phase change, although it will be seen that certain definite speeds, leading to phase changes of 360° or multiples thereof, are indistinguishable from zero speed, at constant pulse-repetition rate. We might further devise means for comparing automatically the result of each phase measurement with the preceding one, and discarding all echoes with unchanging phase.

The first practical embodiment of these principles is the "Coherent Pulse Doppler" system, now available as a Modification Kit, MC-642, on the SCR-584, and on the CPS-1. This system successfully overcomes the practical difficulties inherent in the scheme outlined above by causing the reference oscillator to be rephased, at each transmission, by the transmitter itself, and by further arranging that this reference oscillator operates at relatively low frequency (actually at the intermediate frequency of the system).

If, in an ordinary radar system, a moving target and another (stationary) target return echoes at the same time, the strength of the combined signal will depend on the relative phase of the two echoes. As one target moves, therefore, we observe a single echo the strength of which fluctuates from pulse to pulse. Detection of this pulse-to-pulse change, then, amounts to detection of the moving target. In this case the moving target echo beats with the echoes from neighboring stationary objects. Coherence is provided automatically since both are struck by the same transmitted pulse packet. Because no phase reference is required in the radar set itself the system is called the "Noncoherent Pulse Doppler" method. It is limited in application to targets surrounded by other reflecting objects, but because this is often the situation in which the detection of moving targets is most desirable, and because of the extreme simplicity of the method, it will undoubtedly prove useful. The method has one advantage over the generally more powerful Coherent Pulse Method: it works without further modification (as the latter does not) when the radar set itself is moving.

Full utilization of these methods involves automatic pulse-to-pulse comparison, and the display on the radar indicator of just the wanted echoes. We then have a complete "MTI," or "Moving Target Indicator" system. By means of a video storage device (a supersonic delay line or, perhaps eventually, a mosaic electron storage tube) the echo pattern from one transmitted pulse is preserved and then subtracted from the succeeding echo pattern. The permanent echoes which show negligible change are canceled. The moving target echoes change from pulse to pulse and therefore do not cancel. If the target moves radially an odd number of quarter wavelengths between pulses, the response will be a maximum. If a target moves radially an even number of quarter wavelengths, no response will be obtained except as a result of propeller modulation, etc. For example, at 10 cm, 1000 pps, the first maximum occurs at 49 knots and the first null at 98 knots. At the optimum target speed approximately no loss of signal strength will occur for isolated targets as compared with the normal presentation. The operational importance of the nulls has not been determined. The nulls might be minimized or eliminated by the use of repetition rate jitter (demands mosaic storage) or a dual repetition rate system.

Limitations of the system are connected with unwanted pulse-to-pulse echo change from noise, scanning, echo fading, and equipment imperfection. To avoid scanning trouble the number of pulses should be never less than 15 per beam width (half power one way) and preferably 100. Echo fading effects will probably be found on S-band at low repetition rates on windy days. Equipment stability to several percent is deemed achievable for field use. For S-band service with 100 pulses per beam width a "subclutter visibility" of 20 db for a random phase target is practical. S-band sea clutter is appreciably reduced at rates as low as 300 pps. S-band clouds (neglecting translation) are appreciably reduced at repetition rates as low as 1000 pps. "Window" is intermediate between sea return and clouds. In scaling such effects as a function of wavelength, some as-yet-not-evaluated allowance must be made for the fact that at shorter wavelengths new classes of smaller motions become significant.

FUTURE USES FOR PULSE DOPPLER RADAR

Preliminary calculations predict that MTI in the Coherent Pulse Doppler form will be applicable to airborne use with a pulse-repetition rate between 500 to 1000 pps, although subclutter visibility may be limited to 10 or 15 db. The average velocity of the aircraft in the direction of sight may be removed by artificial means, and the relative radial motion of ground echoes within the beam may be minimized by use of a narrow beam. Unless the system is one in which coherence is maintained from one pulse to the next, "second time clutter" will not be eliminated. Airborne control of interception is one of the most important potential military uses for MTI.

Although radar must compete with beacons in the handling of air traffic, it seems clear that radar will retain a position of eminent importance, and equally clear that MTI will be an indispensable feature of that radar.

Lobe-switching methods of precision position finding are not ideally suited to MTI because of beat effect between the Doppler and the switching frequencies. The recently rejuvenated simultaneous lobing methods should be free of this limitation.

The PPI presentation of moving ground targets is believed to be entirely possible where the radial target speed exceeds that of wind blown trees.

The elimination of clouds is a function of their internal turbulence. Future transports may carry a simple MTI attachment (Noncoherent Pulse Doppler) which will warn pilots away from turbulent clouds.

A subtle means of IFF might entail the return of a beacon signal which is phase coherent with the transmitted pulse.

Pulse-to-pulse coherent integration (utilizing circuit techniques developed for MTI) as a means of improving signal-to-noise is theroetically attractive but of dubious practical importance because moving targets introduce another scanning dimension corresponding to the speed of the target.

COMPARISON OF DOPPLER METHODS

A relative evaluation of the several known methods for utilizing Doppler effects can best be made from the point of view that there exists a close interrelationship between four radar factors namely: (1) scanning time (the time to cover a given solid angle), (2) position data precision, (3) rate data precision (involving the Doppler effect), and (4) the signal-to-clutter ratio. These are not independent parameters because, in general, an improvement in one of these factors can only be obtained by a concomitant loss in some of the others. By the choice of radar method and by the choice of system constants it should be possible to obtain any desired balance among these factors within the fundamental limitation just referred to.

With regard to scanning, azimuthal rates of from 4 to 30 a minute are generally needed to give sufficient position accuracy. Scans of less than two a minute are of little use except for simple warning. The precision of present-position data which is achieved in the most modern pulse radar sets is in nearly every instance the bare minimum which can be accepted. No further sacrifice can be tolerated.

With regard to rate data, several important observations may be made. First of all, simple qualitative knowledge of motion is both all-important and sufficient in many applications. Secondly, if the Doppler effect is to be used to give rate information, it can give only radial rate information which is of limited usefulness. Thirdly, if quantitative total rate information is needed, it can be obtained from the position data by making observations at known intervals. Furthermore, this method of deriving rate information is more convenient than a Doppler method and in some cases may be used without cost in terms of scanning rate or position data precision.

Bandwidth and discrimination against chance fluctuation, whether in noise or other kinds of clutter, are closely linked in the well-known manner. Doppler gives an opportunity to use a periodicity resulting from uniform target translation so as to narrow the bandwidth toward the audio region. This signal-to-noise improvement must of course be paid for.

It is evident that the measurement of a Doppler frequency is essentially a counting process which takes time. FM, ICW and CW radar systems measure the Doppler frequency when they Fourier-analyze the echo so as to separate the Doppler fundamental frequency. Although this quantitative rate information may be discarded before reaching the indicator, nevertheless, it has been achieved and it must be paid for in terms of the four factors mentioned above. FM, ICW and CW radar systems all make serious concessions in scanning time and present-position-data precision in order to achieve rate-data precision and, with that, to achieve some improvement in signal to clutter over the Pulse Doppler systems. Pulse Doppler systems, on the other hand, suffer no appreciable loss in space resolution and in most cases no loss in scanning time. Pulse Doppler systems provide information as to whether targets are moving or not, but in the Moving Target Indication system no quantitative target rate information is obtained. For most applications it is probable that this represents the proper balance between the four interrelated parameters.

Another interesting comparison between Pulse Doppler and CW systems is to be found in the stability requirements for these systems. Because present target velocities are always exceedingly small with respect to the velocity of light, the ratio of Doppler frequency to carrier frequency is always extremely small and the discrimination problem extremely difficult. The stability requirements for the various system components depend also upon the four above-mentioned parameters. It can be said that the requirements are in most cases inversely proportional to the pulse length or effective pulse length. Therefore, the actual stability requirements are for the most part far easier to meet with the Pulse Doppler system than with any of the others.

AIRCRAFT ELECTRIC POWER SUPPLIES

Electric power is needed in aircraft in order to operate most of the accessories and in particular the radio and radar equipment. In most present-day aircraft this power is furnished by one or more generators which are driven by the main propulsive engines of the aircraft, although in some cases small gasoline engines are especially provided for the purpose. These generators in most cases furnish DC power at 27 v. Although this is in general quite satisfactory for operating accessory machinery throughout the aircraft such as is necessary for lowering landing gear, flaps, etc., when it is desired to operate electronic equipment, that is equipment employing vacuum tubes, such low-voltage DC power is generally unusable. The reason for this is that voltages much higher than 24 v are required and the regulation or steadiness of the power supply must be much superior to that which is necessary to operate a simple machine such as an electric motor.

Indeed, it is generally true that the voltages required in radar applications and also for radio applications are sufficiently higher and more varied in magnitude than those conveniently obtained from small DC generators to make it desirable that the prime power generator should provide AC power from which the many values of voltage needed may easily be derived. At the present time when most aircraft installations furnish 24 v DC as the primary electric power, it is customary to use DC to AC motor alternaters or converters; these commonly generate AC power at 120 v and a frequency of 400 cps. These converters have been almost universally unsatisfactory because the light weight required for aircraft installation has implied unreliability. In experimental work at the Radiation Laboratory the most satisfactory performance has been obtained from those aircraft in which the AC power was obtained from generators directly driven by the aircraft engine.

It is of prime importance that this AC power should be well regulated, and the regulating devices which are now applied to such AC generators were a great source of difficulty in the recent war. Amplitude modulation of the output voltage has frequently been traced to faulty adjustment of voltage regulators or to the vibration of voltage regulators in aircraft. It produces the undesirable effect of reducing the total transmitted power of a radar set. It will also cause a blurring of radar indicator displays. In many cases it has been possible to eliminate such amplitude modulation merely by a proper readjustment of the voltage regulator. However, this is usually a temporary expedient unless the voltage regulator is employed conservatively with regard to its current rating and its maximum resistance value, which has not always been true of operational equipment. Variable-frequency generators, such as those which are directly coupled to the aircraft engine, commonly require a very much wider range of total resistance in the regulator in order to produce constant output voltage under wide load variations, and with engine speed changes on the order of 2:1 as are customary in present-day aircraft. When loads larger than 2 kva are to be obtained from variable frequency alternaters very serious consideration must be given to the voltage regulator problem. If relatively large loads such as 8 kva are to be employed, separate exciting generators for the alternaters must be used, and even then the regulator control problem is none too satisfactory. On the other hand, if constant frequency is assured by a constant speed drive, voltage regulators of present-day construction have been found to give more reliable service.

Practically it has been found that voltage variations due to all causes (changes in load, speed, power factor, and temperature) are tolerable if they do not exceed ± 3%. Voltage variations in excess of ± 3% are sometimes permissible, but the performance of radar systems will deteriorate. Because they promise very superior performance in these respects, it is recommended that serious consideration should be given to electronic voltage regulators. The excess weight required for such an electronic regulator may be offset by the increased simplicity of the radar equipment design.

As most of the AC power used in radar systems for purposes other than filament heating is ultimately converted into DC power by means of rectifying devices, there is no inherent reason to reject any particular wave form. For the past four or five years a variety of generators have been used with wave forms departing most markedly from the theoretically desirable sine waves. This departure may take the form of a flattening or of a peaking of the wave shape. It is most important, however, that the wave shape, whatever it be, as characterized by form factors and crest factors, should remain constant with variations in load, power factor, and engine speed or electrical frequency. In the past two years it has been particularly necessary to design electronic equipment for operation with generators characterized by a wide range of wave form factors and crest factors, in order that they might work universally in Army, Navy, or British aircraft. This design problem may often be solved simply by providing voltage taps upon critical power transformers; however, where changes in crest factor or form factor are caused by changes in frequency or changes in load, such an expedient does not completely solve the problem. In such cases it is usually desirable to design the rectifier circuits to use choke input filters in order that the output voltage may be a function of a form factor which varies through a smaller range than the crest factor.

The alterations in the design of radar and radio equipment in order that they may work under the conditions outlined above often cause their weight to be increased. Indeed, there is a clear indication that, were more effort spent upon the design of power-generating equipment, a considerable decrease in weight of the associated power-consuming equipment could be effected. It should be noted that generators which display a wave form varying widely from that of a sine wave also exhibit other undesirable characteristics, for example, high internal synchronous reactance and high internal subtransient reactance, which contribute to changes in wave form with variations in load, etc. It is the recommendation that more effort should be expended upon the design of generators which contain amortisseur windings on the salient poles in order to increase the wave shape stability.

The frequency at which the primary power is generated is important since it determines the weight of the rectifier equipment which must be installed as a part of the radio or radar sets. In general, in order to save weight one prefers higher frequencies. At the present time standard Army equipment generates power at a frequency of 400 cps whereas the Navy and the British services customarily employ higher power frequencies. It is questionable whether the weight saved by using frequencies in the range of 800 to 1000 cps is sufficient to warrant their use as compared to that of the presently employed generators which produce power at 400 cps. In particular, large generators generally produce a more stable wave shape, as discussed above, and more generally satisfactory performance when they are designed to operate at 400 cps. It is not necessary that the power frequency be held constant if its variation is not accompanied by other undesirable phenomena. For instance, very satisfactory operation has been obtained in some large systems requiring as much as 8 kva, where the power frequency varies from 400 to 800 cps. However, it is true that with present designs, variable frequency generators often exhibit the undesirable changes of wave shape with change in frequency which are noted above. This leads one to conclude that if constant frequency power can be supplied without an undue expense in weight and complexity, it is desirable. Another reason for desiring constant frequency power is that is is then possible to use induction motors where torque is required rather than to use the brush-type DC commutator motors. The latter point is particularly important if a coordinated program of radio noise reduction is desired. Such a program would envisage the use of AC power throughout the aircraft for all purposes. In the event that such a program were carried out, it is recommended that 400 cps be the frequency of the power source rather than 800 cps as has also been suggested, since in general, motors can be more readily designed to operate from the lower frequency.

Although until 1943 very few military aircraft used radar power in excess of 1.7 kva, there has recently developed a marked trend toward larger power consumption in such installations.

At the present time there is one system which requires as much as 8-1/2 kva. When more than a few kva are needed, it is recommended that three-phase AC power be generated since the generators required are usually smaller and more efficient than single phase machines of equivalent power. Alternatively, improvements in wave shape and harmonic content may be effected if the size of the generator is not decreased. Moreover, a corresponding decrease in weight may be achieved in the associated electronic equipment, since three-phase or six-phase rectifiers often require magnetic components such as transformers and inductances which are also smaller and lighter than those of similar apparatus operating on single-phase power. In lower power units this effect is offset by the increased number of rectifying elements needed. In general, if an aircraft installation requires more than 4 kva of AC power to operate radar equipment, it is recommended that this should be handled as if it were a three-phase load, even though it may consist of several single-phase loads. In the future the radar power requirements for a large military aircraft may be as large as 20 kva.

The switching on or off or even the operation of certain types of equipment such as gun turrets cause sudden variations or transients to appear in the generated voltage. When radio or radar sets are connected to the same generator to which such other equipment is connected, the effect of these transients on the radar or radio set if very undesirable. In future large aircraft, the diversity of the different loads and the size of the required power plants may be so great that serious transient phenomena will not occur during normal combat operation. Nevertheless, it is desirable that such aircraft should have sectionalized main wiring so that the radio and radar equipments can be powered by an otherwise unloaded generator with emergency provision for the use of this generator for the other loads as well in case of battle damage.

In addition to the requirements mentioned above, it is sometimes necessary to provide a small amount of AC power at some precisely determined frequency. Such power may be required for the operation of selsyns, servomechanism operation, or electrical computers. It is recommended that since such loads are usually small that this AC power be obtained from small, special motor generator sets which may be reasonably reliable and light because of the small total power requirement.

SUMMARY

For large aircraft with complex electrical systems, the following recommendations are made:

1. Three-phase power should be generated unless a separate generator can be provided to power the electronic equipment alone.

2. The power frequency should be 400 cps with tolerances of -10% or $+30\%$ if such tolerances can be achieved without excessive weight and complexity. In the event that such frequency tolerances cannot be economically obtained, then frequency variation must not be accompanied by a change in wave form.

3. For small aircraft variable frequency engine-driven alternators may prove satisfactory power sources. Existing types of voltage regulators may be satisfactory if the power required is not more than 2 kva. The development, however, of more satisfactory voltage regulators, perhaps electronic in nature, is recommended.

4. Consistent with the above recommendation that AC primary power be furnished because it is more satisfactory for radar and radio service, is the recommendation that AC induction motors be employed to operate accessory aircraft machinery in order to decrease the noise produced by such devices in radio receiving equipment.

ASSIMILATION OF RADAR INTO THE AIRPLANE

The experience of the past few years has shown how greatly the performance of an airborne radar is affected by the way in which it is installed. In too many cases, especially early in the war, radar has been regarded as an accessory to be grafted to an already completed airplane. With such a policy a good installation is rarely possible. There is a recent tendency to regard the radar as a part of the airplane in order to enable an early adjustment of the radar to the other structures and equipment. Recently the aircraft manufacturers have been given access to confidential information on radar and are rapidly developing an appreciation of its problems. At the same time the radar development and manufacturing agencies are acquiring a sympathy for aircraft design problems. Increasingly close and very profitable collaboration in the planning of radar installations has thus become possible.

Skillful assimilation of the radar into the airplane requires attention to many important points. For instance, the antenna must have unobstructed "vision" for scanning but it should not require a housing (radome) so large as to prejudice the flight characteristics of the airplane. The radar must of course be as light in weight as possible while meeting the specifications. The station for the radar operator must be designed with full regard for its efficiency; consideration should be given to such items as the convenient placement of the indicator and its visor and the most frequently used controls, and the reduction of ambient light. Each unit comprising the radar must be accessible for adjustment or removal, without requiring the prior removal of any other unit. Certain of the interconnecting cables must not be too long, etc. All these conditions must be met in any airborne-radar installation regardless of its tactical use and regardless of whether the set is operated by the pilot or by a special operator.

Of all the components of an airborne radar the antenna presents the most difficult installation problem and this problem arises anew with each combination of an airplane and a radar set. The antenna is the sensory organ of the radar. Under some conditions it is the main sensory organ of the airplane, and its correct installation is a matter of great importance. The antenna will therefore be discussed in some detail.

From the radar point of view usually the largest antenna is potentially the best. From the airplane point of view the reverse is true. Therefore the choice of antenna size is a compromise, and at present this compromise is often reached by executive decision rather than by analytical study. In discussing the nature of this compromise we must first point out the two principal qualities demanded of any antenna: the ability to receive echoes from distant small objects; and a sharp pin-pointing of the beam so that confusion can be prevented during scanning by irradiating the objects one at a time. Thus the two greatest (but not the only) requirements which can be met by the antenna are range performance and angular resolution. The importance of these requirements depends on the tactical use for which the radar is intended. The range performance of the radar varies as the area of the reflector of the antenna, and the beam width varies inversely as the width of the reflector. The width of the beam also varies directly as the wavelength of the radiation, a fact which has determined a distinct trend toward radars of shorter wavelength from L-band to S to X to K. However, attenuation of K-band radiation by the atmosphere so seriously limits the range performance at this frequency that at present X-band is the most appropriate for most long-range uses.

The case for large antennas* is illustrated, for example, by the navigational and bombing type of radar, which should exhibit long-range (e.g., 80 miles) performance as well as sharpness (e.g., 1.2°) of beam. It is plain that the interests of good navigation are best served by a radar with good range performance and that good resolution facilitates not only accurate bombing of a ship or other isolated target but also enables the radar bombardier to identify the briefed target (factory, bridges, etc.) in a complex of incidental radar echoes. When field test statistics are available which show to what extent navigation and bombing are improved by improved range performance and beam sharpness, the case for large antennas can be stated with confidence. In the absence of these statistics, we can use the following rough calculation of the effect of beam width upon bombing accuracy. With a 3.2° beam (29-inch paraboloid) two targets located side by side and one mile apart appear blended into a single blur on the screen if they are more than 18 miles from the bomber, whereas with a 1.3° beam (60-inch shaped cylinder reflector) these two targets are already resolved when still 44 miles away. On a jet bomber, leaving the initial point at 30,000 ft and 600 mph ground speed, to bomb one of these two targets, the 3.2° radar would not clearly identify the briefed target until it was within 18 miles. Since the bomb track is about 7 miles, the bombing run could be no longer than about 11 miles or 66 seconds, including the time needed to correct the course following target identification. On the other hand if the beam is as narrow as 1.3° the interval between identification and bomb release would be about 37 miles or 222 seconds, better than a three-fold improvement over the above figure. The reduction of bombing errors that could be expected if the narrower beam is used can be determined only by actual trials but calculations of the kind just presented tend to show that the narrow beam is very desirable indeed. On the other hand the case against large antennas can be argued by the aerodynamiscists who design the radomes; to be cogent their case must be backed up by wind-tunnel measurements. It is highly desirable that in the future when a new radar antenna is developed as part of a new airplane, the appropriate study be carried out as indicated above.

For good navigation it is not enough to see displayed on the indicator tube the cities, etc, that lie at a great distance, i.e., at an angle of say 2° below the horizon. The map must also show the terrain and man-made objects on the ground at shorter ranges. This requires that a part of the energy be radiated at depression angles greater than 2°; in other words one specifies that the energy shall not form a pencil beam but a fan beam. The main part of the radiation, forming the "nose" of the beam, illuminates the most distant targets, while the rest of the energy fans out within a vertical plane below the nose (Fig. 4). In scanning, the entire fan revolves about a vertical axis.

Further considering a navigational and bombing radar designed to present a circular map of the terrain below, we point out the obvious fact that the antenna

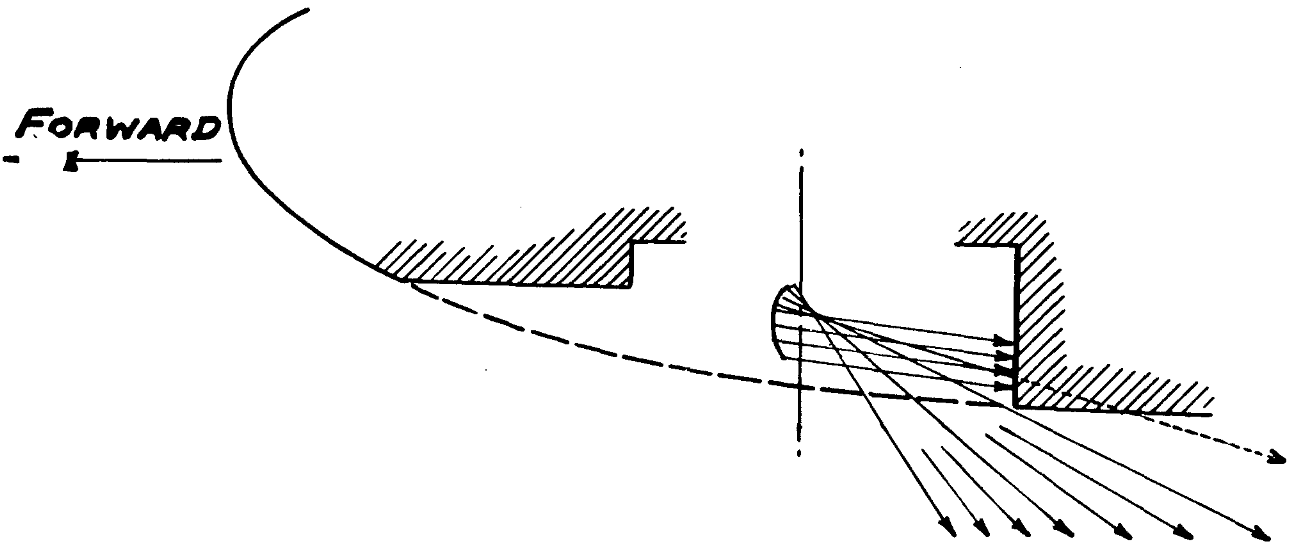


Figure 4

should be so mounted as to have an all-around view of the ground: For this purpose the under side of the fuselage has always been chosen. Circular-mapping antennas have been installed in great variety: distorted paraboloids of 18 in. diameter (AN/APS-10, a lightweight nagivational radar) and 29 in. diameter (AN/APS-15 and AN/APQ-13, the H_2K sets widely used over Europe and Japan for bombing through overcast); shaped cylindrical antennas 60 in. wide and 12 in. high (AN/APQ-13, a modification of the above, for B-29 airplanes); and paraboloids cut to oval contour as large as 8 ft wide and 3 ft high (Cadillac, installed in a few special carrier-based TBM airplanes for early warning against enemy forces). Each of these rotates about a vertical axis in a stationary radome. The radomes of two versions of AN/APQ-13 are shown in Figs. 5 and 6. The installation of AN/APS-23 (an H_2X set currently being engineered) in certain medium jet bombers will probably place the scanner within the lower part of the nose, Fig. 4, in which location the radar performance will suffer in regard to backward vision but the drag of the airplane is completely unaffected. Because the AN/APS-10 antenna is small and because its main use is on low-speed airplanes, it can be mounted with the radiator in a wholly external blister without too seriously hindering the airplane performance. The drag suffered by a B-29 cruising at 25,000 ft and 300 mph TAS as caused by AN/APQ-13 (29 in.) in an unstreamlined radome is about 9 mph; the 60-in. version of this antenna is housed in a radome so shallow that the drag on a B-29 is only 2 mph. Pilots have estimated that the Cadillac radome on a stripped TBM costs only 2-4 mph compared with a standard TBM, a somewhat surprisingly low figure.

It was remarked above that certain installations of AN/APS-23 preclude the observation of objects in a rearward sector. The reason for this is made clear in Fig. 4, in which the energy is shown proceeding from the source to the reflector and thence being reflected into the air as a fan of radiation. The reflector is shown looking aft. The shaded area indicates structural parts of the airplane and the radome is shown dashed. It is plain that an installation of an antenna in a radome beneath the fuselage

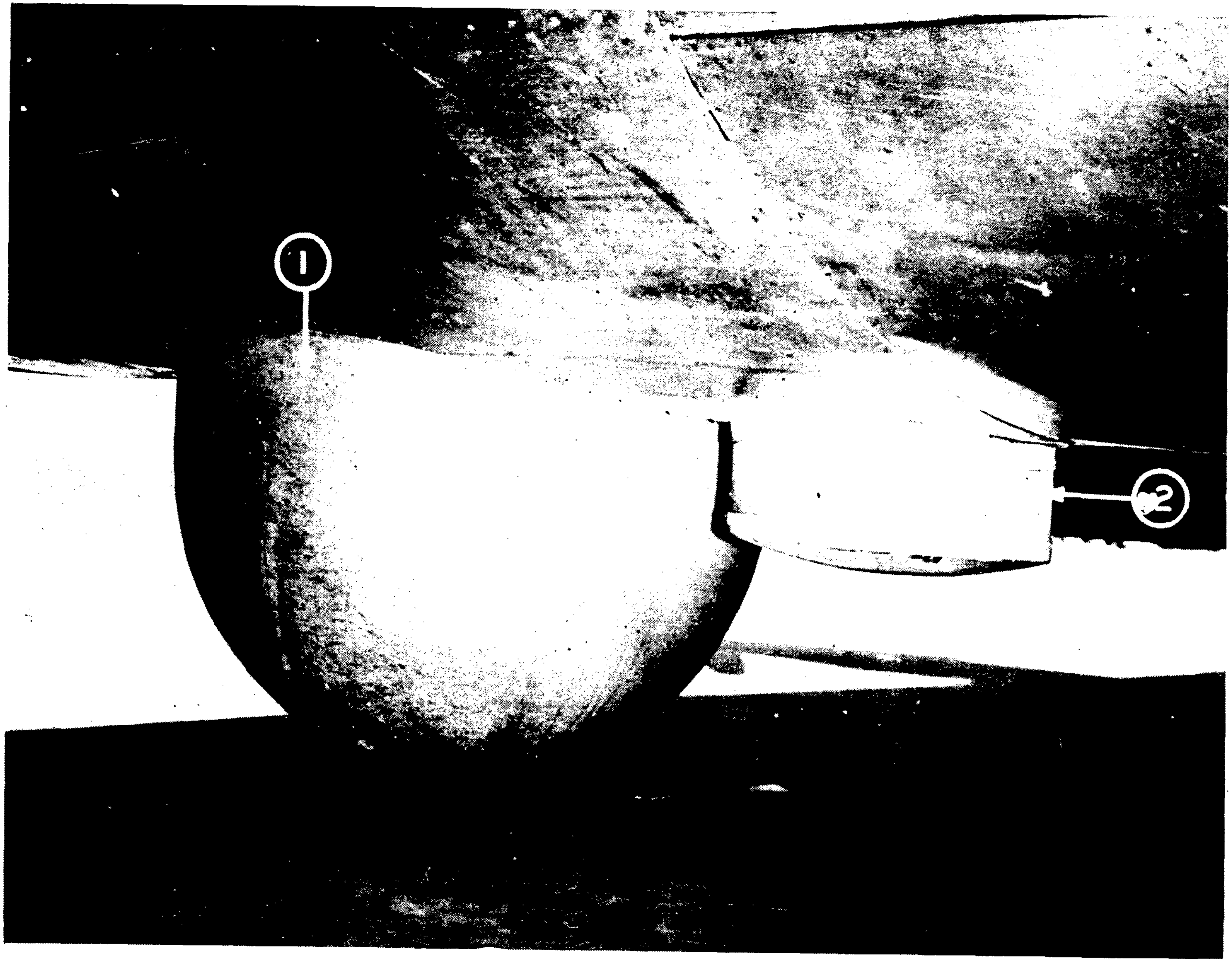


Figure 5

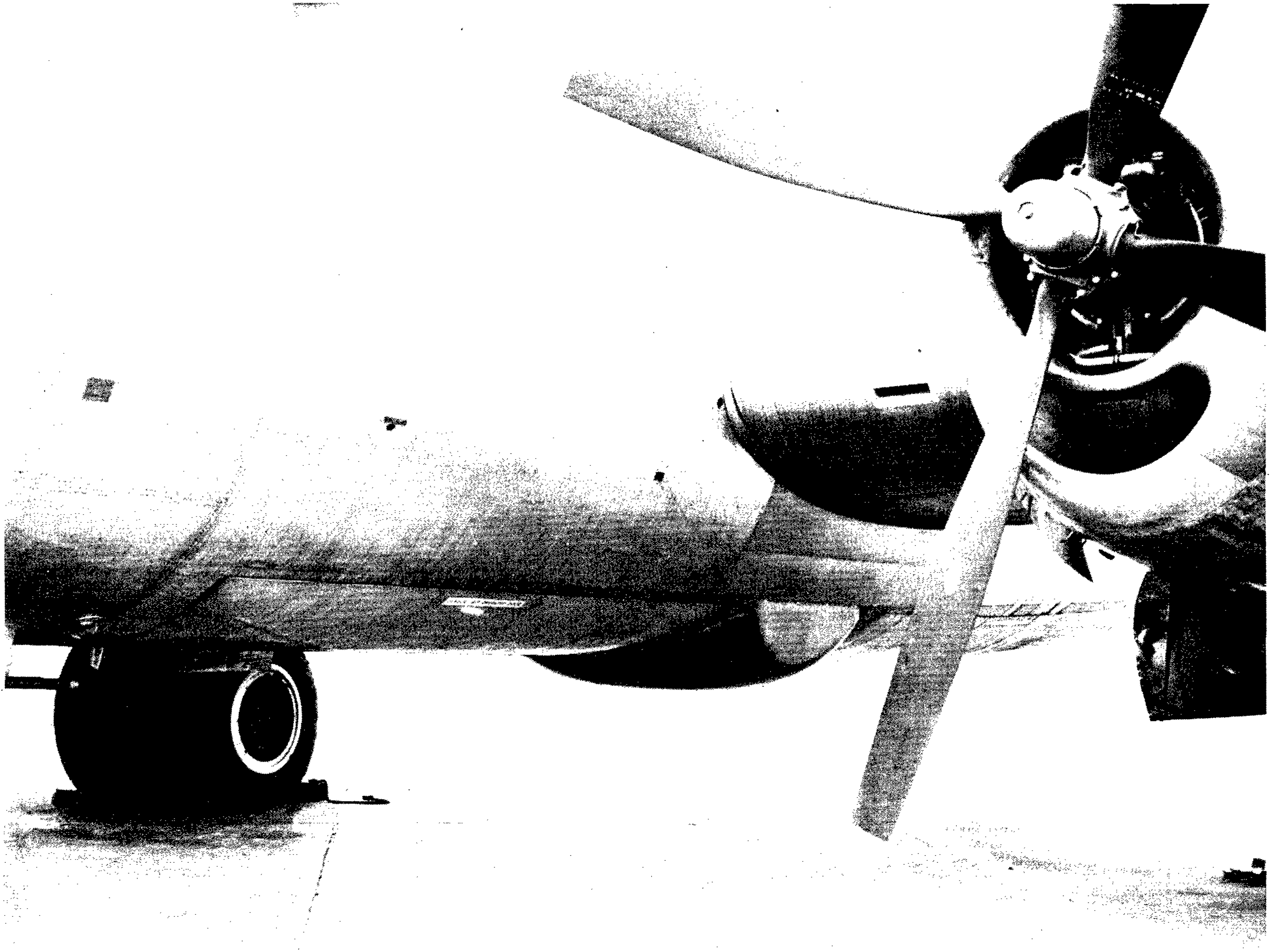


Figure 6

allows vision of the ground in all directions. Such an arrangement is preferable from the radar viewpoint, since it allows certain advanced bombing techniques mentioned before, which requires rearward as well as forward operation.

The considerations advanced above in regard to 360°-mapping antennas apply with obvious modifications to other antennas.

Correct design of the radome is nearly as important as correct antenna design. Beside being strong enough to withstand the wind forces, it must be electrically transparent to the energy from the antenna falling upon it. This transparency must be realized by each part of the radome, whether the radiation falls upon it perpendicularly or obliquely. Present methods of radome construction allow angles of incidence throughout the range from the perpendicular to about 70° off the perpendicular. It is incumbent on the designer who lofts the radome to assure that the radiation from the antenna will not traverse the radome at angles more oblique than indicated above. If good fairing requires a violation of this condition a compromise must be reached.

Antennas have been mounted in a great variety of locations on airplanes: below the fuselage, under the nose, in the nose, above the fuselage, in the tail, in a bomb attached to the fuselage, in a bomb under a wing, in a nacelle at the leading edge of one wing, and at one wing tip. In the face of such variety of installation it is futile to guess what will be the antenna installations of the future. One can, however, point to certain advantageous installations that have not been tried. An antenna which is sufficiently compact in the vertical dimension could be installed in the under-surface of a wing, scanning obliquely downward through a plastic window. Two synchronized antennas having semicircular coverage could be located in the nose and tail of an airplane, thus enabling 360°-ground mapping or detection of other airplanes, without requiring any protruding radome. A complete coverage of all space could also be realized by the hemispherical coverage by a search antenna in each wing tip of an airplane. A heavy bomber with two bomb bays and a very low wing could incorporate a 16-ft AN/APQ-7 antenna in the leading edge just behind the forward bomb bay. A two-engine night fighter with pusher propellers provides two good sites for wing nacelles containing antennas, one for continuous search of the forward hemisphere and the other for following any one desired target. An installation with these two antennas in the tail of a heavy bomber has been suggested for protection against pursuing fighters. For a night fighter with fixed guns, fire control could be instrumented with the help of a paraboloid reflector mounted in the spinner of the propeller, thus executing the conical scan which is common in fire-control systems. Homing antennas analogous to the ASB radar could be merely a series of slots cut in the fuselage, replacing the external antennas. Hopefully, an antenna can be designed in the shape of a flat horizontal plate flush with the flat underside of an appropriately designed airplane. The above ideas are written in order to emphasize that new radar installations of merit are conceivable, and that they commonly require early and continuing collaboration with the aircraft designer. When the aircraft design is so far along that a mock-up is under construction it may already be too late to plan an optimum assimilation of the radar.

RELIABLE ELECTRONIC COMPONENTS

There are at present two chief service criticisms of almost all types of electronic equipment. These are: (1) It is too complicated to operate because there are too many knobs, handles, and switches for the operator. (2) The equipment is unreliable. In order to remedy the first of these criticisms by decreasing the number of knobs and adjustments, more of the equipment must be made automatic. But since the same number of functions or even more functions will need to be carried out by the equipment, this in turn means that its internal complexity must be increased. Thus, if we eliminate a particular knob, we must furnish an automatic device inside the equipment to take care of this adjustment without attention from the operator. This automatic device will require extra parts and these parts in turn may fail and by their failure prevent the equipment from operating. Therefore, not only must we increase the reliability of the individual parts so that present-day radar and radio and indeed all electronic equipment may be made more reliable, but the increase in the component part reliability must be many fold because in the future we may expect more of these parts to be used, the failure of any one of which may cause failure of the entire equipment. Such component parts comprise resistors, condensers, transformers, electric motors, and a large variety of small pieces of equipment which are not generally visible to the operator. It is not possible, without writing a tremendously long volume, to detail all the different types of components upon which improvement is needed. We shall, therefore, give a short history here of just a few types of components which were unsatisfactory at the beginning of the war and demonstrate thereby the great difficulty which obtains during wartime in getting improvements made in such components. Particularly the insufficiency of the service specification should be noted. It should also be remarked that during peacetime there is no industrial incentive which would require that such component parts be made suitable for service operation. Indeed, quite the opposite is true, for it is frequently desirable that parts should be frequently replaced for one or another of several economic reasons. As examples, the history of cable connectors and of certain types of resistors will be described.

CONNECTORS

The standard electrical connectors for aircraft applications are known as AN connectors. They are made in accordance with a specification originally set up as an Army-Navy Aeronautical Standard AN-9534 (Nov 1939), and subsequently revised to AN-WC-591 (June 1942) and AN-WC-591-a (Dec 1944). These connectors even when made and used in accordance with the latest specifications, are inadequate for the intended purposes and will continue to be a primary source of operational trouble when exposed to service conditions of high altitude and high humidity. A few pertinent points are outlined below.

Even in the latest specification, no cognizance is given to tests or ratings at high altitude. The voltage ratings are specified as "limiting operating voltages," given as

DC or AC (rms) in accordance with specified minimum effective creepage distances. No mention is made of whether these apply to dry sea-level conditions or high altitude with condensation. The general practice is to assume that the ratings apply to the worst combinations of humidity and altitude with the result that breakdowns are inevitable. For example, the 500 v (DC) rating is applied to connectors with a leakage path of 3/16 in. Our experience is that for service use where combinations of high altitude and condensation are met, the spacing must be at least 3/8 in. for 500 v.

No connectors are available on the AN complement which can be conservatively used for many of the voltages encountered in modern electronic equipment. The original designs were based on the types of service required in 1940. Thus we have the designations "Instrument, 24 v, 110 v, and 500 v," which were a part of the old specification. In the latest revisions, these classifications are dropped and some new connectors are added but essentially what is left to work with is a large number of connectors with creepage distances between pins of 1/8 and 3/16 in., and a very few with 5/16 in. spacing. There is nothing greater except one high voltage single-contact connector (the 18-16) which originally had a rating of 20,000 v, now reduced to 2,000 v. In present-day applications, voltages of from 400 to 700 v are very commonly used but no connectors with more than two pins are made with a creepage distance greater than 3/16 in. The exception has a specification rating of 500 v (DC) but its safe practical rating is about 300 v. The consequence is that multicontact connectors optimistically rated for 200 v (Service A) are generally used for voltages from 400 to 700 because no others are available with the desired number of pins (6 to 30 or even more).

Conversations with the leading manufacturers of AN connectors revealed, that these manufacturers felt that they had discharged their design obligations if they produced connectors in accordance with the spacing and distance specified by the services. They felt no special responsibility for equipment or connector failures due to voltage breakdown because these connectors had been made in accordance with the service specifications. They were quite aware of the misuse of connectors at the time, but they were not stimulated to do very much by way of altitude-testing or sustained humidity testing because of the protection afforded them by the service specifications.

Indeed, in the particular case of Type 18-16 connector, which as noted above originally had a rating of 20,000 v now reduced to 2000 v, it required many months to convince the manufacturers of this point. When the manufacturers were finally convinced, it took some months more to design a connector which was usable up to only 10,000 v and get it into production. In the interim period, connectors failed in airborne service, and radar systems often failed at high altitudes or in humid climates when they were most needed.

RESISTORS

Wire Wound.

Wire-wound resistors available at present are of two general types: the power type covered in specification JAN-R-26 and the precision type described in JAN-R-93. Neither adequately fills the need for a large number of applications in electronic circuits where the primary requirement is stability and constancy of temperature coefficient but where the power dissipation requirements may be only a few watts. For example, if a 50,000-ohm resistor is needed, it is necessary to use a unit having a length of nine inches and a diameter of one inch for which the wattage rating is 90 w. If the resistor is intended for use by the Navy, the maximum available resistance even in this physical size is 1600 ohms because of the added requirement that only single-layer windings of 2.5-mil wire be used. This is obviously beyond reasonable utility. For circuits in which the power dissipation may be only 5 w, it is absurd.

The accurate wire-wound resistor, JAN-R-93, is more compact because 1.5-mil wire-wound multilayer construction is permitted, but since this type was primarily intended for meter multiplier use, the wattage rating is only one watt. Furthermore, these are not well protected against the effects of humidity and atmospheres bearing salt spray.

To make some practical solution we have had to obtain a series of specification waivers for wire-wound resistors permitting the use of 2-mil and 1.5-mil wire-wound multilayer.

One objection (Bureau/Ships) to the use of 1.5-mil wire is that die marks are left on the wire which weaken it mechanically. If this is so, research should be carried on to develop satisfactory drawing techniques. A more direct solution is suggested by our work with resistors made (P. J. Nilsen Co.) by evaporating low temperature-coefficient metal alloys such as silver-palladium and silver-platinum on grooved ceramic forms. The work is still in its very early stages and completely successful resistors have not yet been produced, but intensive development of such an element would yield resistors having a dissipation of about 5 w, and resistor values up to 20 megohms in a physical form 1/2 in. in diameter and 3 in. long. These units would have a temperature coefficient not greater than 120 ppm/°C with temperature stability and retrace characteristics at least as good as those made with Nichrome wire.

Carbon.

Present-day composition resistors are not too well suited to the demand imposed by precision electronic circuits because of (1) the change of resistance with use, (2) the change of resistance over a period of time as a result of shelf life, and (3) because of the wide tolerances for temperature coefficient allowed in manufacture.

1. Resistors having a stated resistance tolerance of ±5% are widely used in circuits in which wider limits deleteriously affect performance and accuracy. The best types of carbon resistors may change as much as 10% after several hundred hours of operation if the accompanying temperature cycling carries with it some exposure to humidity. Operation at high ambient temperatures accompanied by humidity will accelerate the rate of change. The JAN-R-11 specification permits a 10% change after 200 hr at 85°C ambient, with the resistor dissipating only 25% of its rated wattage.

2. Carbon resistors age with shelf life at a rate depending on humidity and temperature cycles. This change may be only two or three per cent under favorable conditions after several thousand hours, but if humidity is present the change will be greater. Some resistors have been encountered in which the change after laboratory shelf storage was almost 10%.

3. Allowable temperature coefficients for the best grade of one-megohm carbon resistors are -2500 ppm/°C below room temperature and ± 1250 ppm/°C above room temperature. For a given manufacturer the latter value will always be either plus or minus but it is seen that the variation due to temperature changes between commonly encountered ambient limits of $-40°$ to $+80°$C may result in a total resistance change of as much as 20%. Actually the values obtained in production resistors are somewhat better, 12% being an average figure for a one-megohm resistor.

The point of the arguments listed above is that the operational variations in 5% carbon resistors are greater than the initial specified tolerance so that this figure becomes virtually meaningless when the circuit becomes part of a functioning piece of electronic equipment. Development should be carried on to the end of obtaining high-grade carbon resistors of known and specified temperature coefficients and suitably protected against the effects of ageing and humidity. The Bell Telephone Laboratories have made a good start with their glass-enclosed precision composition resistors (type D-161360) but their size, fragility, and mounting difficulty makes them unsuited for general applications in airborne equipment.

Other components which are in much the same state as connectors and resistors are electrolytic capacitors, paper capacitors, ceramic capacitors, R. F. chokes and small inductors, subminiature tubes, ratings and operational data on standard tubes, selenium rectifiers, and video cable and delay lines.

In each case there is a history of deplorable unsuitability three or four years ago, followed by some degree of improvement in the war period, but with many very evident shortcomings still to be overcome if equipment is to be reliable and efficient under all conditions of operation.

It is recommended that the services support a continued program of research and development to produce electrical and electronic components of the durability required for service operation.

BOMBSIGHTS AND COMPUTERS

REQUIREMENTS SET BY AIRCRAFT SPEED AND ALTITUDE

The amount by which a bomb dropped from a moving aircraft is thrown forward may be calculated by multiplying the speed of the aircraft by the time which its takes for the bomb to fall to the ground from the height at which it was dropped. From this figure, there must be subtracted a quantity known as the trail, which is a measure of of the distance by which the bomb is blown backwards relative to the aircraft by its own relative wind. For the purposes of this report, approximate values of bomb trail were obtained from the Ordnance Department, U. S. Army: "These trail values were computed for a ballistic coefficient of 4.0, based on the Gavre resistance function, taking account of Ordnance standard atmosphere including temperature structure. Curves showing trail as a function of true air speed for several different altitudes are shown in Fig. 7. Trail is given in mils and may be converted to feet distance along

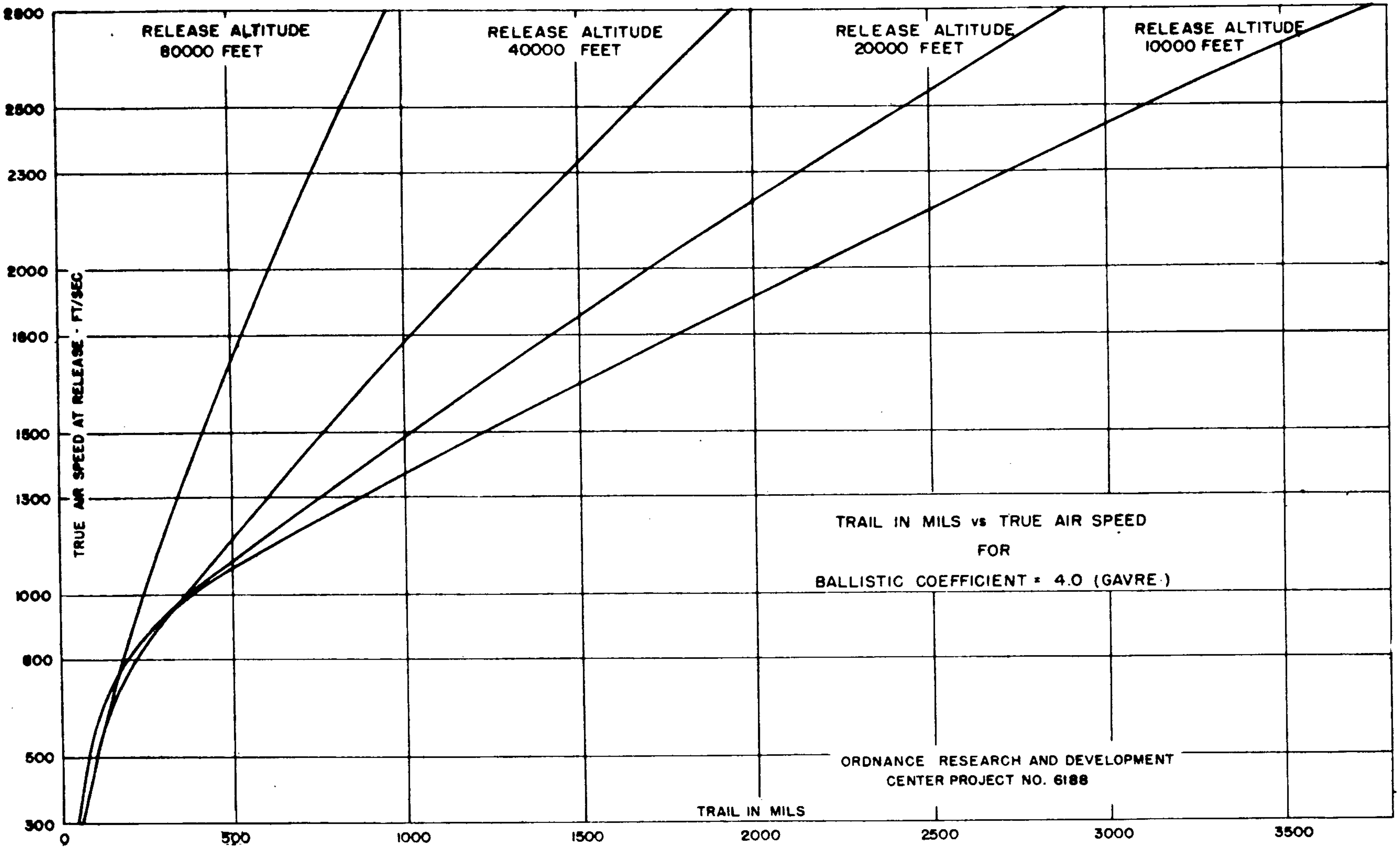

RELEASE ALTITUDE 80000 FEET
RELEASE ALTITUDE 40000 FEET
RELEASE ALTITUDE 20000 FEET
RELEASE ALTITUDE 10000 FEET
TRAIL IN MILS vs TRUE AIR SPEED
FOR
BALLISTIC COEFFICIENT = 4.0 (GAVRE)
ORDNANCE RESEARCH AND DEVELOPMENT
CENTER PROJECT NO. 6188
TRUE AIR SPEED AT RELEASE - FT/SEC
TRAIL IN MILS
2800
2600
2300
2000
1800
1500
1300
1000
800
500
300
0
500
1000
1500
2000
2500
3000
3500

Figure 7

the ground by multiplying by the altitude in feet divided by 1000. As an indication of the significance of a ballistic coefficient of 4.0, the following tabulation of ballistic coefficients for trail listed in current bombing tables is given below."

Bomb	*10,000-ft Alt*	*20,000-ft Alt*	*40,000-ft Alt*
GP, 1000 lb, AN-M65	3.87	3.74	3.65
S. A. P., 1000 lb, AN-M59	3.78	3.77	3.76
GP, 2000 lb, AN-M66	4.45	3.92	3.62
A. P., 1600 lb, AN-MK. 1	6.3	6.3	6.3

The forward throw of a bomb as it varies with the speed of the airplane is shown for the four different altitudes of 10,000, 20,000, 40,000, and 80,000 ft in Fig. 8. It will be noted in Fig. 8 that for an altitude of 10,000 ft there is relatively little increase in the forward throw of the bomb above speeds of 800 mph. However, as the altitude increases, according to Fig. 8 the relative increase of the forward throw of the bomb at higher velocities becomes much greater, so that whereas at 1800 mph with an altitude of 10,000 ft we have a forward throw of only 6 miles; at an altitude of 80,000 ft and the same speed of 1800 mph, the bomb is thrown forward no less than 22 miles.

These curves signify that the airplane must drop the bomb while it is distant from the target by the amount shown as the forward throw of the bomb. Therefore it must normally be able to see the target and distinguish it at least this far away in order to take aim.

But this is not the only factor which requires the aircraft to see far ahead of its present position in order to aim the bomb, for it takes a certain length of time to put the aircraft on its proper course in order that the bomb may hit the actual target desired. Indeed, in order to drop a bomb accurately, we must satisfy two conditions. These are: (1) The airplane must drop the bomb when it is precisely the distance away from the target given by the graphs shown in Fig. 8; and (2) the airplane must be heading in a certain particular direction when the bomb is dropped in order that the bombs may go toward the target. It is obvious that in the absence of any wind, the condition for which the calculations to be outlined herein apply, the airplane must be heading, at the instant of bomb release, for the target itself in order to secore a hit. (It can easily be shown that in the presence of a wind, the airplane must head for a point which is upwind of the target by an amount which is given exactly by the speed of the wind multiplied by the time of fall of the bomb. For the purposes of these estimates, we need not consider this calculation since we are only interested in average conditions.)

It is the purpose of a bombsight to make the calculations outlined above. That is, it must first measure the speed of the aircraft in order that the quantity shown in Fig. 8 as the forward throw of the bomb may be computed. Secondly, it must assist in putting the aircraft on the proper course so that when the bomb is dropped the airplane will indeed be pointing at the target. Thirdly, it must locate the target so that having calculated the quantity shown in Fig. 8, it may lay it off in a direction towards the airplane starting at the target itself. Therefore, we must enter into the bombsight several quantities, namely, speed, heading, and target position. (In the presence of wind, it will also be necessary to enter its value into the bombsight.)

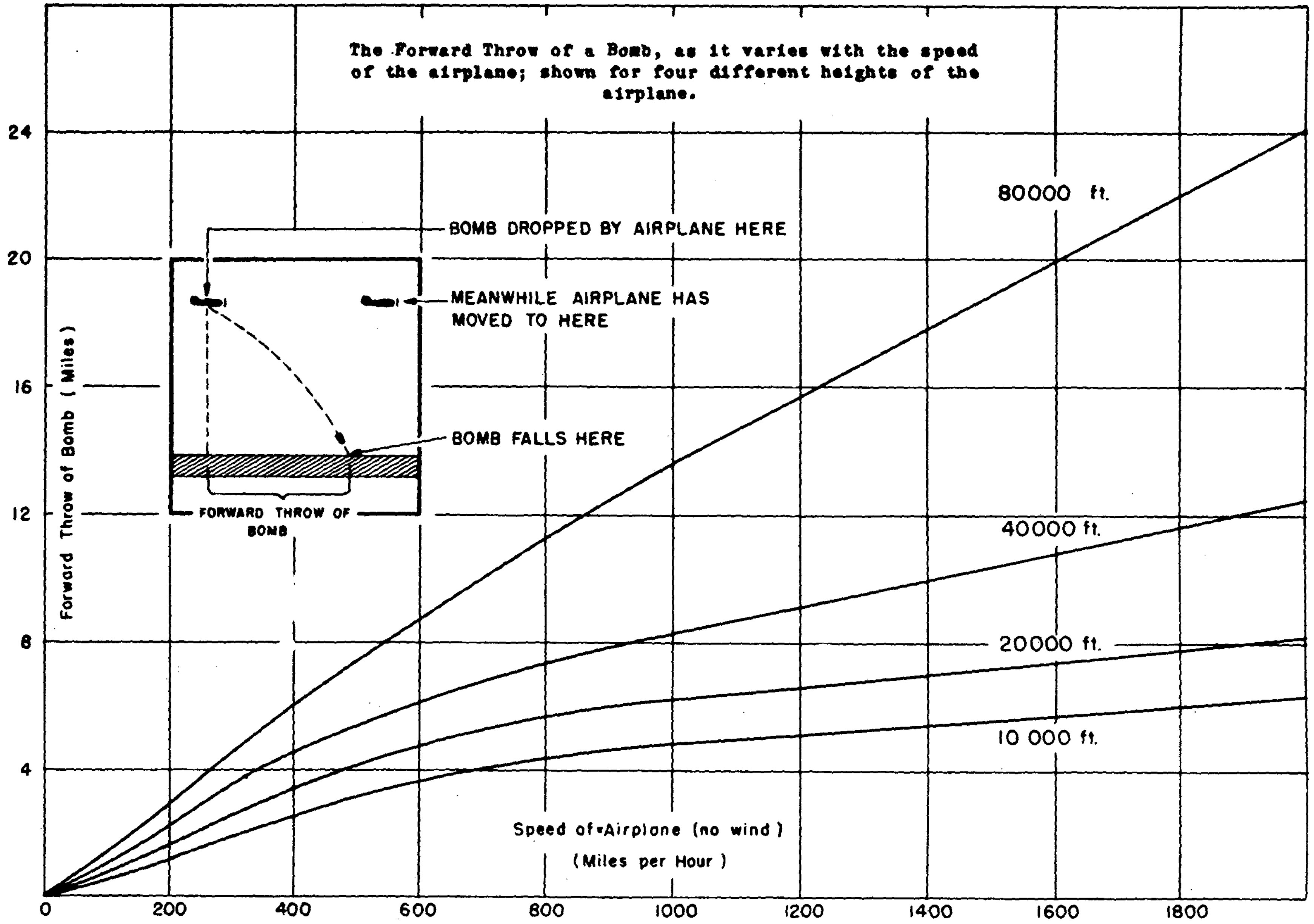

The Forward Throw of a Bomb, as it varies with the speed of the airplane; shown for four different heights of the airplane.

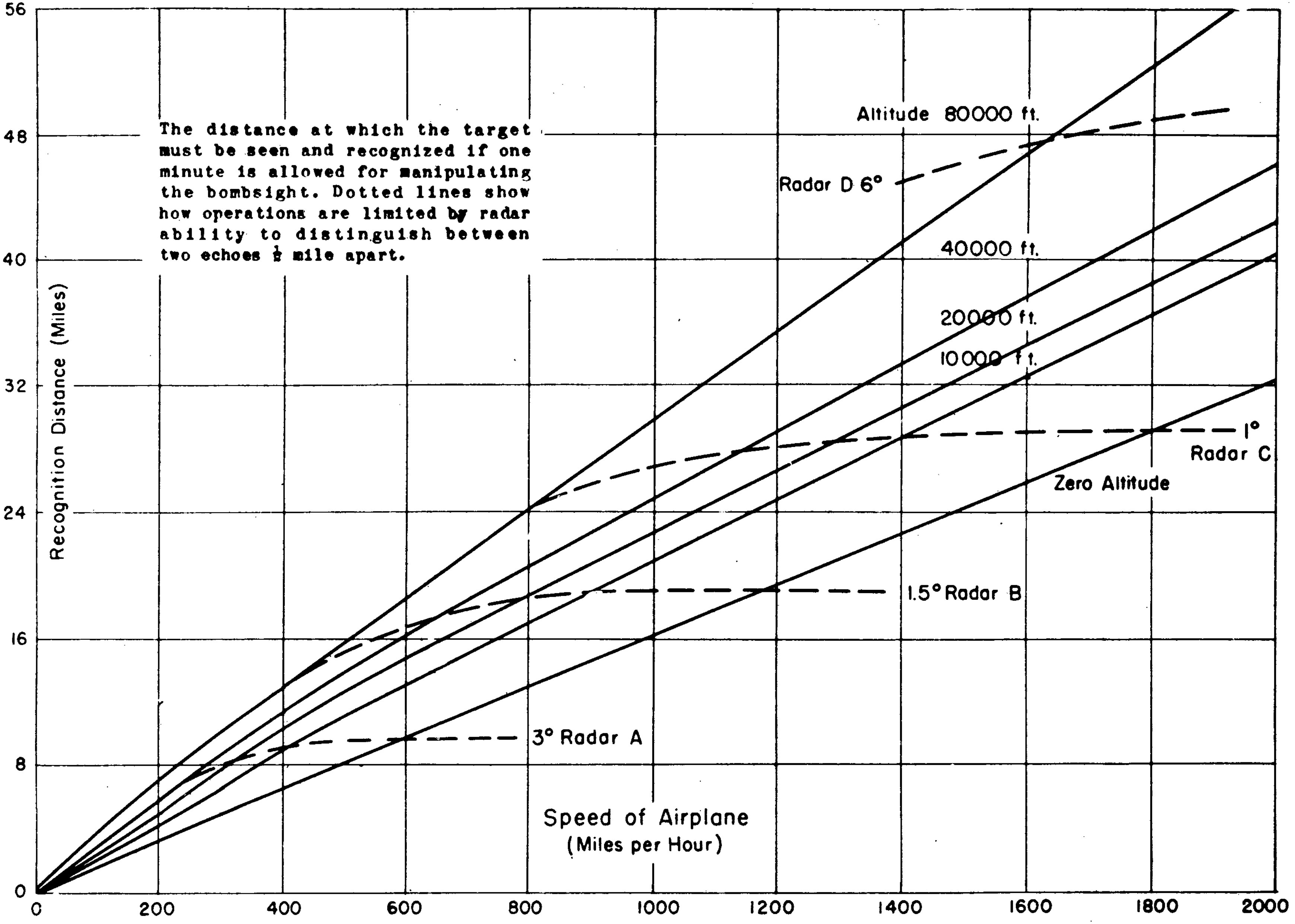
Figure 8

The taking of this data and the making of the necessary calculations all require a certain amount of time.

There are several different types of bombsights which differ from one another according to how these calculations are made. They may be divided into two broad classes: (1) impact-predicting, and (2) synchronous bombsights. We shall not consider here the impact-predicting type of bombsight since it is generally considered to be a rudimentary form whose potential accuracy is low. The synchronous type of bomsight, typified by the Norden Bombsight and also by the AN/APQ-5 Radar Bombsight Attachment, finds the speed of the aircraft essentially by timing the rate at which it approaches the target. In order to get a sufficiently accurate value of the speed, it is necessary to measure successive positions of the target relative to the aircraft over a considerable interval, the speed being obtained by an automatic division of the distance traveled by the time through which it takes the airplane to travel that distance. It is generally agreed that at least one minute's time is required for this operation to be carried out with requisite accuracy. In many cases, and in particular in the case of radar bombsights, it is found that a longer time than one minute is required because of the lower resolving power of radar equipment. We shall, however, assume that one minute is the time which is actually required for a hypothetical bombsight, and proceed to make some calculations based upon that estimate. It is obvious that in the time taken to make this computation, the airplane will fly forward a certain distance. This distance, when added to the previous distance shown in Fig. 8, gives the distance at which the target must first be recognized from the airplane. Curves of this recognition distance for several different altitudes are given in Fig. 9. There it is shown that for an altitude of 80,000 ft and a speed of 1900 mph the target must be recognized while it is still about 54 miles distant from the airplane. It is further shown that even at zero altitude and a speed of 1900 mph the target must be recognized while it is still 31 miles distant. These two figures may also be compared with those corresponding to present-day practice, say a speed of 300 mph and an altitude of 20,000 ft, for which, according to the curves of Fig. 9, the target need only be recognized while it is approximately 8 miles away.

This has a very important bearing upon the construction of bombsights for high-speed aircraft. In the first place, if the instrument is to be of the type represented by the Norden Bombsight, it will be necessary to recognize targets through its telescope while they are extremely long distances away, that is, between 30 and 50 miles. There are very few localities where the air is sufficiently clear that one can see as far as this. We therefore reach the conclusion that a bombsight which is synchronized in the fashion of the Norden Bombsight cannot in principle employ an optical sighting system, but must use some type of sighting system which can see much further.

It is well recognized that radar equipment mounted in aircraft can indeed see for distances of 50 to 75 miles, and this is one of the several attractive features of radar bombsights. There is, however, an additional consideration which must not be neglected. For it is not only necessary to be able to see something in the instrument, but it is also necessary to distinguish the particular "something" in which one is interested. The ability of an instrument to distinguish one of several closely spaced objects is known as its resolving power. The resolving power of a radar is usually less than that



The distance at which the target must be seen and recognized if one minute is allowed for manipulating the bombsight. Dotted lines show how operations are limited by radar ability to distinguish between two echoes ½ mile apart.

Figure 9

of a telescope so that although the radar may be able to detect a group of objects at a much grater range than can the eye equipped with a telescope, it may not be able to distinguish the actual target from the rest of the group at a sufficiently greater range to make it worth while. This consideration of course does not apply to isolated targets, such as ships on the surface of the water, but to such targets as factory buildings in a city. We must therefore consider what the resolving power of the radar set can be in practice.

The resolving power of a radar set can be increased by making the width of its transmitted beam less. In order to do this, we must make the width, as measured in the horizontal direction, of its antenna greater, or we must make the wavelength of the radiation emitted by the radar smaller.

Indeed, the beam width of a radar set is given by the equation $\theta = 70\ \lambda/D$, where λ is the wavelength and D is the diameter of the antenna, both given in the same units. A tabulation of the pertinent figures of certain actual and hypothetical radar equipments is given in the following table.

TABLE 1

Wave-length	*Diameter of Antenna*	*Beam Width in degrees*	*Slant Range*	*Remarks*
3 cm	30 in.	3°	9.6 miles	These figures pertain to the current radar H_2X bombsights AN/APS-15 and AN/APQ-13.
3 cm	60 in.	1.5°	19 miles	These correspond to the AN/APQ-13 equipment as it has recently been modified for installation in the B-29 airplane.
2 cm	60 in.	1°	20 miles	These are for a hypothetical radar which might be similar to that directly above except that it would operate on the as-yet-undeveloped wavelength, 2 cm.
3 cm	144 in.	.6°	50 miles	These correspond to a radar whose resolving power would be slightly less than that of an Eagle or AN/APQ-7 equipment.

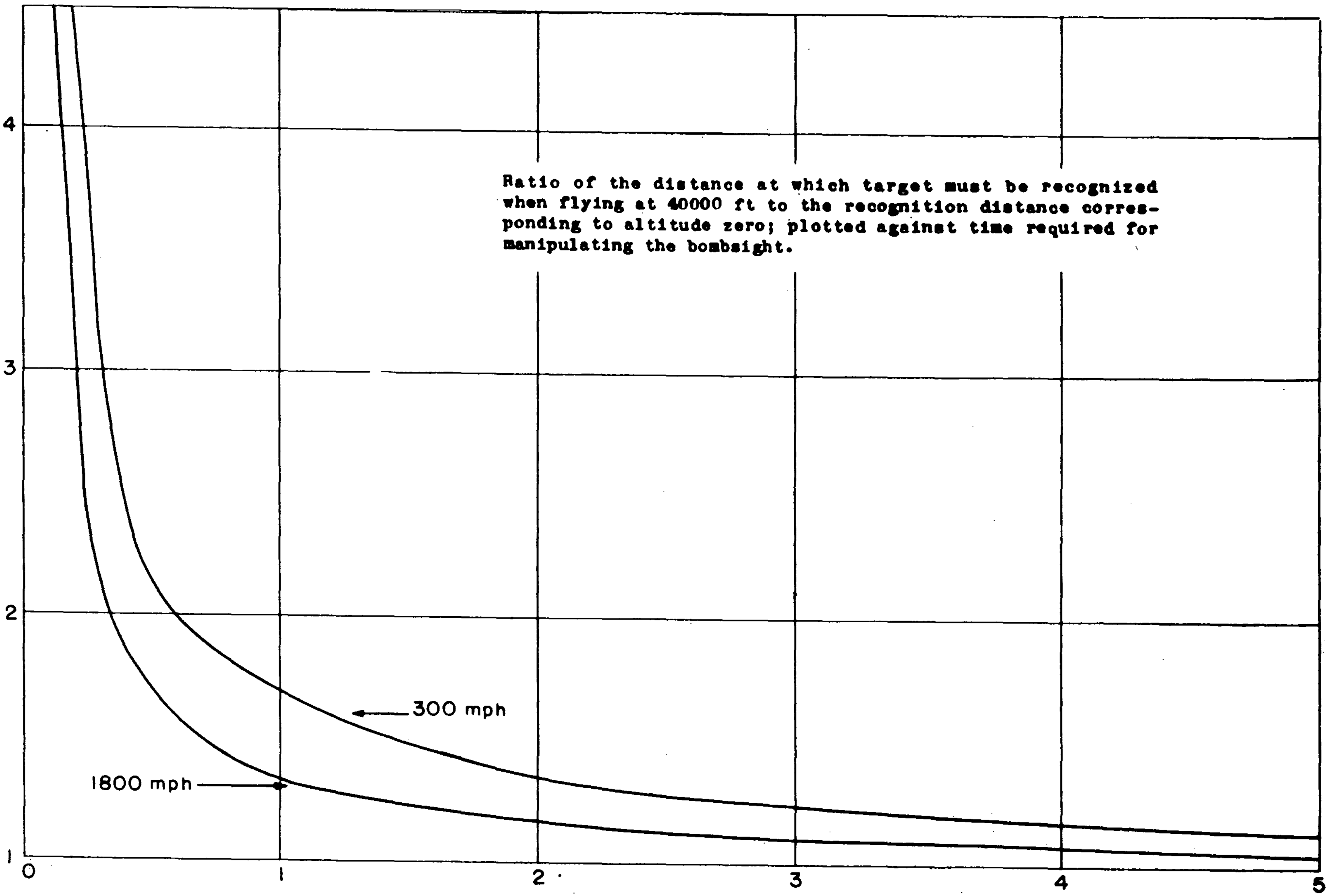
The numbers shown under slant range in the table above are the maximum distances as measured from the airplane to the mean between two point targets one-half mile apart on a line perpendicular to that of the line of sight, and such that the radar is just able to indicate these as two separate and distinct points. Thus, if the airplane is further from the target than the distance shown, it will show as one single object; whereas, if the airplane is nearer than this distance, it will be distinctly resolved into two objects. These values of slant range are only approximate since the observed values vary considerably with the types of target under attack. They agree, however, to the estimates most widely used.

Taking into account that these data are slant ranges, measured along the direct line of sight between the aircraft and the target, and that in Fig. 9 the ordinate represents recognition distance in miles measured along the ground, we have also plotted on Fig. 9, dotted lines showing how each of these four radar sets would limit the range of operation of the aircraft into which it might be installed. For instance, let us consider the first of these radars whose beam width is 3°. We see in Fig. 9 that if the aircraft flies at an altitude of 10,000 ft, the target can be recognized in time for the bombardier to spend one minute adjusting the bombsight computer, if the speed is no greater than 400 mph. The same aircraft and radar set at 40,000 ft altitude can fly no faster than 200 mph under the same conditions. Notice also in Fig. 9 the great value of having the beam width narrowed by a factor of two. For in the case of the radar whose beam width is 1.5° we find that at 10,000 ft altitude we can travel as fast as 900 mph, at 40,000 ft altitude we can travel at 650 mph, and even at altitudes as great as 80,000 ft we can still travel as fast as 300 mph and pick up the target and recognize it in time to spend one minute manipulating the bombsight computer. A still greater improvement is effected by utilizing a radar whose beam width is only 1°, for then at speeds of 1400 mph we are permitted to travel at altitudes of 10,000 ft, and at 80,000 ft altitude we can go as fast as 800 mph and still see the target in time to spend one minute manipulating the bombsight computer. Finally, with a radar set whose beam width is .6° very little restriction is placed on the operational behavior of the airplane at all. With such a radar set we could fly nearly as high and as fast as we wanted, provided that we had a bombsight computer so well designed that it required only one minute to operate after recognizing the target.

It must be emphasized that the curves of Fig. 9 represent only one set of conditions. They have been chosen to be such as to give a reasonable estimate of the situation, but actual conditions can vary widely. In particular, the present radar bombsights such as AN/APS-15 and AN/APQ-13 are not constructed to require only one minute for their manipulation; instead, they may require as long as five minutes for their adjustment after the target has been recognized.

We could also plot curves similar to those in Fig. 9 but pertaining to bombsights whose computers required longer periods of manipulation; we would then find that the speeds and altitudes to which we were restricted by the resolving powers of radars A, B, C, and D would be much lower than those shown on Fig. 9. A converse tendency, however, comes from considering that we have assumed it necessary to resolve two points separated by one-half mile. This figure roughly corresponds to an accuracy on the order of 1000 ft probable error. If we are willing to accept lower precision, then the restrictions placed upon the operation of the aircraft by the radar set are less severe. For instance if we required only to resolve points separated by one mile instead of half a mile, we would find that the three-degree radar placed no more severe restrictions than the 1.5° radar did in the half-mile case. In other words, all of the dotted lines move upwards along the solid lines of Fig. 9. It is felt, however, that the estimate based on a one-half mile resolution separation more nearly approximates the conditions of precision bombing.

Inspection of Fig. 8 as well as of Fig. 9 shows that the forward throw of the bomb is small at low altitudes. The double question arises, therefore, what benefit would be derived from bombing from low altitudes in distinction to bombing from high altitudes, and what advantage would be gained by using a bombsight computer which required only a short time after recognition of the target had been achieved for its adjustment? Fortunately it is possible to answer both these questions by the same computation. Pertinent curves are shown in Fig. 10. The ratio of two distances



Ratio of the distance at which target must be recognized when flying at 40000 ft to the recognition distance corresponding to altitude zero; plotted against time required for manipulating the bombsight.

Figure 10

is plotted as a function of the time required to manipulate the bombsight prior to dropping the bombs and after the target has been recognized. The two distances whose ratio is plotted are, first, the distance at which the target must be recognized when flying at 40,000 ft, and second, the distance at which the target must be recognized at essentially zero altitude. The meaning of this ratio is that when its value is one, there is no advantage in flying either high or low, but when its value is greater than one there is a corresponding advantage in flying low. Inspection of Fig. 10 shows that there is a very great advantage in flying low provided the bombsight computer does not require a long time to adjust. Furthermore, the two curves shown for speeds of 300 mph and 1800 mph are similar to one another. Therefore, we may conclude that at all aircraft speeds, it is advantageous to fly low when bombing, if we use a bombsight computer so designed that it requires less than one minute to adjust. Conversely, if we have a comparatively crude computer in our bombsight which requires considerably longer than one minute to adjust, there is no particular reason for flying either high or low regardless of the speed of the aircraft.

We may therefore summarize the requirements for a radar bombsight suitable for installation in very high-speed aircraft:

(1) The first requirement is that the transmitted wavelength be as short as is possible, limited only by atmospheric absorption.

(2) The second requirement is that the width of the antenna be as great as possible, limited only by aerodynamic characteristics of the airplane.

(3) The third requirement is that the bombsight computer requires the absolute minimum of adjustment after the target is recognized. It should be noted that in the calculations described above we have neglected the effect of the earth's curvature. Although some curves are shown corresponding to zero altitude it must be remembered that at zero altitude one cannot bomb at all because in principle one cannot see ahead any distance. In practice, however, zero altitude corresponds to a few hundred feet, and at these altitudes and above, the other restrictions noted predominate.

POSSIBILITIES OF SATISFYING THE REQUIREMENTS SET DOWN ABOVE

The preceding discussion indicates that it is desirable to regard the radar as a sensory device, and to separate its consideration from that of the associated computer. A consideration of practically obtainable ranges and resolving powers of radar equipment is given in the section "Pulsed Radar" page 39. We shall not, therefore, repeat any of the conclusions except to note that all of the assumed characteristics of the radars A, B, C, and D (Fig. 9) are quite feasible. Furthermore, all such practical radars restrict the operation of the aircraft by virtue of their limited resolving power and not because of their maximum range of perception. There is one exception to this, namely, for radars utilizing wavelengths shorter than approximately 1.8 cm. Such radiation is considerably absorbed by the atmosphere and in the case of equipment utilizing it, it is the maximum range and not the resolving-power range, which limits operational use of the aircraft.

The conflicting requirements of aerodynamics and radar resolution as they pertain to the installation of large radar antennas in high-speed aircraft have been discussed in the section "Assimilation of Radar into the Airplane," page 63. Again we shall only point out here that the sizes of antenna which have been considered in the previous calculations, are such as have already been installed in several different types of aircraft and may therefore be regarded as practicable.

This discussion, therefore, of how the requirements set down above can be satisfied, will be restricted to the bombsight computers only. Although it is difficult to estimate precisely how much time will be required to adjust and manipulate bombsight computers when they have been developed as highly as present information indicates they can be developed, it can definitely be said that a very considerable improvement over those presently in operational use can be effected.

The first possibility for decreasing the time required to adjust the bombsight lies in the use of what is known as "presynchronization." Bombsight computers employing presynchronization contain facilities whereby the speed of the aircraft may be measured previous to the actual bombing run. They contain means which allow the speed of the aircraft to be continually measured and "remembered" by the computing mechanism until needed. Such computers generally require to be connected to a true-air-speed meter as well as to the radar equipment. Their method of operation is essentially to add to the true-air-speed vector, as indicated by the air-speed meter and the compass of the aircraft, another vector which corresponds to the prevailing wind. The latter may be found in one of several ways. The first way utilizes a sighting upon any objects which may appear within the field of view of the radar. In this case the procedure is simply to track whatever object comes into view for a sufficiently long period of time until the computer is so adjusted that its cross hairs continue to follow the object without further adjustment. A computer which already knows how fast the airplane is going requires only to be set once upon the actual target itself, whereupon it immediately indicates to the pilot his correct course. It is estimated that a computer operating in this fashion would, indeed, require only one minute for additional manipulation after the actual target was sighted. In other words, such a presynchronous computer would correspond well to that for which the estimate shown on Fig. 9 was made. Another way of achieving presynchronization would be by the use of the Doppler effect. The possibilities of using the Doppler effect to determine the speed and course of an aircraft have not been fully exploited. However, sufficient work has been done to indicate some such possibilities may exist. The advantage of applying Doppler methods to determine the speed of the aircraft would be, first, that no connection would be required (in principle at any rate) with the air-speed meter, and second, that the taking of this data could be made more nearly automatic. It might be disadvantageous in requiring a separate radar equipment and an additional antenna for this purpose alone; however, the antenna might be a relatively small one in comparison to the main sighting antenna.

At the present time the Army has under development two bombsight computers for use with the APS-22 and APS-23 radar equipments. These two computers are the Western Electric AN/APA-44 computer and the Sperry SRC-1 computer. The U.S. Navy also has under development by the Norden Co., a bombsight computer known as the Mark 22. All three of these computers are presynchronized according to the first method described. In principle they would be suitable for high-speed aircraft except that according to the present specifications the altitudes and the maximum aircraft speeds for which they are designed are both too low. These, however, are not regarded as fundamental difficulties, since they are due to a particular choice of design parameters of a straightforward extension of the present designs, and should easily accomodate more extreme requirements.

A more serious consideration in connection with these computers, however, is that they require to be connected to a true-air-speed meter. Although there are some more or less satisfactory true-air-speed meters available for subsonic speeds, it is not known that any suitable devices are being developed for supersonic speeds. It is recommended, therefore, that a development be set underway to design a high precision supersonic air-speed meter suitable for tying in with radar bombsight computers. It is desirable that such meters should indicate air speed either as the speed of a rotating shaft or as the value of an electrical voltage. Information supplied *ab initio* in either of these forms may be converted into the other if required by the particular computer mechanization adopted.

Since according to Fig. 10 an advantage may be obtained by flying and bombing at low altitudes, if the computer required considerably less than one minute for its manipulation, we should investigate if computing devices which actually require less than one minute for their manipulation period can be devised. It is obvious that a considerable change in our approach to the problem must be made if we are to use less than one minute for manipulating the computer, because this one minute interval also includes the time required to put the aircraft on the proper approach course. The time required to steer the aircraft is, of course, something which cannot be controlled by making the computer fancier, and so we must consider computers which allow the use of radically different bombing tactics as well as the employment of different methods of solving the actual numerical problem.

A solution has already been suggested for this problem. It is called offset sighting. Offset sighting is a tactical and instrumental technique whereby one "points" the bombsight at one object which is called the aiming point whereupon the bombsight causes the aircraft to point itself and aim its bombs at a second object, the actual target. The geometry of this problem is made clear in Fig. 11.

In Fig. 11 the point marked T is the target which we desire to bomb, and the point marked AP is an aiming point which is some distance, R, from the target. It is assumed that prior to the bombing mission we know by means of reconnaissance studies the actual distance, R, between the aiming point and the selected target, as well as the angle φ between the direction of true north and R.

Knowing this data ahead of time, we can set it, prior to take-off, into the bombsight computer. Upon our approach to the vicinity of the aiming point, we measure the distance S between the instantaneous position of the aircraft and the aiming point and also the angle between north and the direction at which the aiming point appears. This is the angle α in Fig. 11. If we know the angles α and φ, we can compute the angle δ, which is the obtuse angle of the triangle shown in Fig. 11, according to the second equation shown. We now know one angle and two sides of the triangle formed by the target, the aiming point, and the instantaneous position of the airplane. From these three data we can calculate the angle ε at which the aiming point should appear from the nose of the aircraft if the aircraft were actually heading at the target T.

$$r^2 = R^2 + S^2 - 2\,RS\,\mathrm{Cos}\,\delta$$

$$\delta = \pi - \alpha + \gamma$$

$$\mathrm{Sin}\,\varepsilon = {}^2/rS\sqrt{x(x - r)\ (x - r)\ (x - s)}$$

$\beta = \alpha - \varepsilon$ is the steering angle which must be held constant to approach T

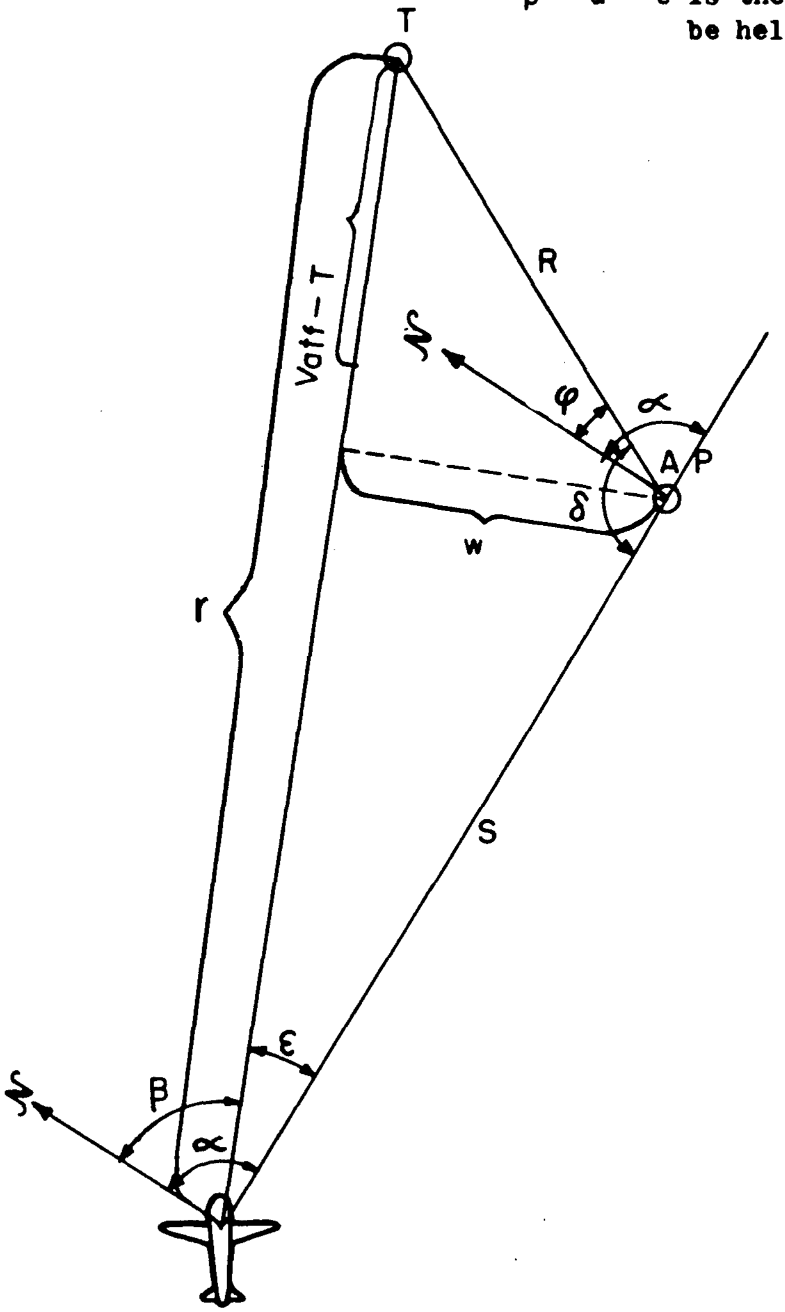


Figure 11 — Computations Necessary for Offset Sighting Computer

This angle, of course, will continually change as we approach the target; however, the angle β, which is gotten by subtracting ε from α, is the desired aircraft heading and should remain constant if we are on the correct course. This angle β is therefore suitable for presenting to the pilot in the form of a right-left steering meter indication to keep him on the correct course to approach the target. Moreover, we can not only compute the steering angle β from the measurements of the aiming point, but we can also compute the distance from the instantaneous position of the airplane to the true target which is shown as r in the diagram of Fig. 11. Use may be made of r just as the distance between the airplane and the target is used in ordinary synchronous bombsights. We now see immediately the great advantage of offset bombing, for the distance S can be much smaller than the distance r, so that even if the speed and altitude of our aircraft require us to recognize the target many miles farther away than we are able to by virtue of the resolving power of our radar equipment, we can still make a bomb run by recognizing AP instead, which is only at a distance S from us, and this distance may be well within the limitations of the radar set. In fact, it can be seen that if the triangle is sufficiently narrowed so that the distance shown as W in the diagram becomes zero, there is actually a case where we can drop the bomb while sighting upon an object which is behind us.

This last consideration, which is by no means a facetious one, indicates very strongly that radar equipment should be installed in aircraft so that it can see to the rearward as well as in front. What this means in so far as the installation of the radar antenna in the aircraft is concerned has been discussed previously.

At the present time, there are indeed bombsight computers being developed which allow one to do offset bombing according to the principles outlined above. These are the same computers previously mentioned, which also allow us presynchronized bombing. However, there is a great difference between the desired conditions and the conditions for which these computers have been designed; i.e., the APA-44 and the SRC-1 are designed to allow offset bombing for a rather small range of values of R, the distance separating the aiming point and the target. Offset bombing in this connection is chiefly of value for bombing hidden targets from rather slow-moving aircraft. In the case of high-speed aircraft where offset bombing is rendered necessary by the limitations of the radar and the very high speeds and altiudes contemplated for the aircraft, the quantity R should be very much greater. This requires an extension of the capabilities, although not a fundamental redesign, of these computers.

A compass which points to the true north is of prime importance in such a bombsight. Indeed, its reading enters the calculation twice; first, we need to know the angle φ between the line connecting the target and aiming point and north; and second, we need to know the angle α between the north direction and the apparent direction of the aiming point as seen by the radar set. Now either of these angles may be in error if the compass reads incorrectly. Such an error will cause a corresponding deflection error in the impact point of the bomb. There are so many different assumptions which could be made in calculating how big this deflection error might be that it is somewhat arbitrary as to which of them we choose. However, let us consider one such error to be proportional to the product of the error in the compass and the separation of the aiming point and the target. It is actually found that the most advanced magnetic compasses such as the Sperry Gyrosyn compass and the Pioneer Fluxgate compass, have residual errors in operational practice as great as ±1.5°. If we desired to use an offset distance R as great as 30 miles, we might therefore expect to find an error of about .8 mile. This error, however, would only be the error in computing where the target actually was. To this we should add the error of 1.5° that the compass would cause the steering meter to indicate. Therefore, the airplane would only fly to within an error of ±1.5° toward a point located only to within ± .8 miles. Since the forward throw of the bomb as we have seen in Fig. 9 might amount to 20 miles, we have an additional error of about .5 mile coming in from this cause. We therefore have a probable error of nearly a mile caused by the compass. It is evident, therefore, that before we can utilize the offset technique in order to take advantage of the conditions shown in Fig. 10, we must develop a superior method of finding out the exact location of true north: we must develop a compass capable of indicating true north to within ± .1° or ± .2°, if the compass errors are to be negligible compared to other errors in bombing.

Before considering what improvement can be made in magnetic compasses we must consider with what accuracy it is possible to determine the actual direction of the earth's magnetic field as a primary datum. It is well known that a magnetic compass does not point towards the true north but towards magnetic north and the position of magnetic north with respect to true north is a varying and often arbitrary function of latitude and longitude. Indeed, the best geomagnetic surveys of the earth's field are not sufficiently precise at the present time to allow us to use a very much more accurate magnetic compass even if we had one. Moreover, even if geomagnetic expeditions could be sent out to remap the earth's magnetic field at all points on the globe, there is some doubt as to whether this data would be of any benefit to us. There are two reasons for this: first is that magnetic storms cause the earth's magnetic field to vary within the tolerances of which we are speaking, namely, ± .1° or ± .2° and second, there is some doubt that the values and directions of the earth's magnetic field measured on its surface will be the same as those measured in aircraft flying at altitudes of 40,000 or 80,000 ft. This causes us to doubt whether magnetic compasses can ever be developed to the accuracy needed for bombsights. It has been suggested by Dr. Britton Chance of the Radiation Laboratory that some use might possibly be made of gyroscopic compasses for offset bombing. As is well known, gyroscopic compasses are widely used on surface vessels; such compasses, however, are subject to serious Coriolis errors due to the speed of the craft, which only disappear when the craft is going either east or west. The sensitivity of such a gyroscopic compass would only be sufficiently great in a high-speed aircraft if it were heading due east. It is therefore suggested by Dr. Chance that a gyroscopic compass might be initially orientated by reference to a magnetic compass to within a few degrees of north, and then prior to the bombing run, the aircraft might fly due east for a sufficient period of time to allow the gyroscopic compass to come to a position of true north, whereupon the gyroscope would be disconnected from its north-seeking apparatus and used as a free directional gyroscope for the next 15 or 20 minutes during the bombing run. In order for this to work it would be necessary to have the compass continually corrected for the rotation of the earth and for the changing position of the airplane; thus the compass would have to be very intimately connected with the bombsight computer and with the navigational computer. This of course is a very complicated contrivance and in order to get some expert opinion as to whether it might practical or not, the writer has discussed it with Mr. Carl Frische of the Sperry Gyroscope Company. It is Mr. Frische's opinion that it would be possible in principle to build such a device for carrying in an airplane.

It would be of considerable importance in the development of accurate bombsights for fast aircraft if a determination of an absolute vertical reference line could be made without reference to gravity, since the acceleration of gravity and any other acceleration due to the motion of the plane are essentially indistinguishable. It appears that such a determination might be possible by virtue of the strong absorption of microwave radiation by the oxygen in the atmosphere, at wavelengths in the neighborhood of 5 mm. By making use of a recently developed technique for measuring the thermal radiation from the atmosphere at microwave frequencies, it is possible to measure the total absorption of the atmosphere in any direction. One can thus determine the direction of minimum absorption which is straight up, providing there is horizontal uniformity in the distribution of oxygen in the atmosphere. How accurately the latter condition is fulfilled is not known. The operation is easily carried out automatically and the equipment required is neither bulky nor complicated, consisting essentially of a very small antenna and a microwave receiver. Further investigation of this method would appear desirable.

We see therefore that, although in principle we can make very remarkable improvement over present bombsights even for extremely high-speed and high-altitude aircraft, such improvement would only be at the cost of a very great complexity of the bombsight computer. Thus it is particularly pertinent that the component parts of which such a computing device would be made should be of the utmost reliability since so many of them will be necessary. Attention is directed therefore to the preceding section "Reliable Electronic Components" which discusses the general problems of electrical and electronic instrument components and recommends that the services should not only support the development of more perfect mechanisms but should also vigorously support the development of more perfect component parts from which to make these mechanisms.

Thus far we have considered first the requirements for a radar set by which one might be able to recognize the target at a sufficiently great distance in order to do something about it, and second we have considered how a bombsight computer might be designed in order to allow it to operate in the time available. We have yet to consider how the data is to be presented to the bombardier in order that he can make an intelligent decision as to what he is looking at. If he is using a radar bombsight, the target will appear on some sort of a plan-position indicator. Such an indicator, in order to present the data to its fullest advantage, would have a map scale of perhaps one inch to the mile. Now an airplane traveling at a speed of 1200 miles an hour goes 20 miles a minute, and furthermore a cathode-ray tube of practicable size would cover a total distance of at most five miles for a scale of one mile to the inch; thus any particular target would appear on such a cathode-ray tube for only 15 seconds. It is therefore immediately apparent that automatic means should be provided so that the picture on the cathode-ray tube is caused to stand still regardless of the speed of the airplane. The present design of the Navy Mark 22 bombsight equipment incorporates such an indicator, and it is to be recommended praticularly for high-speed aircraft, although its necessity for aircraft of present speeds is dubious.

Antennas of the type which are normally employed on the AN/APQ-13 and AN/APS-23 equipment have a maximum speed of azimuth rotation of about 20 rpm; in an aircraft traveling at a speed of 20 miles per minute the target would be detected by these but once every mile. It would be much more satisfactory if the target or the aiming point were observed more frequently than once per mile, and this suggests that a special type of rapid-scan antenna should be employed. Again this feature is to be found in the Mark 22 equipment and is to be recommended for use with radar bombsights in very high-speed aircraft.

Conclusion.

The following recommendations are made:

(1) Radar should be employed whose beam width is as narrow as can be made subject to aerodynamic restrictions.

(2) It should be possible for the radar to see equally far in all azimuthal directions from the aircraft.

(3) It is advantageous to use bombsight computers which require the very minimum of time for their manipulation after the target or aiming point has been recognized by the operator.

(4) Presynchronized bombsights suitable for high-speed aircraft should be developed.

(5) The technique of offset bombing using very large offset distances should be studied particularly with reference to high-speed aircraft.

(6) A high-precision compass should be developed as a long-term development.

(7) A precise supersonic air-speed meter should be developed as a long-term development.

(8) Rapid-scan antennas should be developed which allow one to have a full 360 °of azimuthal coverage.

(9) The Doppler effect should be investigated with a view toward using it to determine aircraft heading and true ground speed without the use of an air-speed indicator.

Finally the entire radar, altimeter, compass, airspeed, navigational, and bombing equipment of a heavy bombardment aircraft should be regarded and designed as one integrated unit. The electrical components of which this complicated device is to be constructed should be strenuously developed so that their reliability will not be a limiting operational factor.

THE MEANS FOR STRIKING EXACTLY

The means by which we strike exactly are called fire-control instruments. These may be classed in several categories, as gunsights, bombsights, torpedo sights, etc. Since there are important broad ideas common to the design of all fire-control apparatus, this discussion of the design of particular kinds of such apparatus for future aircraft will begin with some general considerations.

Fire-control apparatus is used to enable a man to detect the enemy and to aim a missile at him, such as a bullet, rocket, torpedo, etc. Thus there are two functions which the apparatus must perform: detection and aiming. It must do these in conjunction with a human being. The latter circumstance is so often neglected and is so important that we shall here speak of it as a third function; the apparatus must fit the capabilities of its operator.

Those are the functions which every fire-control equipment must perform. What then are the additional characteristics of a good piece of fire-control equipment? Many people are inclined to think that it is sufficient for the equipment to achieve the highest attainable accuracy, but this is only a small and not even always significant fraction of its desirable qualities.

Broadly speaking it must do the maximum damage to the enemy in the shortest time when operated by the type of personnel available. Therefore, several factors are involved: (1) The enemy should be detectable as often as possible, which is nearly the same as saying that we desire to detect him in all sorts of weather over as large an expanse of territory as possible. (2) The equipment should fire the maximum number of missiles at the enemy in a given period of time. (3) It should fire accurately. (4) It should be operable by the man who is supposed to operate it. Thus a highly accurate instrument is no good at all if the other requirements are not fulfilled in some measure at least, for the most accurate device imaginable, if it were so complicated as to be broken down 99% of the time, or to require an Einstein to operate it, might easily be defeated by an enemy moron equipped with a pea shooter. Of these four desirable characteristics, only two, detection and accurate aiming, are set by the actual military tactic.

A consistently high rate of fire is not in the long run to be achieved by particular design details which cause one bombsight, for instance, to differ from another, but by a general philosophy of reliable and rugged construction. Now all types of instruments are made of the same kinds of things: motors, gears, vacuum tubes, condensers, coils of wire and so on. Therefore, if we want to achieve high fire power, we must pay attention not only to the design of the "secret weapon" but also to the not-so-secret bits and pieces of which it is contrived.

The Air Forces must support a continued program aimed at developing these bits and pieces to the degree required to make them reliable in aircraft. Industry will not do this; radio manufacturers are not interested in making sets to operate 50,000 ft above the Sahara Desert, and neither are the manufacturers of capital goods: we asked them. It must be realized that the present components which we now have available are just not good enough under present military conditions and that these conditions are rapidly becoming worse. Moreover as the functions which our "black boxes" are called upon to perform become more and more difficult, because the airplane goes faster whereas the man doesn't think any faster, more components will be required for any one device. It is necessary to conclude: (1) Components are unsatisfactory under present military conditions. (2) Military conditions are going to get worse. (3) The number of component parts per soldier is going to increase. (4) Industry finds no economic incentive to develop more reliable components, peacetime conditions being so easy that the ones we have are already too durable to make any money out of. A more detailed and technical discussion of these matters is included in another section of this report, "Reliable Electric Components," page 69.

The other element which can be considered as applying equally to all fire-control devices is the human one. There are two problems: fitting the machine to the man and fitting the man to the machine.

Left to himself, an engineer tends to design any device in the most technologically expedient way; he tries to make it mechanically simple, reliable and cheap. More often than not this results in a device that only he or another engineer can operate; but G. I. Joe is no engineer.

Usually a device which is internally simple is one which has a large number of knobs and levers which its operators are called upon to adjust; the early radio sets were examples of this. At the present time anybody can work a radio set but few can fix it; time was when anybody could make one which practically nobody could get to work. That is just where we are today as far as airplane instruments including fire-control gear are concerned. It is fundamentally true that what the machine doesn't do, its operator must.

Now just as the contemplated increase in airplane speeds and operating altitudes makes it harder to construct reliable equipment, so does it make the equipment harder to operate. Neglecting such circumstances as the fact that the operator is already reduced nearly to immobility by the flak suits, altitude suits, parachutes, life vests and life rafts, microphones and earphones, and oxygen masks which he has to wear, we have two important limiting factors: One is that a man's reaction time is unalterable. If he has to sit for long hours doing nothing at all, he must of necessity take some time to get going when the emergency arrives. Second is the fact that the human body cannot withstand infinite hardship. Now as airplane speeds increase, the speed with which emergencies arise also increases and other things being the same, eventually they will happen before our man realizes them. Suppose, however, we have detection equipment like radar which can give ample warning of the approach of danger, there is still a limit to how fast we can maneuver the airplane in reacting to the danger. This is set by the centrifugal force which the crew can withstand without blacking out. Both of these factors must therefore be considered in fitting the machine to the man.

The easy way of getting around this is to make machines which are more and more automatic. In principle one can design a machine to do nearly all the things that need to be done in military airplanes if one is willing to pay the price. The price, however, is high for it is measured in terms of weight, size and internal complexity. The undesirability of size and weight is obvious to those who have to make airplanes that fly, whereas internal complexity as we have seen is likely to lead to unreliability and so to the substitution of one kind of military ineffectiveness for another. Thus we find conflict between the psychological and physiological demands for more automatic gadgets and the more mundane shortcomings of the bits and pieces of which the gadgets are to be made. But even if these things were not true one still could not fight with automatic machines alone. Somebody must be there who wants to fight, and this is a trait not characteristic of any machines yet invented. Therefore, although increased automaticity will help, it is not a complete solution, for we must still employ men.

Since this is true it is reasonable to suggest that the machines be designed from the beginning so as to be easy to operate. Designs should be planned not only by technicians but also by persons who understand how human beings function. There is a place for an as yet largely nonexistent type of expert: the engineering design psychologist.

Military instruments are going to get more complicated than they are now because they will have more complicated jobs to do; they will be even more complicated because the innate shortcomings of their operating personnel will force them to be partly automatic. In order that these devices shall be technically reliable, a great deal of attention must be paid to the development of satisfactory components. In order that they shall be operationally usable they must be designed by people who understand how men work as well as how machines work.

In what follows, we shall consider the technical problems of designing various sighting equipments for specific purposes, such as aiming machine guns or bombs. Although no further stress will be placed upon the problems which arise from the fact that it is a man which is going to operate these equipments, the reader should bear in mind, while reading, the pertinent statements in this regard made above.

GUNSIGHTS

The problem of firing a gun from one airplane to another airplane is very similar to that which would face a duck hunter were he in a blind which was rapidly drifting down a fast and turbulent stream. If we are now to go on and discuss the problem of firing guns between airplanes which are moving with speeds on the order of 1000 mph, we should replace the turbulent stream by a waterfall and assume that we are trying to shoot ducks while going over Niagara Falls in a barrel. This is said by way of emphasizing the purely mechanical difficulties associated with the problem, compared to which the fact that we may be fighting in complete darkness is but a mere detail. It is not made any easier by the fact that, relatively speaking, the best machine guns and cannon which are available for air-to-air fighting are in all ways inferior to the cheapest of shotguns. In particular, their accuracy is not sufficiently great, the ranges of the bullets which they fire are not long enough, and they fire too slowly. It is not our purpose here to discuss whether the guns can be improved, but rather what can be done to make the firing of them more effectual. We should point out, however, that it will do little good to produce superior fire-control equipment if the guns are not proportionately improved. Let us give an example: At the present time the maximum range at which it is worth while to fire a 50-caliber machine gun is about 1000 yd or one-half mile. If we are firing such a gun from an airplane which is moving on the order of 1000 mph toward another airplane which is also moving at the speed of 1000 mph, the relative speeds of these two airplanes in the extreme case can be 2000 mph. How long does it take us to travel the 1000 yd maximum firing range if our speed is 2000 mph? The answer is approximately one second. Now if the gun fires approximately 600 shots per minute, the maximum number of bullets which we can fire at the enemy in this time is just ten. Considering the present accuracies of these guns, this is so small a number of bullets as to hardly make it worth while to shoot at all.

Let us now consider what kind of detection equipment is necessary in order that a pursuit aircraft whose speed is on the order of 1200 mph shall be able successfully to intercept and attack another aircraft whose speed is also 1200 mph. We will suppose that the attacking aircraft, after picking up the enemy, needs to make a right-angle turn in order to pursue him. Now the speed with which this turn can be made, or rather the time which it takes to make it depends upon the speed of the spursuit plane and also upon the physical durability of the pilot: how many g's acceleration he can stand. If we assume that the pilot can withstand a maximum of 8 g acceleration, so that a 200-lb man would find that his body weight increased to about 1500 lb, we find that the 90° turn can be made by the 1200-mph airplane in about four sec. However, in these four sec the enemy aircraft also traveling 1200 mph can travel a distance somewhat greater than one mile, possibly far enough to escape. If now we compare this with the situation which obtains when both aircraft are traveling at speeds of about 300 mph, we find that in the first place the 90° turn can be made in only two sec, and furthermore, that the enemy in those two sec can only travel about one-fourth mile. We see, therefore, that increasing the speed of the two aircraft from 300 mph to 1200 mph, we have placed the attacking aircraft at about an 8:1 disadvantage assuming that the distance at which he first picks up the enemy is the same in each case. One way of compensating for this disadvantage would, of course, be to subject the pilot of the attacking aircraft to even larger accelerations than those corresponding to 8 g. This figure, however, is already very near to the maximum which the human body can withstand even when supported by special harnesses. We must therefore look to some alternative means and this would appear to be supplied by anything which would allow the enemy to be found and recognized at correspondingly greater distances than are normally possible. This consideration and other similar ones lead us to suggest that it may prove desirable in the future to equip all fighter aircraft with radar gunsights regardless of whether it is intended that they should fight by day or by night. The ability of radar to find the enemy at greater distances will give the attacking pilot a correspondingly longer time in which to maneuver and at the same time will allow the enemy aircraft to travel greater distances during the maneuvering without being lost.

Another kind of an estimate leading to the same conclusion would be to consider how many square miles of territory are required for two airplanes to have a dog fight. We find that if the maximum number of g's which the pilots can stand is fixed, the radii in which they can turn their aircraft are multiplied by four every time the speeds of their aircraft are multiplied by two. This means that if 20 square miles of territory are required for a dog fight between two aircraft traveling at speeds of 300 mph, no less than 5000 square miles of territory will be required by two aircraft dog fighting at speeds of 1200 mph. Since it is obvious that the two pilots must keep track of one another as they maneuver over this vastly increased territory, the means whereby they see one another must have a vastly increased range of perception. This again is an argument for installing radar in conjunction with the gunsight equipment of very high-speed pursuit.

Not only must we expect a wider use of radar-sighting equipment in airborne fire control, but we must also provide improved computers to go with the radar in order that the guns may be accurately aimed under the more stringent conditions postulated. At the present time a considerable variety of so-called automatic or electronic gunsight computers are being procured by the Air Forces. It is characteristic of these computing devices that they are based on the fundamental assumption that both aircraft are traveling in straight lines. Whatever consideration their designers have given to the actual fact that aircraft while fighting do not travel in straight lines has been in the nature of approximate corrections to this basic philosophy of design. It is now recognized that the assumption of straight-line path, while it makes for relatively simple computing mechanisms unfortunately does not make them be of adequate precision and accuracy. We must now face the fact squarely that aircraft while fighting move in complicated paths. It is necessary to undertake a fundamental theoretical and mathematical investigation of the types of paths which aircraft in combat most usually follow and to redesign gunsight computers on this basis from the ground up. This will require a program of extensive theoretical and experimental research. It should be instituted at the earliest moment and vigorously pursued.

In order to implement such a development program seeking to produce adequate gunsight computers, an improvement in the means and facilities for experimentation must be effected. In particular, means must be found for making careful and worthwhile measurements of the various factors involved under actual operating conditions. This means that fairly extensive measuring equipment of all sorts must be installed in actual aircraft and flown. Moreover, methods must be developed to simulate by means of models on the ground the performance of the aircraft and their accessory gun-aiming equipment, so that more leisurely and contemplative experiments may be carried out. The art of simulating the maneuvers of aircraft and the actions of their guns has thus far been pursued chiefly with the object of providing superior devices for training gunners. It must not be overlooked that similar but possibly more extensive equipment may have a great use in the actual investigation and development of the gunsights themselves.

The problems connected with firing the guns mounted in large aircraft of the bomber type are in all ways similar to those previously discussed with respect to fighter aircraft with the exception that there are more guns and that generally they are mounted on movable platforms or turrets instead of being fixed with respect to the airframe. The computers with which these guns are to be fired must be correspondingly more complex; however, the basic problem remains the same, and all of the recommendations made above apply in this case also. An additional problem only indirectly connected with that of the sighting and computing equipment enters into the picture here, however. This is the fact that turret-mounted guns are not in general as accurate as those which are installed in the more rigid structures typified by the wings of a fighter plane. A program of development is urgently needed in order to make the movable turrets more rigid, so that vibration caused by the firing of the guns does not so shake the gun barrels as to scatter the bullets all over the sky as is now unfortunately all too often the case.

Central-station fire-control systems such as are now installed in B-29 aircraft must be more highly developed than they are at present if future bombardment aircraft are to be equipped with turret-mounted guns. In this connection the present equipment suffers badly from the fact that it has not been designed as an integral part of the airplane organization including the men who are supposed to operate it. A considerable amount remains to be accomplished not only along the lines of technical design as outlined above but also in rendering the equipment psychologically suitable for the operator. Attention is directed to the paper by Dr. C. W. Bray (Psychological Research in the Army Air Forces," in the SAG report "Aviation Medicine and Psychology") in which this case is particularly treated.

Radar which is mounted in aircraft to be used for the detection of other aircraft must be especially constructed so that it can distinguish between radar echoes which come from airplanes and the much stronger echoes which are likely to be received whenever its beam is pointed towards the ground. Such ground reflections, as they are called, can very easily completely mask the reflection from the aircraft of interest. Means are now under development, although they have not yet been applied to this particular case, whereby the ground echoes can be removed from the radar signal and only those corresponding to aircraft presented. This is an extension of the technique described in the section on "Moving Target Detection."

An additional requirement for aircraft in combat is that some means be provided for keeping a lookout, so that while attacking one aircraft, the attacker shall not in turn be attacked by a third. Bombers in particular, but also possibly fighter aircraft, should therefore be equipped with some sort of an early-warning radar system which need not be of the utmost precision. Its sole function would be to detect and to give warning of the approach of another aircraft in sufficient time for protective action to be taken. Since it must also work during an attack, it is obvious that this radar cannot be identical to that which is connected to the gunsight. It also must be equipped with the moving-target indicator device in order that a continuous alarm shall not be given due to the presence of ground beneath the airplane.

The installation of radar equipment which is able to detect fighter aircraft at ranges of perhaps 25 miles in all airplanes presents us with a serious aerodynamic problem. This is due to the fact, as pointed out in section on "Pulsed Radar" that in order to increase the range and precision of radar, it is necessary to increase the size of its associated antenna, a procedure which is likely to destroy the clean lines of the airplane and thereby prevent it from attaining high speeds. Some consideration of this problem is given in section on "Assimilation of Radar into the Airplane."

So rapid are the motions of opposing aircraft likely to be in the future and so great the area over which they are likely to maneuver, that it is highly questionable as to whether two such high-speed aircraft can fight one another at all if their steering depends upon the capabilities of their pilots alone. We should therefore investigate whether or not it is desirable to provide automatic or semiautomatic means of causing the attacking aircraft to head in the proper direction to pursue its enemy. If such apparatus is needed, we would find that even ordinary pursuit craft which are supposed to fight one another with guns become very similar in their general performance to pilotless aircraft or guided missiles. We must then ask ourselves the question of what the man is doing in the aircraft anyhow. Possibly the answer is given above, namely that only men *want* to fight and therefore a man is necessary to supply aggressiveness. At any rate it is obvious that this is an extremely complicated question and one that can only be answered by a good deal of practical experimentation. The problems associated with the automatic guiding of aircraft are discussed in other volumes of the SAG report, "Guided Missiles and Pilotless Aircraft," by Drs. Dryden, Tsien, Pickering and Schubauer, and "Guidance and Homing of Missiles and Pilotless Aicraft," by Drs. Dryden, Morton and Getting.

It goes without saying that sighting equipment which is suitable for firing guns from one airplane at another will not be suitable in general for attacking targets based on the ground, that is, for example, in ground strafing of troops and convoys. We find that the equipment designed for this latter purpose requires only rather rudimentary types of computers in order to aim the guns, and indeed that the present types of computers are quite satisfactory for this purpose providing only that rather simple extensions in their capabilities be made in order to fit them for the higher ranges of speed. Contrary to this circumstance, however, in the case of the radar or other sighting equipment, considerable difficulties exist. The problem is to provide sighting equipment of sufficient resolving power in order to distinguish the rather small targets from their surrounding objects on the ground. By resolving power is meant just this ability to distinguish one small object in which we are interested from among a group of other objects in which we are not interested. Roughly, it is a measure of how little blurred is the picture which the equipment presents to its operator. It is characteristic of radar that this blurring effect, or lack of resolution, is worse than is the case in optical or telescopic equipment. As is pointed out in another section of this report, a solution to the problem of blurring lies in the direction of either decreasing the wavelength of the transmitted radio waves or of increasing the size of the radar antenna. The problem is in all ways similar to that which is met in bombing. It may however, in distinction to the bombing problem, be possible to employ much shorter wavelengths since the maximum range in which we are interested is somewhat less. The problems associated with the scanning of the antenna sufficiently rapidly and providing of a satisfactory indicator for the radar set are quite similar to those discussed in the bombing paper. It should therefore be recognized that although extensive computer development is not required for ground strafing purposes, it may be necessary to make rather extensive studies of the radar-sighting equipment needed.

BEACONS

BEACONS AS AIDS TO NAVIGATION

Radar beacons afford information to radar-equipped aircraft which has been found to be of value in navigation. As long as aircraft are provided with pulsed-radar systems, it will undoubtedly continue to be valuable to provide ground-radar beacons, since at a very slight expense in weight and complexity in the aircraft this provides a new and accurate navigational aid for all such radar-equipped aircraft. Radar beacons permit accurate homing, and they permit accurate navigation across country with respect to any point designated by beacons. With suitably designed radar sets they require less equipment in the aircraft than almost any other navigational system except ground-radar sets working on the echo from the aircraft.

In general, however, radar beacons constitute a secondary navigational aid rather than a primary one. There are two reasons for this.

The first is that they are available only to radar-equipped aircraft or to aircraft which carry special interrogator-responsors. Since it appears unlikely that every aircraft will be so equipped, this limits their usefulness.

The other is their limited range. Radar beacons, on frequencies above 100 megacycles are limited to horizon or line-of-sight range, and this depends upon the altitude of the aircraft. Thus, aircraft which fly on very long-range missions will require a long-range navigational aid of the nature of Gee or Loran in any case. Furthermore, radar-equipped aircraft will often be equipped with computers such as the GPI for navigational purposes and a well-designed microwave radar is itself a quite useful navigational instrument. There are, to be sure, many occasions on which radar navigation becomes unsatisfactory for a variety of reasons, such as inability to recognize difficult terrain and atmospheric disturbances such as clouds and storms. All in all, radar beacons constitute a secondary navigational aid.

Radar beacons are particularly adapted for rendezvous purposes and their use on ships is of particular value for joint aircraft-ship operations.

The design of radar beacons to be used in the future must, of course, be contingent upon the type of radar that will be installed in aircraft. During the recent war a considerable variety of ground beacons had been developed to work with a considerable variety of airborne radar sets. The only extensive development of airborne radar sets with which beacons have not been associated has been K-band radar. In this case the development of K-band beacons was not undertaken because of the technical difficulties which were involved at the time and because of the large amount of atmospheric attenuation which might be encountered. The first of these difficulties has already disappeared to a large extent; however, the difficulty of atmospheric attenuation will almost certainly continue to make it inadvisable to develop radar beacons for long- (horizon) range navigation at those frequencies at which atmospheric attenuation may become large. In practice this will limit long- (horizon) range radar beacons to wavelengths of 1.8 cm or longer.

Beacon Policy: Universal vs. Ad Hoc Beacons.

It is not necessarily self-evident that the radar-beacon frequency and the radar frequency should be the same, and there is a philosophy which says that beaconry is distinct from radar and ought not to be tied up thereto. This philosophy has, in fact, been adopted in the Mark V, IFF-UNB program, in which a complete beacon system has been developed, quite independent of all airborne radar, in the 1000-megacycle region. By a complete beacon system is meant a system containing transponders, airborne interrogators and display systems which permit the use of these beacons independently of any radar equipment. The advantage of such a system is that it provides a universal beacon system in the sense that anyone carrying the proper interrogator-responsor can see these beacons and that no change in the frequency or characteristics of the beacon will be required because of the introduction of a new radar set which is different for some reason from previous radar sets. The improvements which have followed upon one another so rapidly in radar sets have rendered beacons obsolete as they render radars obsolete, and the universal beacon system is designed to eliminate this obsolescence. This argument is accordingly based on expediency rather than principle, since the improvements that warrant new radar sets may apply as well to new beacons.

The development of a universal beacon system has in fact been associated with the development of a universal IFF system, the need for which is a subject which it is not necessary to discuss here. It has accordingly been rather consciously divorced from the development of airborne radar equipment. It is proper at this point to say that this very fundamental question, which is of prime interest in the development of beaconry, is one on which general agreement does not exist. There are able exponents of the universal beacon system, whose ideas have been outlined above.

We propose here the counterargument, which holds that the development of ground beacons is associated with that of airborne radar, and not with IFF. The technical similarities between IFF and beacons (both are transponder systems) ought not to prevent us from seeing that tactically they are entirely dissimilar. The major employment of IFF transponder equipment is in aircraft, for identification from ground, ship, and to a slight extent, airborne radar. The employment of navigational beacons is on the ground, in conjunction with airborne radar only. Ground and ship radar are very different from airborne radar, which tends to the shortest possible wavelength. Transponder requirements are correspondingly dissimilar.

During the present war, the divergent viewpoints presented above resulted in the parallel development of two entirely different kinds of beacons. The Mark III IFF 176-megacycle beacons and the Mark V IFF, United Nations Beaconry systems represent the universal system of beaconry, and the AN/CPN-3, 6, 8, and 17 and the AN/UPN-1, 2, 3, and 4 are examples of the *ad hoc* beacons built especially to work with microwave airborne radar. So far as beacon navigation alone is concerned, the results have entirely justified the proponents of *ad hoc* beaconry. In England, unlike the U. S., an official decision between these systems was quite unnecessarily made, and as it happened, was in favor of the universal beacon system. The pressure of reality has even there forced the designers of British airborne radar to incorporate *ad hoc* beacon provisions in their equipment, showing, perhaps, the unwisdom of making decisions on philosophical rather than technical and empirical grounds. It may be argued that had the proponents of universality carried the day entirely, the results would have been disastrous in hampering both technical development and military application.

The entire argument above is based on the navigational use of ground beacons only. In fact, however, it has turned out that since the *ad hoc* beacons were microwave beacons and the universal beacons were not, that many other applications, such as beacon bombing (Microwave-H) were possible, so that the military value of the beacons was vastly enhanced over what it would have been had they been used only as secondary aids to navigation.

The Design of Navigational Beacons.

Since the airborne radar of the future will almost certainly be a microwave radar, it follows that the radar beacon of the future will likewise be a microwave beacon.

Should airborne radar become standardized at one particular frequency band or at a few frequency bands the problem of ground beacons will be relatively simple. Should the frequencies of airborne radar be considerably diversified covering, say, thousands of megacycles, a somewhat more difficult technical problem will arise. However, it is certainly true that making radar beacons to conform to the existing radar set requirements is the proper philosophy to follow; this must be considered an argument against too great a diversification of radar frequencies.

The important characteristics of microwave beacons which distinguish them from other types of navigational aids are: (1) the extremely precise range measurements possible, (2) the very accurate homing which can be done with a microwave beacon, and (3) the comparative independence from all meteorological disturbance.

Design of Radar Sets for Beacon Operation.

It must be emphasized that beacon reception must be considered while the radar is in the design stage, and the radar set should be built with the best beacon reception possible.

In order to make the most efficient use of beacons, airborne radar sets as well as ground radar sets which are to work with beacons should be designed with that end in view from the beginning. It is not satisfactory to design a radar equipment and then add beacon provisions as a minor afterthought. The fact that many of our early radar sets were designed this way has been a considerable handicap for many purposes. Recent radar sets have been designed with beacon operation in mind, much more than was previously the case, and their beacon operation is accordingly far more satisfactory.

Radar sets should have the following facilities on beacon operation:

(1) The turning for beacons should be automatic. No local oscillator adjustment by hand should be necessary.

(2) The bandwidth of the receiver during beacon reception should be sufficiently great so that all beacons will be received which are operating properly. This means that all tolerances in frequency drift both within the radar set and within the beacon must be so accounted for that sets which are operating properly will all work together. In fact, a certain amount of excess bandwidth in the beacon receiver in the aircraft is desirable to provide for some leeway in adjustment.

(3) Provisions should be made for radar reception alone, beacon reception alone, and for simultaneous beacon and radar reception. None of our present-day airborne radar sets have this feature, but it has proven to be extremely valuable on ground radar equipment. The APS-10 does not have simultaneous beacon and radar but can be quickly switched back and forth between beacon and search functions. It has been shown that the provision of this possibility would be of great value.

Provisions of more than one beacon frequency is worth considering in the design of beacon systems. This will increase the amount of information which can be conveyed to aircraft by beacons.

It is further true that nagigation with ground beacons is not the most important function of beacons, nor is it the major reason for including beacon facilities in military airborne radar sets. The tactical functions of beacons discussed elsewhere provide the major military uses of beacons.

TACTICAL EMPLOYMENT OF BEACONS

Beacons for Paratroop Use.

The use of beacons for paratroop operations has thoroughly justified itself. More than any other aid, beacons have helped to insure the success of hazardous paratroop missions. Their use for this purpose is firmly established.

In paratroop operations, beacons are used in several different ways:

(1) As navigational aids at home bases and at points along the route taken by the troop-carrier aircraft.

(2) As H-system markers for dropping pathfinders. This use was about to be tested in the ETO when the European war ended.

(3) As markers for DZ's (dropping zones). In this use the beacon is carried down by the pathfinders and set up by them, so that subsequent serials of the main force may home upon them.

Beacons for paratroop use do not require a very long range. They must be light, rugged, and dependable. In the past the standard paratroop beacon has been the Eureka. This was used in conjunction with the Rebecca interrogator. These equipments have proven dependable and very valuable. Recently the use of microwave beacons for paratroop operations has been considered and, in fact, introduced on a small scale. Large-scale use has not yet been tried.

Paratroop beacons require a considerable degree of security. This is because there is always danger that a beacon may in the course of a paratroop-dropping operation fall into enemy hands and be set up by him as a decoy. This has, in fact, happened in the war. The situation is saved in this case by providing some means of coding as a security measure. In Eureka, a hand key for Morse coding is provided.

It is also extremely desirable that beacons be viewed on a PPI scope so that disposition of a series of such beacons on the ground may be viewed. This requires high resolution. Since only short range is required the possibility of using very short wavelengths which increases the ease of getting good resolution must be strongly considered. This must be weighed against the desirability of a presentation which only shows to the radar operator the particular beacon in which he is interested. This question cannot be considered to have been settled.

Beacons for Air-Ground Cooperation.

The use of beacons for air-ground cooperation has hardly been touched upon as yet. A great deal of experimental work needs to be done to discover just how beacons on the ground near the front lines, on the front lines, in armored divisions, moving columns, self-propelled guns, and all the infinite variety of ground units can best be used to communicate information to supporting aircraft. (We are assuming that it will continue to be necessary to support ground troops with piloted aircraft.) Very little is known as yet as to how such cooperation can be enhanced by the use of beacons. It seems clear, however, that beacons can contribute to it in some manner. Certainly the use of beacons on the ground, together with suitable radar-equipped aircraft in the air, will be of enormous advantage to the ground commander since the use of beacons and radar simultaneously offer him a method for telling where his troops are even if they themselves do not know. The greatest need in this field is not for the development of new radar or new beacons but for experimental work in maneuvers or preferably under battle conditions to discover just how this cooperation can best be carried out. Such experiments have been, in fact, projected. Any recommendations for future action must depend upon the results obtained. The provision of relay radar at fighter control centers for receiving the display information from a remote MEW opens up the intriguing possibility of using an airborne radar set to superimpose a beacon-marked frontline on a painted-in radar map of the vicinity, and to display this directly at headquarters.

Airborne Beacons for Air-to-Air Use.

Airborne beacons which work against airborne radar for air-to-air beaconry have been developed but had not, in fact, been much used in the war. Such beacons are of use in rendezvous and assembly problems. The application of such equipment in the future will, of course, depend upon the existence and nature of such problems. Perhaps aircraft in the future will not fly in formation, in which case assembly problems will not arise, nor may there be any rendezvous needed, which would eliminate the requirement for such beacons. Both of these developments appear unlikely, if only for the reason that until the techniques of navigation, bombing, and traffic control become very much simpler than at present, it does not appear that the average air crew will be able to cope with the military problems involved independently.

The uses that have been contemplated for airborne beacons in conjunction with airborne radar include use in pathfinders or flight leaders on which following planes can assemble. This is only possible where all aircraft are radar equipped as in the Twentieth and Twenty-first Bomber Command. Their use in fighter escort planes has also been considered.

Miscellaneous Uses of Beacons.

Lightweight or portable ground beacons and airborne beacons will undoubtedly be discovered to have many uses which had not come up in the war. The possibility of being able to mark any desired point or aircraft or vehicle with a distinguishing tag gives a dimension to radar which can be of extreme value. This has been demonstrated in the use of airborne beacons with ground radar for all sorts of control purposes. Beacons have been used on ships at sea as identifying markers for aircraft, to guide them over previously designated positions as in troop-carrier operations. They are used also to designate routes, as markers, and to designate and outline runways as a beam-approach landing system. They have been used in this way by night fighter planes equipped with radar.

Other applications include the use of beacons as "Jellyfish," a droppable buoy containing a beacon, used as an aid in sea-search operations to mark a point on the ocean, "Walter," a very light air-sea rescue beacon to be used in life rafts, and possibly as target markers, dropped by pathfinder aircraft to designate targets to the main bombing force.

THE USE OF BEACONS FOR BOMBING

Ground Beacons.

The use of ground beacons at known locations to permit the bombing of targets by aircraft within radar line-of-sight range of the beacon is known as the "H-system." In this system two beacons at known points are used to survey in an aircraft which can accurately measure its range from these two ground beacons. Since the range measurements depend ultimately upon measurements of time, and very accurate standards of time are available in the form of crystal oscillators, it has proved possible to make extremely accurate measurements of range even in moving aircraft. No angular measurements are required in H-bombing. Accordingly, the errors that are encountered can be reduced almost entirely to operational errors and the instrumental errors can be eliminated almost completely.

Of all the existing H-bombing systems, Shoran is the only one in which instrumental accuracy has in fact been carried to this point. In the other two systems, Micro-H and Gee-H, this point has not yet been reached. This is perhaps not too surprising since Shoran is the only one of these systems which was conceived, engineered, tested and produced in an orderly and logical fashion. Both of the other systems have been afterthoughts imposed upon already existing equipments.

The proven accuracy of the H-type bombing is thus due to the excellence with which range measurements can be made and the relative simplicity of computers which use data which are already given in ground coordinates. There are several features of the system which are, however, susceptible to improvements. In the first place, present H-systems are confined to the use of a limited variety of courses. The most popular courses in all systems are the circular courses flown with one of the ground stations as a center. Such courses are often the easiest to fly and the easiest to compute. However, they severely limit the tactics of the operation and they have in addition the operational disadvantage that an alert enemy can infer from the courses flown the nature of the equipment being used and the location of the ground station. This, in fact, is what did happen in the case of Oboe, which also employs circular courses. Hyperbolic courses are also possible in these systems without much difficulty, and the combination of one hyperbolic and two circular courses does give a choice of approach which has proven nearly adequate for most tactical situations.

However, a very high traffic density at the target is desired and thus more courses should certainly be one of the aims of further development. Any limitation of approach is undesirable.

The generalizing of the approach to make it possible from any direction is perfectly possible at the expense of some complications in the computer. However, the principles of the design of such computers are perfectly well known and, in fact, certain of these are already under development. One of the advantages inherent in a computer which would permit an approach from any direction would be the removal of the necessity for flying quite as long an approach course to the release point. It has been shown that, in general, a somewhat longer approach run is required with a circular or a hyperbolic course which is fixed in space than would be needed if a truly general approach were possible. Thus the provision of a computer which allows approach from any direction would not only increase the traffic capacity and the generality of application of the system but also would decrease the possibility of the plane being shot down. Computers could undoubtedly be developed to be as complex as may be required, and in fact evasive action may be taken into account as well as change of direction.

The most important limitation of the H-system as we have it at present is, of course, the limitation of radar line-of-sight from the beacon. In the early stages of the war this was considered an extremely serious drawback and in fact, the development of suitable H-system bombsights suffered considerably because of the prejudice against short-range systems. It was not adequately realized that there are uses for short-range bombsights as well as for long-range equipment, and that enemies within 250 miles often deserve the attention of bombers as much as enemies who are further away. This fact has now been more generally recognized, and in fact, the H-system came into its own in that period of the war in which front lines existed. A vital important need was fulfilled by providing an accurate bombsight for distances of up to 250 miles from the front, an area embracing almost all tactical targets and many strategic targets.

However, the great precision of the H-system and its undoubted superiority over any radar system involving target recognition with present radar techniques makes it especially urgent to investigate any possibility of applying the procedure to long-range bombing.

Several possibilities for this have been suggested. In the first place the direct range of radar line-of-sight bombing may be expected to increase in the future as the operational altitude of aircraft may increase. Not much is to be hoped for in this direction since the range only increases as the square root of the altitude and in order to double the range four times the altitude must be attained. Thus to increase the range from 250 to 500 miles would require an increase in altitude from 30,000 to 120,000 ft.

There are other more promising possibilities that may be considered. One is to relay both the interrogations and responses of the beacon by means of equipment in a special aircraft flying a fixed course, of geometry so chosen as to minimize the errors introduced into the range measurements. In practice this would place the aircraft on a line joining the beacon and the target. This is a procedure that has been adopted by Oboe in attempting to extend its range. This procedure suffers from a considerable number of drawbacks.

Another possibility is the location of the beacon (the fixed point from which the ranges are measured) at high altitudes which are attained by placing the beacon in an aircraft. Lighter-than-air craft, helicopters, and conventional aircraft have been suggested. Immediate objections will, of course, be apparent to each of these. However, there exist methods for overcoming these objections.

The most promising method that has so far been suggested is one that involves a considerable increase in computing complexity but which offers such great advantages that it is now clear that it must certainly be investigated very fully in any attempt to increase the scope of this very accurate method of bombing. We refer to the extension of range by means of the procedure of using airborne beacons whose responses are adjusted to convey information as to the position of the aircraft carrying the beacon. In ordinary H-bombing the positions of the two beacons are known at all times and computations are made with respect to them, this being simple because the two beacons are at stationary points on the ground. However, we can see that if information were continuously available in the bomber as to the position of these beacons it would be quite possible to correct for motion in the beacons. It is exactly this procedure which is recommended as worth investigation for the case of airborne beacons.

There are three problems involved: (1) The aircraft in which the beacon is located must at all times know its location with very great precision. A precision comparable to that with which ground stations are located must be the objective of the equipment it carries. (2) The replies of the beacons thus carried in aircraft must be modulated in such a way as to provide this information as to the instantaneous position of the beacon to all aircraft interrogating the beacon. This system sacrifices nothing in the way of ultimate performance except the inaccuracies inherent in introducing additional computing operations and additional observation of distances. Since, however, instrumental error can be made exceedingly small and automatic computations can be carried out, we conceive it to be quite possible that the inherent accuracy of the system should be compromised only very slightly by the introduction of a moving rather than a stationary beacon. (3) Computers would have to be carried on all the bombing aircraft, which will take into account the present position of the beacon.

A simplified version of this scheme is also possible, especially if one restricts oneself to a single target or a single target area of somewhat variable dimensions depending upon the precision required. Here the airborne beacon returns a response delayed in time in such a way that, to a radar set stationary at a point directly above the target, the range of the airborne beacon would appear to be constant. This is a simpler version of the general case described above, and is a rather attractive one, since it dispenses with the need for the special computer in the bombing aircraft which is to take account of the motion of the beacon. Thus it could be used with existing H-system radar sets. The motion of the beacon has already been taken out by the computer in the beacon aircraft.

In either of these two cases it is necessary for the aircraft carrying the beacon to have some means of measuring its present position accurately at all times and of translating this information into electrical characteristics which can be superimposed on the beacon response. In the case of microwave beacons this characteristic may well be the spacing between successive code pips of the beacon reply. Any number of other characteristics of the reply signal could be used, such as frequency, pulse width, etc.

The range of the system would now depend upon the maximum possible range from home bases at which one can fly beacon-equipped aircraft and still retain very accurate knowledge as to their instantaneous position. The development of pulsed radar has reached a point where, with adequate radar reconnaissance and with improved fundamental knowledge of the nature of radar echoes, it should be possible to find within horizon range of the target isolated objects which give clear and identifiable radar reflections. These objects must be small and at a known location on the map. Let us assume, for the moment, that such objects can be located. Suppose an isolated radio tower can be found which fulfills the prescription; then a radar in the aircraft carrying the beacon can be used to measure continuously the position of the aircraft with respect to the single fixed object. If sufficiently precise measurements can be made (and the precision needed is not beyond the capabilities of present radar systems if the beacon aricraft does not travel too far away from its reference point), then a computer of the general type of the GPI will suffice to grind out information which gives the present position of the aircraft at all times. This data output can be used to modulate the reply of the airborne beacon with information corresponding at all times to the present position of the aircraft. This system can be operated over enemy territory so that all restrictions on the range of the H-system have been removed, and the airborne beacon made useful anywhere on the face of the earth, provided that suitable radar echoes can be discovered, identified, and used.

An alternative to this radar method is the location of the beacon aircraft by means of Shoran, or any other accurate navigational system, this implying that the beacon aircraft is within range of ground beacons maintained by friendly personnel. Still another alternative is the use of a very precise ground radar to track the aircraft and transmit information as to its position to its continuously. Clearly the most general of all these is the first procedure, namely the one in which a beacon aircraft determines its position by means of radar observations on a single radar target.

If we assume that the beacon aircraft may fly at altitudes up to 30,000 ft and that the bombing aircraft is also at 30,000 ft, then a line-of-sight range of 500 miles between the bomber and the beacon aircraft becomes permissible. It would be a rare target, indeed, within 500 miles of which two suitable radar reference targets could not be found. Still another interesting possibility is afforded by the realization that if the reference points are within 200 miles of the target and the beacon aircraft are at 25,000 ft or higher, all restrictions as to the altitude of the bombing aircraft are removed and these aircraft may, if desired, go in at ground level. The accuracy of location of a plane in space in the H-system is extremely high. In Shoran, for example, the plane is located in space with an error not greater than 50 ft. If advantage is taken of this fact by the use of low-level bombing, then extremely precise bombing indeed can be envisaged.

Bombing by the Use of Airborne Beacons.

The systems which have been used up to date in which airborne beacons on the bomber plane are used to give the position of the plane accurately to ground stations are the Oboe and SCR-584 systems. The use of MEW for this purpose is also being considered and investigated. Experience has shown that while Oboe can in fact yield fairly accurate bombing the organizational problems inherent in a system of this nature are enormous. Two ground stations are required, with reliable and secure communications between them over large distances, and with reliable and secure communications with the aircraft; such a system almost falls down of its own weight. It proved just barely possible in England, with the very best of organization and of expert attention, to keep an Oboe system in operation as long as the bases were in England. It proved to be extraordinarily difficult to transport the ground stations to France and get them working satisfactorily there. In view of this experience it must be admitted that the generally held concept of Oboe as an extremely difficult system operationally has been borne out by the facts and experience of the war. That Oboe should ever have been made to work at all is indeed a reason for congratulation of the organizations which fulfilled this difficult task.

Oboe has inherently very little to recommend it as compared with H. Its organization is enormously more complex, the problem of traffic capacity is inherently extremely difficult with Oboe (in fact practically almost insoluble, as witness the enormous difficulties of the British Oboe Mark 3) and the accuracy in the Ninth Air Force has ever been inferior, because of the great operational difficulties, to that attained by the H-system (Shoran). Accordingly it should be adopted as a policy that beacon bombing of the triangulation type should all be of the H-system variety and that Oboe should not be used.

One cannot, however, dismiss as readily the variety of beacon bombing which uses a single ground station as exemplified by the single-station 584-Oboe system, so-called, and by MEW bombing. Here the organizational difficulties have been enormously reduced and in the case of the MEW the traffic capacity is theoretically almost infinite. The 584 is restricted to one plane at a time because of the nature of its antenna and its angular measurements. A large ground station of the MEW type can do bombing, in principle at least, of very great accuracy, and can control a sufficiently large number of planes. It is believed that only stations of this type should be considered for future development. The extension of range beyond radar horizon is, of course, inherently extremely difficult with such systems.

It should perhaps be pointed out that the use of the H-system with guided missiles is an obvious extension to its use with bombing aircraft. In principle this simply involves a change of instrumentation. Instead of presenting the data on dials or scopes to radar operator, pilot, and bombardier, it is simply necessary to feed the same data into automatic equipment (all of which already exist) to permit the use of synchros, servos, relays, etc., instead of operators. It is worth pointing out that the airborne beacon system of H operation described above lends itself admirably to the use of guided missiles at great distances from the point of origin. It is merely necessary to direct these missiles in such a way that they arrive within the area of coverage of the beacons and then the radar will take over control automatically and direct the missiles into the target, including the final dive down to the moment of impact.

THE FUTURE OF HYPERBOLIC NAVIGATION

HYPERBOLIC SYSTEMS

Hyperbolic navigation is achieved when synchronized signals having a known velocity of propagation are transmitted from at least three known points, and when the relative times of arrival of these signals are measured and interpreted by a navigator. The signals may be transmitted and received by any known means, but radio is at present the only mechanism which offers interesting accuracy at long ranges. A number of kinds of signals, ranging from continuous waves through modulated waves to pulses, may be used. In the more useful current applications, pulse transmission is preferred as ambiguity is minimized and the power supplied to the transmitters may be kept low. The apparent increase in the bandwidth required for the system, because of the use of pulses, may be entirely illusory because by their use a number of methods of identifying signals become available. Thus a large number of pulse signals may be transmitted within a common radio frequency channel without excessive confusion, while continuous wave systems require the use of a separate radio frequency for each component in order to provide identification.

At present the hyperbolic principle is used by only three operating systems if we exclude those (such as Sonne and the Omnidirectional Range) in which the base lines are so short that each is contained within a single transmitting site. Of these three, the pulse method is exemplified by two, Gee and Loran, while the continuous wave technique is used in the Decca system.

Consider two fixed stations to transmit signals at the same instant. If a navigator receives these signals simultaneously, and if the velocity of propagation can be considered to be equal over the two paths, he knows that his position must be somewhere along the perpendicular bisector of the line connecting the transmitting stations. If one signal arrives before the other, a measurement of the time difference identifies some other line of position on which the navigator must be. These lines of position are approximately spherical hyperbolas but may usually be represented by plane hyperbolas drawn on a conformal conic projection if the distances involved are not too great, say, less than 300 or 400 miles in the case of a system whose errors are expected to be several hundreds of yards.

In practice, in the pulse systems, the signals are not transmitted simultaneously but are separated by an arbitrary, constant, time difference. This is done partly to avoid uncertainty as to which signal is which, and partly so that the state of the receiving equipment may be altered as required to accomodate each signal individually. The signals are ordinarily repeated in an endless sequence so that the measurement to be made is actually one of relative phase rather than a time difference between single impulses, although the units usually used have the dimension of time.

The navigator obtains a fix by finding his lines of position relative to two or more pairs of stations. These readings may be made individually or simultaneously, or may be continuously indicated by semiautomatic equipment. In air navigation, a few of the available lines of position are usually precomputed and exhibited on special charts so that any line of position may be obtained by interpolation, while on surface vessels the navigator may use similar charts or may reproduce a portion of each line of position on his plotting sheet by taking the requisite data from special tables.

The number of distinguishable lines of position in the pattern surrounding a pair of stations is equal to twice the time taken for a signal to travel from one ground station to the other divided by the smallest change in time difference which can be observed on the navigator's indicator. In Gee there are typically a thousand resolvable lines for a single pair, while in Loran or Decca the number may be as much as 8000 or 10,000. Since, at considerable distances from the ground stations, the lines of position are approximately radial with an origin at the center of the base line, the positional accuracy of a hyperbolic system is about that which would be obtained with a direction-finding system capable of resolving one-fifth to one-fiftieth of a degree.

The labor involved in computing these lines of position is large, so large that several hundred thousand man-hours have already been spent in the construction of Loran charts and tables, but the results of the computations are permanently available as the lines are fixed with respect to the surface of the earth. Thus the time spent, per navigator, decreases with increasing use of the system and becomes small compared with the computing time required for celestial navigation, and the process of taking a fix is greatly speeded by the precomputation.

The whole process of hyperbolic navigation may easily be compared to celestial navigation. The determination of lines of position is essentially similar except that the hyperbolic lines involve a more complex mathematical solution than the circular lines obtained in celestial navigation. This additional complexity becomes unimportant, however, because as explained in the preceding paragraph, the unchaning character of the lines permits procomputation. The hypercolic system may therefore be thought of as equivalent to one which would be obtained if a number of stars could be permanently established above fixed points on the surface of the earth, thus providing lines of position which would immediately be known upon measurement of the stellar altitudes.

An important feature of hyperbolic navigation, as of some other radio aids, is that the act of navigation may be carried out in the future rather than in the past. A navigator may determine, from charts or otherwise, the indications which obtain at some distant point (such as his objective or one of a series of points on the route to his objective) and may preset his equipment to the constants applicable at that point. His vessel may then be so steered as to follow a simple path until the predicted indications are obtained at the instant of arrival. Thus, at certain interesting times and places, the taking of a fix is made instantaneous instead of yielding the position occupied at some previous time.

The great advantage of hyperbolic navigation over radar beacon systems, which do or could offer equal or greater precision over the same ranges, lies in the fact that saturation of the ground facilities is impossible. The transmitters of a hyperbolic system are essentially a family of lighthouses whose keepers simply transmit intelligence according to prearranged standards. Thus there is no correlation between the activities of the navigators and those of the transmitter operators and the behavior of the system does not at all depend upon whether one or ten or thousands of navigators are making use of the service it provides.

GEE

The Gee system has been the primary radio navigational aid of the European war and its successes have been far too numerous and are too well known to need recounting. The system went into operational use in March, 1942, and, while its usefulness over Germany varied somewhat with changes in types and magnitude of enemy jamming, it has continuously served as an invaluable homing system for the Royal Air Force and the American Air Forces.

Gee operates with about 300 kw of power radiated on frequencies between 20 and 85 megacycles and therefore gives service at somewhat more than optical ranges. Near the surface of the earth, the useful range is not over 150 miles but the reliable service radius increases with altitude to a maximum of 450 miles, in the case of fixed stations with high antennas, for aircraft of 30,000 ft. The pulses used are about 6 microsec in length (as seen on the oscilloscope) and the method of comparison is such that a time difference can be estimated to perhaps one-tenth of the pulse length.

The pulses from three or four stations are presented on a cathode-ray tube on a double-time base whose total length is 4000 microsec. The base lines are usually about 75 miles in length and are disposed with the master station in the center and the two or three slaves dispersed around the circumference of a rough circle. Each of these groups of stations operates on a different radio frequency and half a dozen frequencies are available in each of four bands. This flexibility is, of course, of great value in avoiding the worst effects of enemy jamming. The navigator's indicating equipment presents visually a family of four or five pulses, two being transmitted from the master station and one from each slave. By the use of delay circuits, four fast cathode-ray sweeps can be initiated at such times that two of the sweeps contain and exhibit the master-station pulses and the other two exhibit in inverted form two of the salve pulses. Each of the slave pulses may be laterally adjusted to lie with its base coincident with the base of one of the master pulses. When this adjustment has been made, the two time differences (between each of the master pulses and its corresponding slave pulse) are read from the relation between families of markers which can be switched onto the cathode-ray traces. The most closely spaced family of markers has a unit separation of 6-2/3 microsec and interpolation to tenths permits a reading to 2/3 microsec.

On the line between master and slave stations this matching and reading accuracy corresponds to a precision of about 100 yd relative to a line of position, but since the hyperbolic lines diverge approximately in proportion to the distance from the two stations, a reading error of 2/3 microsec will correspond to a line-of-position error of somewhat more than a mile at the maximum distance of 450 miles. The error of fix varies even more with distance because it is proportional to the linear errors and also varies inversely as the sine of the angle between the two lines of position. Since this quantity decreases approximately inversely with distance, the error of fix varies roughly as the square of the distance from the transmitting stations. In the case of Gee, the average error in reading a time difference is about equal to the least reading (2/3 microsec) and this corresponds to an average error of fix which increases from about 200 yd near the stations to about five miles at the maximum distance of 450 miles.

As suggested above, two lines of position can be determined at once, as two of the slave pulses can be compared simultaneously with the two master pulses. It is this important property of Gee which makes it especially suitable for homing operations, otherwise known as "instantaneous fixing" or "navigation in advance." As mentioned in the section on "Target Properties," the navigator's equipment may be preset to the constants applicable, say, at the home airport. The two pairs of pulses will not then appear in coincidence, on the fast sweeps, but may be brought closer together, in general, by flying any course which brings the aircraft closer to the desired place. If one of the pairs of pulses comes into coincidence and is held so by flying the proper course, the aircraft then proceeds along one of the hyperbolic lines of position which passes through the airport. The rate of approach to the airport and the instant of arrival there may be determined by observing the decreasing separations of, and the coincidence between, the second pair of pulses. Without searching out either line of position, the Gee navigator can approach his objective by any course, knowing that simultaneous coincidence of the two pairs of pulses can only be obtained by his arrival there.

Whether Gee or Loran be used for navigation in advance or for obtaining occasional fixes to be used with dead-reckoning methods, the most important feature of hyperbolic navigation is used to full advantage. Since the hyperbolic lines are fixed with respect to the earth, all courses derived from them are true courses and all speeds are ground speeds. Thus the effects of drift are compensated automatically with the result that a tyro can navigate an aircraft with amazing ease and accuracy.

As a permanent navigation system, Gee has much to recommend but it suffers from four limiting factors.

(1) The choice of frequency yields good range only at high altitudes and results in a system having high accuracy over only a small area. Thus a very large number of chains would be required to provide service over a continental region.

(2) The choice of recurrance rate would limit the length of the base lines that could be used, even if the frequency or synchronizing technique should be changed, and it therefore forbids much expansion of the linear dimensions of the service area.

(3) Because only one chain of stations can be operated in a half-megacycle radio-frequency channel, the problem of finding sufficient room in the radio spectrum would inhibit the operation of an extensive system.

(4) The pulses to be compared are in general of varying amplitudes, so that some experience and judgment are required in making a match. This factor would probably result in either additional complication or reduced accuracy if automatic matching equipment were to be used.

LORAN

Standard Loran is a hyperbolic system which was developed primarily for over-water navigation. It operates on one of several frequencies between 1700 and 2000 kc and therefore enjoys propagation characteristics determined primarily by soil conductivity and ionospheric conditions. The transmitters currently in use radiate about 100 kw and give a ground wave range over sea water of about 700 nautical miles in the daytime. The daytime range over land is seldom more than 250 miles even for high-flying aircraft and is scarcely 100 miles at the surface of the earth. At night, the ground wave range over sea water is reduced to about 500 miles by the increase in atmospheric noise, but sky waves, which are almost completely absorbed by day, become effective and increase the reliable range to about 1400 miles. The transmission times of the sky waves are somwhat variable, thus reducing the accuracy of the system, but the timing errors grow smaller with increasing distance and partially compensate for the increasing geometrical errors, so that navigation by sky waves, appropriately enough, compares tolerably well with celestial navigation. Except in the case of overland ground wave transmission, the signal strength, and therefore the usefulness of the system, does not vary at all with the altitude of the receiver. Even in the overland case the signals increase rapidly with height so that there is little improvement to be had by going to altitudes greater than 3000 ft.

Because of the medium frequency used, and the consequent necessity for conserving bandwidth, the use of pulses whose length is of the order of 50 microsec is unavoidable, and it is wise to operate as many stations as possible in a single radio-frequency channel. The large pulse length creates the necessity for careful matching techniques in order to obtain reasonable precision. The method employed is to alter the gain of the receiver as requisite in order to produce pulse of equal amplitude on the oscilloscope no matter what distances or attenuating factors may be present in the two transmission paths. The pulses may then be accurately superimposed, provided that they are made sufficiently identical by all transmitters, and a measurement may be made with a precision of one percent of the pulse length if the signal-to-noise ratio is sufficiently good.

In other respects, the method of measurement is similar to that used in Gee, except that no effort is made to indicate two lines of position at once. This is a very important exception. The reason for it is somewhat involved and will be discussed below. The navigator can make readings to the nearest microsec, two-thirds of the precision of the Gee reading. The base lines ordinarily used are about 300 miles in length so that the geometrical factors at 1400 miles are similar to those of Gee at 350 miles.

If three Loran stations are used as a triplet, a common orientation, the accuracy of fix may be compared to that of Gee, as all of the same factors apply. The average error at short distances is of the order of 300 yd and increases smoothly throughout the ground wave service area to a little more than one mile at 700 miles. At night, sky waves may be used at distances between 300 and 1400 miles with average errors ranging from 1-1/2 to about 8 miles.

The average errors of fix are frequently smaller than these estimates at long ranges, because pairs can often be found with crossing angles better than those obtainable from a triplet. Loran stations are often installed in a chain, along a coast line or between islands. The number may be anything greater than two, and each station may or may not operate as a member of two pairs with the stations at each side. In each pair pulses are transmitted at a special recurrance rate, one of a family which have the ratios 400:399:398:397:396:395:394:393. Thus eight pairs may operate in a single radio-frequency channel. The navigator's equipment can be adjusted to synchronism with any one of these rates; the pulses at the chosen rate then appear stationary so that their time difference can be measured, while the pulses from all other stations pass across the screen at speeds such that confusion is negligible. Stations intermediate between the ends of a chain ordinarily are "double," that is, they act in all essentials as two independent stations at the same location, so that a chain consists of a number of separate pairs set accurately end to end.

The navigator can choose from among these the pairs he will use for determining a fix in the same way that he would choose stars for celestial navigation, that is, by taking those whose lines of position cross at the most favorable angle. In fact, he frequently uses three or four line fixes if he wishes to attain maximum precision, the reading of a single line of position at a time permitting great freedom of choice. This arrangement stems directly from the concept that Loran navigation is to be effective over an area large in comparison to that which could be served by a single pair or triplet.

The system in the North Atlantic, for example, consists of a chain of four stations along the east cost of the United States, Nova Scotia and Newfoundland, a triplet between Newfoundland, Labrador and Greenland, and a triplet extending from Iceland through the Faroes to the Hebrides. These stations form a total of seven pairs, so that often a total of three, four or five lines of position are available to the navigator.

Because of the superposition of several pairs of Loran stations on the same radio frequency it would be necessary nearly to double the number of components in the navigator's equipment in order to give him the advantage of simultaneous determination of two lines of position, as in Gee, if his freedom of choice of lines is to be maintained. It has therefore seemed better to reduce the complexity of the receiving equipment and to recommend the use of two complete receivers for the cases in which instantaneous fixes must be had.

With Loran equipment a fix is ordinarily taken in about three minutes, or about twice the time taken with Gee. Homing to a point can be accomplished by following one line of position until the correct compass heading has been determined and then switching to a second pair of stations to determine the progress along the first line. This process is cumbersome and finds favor only with those operators who have not had experience with Gee.

The chief disadvantages of Loran are:

(1) The impossibility of instantaneous fixing without dual installations.

(2) The fact that the use of sky-wave transmission requires the application of corrections before the charts or tables can be entered.

(3) The presence at night of long trains of pulses reflected from the ionosphere. In one of these trains only the first reflected pulse is useful for navigation, but from one to twenty useless pulses may follow it, thus greatly increasing the difficulty of identifying the correct one and interfering with the operation of other pairs in the same channel.

(4) The fact that ionospheric transmission is not homogeneous, so that the shapes of the sky-wave pulses are often distorted, making them hard to match, while the time of transmission varies from hour to hour creating minor errors which cannot be eradicated.

(5) The rather embarrassing difference between the ground wave ranges over land and over water. This difference is so extreme as to inhibit the free choice of station sites in many cases, and to reduce the base lines for overland triplets to about the scale of Gee.

SS LORAN

An alternative technique for using the equipment developed for standard Loran takes advantage of the long nighttime range of E layer transmission to extend the base line of a pair of stations to 1200 or 1300 miles. This kind of operation is known as Sky-wave Synchronized Loran. It is effective because of the large increase in geometrical accuracy which derives from the long base line.

Because sky-waves are used for transmission paths between stations and from the stations to the navigators, there is no escape from the timing errors produced by variations in the height of the reflecting layer. The total error has an average value of about eight microsec for a single reading. This establishes the minimum average error of fix at about 0.9 nautical mile, the case where the navigator is at the intersection of two base lines which cross at right angles. This condition is obtained in the preferred orientation of stations, the SS Loran quadrilateral where, ideally, the stations occupy the corners of a square and the base lines are the diagonals. In this case the useful service area is nearly the area of the square, say 1,000,000 sq miles, and nowhere does either the crossing angle or the separation between hyperbolas become greatly inferior to the value at the center of the pattern. The distance corresponding to a change of a microsec in the time difference may degenerate from 500 to 800 ft, and the crossing angle may change from 90° to 60° at the outer edges of the service area, but these variations increase the average error only from 0.9 to about 1.7 miles. Unfortunately, the timing errors may make consistent and unpredictable excursions at times, especially during ionospheric storms, but the maximum errors of fix seem to be about five or six miles and to occur not more than about one percent of the time. The serviceability of the system, or the fraction of the night hours within which satisfactory synchronization can be maintained, is remarkably high, about 99.8%, except where the points of reflection are close to or in the auroral zone.

LOW-FREQUENCY LORAN

Another variant of Loran is under development (and should soon be in operational use) to take advantage of the increased range of propagation at low radio frequencies.

The LF-Loran system will probably offer a daytime range about equal to the nocturnal range of standard Loran and will permit base lines two or three times as long as those now in use. Its greatest single advantage seems to be a tremendous improvement in range over land at low frequencies, an increase which gives promise of a system with at least 1000 mile range over land or sea, by day or by night. A service radius of 1500 miles over land obtains at present [May, 1945] in the trial system in the United States, but this range depends upon daytime sky-wave transmission which is not yet fully understood and which may well not be dependable in the summer in some latitudes.

The timing accuracy of LF Loran is not equal to that of standard Loran, primarily because it is necessary, for technical reasons and also because of the limited available spectrum, to operate with a smaller bandwidth and correspondingly longer pulses. The pulse length is about 300 microsec and the average reading error at short distances seems to be about four microsec, or four times that of standard Loran. The errors at long distances are not yet well known but there seems to be evidence to indicate that the extreme timing errors are not larger than in SS Loran, and that therefore the errors of fix may be comparable if the crossing angles are made equally good.

A very great advantage of LF Loran is that, since the radio-frequency energy never penetrates beyond the E-layer of the ionosphere, the long trains of nighttime sky waves (which make identification difficult at two megacycles) are not present in 200-kc transmission. Because of the great pulse length, the various orders of E-layer reflections overlap the ground wave and result in the arrival of most of the energy in a single pulse. Thus, ambiguity is avoided to a degree which permits the use of more complex and more useful pulse patterns than in standard Loran.

The first step towards more versatile Loran systems is the operation of three stations at a common recurrence rate, as is done in Gee. If two slave stations operate in synchronism with a common master station midway between them, the slaves themsleves are then in synchronism. Since the base line connecting the slave stations is twice either of the other base lines, the slave-slave hyperbolas diverge only half as much as those associated with the master station. Thus the three stations generate three families of hyperbolas and the "extra" family has important properties which provide greater accuracy at long distances and nearly straight lines of position in the center of the coverage pattern.

Another interesting orientation of stations is the quadrilateral in which four stations occupy approximately the corners of a square. If the four stations operate on the same recurrence rate, any one of them may be the master while those at either side are normal slave stations. The fourth station may be a secondary slave operating against either of the other slaves. In this arrangement, six families of hyperbolas are available, the two of greatest interest being those which are erected upon the diagonal base lines and provide crossing angles of 60° to 90° over the whole area of the square. An advantageous feature is that the diagonal geometrical base lines are 1.4 times the length of the synchronization paths, thus providing double the service area of a quadrilateral system of two independent pairs, since transmission and noise conditions always determine the maximum separation of a synchronized pair.

Other more complex groupings of stations are possible and may eventually become useful. All of these arrangements involving the use of more than two pulses, on a common recurrence rate, require that one or more of the pulses be identified by a peculiar shape or in some other way, but innumerable identification methods can be used and undue confusion is not to be feared. The method being used in the triplet now under trial is to vibrate one of the pulses slightly in phase so that, in addition to a steady pulse used for measurement, there appears a "ghost" pulse partially overlapping the steady pulse.

The use of more than two pulses at a rate will permit the easy exploitation of instantaneous fixing as in Gee, but this feature will have to await the construction of new and improved Loran indicators. The immediate steps being taken to add low-frequency service to Loran assume the use of existing receivers and indicators with the addition of a simple frequency converter which cahanges the low frequency to that at which the existing equipment operates. The converters have been designed to permit extremely simple installation and operation, so that low-frequency service can be provided without requiring any extensive additional training for operators and navigators. Low-frequency transmitting stations are more complex and require new construction, except for most of the timing elements, but the number of them is small so that the total effort required to add low-frequency operation to the present Loran system is entirely within reason.

A version of LF Loran which may become extremely important, at least for certain applications, is called "cycle matching" and consists in comparing the phase of the radio-frequency or intermediate-frequency cycles of a pair of pulses rather than in comparing the envelopes of the two pulses. Equipment for utilizing this technique is still in such an early state of laboratory development that an accurate appreciation is impossible, but it seems reasonable to expect that measurements may be made to 0.1 microsec over ground-wave ranges. The facility with which such readings can be taken is as yet unknown, but it is probably safe to predict that, after a difficult development program, cycle matching can provide a blind-bombing system with accuracy nearly equal to Shoran and with a range of 600 or 800 miles.

In the current experiments in cycle matching, intermediate-frequency cycles are exhibited upon the oscilloscope and superimposed in almost exactly the way that pulse envelopes are superimposed in standard Loran. While this may not, in the long run, be the most satisfactory method, it yields matches which are easy to control to at least 2° or 3° of phase, and appears to be the path which will lead most directly to results of military value. Even so, the most that can be hoped is that a few model shop sets may be in tactical operation in about a year.

While cycle-matching receivers and indicators for aircraft or shipboard use present a severe technical problem because of the continually changing phase of one received pulse with respect to another, and because of the extreme stability required of all timing elements, the technique is easy to apply to the synchronizing receivers at the ground stations where all phase and timing relations are fixed and where highly stable timers are already available. Because it is easy both to build and to use them, cycle-matching receivers are being provided for the first low-frequency ground stations. Thus, for the low-frequency envlope-matching program, the synchronization of the ground stations will be more than adequate, and the stations will be ready to provde transmission suitable for the high-precision cycle-matching navigator's instruments which may be available soon.

DECCA

Decca is a low-frequency continuous-wave hyperbolic system which has been undergoing service tests and operation by the British Admiralty for some years. Transmissions are made on two frequencies which are simply related, as by one being three-fourths of the other. As in Loran and Gee, one station monitors the transmissions from the other and maintains its own emissions at the appropriate frequency and at constant phase. The navigator's equipment consists of two receivers, multiplying or dividing networks to reduce the two received signals to a common frequency, and a simple phase meter. Maintenance of a constant reading on the phase meter indicates that hyperbolic course is being followed and changes in phase may be summed up when cutting across the hyperbolic zones.

In practice, a three-station three-frequency system is used with continuous indications of the phases in each pair. The wavelengths used are of the order of 1 mile and the reading precision is variously quoted from 1/1000 of a wavelength to 1/50 of a wavelength.

This simple form of Decca is highly ambiguous in that there can be no identification of a cycle. Thus, although a great many lines of position are available, the lines have no names and identification depends upon a vessel's departure from a known point and upon continuous operation of the equipment. The ambiguity can be reduced as far as desired by modulating the carrier frequencies with lower-envelope frequencies, which give coarser identification of the hyperbolic lines, but this technique apparently makes the receiving equipment prohibitively complex.

In any case, the system suffers from two other defects which militate against its extensive usefulness. One is the rather extravagant use of the radio spectrum. When a careful comparison of pulsed and continuous-wave navigation systems is made, it is found that the pulsed systems are quite likely to require a smaller total bandwidth to provide service over a given large area. The reason for this paradoxical behavior is that a number of pulse families can operate in a single radio-frequency channel while the continuous-wave systems require a distinct channel for each station in order to provide identification. Unfortunately, the channel width, for the continuous-wave systems, is determined not by the nearly-zero width of the transmitted spectrum but by the receiver bandwidths and the degree to which the receivers can be relied upon to maintain frequency calibration. The German Sonne system (a highly refined form of direction finding), for example, uses a total bandwidth greater than that required for LF Loran in order to provide service over the eastern North Atlantic between Norway and Spain, whereas LF Loran itself could provide service over the entire North Atlantic, if not North and South together, in the same channel.

Decca does not necessarily suffer from this defect as much as Sonne, since the receivers for Decca are highly specialized and may be made very selective, but the disadvantage of requiring two frequencies to establish a line of position may go far to offset this advantage.

The second, and more serious, defect of Decca is that interfering continuous waves can distort the readings almost without limit. One serious form of this interference arises from the sky-wave transmission which is often or always present at the low frequencies. The effect of these sky waves is to prevent the use of base lines of more than 100 miles, and to limit the service radius to perhaps as little as 200 miles. For military purposes the use of Decca is even more unsatisfactory since, like all continuous-wave systems which depend upon phase or direction of arrival, enemy jamming may take the subtle form of insertion of additional energy of the same frequency and random phase so that the navigator sees or hears no evidence of jamming except that the system loses its accuracy.

It should be noted that cycle-matching LF Loran, which is superficially very much like Decca, can avoid the sky-wave pitfall because the navigator should examine only those cycles, at the beginning of the pulse, which are propagated by ground-wave transmission and can neglect the anomalous effects produced by sky-wave interference.

POTENTIAL ACCURACY AND RANGE

The factors which control the timing accuracy with which two pulses can be compared do not, in general, vary except with radio frequency. If the pulses are visually superimposed and have their amplitudes made equal, and if the signal-to-noise ratio is really good, the precision of measurement is of the order of one percent of the length of the pulses. This accuracy can be realized in practice because, in the hyperbolic systems, the two signals to be compared pass through the same receiving networks and encounter exactly the same artificial delays and distortions, so that their time difference is not at all affected by the circuit parameters, except to the extent that the pulses are lengthened beyond their proper duration.

The length of pulses which can be used effectively cannot easily be made less than some 50 or 60 cycles of the radio frequency employed. In fact, in many services, attempts to shorten the pulses beyond this limit result in inefficient use of the radio spectrum because careful control of the pulse shape and the spectral energy distribution become difficult or impossible.

Combination of the estimates in the preceding two paragraphs indicates that a Loran system, if by that term we mean one in which the pulses are equalized and superimposed, should yield matches which are accurate to about half a wavelength. This accuracy corresponds to a minimum error of line-of-position of a quarter wavelength of 125 feet at the frequency used for standard Loran. Actually the minimum error in standard Loran is about 500 feet, an increase due in part to the use of pulses about twice the length quoted above and in part to the use of reading techniques which are not as precise as they might be.

The accuracy of Loran, in the ground-wave service area, could no doubt be quadrupled by the use of shorter pulses and navigator's indicators having more stable circuits and more closely spaced families of marker pips, but these improvements would not enhance the sky-wave service (which contributes a large part of the usefulness of the system) because in that case the accuracy is controlled by propagational variations which seldom permit an average error of less than two microsec, which is twice the current reading error.

A similar argument for Gee must be modified by a factor of ten as the Gee pulses are not equalized in amplitude or superimposed and therefore a measurement is good only to the order of one-tenth of the pulse length. In this case the practical maximum accuracy is about a hundred yeards while the "theoretical" accuracy is about one-fourth as much, or even less at the higher frequencies. Here again the departure from the optimum is accounted for in part by the use of long pulses in order to reduce bandwidth requirements and in part by a certain crudity permitted in the indicating equipment in the interests of simplicity.

For LF Loran the same analysis leads to an estimate of average errors of the order of a quarter mile in the best areas. It appears at present that this figure may be attained at short distances, but propagational factors as well as geometrical ones will probably operate to increase these errors over a large part of the service area.

In the case of Decca or other phase-comparison systems it seems reasonable to expect that a precision of one degree of phase may be attained although both Decca and cycle-matching LF Loran do not yet seem to have reached that accuracy in practice. Even the presently indicated precision of about one percent of a wavelength, however, is extremely interesting in comparison with the pulse-envelope methods.

Transmission ranges and service areas also depend primarily on frequency, but in this case the lower the frequency the better. Throughout the microwave region the reliable range is little more than the optical range. Even in the ultrahigh-frequency, band ranges are not more than, say, one and a half times the optical range. This often results in good cover for high-flying aircraft, as in the case of Gee, but the distances usable at the surface of the earth are discouraging from the point of view of navigation.

As the frequencies decrease through the high- and medium-frequency regions, ground wave ranges increase and the differential between high- and low-altitude behavior grows smaller, especially over sea water, but the propagation of signals is no longer simple because of the complex structures of multiple sky-wave reflections which vary tremendously with the time of day and which, at the higher frequencies, are extremely unpredictable.

These sky-wave phenomena become more simple and predictable in the lower part of the medium-frequency range, but only at the low frequencies is there such a degree of stability that sky waves can be used without some undesirable confusion of the navigator. At the very low frequencies, propagation over thousands of miles is easy and reliable, but wide-band antenna systems are not available (because the required size is prohibitive) so that, so long as current techniques prevail, the pulse methods cannot be expected to operate there. It seems at present that 100 to 150 kc is about the lower limit to which pulse systems can be used. At these frequencies, ranges of 1500 miles should be easily obtained over land or sea and at any altitude, and either pulse- or continuous-wave systems may be used, although the pulse systems will require the larger and more expensive antenna structures.

If there is a requirement for reliable ranges greater than about 1500 miles, recourse must be had to the very low frequencies and to continuous-wave systems or to pulse systems involving very long pulses and relatively low accuracy.

All of these considerations lead to the conclusion that there are theoretically two infinite families of hyperbolic navigation systems, the pulsed- and the continuous-wave methods, and that for each method the choice of frequency establishes the desired compromise between range and accuracy. The continuous-wave systems have inherently greater precision but suffer from ambiguity to such an extent that they are of interest only at the low-frequency end of the spectrum. The pulse systems, on the other hand, may be useful at any radio frequencies except the very lowest, but suffer from limited range at the higher frequencies, from sky-wave interference and ambiguity problems in the middle range, and from limited accuracy at the low frequencies.

The choice from among these many possibilities is easy. In a permanent navigation system the ambiguities inherent in the continuous-wave method and in the pulse method in the high-frequency range are intolerable. Therefore the choice lies between low-frequency and ultrahigh-frequency pulse methods. Of these the ultrahigh-frequencies cannot stand alone because of the very short ranges at the surface of the earth, while a secondary factor of great economic importance is the far smaller number of low-frequency stations required to cover a given area. An LF Loran system should give navigation within five miles or so over tremendous areas and errors well under a mile in certain areas. For most purposes this accuracy is sufficient. In case much greater accuracy is required there are two alternatives whose relative merits have yet to be investigated. The more attractive possibility is that of reducing cycle-matching techniques to practice so that either high-precision (blind-bombing or local approach) or medium-precision (general navigation) problems may be solved with the aid of the same network of transmitting stations. If this attempt should fail because of undue complexity of the navigator's equipment or techniques, the obvious step is to add local-approach ultrahigh-frequency chains to the low-frequency general navigation system, maintaining all timing elements the same at the two frequencies and thereby adding little or nothing to the navigator's equipment or to the training problems.

AUTOMATIC DATA ANALYSIS

It requires only limited acquaintance with a Gee or Loran receiver to realize that it is possible to perform all of the set manipulations automatically. That is, there is no technical problem in producing a receiver which will automatically present, say, the Loran readings on two lines of position on a pair of dial counters. For military purposes there has been little or no requirement for this sort of receiver and it has been advisable so far to apply the available research and development effort to standardization and rapid production of manually operated sets.

With the application of hyperbolic navigation to commercial transportation, however, there will be a demand for a position-determining set which operates continuously, like the chronometer in the chart room, and at which the navigator may look when he wishes to know his position. There are a great many ways in which such machines can be built but all, or most, of them may be so complicated that the navigator would be properly skeptical of their reliability.

The most common suggestion for a device of this kind is that, essentially by recording Loran charts or tables in mechanical form, the machine be made to read directly in latitude and longitude rather than in Loran coordinates. This is a natural but a misguided desire as there is little that is inherently more desirable in latitude and longitude than there is in the Loran coordinates themselves. The two things a navigator always wants to know are the distance and direction to one or to several points.

The next picture which comes to mind is that of a black box containing a number of push buttons and a pair of visible countermechanisms. A navigator might push the button marked "Bermuda" whereupon the counters would spin and stop so that he could read "Distance 342 miles; Course 114 degrees." This device, however fine a toy it may be, fails because the navigator should not be satisfied unless he is told his relation to a great many different places. To obtain this information he must, with either the black box or the latitude-longitude indicator, proceed to plot his position on a chart before he can understand the interrelations between his position and all other interesting points.

Obviously the only really effective automatic aid to navigation will plot the vessel's position continuously, and preferably leave a permanent track on the chart, so that the navigator can see at a glance his current position in its relation to all other points on the chart, and also can have the history of his voyage presented before his eyes.

There are many ways to build a device of this sort, and most of them suffer from a high degree of complexity. The desirability of such an instrument, however, will be especially obvious to the sales managers of our larger electronic corporations who, now as before the war, may be expected to be in a position to see that the necessary development time is spent to reduce such a device to practice. The only prerequisites are that ground stations must be in operation to provide the necessary coverage, and that the control of the ground stations be in responsible hands.

It is worth while here only to point out a single concept, which while it violates sea-going tradition, may have some influence because of its simplicity. In any Loran or Gee indicator there is sure to be a shaft whose rotation is more or less linearly proportional to the Loran reading. This shaft may be connected to a pen through a mechanism such that the lateral position of the pen also bears a linear relation to the Loran reading. A second shaft from the same or a second indicator may be connected so that a rotation of that shaft in accordance with a second Loran reading produces a linear motion of the pen at an angle to the first motion. With this arrangement any pair of Loran readings which define a point on the earth's surface also define a position of the pen point on a plane. A sheet of paper over which the pen moves is therefore a chart drawn in Loran coordinates. This simple system has the defect of considering all Loran lines in a family to be straight and parallel and also considering that the angles of intersection between the lines of the two families are constant all over the chart. These limitations, however, may not be too severe, especially in the case of an area at some distance from the ground stations. The angle between the two directions of motion of the pen may be set at the mean value of the crossing angle of the Loran lines in the area and the rates of motion in the two directions may be set to be proportional to the relative separations of the lines in each family.

This plotting-board concept has the immense advantage of mechanical and electrical simplicity. In many cases, if the area on a chart is not too great and if the ground stations themselves are not in the charted area, the distortions encountered in drawing such a chart in Loran coordinates are no greater than those involved in many other projections.

Some experiments have been conducted using a plotting board of this sort with SS Loran. An ordinary Lambert chart was used to cover an area whose side was 150 miles, about a sixth of the length of the base lines, and the Loran lines were sufficiently straight and uniform so that the errors due to the assumptions mentioned in the preceding paragraph were no larger than the errors inherent in SS Loran.

AUTOMATIC PILOTING

It is mentally only a very short step, and mechanically not a long one, from automatic presentation of position on a map to the making of a connection between the map and the rudder of a vessel so that a predetermined track may automatically be followed. The means are easy to visualize and are already at hand. Only a little incentive and time are required, so that here, again, commercial enterprise may be relied upon to bring a family of such devices into being.

One variant from past experience with direction finding must be pointed out. When using a direction-finding system, any change of course is immediately indicated and measured so that its correction, if it be accidental, may be made instantaneously. When a hyperbolic system is used, however, a change of course does not lead to any change of indication until after the new course has been held for a finite time. That is, the hyperbolic system gives an indication of position, not of direction, and the indication does not at all depend upon the attitude of the vehicle. This is an important point and a valuable one. It makes navigation independent of currents in sea or air because, as pointed out above, all courses and speeds directly derived from hyperbolic systems are ground courses and ground speeds.

If a simple right-left indicator be built to show an airplane pilot whether he is to the right or left of a Loran line he wishes to follow, and even how far to the right or left he is, it will not be very successful as a means for aiding him to follow the line. This is so because there is no appreciable relation between the indications on the meter and the course the pilot should follow, so that he tends to turn more and more to the right, if the meter shows him to be to the left of his desired track, until he crosses the line at a large angle and has to repeat the process in reverse. The net result is a very zigzag track which does, in fact, pass nearly over the objective but which wastes unconscionable quantities of time, fuel, and pilot's energy on the way.

This difficulty could theoretically be removed if the pilot would study the right-left meter in enough detail to appreciate both his displacement from the line and his rate of progress toward or away from it. With a knowledge of both these factors he could determine a reasonable course change which would bring him gently to the desired track and maintain him on it with only small excursions. The pilot is, however, too much occupied with his proper business to enter into such a study, so it is necessary to advance the equipment another stage and to present to the pilot both his rate of approach and the distance to the line he wishes to follow. Thus, he may be shown two meter readings, as is currently done with Shoran, one of which tells him, say, that he is 1000 ft to the left of the line while the other shows him that he is approaching the line at 50 ft/sec. It is immediately clear that, if he continues on the same course he has been holding, he will reach the line in 20 sec and that, if he wishes to come smoothly onto the line, he should begin to change course to the left. This conclusion is, of course, the opposite to that which would be derived from the simple right-left indicator and shows clearly the defect in that presentation.

Within certain limits it is possible to combine the factors of displacement and rate of change of displacement automatically so that instead of the two meters mentioned in the preceding paragraph the pilot could be presented with a single indicator calibrated in terms of the appropriate course correction such as "two degrees to the left." The only defect in this instrument would be the existence of a time constant dependent upon the time required to analyze the rate of approach to the track, so that the pilot would have to learn not to make a second correction too closely upon the heels of the first.

This difficulty would vanish if the meter indication, instead of being presented to a human pilot, were connected to a gyrocontrolled automatic pilot, because in that case the linkage to the automatic pilot could easily be given the appropriate time constant to prevent overcorrection.

The mechanism suggested above is the simple and natural way to build a device which will automatically follow a Loran line. This is a worth-while thing to do because there is always a line passing through any target in a Loran-service area, but it falls far short of the really desirable solution. The most important quality which the automatic equipment, like the human pilot-navigator combination, should have is the ability to proceed by a simple and reasonably direct course from wherever the vesesl happens to be to wherever it should go.

This ability can only stem from simultaneous examination of two families of hyperbolas. There are many ways to make this examination, as there are many ways to make a plotting board, but one of them offers such great advantages of simplicity that it should be developed here.

Assume a Loran receiver capable of automatically following two Loran readings in two families of hyperbolic lines. The shaft rotation corresponding to either of these readings could be connected through the displacement-and-rate device mentioned above to the rudder of the vessel so that any desired Loran line in the corresponding family could automatically be followed. A Loran line passing through the initial position of the vessel could, for instance, be followed until it intersected a line passing through the objective after which instant the second line could be followed. This would produce the desired end result, but it might be by a very indirect route indeed.

A much more direct path would be one cutting across both families of lines in such a way that the rates of change of the two Loran readings constantly bore the same ratio to each other as the total changes between initial and final readings. Along such a path, if the changes in one Loran reading were automatically followed while the delay between the second pair of cathode-ray traces were constrained to vary in the designated ratio to the variation in the first reading, then the second pair of pulses, once set to coincidence, would remain so. The steering mechanism might be controlled by the second pair of pulses so as to maintain the coincidence, directing the vessel along the chosen path.

For example, if the readings were 3500 at the initial point and 2700 at the objective on the first Loran pair, and 1400 and 1800 on the second pair, the linkage between the indications would be set at one-half. The vessel would then follow a course such that it would successively pass through points whose Loran coordinates were 3400-1450, 3300-1500, 2800-1750, to the objective at 2700-1800. The course would be quite direct unless it passed very near one of the transmitting stations. In fact, the course would differ from a great circle only in proportion as the Loran lines differed from being straight and parallel.

This sort of path has been called the "Lorhumb line" because it is the exact parallel, in hyperbolic navigation, of the rhumb line in Mercator sailing. Various Lorhumb lines might be connected together by the navigator to form an approximate great circle or any other desired path. Devices utilizing this principle will probably be adequate for all navigational purposes (as distinguished from problems of pilotage) and will presumably be more simple than others which, through more complete analysis of the exact forms of the hyperbolic lines, could follow slightly more direct paths. The advantages of design are so obvious that devices which embody this principle may be expected to be ready for experimental operation soon after the release of engineering talent from more immediate military requirements.

RELAYED FIXES

A device for retransmitting the hyperbolic indications from the receiving point to a remote indicator has been used to some extent with the Gee system, under the name "Gee sendback," but has not yet been applied to Loran. Equipment of this sort may take the form of a pulse transmitter which is triggered by the various pulses in the output of a receiver tuned for a hyperbolic system, or may be essentially a superheterodyne receiver in which the intermediate frequency is sufficiently amplified and radiated. A timer, of course, may or may not be used at the relay point.

The frequency used for relaying time differences in this way should be either very high or very low, as the interfering effects of multiple sky-wave reflections would operate exactly as in standard Loran to confuse the picture. The technique is so simple, especially in the case where no indication is provided at the relay point, that there is no need here to do more than mention one or two operational uses of such a mechanism.

The obvious uses for a system involving relayed fixes are those in which it is more necessary or convenient for a distant controller to have knowledge of position than it is for the occupants, if any, of the vehicle under control. Probably the only really military use might be in the control of fighter aircraft (or pilotless aircraft) where it could be expedient to relay fixes to a carrier or other base for analysis and appreciation, and then to retransmit the appropriate action information through a communication circuit.

A somewhat similar use may be for extensive study of ocean currents. In this case a number of automatic drifting buoys could relay their fixes to one or more control stations, afloat or ashore, and thus permit the gathering of precise continuous data in any weather and over long periods of time.

Probably the most important peacetime use of such a system, however, would involve the standardized installation of relay equipment in lifeboats. The information received from them would be far more useful for rescue work than directional data because it would permit potential rescuing vessels to determine at once not only the direction but the distance to those in need of assistance. Such a program must await the general use of Loran receivers on shipboard, but could then easily be integrated with an automatic distress signal-receiving mechanism, provided that a frequency channel entirely devoted to such operation can be made available.

GUIDANCE OF PILOTLESS AIRCRAFT

Since hyperbolic navigation does not call for the transmission of any information from the vehicle under control, it is a mechanism with vast potentialities for the two-dimensional guidance of automatic projectiles. If flying bombs are to become the all-weather air force of the future, no other system offers such immediate possibilities for the mass control of very large numbers of projectiles.

Systems which require some contact between a projectile and ground operators other than the launching crew may well have many tactical uses in close-support operations, but the possibility of maintaining strategic bombardment by such methods is remote. A hyperbolically-controlled flight of pilotless aircraft, on the other hand, could be operated without any close coordination between launching crews and the controlling group, and without saturation of the guiding facilities.

The receivers for hyperbolic operations of this sort would differ greatly from the present Loran and Gee receivers. In fact, their evolution should be in nearly the opposite direction from that suggested in the last few pages. Instead of being adapted to more flexible and versatile methods for general navigation, the equipments for pilotless aircraft should be reduced to the stage where they know only a single time difference, but know it well. The corresponding ground equipment, however, must have a degree of flexibility not now in use, so that the hyperbolic lines recognized by the aircraft might be made to lie across any desired target. A pair of ground stations would establish a line of position extending from the launching area to the target while a second pair would define the intersecting line at which the projectiles would descend. Under gyroscopic control the projectiles could be launched at any time and in any number, and the accuracy of their initial courses would need only to insure an intersection with the first hyperbolic line before passing the target.

With a system of this sort, aircraft could be launched from many points in a large area. Dozens or hundreds of launching sites would independently send off aircraft sensitive to a single line of position, without any requirements for coordination except that the control system would have to be in operation. These aircraft would follow their independent courses, perhaps for half the distance to the target, until they came within the zone of influence of the hyperbolic line, whereupon each would change its course and come about exponentially to ride the line to the objective. The effect would be that of raindrops falling into a gigantic funnel and being concentrated into a steady stream playing upon the target.

Such a stream of bombs would, of course, rapidly obliterate any objective. In practice, therefore, the ground-station operators would steadily alter their timing constants so that the line followed by the projectiles would be caused to sweep back and forth over the target area, while the constants of the release line would be altered, perhaps in steps, to provide the requisite variations in range. Thus the streams could be played back and forth across the target area like the stream of a fire hose or more exactly, like the stream of electrons scanning a television screen; all this control could be exercised without any cooperation from the launching crews who would, like the loaders on a battleship, simply maintain the flow of projectiles without giving thought to their destination.

Similarly, the beam of pilotless aircraft could be swung from target to target to satisfy tactical requirements without requiring any change in the launching technique or orders, provided only that the rate of sweep of the beam must be commensurate with the transverse acceleration available in the aircraft.

This use of the hyperbolic principle differs from Loran, Gee, and Decca, in that many types of transmission should be made available for it. While coding and other features may reduce the susceptibility to jamming, the best defense is unexpected variation of the operating frequency. If this sort of mass control of pilotless aircraft is to be developed, great attention should be given to all the timing elements to insure that none of the boundary conditions of the system shall inhibit the free choice of radio frequency. The indicating and control mechanisms should be standardized and reduced to practice in the simplest and most reliable form, but the method of transmission and detection of the hyperbolic information should be capable of alteration at a moment's notice, so that while LF-Loran frequencies might be used for one tactical operation; Gee frequencies, or microwaves or infrared might be used for the next.

In this respect, as in the additional flexibility of the ground stations and the simplification of the airborne equipment, the development of hyperbolic control of pilotless aircraft lies in a direction different from that in which commercial development of a general navigation system may be expected to go. It is, therefore, clear that, while the exploitation of the new methods of navigation may be left to private enterprise, the development of a "hyperbolic air force" must, if it is desired, be obtained through direct and positive action by the armed services.

HYPERBOLIC SURVEYING

There is one other aspect of hyperbolic navigation which deserves examination by government agencies or by the large philanthropic organizations. Whatever the merits of cycle-matching LF Loran for navigation, it shows great promise for the precise measurement of distances of several hundred miles. Under laboratory conditions it seems reasonable to expect an error of the order of ten feet in a single measurement of the distance between two transmitting stations, and the average of a number of observations made under good conditions in the field should exhibit about the same precision in the hands of skilled crews. This is about the accuracy which a good trigonometrical survey measures a distance of 100 miles.

It seems probable, therefore, that radio surveying can supplement the ordinary methods for regions in which the basic triangulation system can be on a large scale. The procedure might be as follows: Three stations could be set up at the vertices of an equilateral triangle several hundred miles on a side, and the lengths of the side determined by repeated measurements of the bounce-back time over a period of several weeks. During these measurements a number of navigator's receivers could be set up and operated for brief periods at points which could be identified on airplane photographs, thus providing a network of points of secondary accuracy, based upon the original triangle. After thus surveying the area contained in the triangle, one station could be removed to a new location on the opposite side of the remaining base line, and the process could be repeated. Thus, a precise triangulation would be extended over immense areas in a relatively short time, while as many points as desired could be located with respect to the basic network. Neighboring secondary points would not be known, with respect to each other, with the precision obtainable by optical survey, but the absolute errors should not be more than a few yards and the speed of the whole operation should make it economically available in parts of the earth's surface which could not otherwise be surveyed for many years to come. By this method, of course, islands and shoals which cannot be reached by optical means could be accurately charted.

Unfortunately, this is the sort of enterprise which cannot be undertaken on a small scale but which must be attacked with vigor and with the expenditure of considerable money and time. It appears obvious, however, that, once in motion, the method could produce surveys of an accuracy comparable to that of any other method, and produce them in a time far shorter than that now required. Good coordination of these methods with airplane photography may permit the charting, within the next few years, of very large areas which are relatively inaccessible and therefore not well known, but which, nevertheless, may be of actual or potential military or economic importance.

GROUND CONTROL OF AIRCRAFT

TECHNICAL ASPECTS OF THE CONTROL AND AIRCRAFT LOCATION PROBLEM

In parallel with the trends in air weapons, there are definite tendencies in radar equipment which provides for more effective use of the air weapons, and are necessary for building a defense against them. In the following discussion, certain fundamental limitations imposed by nature must be kept in mind.

(1) The range of any radar equipment, regardless of its power, is essentially limited by the optical horizon. It is possible to see slightly farther beyond the horizon by increasing the performance of the equipment, but this increase is a negligible fraction of the horizon distance.

(2) Measurement of absolute position of aircraft is limited by uncertainties caused by moisture and temperature gradients in the atmosphere. These gradients, in general, cause more uncertainty in height measurements than in plan position. Although the error in absolute position may be rather great, the error in relative position of two targets decreases as they approach and becomes zero as they come into coincidence.

(3) Atmospheric phenomena are more pronounced as the wavelength decreases. Absorption by the atmosphere will probably prevent the use of wavelengths shorter than 2 cm for long-range equipment.

(4) For detection of aircraft over water, low-frequency radar suffers the disadvantage that interference between the direct and the reflected rays prevents the detection of low-flying aircraft. The shorter the wavelength, for a given antenna height, the shallower is the region thus excluded. Even over land such interference may be serious for frequencies below 1000 megacycles roughly depending, naturally, on one terrain.

It is now technically possible to build a ground- or ship-based radar equipment capable of detecting and accurately measuring (subject to atmospheric uncertainties) the position and height of all aircraft flying below any given altitude and above the optical horizon. Weight and size might make such an equipment impractical for many uses, but would not be a serious drawback for fixed ground stations. Airborne equipment has so far been limited by the size of the aircraft, but there is no reason to suppose that ranges of 200 miles or more for detection of small aircraft will be impractical in the near future. It may therefore be assumed that horizon rather than equipment will impose the eventual limit to the coverage attainable by all long-range radars.

Since it is possible to eliminate targets which are not moving, the area covered by a single equipment will be determined by the height of the set and by screening by surrounding hills. In general, where maximum coverage is desired, the highest sites will be selected. Further implications of this statement will be discussed later.

Since the control of aircraft requires an accurate knowledge of its position and height, future development may be expected to go in the direction of increased accuracy and resolution. Under normal atmospheric conditions, a resolution and absolute position accuracy of the order of 50 yards may be expected at long range. Studies of atmospheric phenomena may eventually result in techniques for correcting the data on abnormal days to preserve a large proportion of this accuracy under all conditions.

Techniques of presentation of the traffic picture may be expected to advance to the point where the controller can be given a three-dimensional view of the traffic where required. It is probable that the bulk of the controlling will be carried out from a two-dimensional map presentation, however. On this map, the direction of travel and identity of all aircraft will be displayed. It is probable that each aircraft controller will have the choice of operating from the map plotting board covering the whole area, or from a three-dimensional expanded view of a limited area. Specialized indicators may be expected for air-to-ground operations such as blind bombing or control of pilotless aircraft. Through the use of radio relay systems, the control can be centralized in one place distant from the radar equipment, and may have information from a number of equipments immediately available. The time delays and errors now caused by verbal relaying of the aircraft's coordinates will be eliminated by the transmission of the radar signals and the direct displaying of these signals to the controller.

One of the major problems is still the identification of aircraft. Beacons in the aircraft present a partial solution, and will probably continue in use but will be combined with other functions.

Since all friendly aircraft will operate under control from centralized stations within the areas crossed by the flight, combination of the beacon with the communications equipment would aid greatly in identification. The use of a directional antenna at the control station and pulse-communication system coupled with the beacon would give secure communications and reasonably certain identification by limiting the azimuth and range from which the ground will receive synchronized signals.

In the case of pilotless aircraft, the beacon could be combined with the control mechanism and could even be used to transmit to the ground information necessary to complete the calculations for the bomb run.

Finally, ground-to-ground and ground-to-air communications must be considered as an integral part of the aircraft control problem. Ground-to-ground communications from fixed stations will be handled by wire or cable in most cases, because more channels can be made available without mutual interference. Standby radio channels must be provided for cases of failure of the land lines. These radio channels will be point-to-point, using narrow radio beams to prevent interference with adjacent stations and to reduce power requirements for reliable transmission. Security will be obtained by use of directional transmission, and also by use of speech scramblers and pulse communication systems.

Ground-to-air communications will fall into two classes. An omnidirectional antenna will be needed to provide communications with aircraft whose position is unknown, and for information of a broadcast nature such as weather. Directional equipment will be used for communication with a particular aircraft. For security reasons, this transmission will be coded or scrambled in some manner. The cost of a secure communications system during war will be jamming by the enemy. Since the present ground-to-air communications are now open to monitoring, both the Axis and the Allies usually found it more desirable to monitor radio transmissions than to jam them. Because jamming techniques are well known and are available for the frequencies now in use, present equipment may be jammed at any time the enemy finds it to his advantage to do so. This means that secure communications systems must provide means for working through heavy jamming.

Voice and teletype communications may, for specialized applications, be augmented with picture-transmission devices. Transmission of weather maps to planes on long-range flights, for example, can be handled by a narrow radio channel, since considerable time can be taken relaying the information. This will permit the use of wavelengths which are not restricted by horizon. On the other hand, television pictures from an observation plane may have to be transmitted in a very short time, thereby requiring a wide band of frequencies. This will probably restrict the equipment to the use of high radio frequencies, and will therefore impose line-of-sight transmission. Suitable relay equipment can be used, however, to extend the range beyond the horizon of the first transmitter.

TACTICAL EMPLOYMENT

The prime function of ground radar is rapidly becoming that of control. Tightness of control will vary from the complete control of pilotless aircraft to merely having an over-all air picture which can be called upon to help an aircraft in difficulty. Since all of these control functions require a picture of the air traffic and a coordination of this traffic, a centralized control organization must be established to handle a given area. This organization must have radar information and communication facilities. The communication facilities must provide for passing information on aircraft movements from one organization to adjacent area control centers, and may include provisions for transmission by television of the air-traffic picture.

The radar information must be presented to the controllers in a form which shows the present position of the aircraft, the direction of flight, and identification. At present, the over-all picture is obtained by plotting, but at the cost of time delays. In order to eliminate the time delay, the controller is given an indicator, but then has only the present position of aircraft displayed, unless he chooses to plot on the tube face. He therefore has to watch both the plotting board and the tube to obtain the complete picture. In the ideal situation, the plotting board would be made to present an up-to-date picture or the track identification, and direction would be displayed on the control tube. The former could be accomplished by a suitable projection indicator coupled with a plotting technique, while the latter could be provided by electronically placing the tracks and identification symbols on the tube. In both cases, prominent map features should also be displayed. When the controller display progresses to a three-dimensional picture, plotting techniques in three dimensions for presentation on the indicator would be desirable.

Functionally, the radar control network will be called on for (1) navigation, (2) warning, (3) air-sea rescue and (4) meteorological data.

Navigation, in the broad sense, may be considered to include everything from keeping an aircraft on the proper course on a routine flight, to blind bombing or blind landing. During peace or war, there is a requirement for backing up other navigational systems with ground radar. The need for the ground radar control becomes increasingly great as the planes approach congested areas such as airports because at these points, in bad weather, the failure of navigational aids may leave the pilot in a critical situation. Furthermore, the use of several methods of checking the aircraft position will minimize the danger of errors and of freak atmospheric effects.

In addition to long-range moderately-accurate navigation, there is need for precision navigation. For control of traffic at an airport, an accurate short-range system is needed to handle the traffic from the control tower and to place planes in the proper position for a landing. For this purpose, a high-resolution three-dimensional presentation is badly needed. A further requirement is an adequate identification system which can select a single plane from a snarl of traffic. This identification will probably be based upon the use of an airborne beacon. The beacon system should have provisions for coding, and should have a resolution at least as good, if not better, than the radar. It would also be desirable to combine this beacon with a communication system which would be sufficiently localized in space to insure that the wrong plane was not responding by mistake. This should be feasible by combining a highly directional antenna with a pulse communication system which is so gated that replies could be received only from planes at approximately the correct range. This requirement exists even during peace.

For ground control of blind bombing and control of pilotless aircraft, a long-range precision system is required. Although a partial solution of this problem exists in the "Close-Support Bombing" modification of the SCR-584, some system should be developed which avoids the difficulty in picking up aircraft and has a greater plane-handling capacity. The ground control of bombers is limited by horizon, but has the advantage that the man upon whom the decisions rest is working in a relatively quiet room and is not under the stress caused by enemy fire. It also permits last minute change of target in a simple manner, and provides the commanding officer an opportunity to obtain a preliminary evaluation of the mission.

Another precision navigation requirement is interception of hostile aircraft. Since this problem received considerable attention in the war, it is reasonably well solved by present ground radar. Limitations in aircraft performance are at present one of the main factors contributing to interception failures. The main lack in the present system is an adequate identification system. Here again, there is a requirement for a beacon system which will provide suitable coding, and will have a resolution at least as good as the radar. Increased radar resolution could improve interception results, but is not essential if suitable navigation equipment is used.

The warning function of radar falls into two categories. Even during peace, there is a requirement for warning aircraft of the presence of other aircraft. Although collision avoidance can be solved by airborne equipment, there is still a need for the airport control tower to be able to alert pilots to the presence of other aircraft. During war, there is the additional requirement for warning aircraft of the presence of enemy planes even at great distances. This function has been successfully carried out in the ETO by the British Type 16 and the American AN/CPS-1 equipments.

Air warning of enemy attack to ground installations is only a partially solved problem. The solution has failed in two ways: There has been failure to establish the existence of hostile aircraft, and there has been failure to appreciate that warning without thwarting the attack is of little value.

Failure to pick up enemy attack has been caused by "on the deck" flying which results in screening by the horizon, and by the extreme high-altitude trajectories of the German V-2 rockets. The low-altitude attack can be met by elevation of the warning radar. This can best be accomplished by the use of a long-range airborne set. A start toward the solution of this problem has been made with the introduction of the AEW. In order to complete this solution, it will be necessary to remove sea return and ground echoes, and to increase the range of the equipment considerably. V-2 warning must be accomplished by improving the high-altitude coverage of radar equipment. Since the rocket weapons of the future will go to fantastically high altitudes, it may be impractical to provide coverage for warning purposes over more than a limited portion of the trajectory.

The provision of warning, without measures for preventing the attack, is almost useless. In the case of low-flying aircraft, the use of airborne warning systems must be coupled with control of defensive measures. As in the case of ground radar, the warning function must take second place to the control function. Two possibilities exist: control must be carried out either from the aircraft, or from a ground station to which the air picture is relayed.

Since rocket weapons of great size and long range are likely to be one of the main weapons of the next war, the defense against these must be developed. The unsolved problem of this war is the provision of warning of the approach of such rockets, and, much more important, their destruction at a safe distance from the target. Obvious requirements of the battle against super rockets are a maximum period of warning, and a projectile capable of destroying them at high altitudes. Both of these requirements remain to be met.

Air-sea rescue requires little comment. The two necessary factors are a means of spotting the aircraft in trouble and the crew in the water, and rescue craft which can be controlled to the pick up. Airborne and life-raft beacons, coupled with ground and airborne radar, can provide for expeditious rescue. Provisions for an emergency beacon code should be made to distinguish the plane in distress.

Meteorological data can be furnished by tracking free balloons to obtain upper-atmosphere winds, by noting storm positions on microwave radar, and by observing anomalous propagation. The second of these items is perhaps the most interesting. It has already been demonstrated that it is possible to guide aircraft safely through gaps in tropical storms, and that short-range weather predictions can be aided by tracking rain squalls.

V-Beam.

The most complete organization for the use of ground radar is that used for tactical air command. This can be used for almost any purpose since there is nothing lacking for complete control.

The basic set which is now used to keep track of what goes on in a tactical air command is the AN/CPS-1, or MEW, and this will shortly be supplanted by the V-Beam. The V-Beam enables even small aircraft to be followed with certainty within a radius of 100 miles from the station and enables heights on all aircraft to be found. The coverage is shown in Fig. 12, and this represents present technique. Future technique could add at least 12 db to the performance of this set, and if that were done, the existing V-Beam, with no change in antenna size, merely change in feed, could give coverage on aircraft out to 150 miles no matter what the size of aircraft. On formations of aircraft, the range would be very much greater, consistent with the horizon limitation.

This set is used to give a complete picture of all flying within a radius of say 100 miles. At present the data is handled by a rather clumsy technique involving plotting from data given on B-scans. Even with present-day technique this can be improved by, for example, the use of a photoprojection PPI developed by the Eastman Kodak Company which enables the picture of a PPI to be put on a vertical operations screen three times a minute. Plotters standing behind this screen can give a reasonably good interpretation of all the plots turned in by the radar set. Whether this is the best way to handle the data or not remains to be seen. It leaves something to be desired in that it is not possible to present height directly. The presentation of height is best done in the old-fashioned scheme of small posts with labels put on a large, flat map, as is familiar to all who have seen an information center. On these posts are displayed the number of aircraft, whether hostile or friendly, and also a number representing the height. The disadvantage of this scheme of plotting is that it is inevitably cumbersome, and the data so presented is not up to date. Therefore the vertical-plotting board which can be brought up to date with the use of the photoprojection scheme and a separate presentation of height on some tabulating board (now known as a tote board) is probably the best that can be done.

This being the case, we can envisage one V-Beam with a complete operations room with a general-situation board or vertical-plotting screen on which are carried up to 50 or so separate tracks. These are handled by means of the photoprojection screen. In front of these will be placed various control facilities. These are, at present, eight to ten off-center PPI's with height tubes interspersed among them as required. The functions of these off-center PPI's are varied. Mostly they are used for control which is carried out by means of an ordinary VHF system. In addition one could be used for describing weather; others could perhaps be used for liaison with other units in which flights are passed accurately from one controller to another. In any event the basic philosophy is that of knowing what is in the air and having equipment to do something about it by means of VHF control.

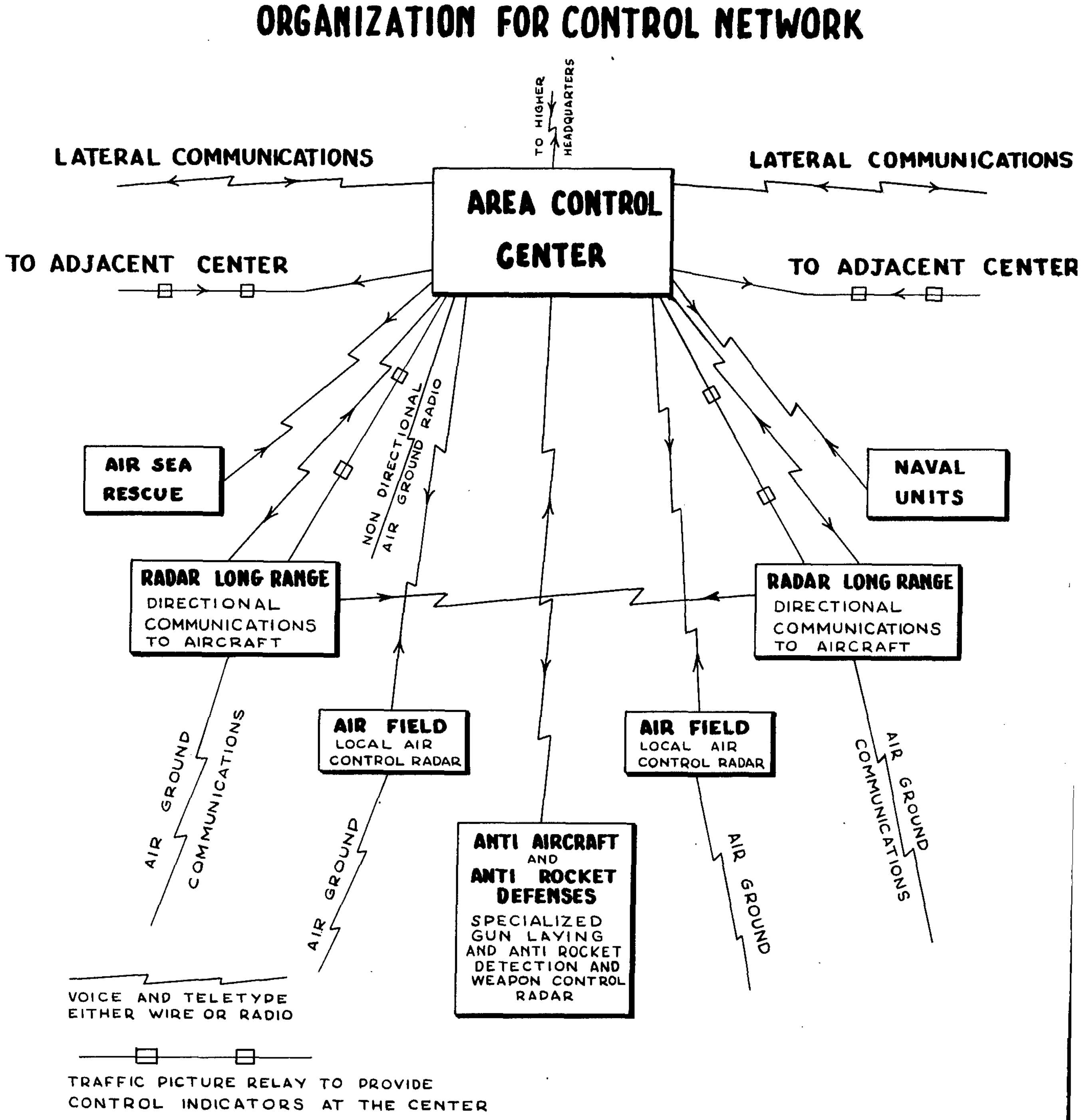


Figure 12 — Organization for Control Network

Control Aids.

Many aids to this scheme of general control exist. One, for example, is the scheme known as video mapping. This consists of a means of developing in the video the information necessary to write a map or any information needed on the off-center PPI. This is then kept as a facility which the controller or scope operator can fade into his whenever he wishes. In this way it is possible to marry-up radar targets with points on the ground.

A second aid is a beacon such as the AN/APN-19 which locates friendly or otherwise specialized targets at will.

A third and most important aid is the VHF direction-finding equipment which will locate an airplane, in direction only, to an accuracy of one degree. This enables particular planes to be sorted out.

When equipment is available for general control, the necessity for accurate control now arises. This can be achieved in several ways. Either one can extract maximum accuracy out of the general control radar, or one can design a specific radar intended for accurate control. Up to the present this latter has not been done, but a modification of a fire control radar, the SCR-584, has been used in which for accurate control of a single aircraft an accurate track is carried on a plotting board by means of the locking-on feature of the SCR-584, and this is used to give vectors to the plane. It is felt by many that it would be better to build a set which did not forego the ability to see everything else in the neighborhood while controlling, and this would involve essentially a rapidly rotating V-Beam set with rather small antennas perhaps set at X-band rather than S-band, and a number of these sets would be fixed up appropriately so as to permit accurate control. A preliminary specification of a possible set is given:

Wavelength, X-band

Dish size, 15 x 3 ft giving 0.5° beam for vertical and slant beams

Three feeds for each beam to give lower, middle, and upper coverage

Pulse width, 1 microsec

Power out, 300 kw

MTI on both lower beams

Scan rate, 6-12 rpm variable

Receiver sensitivity about 8 db below KTB

Skiatron general indicator

Up to six special control scopes of the off-center type with special tracking equipment similar to the APA-44. These would feed six controllers with the necessary data for precise bombing or close cooperation. The six controllers sit around the skiatron in the "soda fountain" technique proposed for C.I.C.

The use of radar offensively for a tactical air command follows, therefore, the following general pattern. First, the planes take off and are vectored by a tower search set; second, they report in to a V-Beam for general control; third, they are vectored by general control to accurate control, where they are controlled until their mission is completed; then they are returned to general control and finally are put in to the tower-search set which controls them for landing. It has proved necessary to construct for this purpose a special tower-search set. The complete design of this is not yet in. At the moment a modification of the SCR-584 is contemplated. This modification uses moving target indication, has provision for beacon reception for identification, and contemplates four indicators with a central indicator of an expanded type such as a skiatron or possibly a photoprojection tube. With this a survey of the aircraft interested in landing can be carried by each airport, and they can keep planes not interested in landing flying along a definite lane overhead and can bring the planes in with reasonably good control so that stacking is not necessary, or if necessary can be used for only a short time.

Future Problems.

Atmospheric reflections from clouds, i.e., from rain drops, are a very annoying feature when detailed control has to be carried on. In wartime one has to envisage the possibility of an aircraft flying through a storm area since it affords him a certain measure of protection from the radar and since, moreover, he has a certain degree of immunity there. In peacetime it is quite likely that a knowledge of the position of such rain storms could be a great asset and would help in controlling aircraft so that they would be able to fly in clear weather all the time even though flying at night. Microwave radar, and indeed any radar sees these rain storms quite definitely. When the performance of microwave radar is brought up close to theoretical, these rain storms will be still more apparent than they are at present. The development of circuitry to enable these to be eliminated is one of the important jobs that has to be done before radar can be considered to have arrived. In other words, it is necessary to see the aircraft where or when desired and to see the rain storms when desired. This has not yet been achieved although some palliatives are in existence. Considerable research should be put on this phase and possible directions of research lie along moving-target indication techniques with delay lines of variable length so that the variable motion of the clouds can be eliminated. Circuitry such as fast time constant and instantaneous automatic volume control have been proved to help a little. By very careful circuitry this assistance is such that it is quite appreciable at the present moment; however, much more and better remains to be done.

A second important problem that remains to be tackled is that of indication. We have never had any means of appraising instantly the situation of aircraft in the sky. The eye is not very good at this; the estimate of height and range of this is very slight and very inaccurate, and the ranges of detection are very low. Radar gives such a wealth of data that it far outstrips the eye, and therefore some means of using the data involves a considerably difficult psychological as well as material problem. Various things have been suggested, one of which is a continuous tracking mechanism on each aircraft, which by means of a servodrive moves (for example) small luminous dots up and down thin wires, and which therefore gives you a three-dimensional picture. Change in colors of the lights would indicate different aircraft. Such an indicator would be extremely elaborate and while perfectly possible would be something which would have to be embarked on only in an area of very high traffic. It would be a little difficult to build this unless one were sure of its ultimate success since the cost involved would be rather large. However, if the future of aircraft is such that aircraft becomes as common as automobiles, then something of this nature will be absolutely necessary. Otherwise the direction of flying from the ground will be extremely difficult.

One further thing remains unsettled. It has always been argued in the past that a pilot is one who likes to fly his own plane and to keep freedom of action. On the other hand, if he is controlled from the ground, his movements are much more certain and he is sure to get where he wishes to go more quickly and accurately. Moreover, he will be safer from enemy attack and he will get there in greater comfort since he will be vectored around the various cloud positions. It has been argued that this control from the ground will never be greatly liked by pilots. At this stage we do not have the answer to this problem. Many pilots who have flown missions closely controlled from the ground like it very much. Many pilots who fly navigational systems like those better; in this case they have, essentially, control in the aircraft. A period of extensive testing, lasting possibly as long as ten years, will remain to decide whether equipment will be procured and put in aircraft to enable the pilot to fly his own course using data fed in from the ground or whether he will merely listen to his radio and follow the instructions given to him.

A proposal has been made, by Griggs and the writer among others, for relaying back up to the aircraft the information from a ground radar set together with beacons and video mapping. If this were done, then the pilot could fly his own course and see where he was on a map instantly and would have no problems whatsoever. On the other hand, he would have one more thing to look at, one more thing to maintain in his aircraft and one more thing to learn to do without when it fails.

The other philosophy is that of control solely by radio, making sure, as is at present done on ATC aircraft, that enough radio is carried so that it can't possibly go out. Then by merely taking verbal instructions from the ground the plane, with no further equipment, can be vectored wherever he needs to go. This form of divine guidance, however, may not be psychologically satisfactory. Either way will achieve the necessary result of letting an aircraft reach his objective in bad weather or at night in complete safety.

Before such decisions can be made, however, we have to develop and make these systems absolutely reliable: (1) V-Beam, (2) tower search, (3) landing control, (4) beacons, (5) video mapping, (6) relay radar, (7) accurate control radar. After this equipment is as good as the ordinary human being for reliability, ground radar control can be said to have arrived.

THE CONTROL SYSTEM

Communication links for a control system are shown in Fig. 12. All control except a few specialized functions is concentrated at a convenient location within the area. The main difference between this system and those now in use lies in the transmission of the radar data to indicators in the control center. Under present operational practice, data is transmitted to the control center by verbal relaying of coordinate positions. This step introduces delays and errors which make reliable control from the retold plots an impossibility. The alternate solution now in use is to pass control to the radar station. This is undesirable because the control is no longer centralized, resulting in difficulties in coordination between the operational planning group and the control group. The use of a relay link to transmit the radar data to the control center avoids these difficulties. It is probable that no advantage would be gained by bringing the control of traffic at an airport into the control center. Therefore, the airport control radars are indicated as operating with only voice and teletype communications to the control center. On the other hand, it may prove desirable to provide the over-all air picture to the airfield control tower by a relay transmissin from the control center.

Antiaircraft defenses must also operate as semi-independent units, because of the requirement that the gun-laying radar must be near the guns. These units will be alerted from the control center and will be kept informed of friendly aircraft movements.

Antirocket defenses will probably have to operate amost independently because of the very short time available for carrying out defensive measures. Time delays in alerting cannot be tolerated. Furthermore, the equipment used for this purpose will probably be highly specialized and may be of little use in aiding in the control of aircraft. Certainly the present types of aircraft-control equipment will contribute virtually nothing to rocket defenses.

The directional air-ground communications systems are placed at the radar sites in order to provide easy orientation of the antenna to correspond with the radar picture. This feature also provides an identification aid by using the communication equipment as a direction finder.

Since the equipment is merely a means to an end, the organizational command will be operational rather than technical. The two main lower echelons will be air-control and technical, with suitable subdivisions to cover the functions and to provide for proper units at the various stations. Regardless of the classification as control or technical, all men on the system should be administratively under the same chain of command. The Army practice of having the control personnel in the Air Corps and the technical personnel in the Signal Corps had resulted in considerable conflict at times, and had been detrimental to the proper functioning of the system. It should be possible for either the control or the technical personnel to rise to the commanding position in the organization. In either case, the man should have a good grasp of the over-all functioning of the system.

The control network, if used to handle civil as well as military aviation during peacetime, can be kept an alive and progressive organization. On the other hand, if only simulated missions are carried out, crews will become indifferent and improvements will lag. This does not mean that simulated interception and bombing missions should be omitted, but it does mean that the organization should function continuously between these maneuvers.

This system can and should be set up to cover the United States and its possessions. At this time, the main ground radar should be the AN/CPS-6 and the main air-ground communications should be VHF. Development of improved communications should be pushed and substituted for the VHF. Mark V IFF can be used as a temporary beacon system while a higher resolution sysem is being developed. To obtain coverage out to sea, a long-range airborne system is needed, although this function could be carried out by picket ships. During peace, the main function of this airborne system would be to provide navigation, traffic control and aid to planes and ships in distress. Further development of equipment and techniques of control would be indicated as operating problems developed.

In addition to the relatively fixed defense installations, there is a requirement for a highly mobile control system to be used with armies in the field. For air-ground cooperation, a control network must be available which includes provisions for precision navigation of aircraft and rockets from the ground. Although the ground-control system is limited by optical horizon, many targets are suitably located for attack by aircraft under ground control. Control at greater distances can be accomplished by augmenting the ground radar with long-range airborne radar which can effectively raise the antenna height. This radar must be capable of seeing aircraft in the presence of fixed echoes, and if possible should be capable of detecting moving vehicles. The actual control should probably be carried out on the ground because coordination with other radar equipment would be easier. The aim of this control system, together with airborne bombing and navigation equipment, should be to prevent all movement of the enemy's supplies, equipment and troops on an all-weather, 24-hour basis, and to make enemy air force, rockets and artillery completely inoperable by destruction of enemy equipment on the ground and in the air. Complete paralysis of enemy supply lines would eventually cause collapse, even if the destruction of weapons at the front could not be accomplished.

Strategic operations introduce one additional requirement. Because of the distances involved in attacking the enemy's manufacturing facilities, airborne control centers must accompany bombers on long-range missions. These centers should be capable of carrying out limited operations of the same types needed on the ground. In addition, there may be a requirement for precision control of rockets, the rockets being launched either from aircraft or from distant ground installations. These aircraft may act either as "shell spotters" or may actually control the rocket. Techniques to accomplish the latter should be developed. The strategic aim should be to wipe out all production facilities and storage depots. This too will cause collapse of the enemy, but the effects will take longer to show than the paralysis of the enemy's transport system.

The ultimate goal of all air-control systems should be to provide complete and usable position information on all aircraft in flight, and to provide for the use of this information to aid any aircraft in safely completing its mission in either peace or war. In war, there must be the additional aim of maximum damage to the enemy, with minimum losses from enemy actions.

AIR BASED CONTROL OF AIR OPERATIONS

THE PROBLEM

The existence of ground radar equipment, which has been used so successfully for fighter control since the Battle of Britain in 1940, and the existence of airborne radar, which has been employed for individual fighter contacts and interceptions, have inevitably led to the sugestion of mounting in an airplane a radar set which could be used for general surveillance of the air situation and control of friendly aircraft in accordance with the demands of enemy air dispositions. The origin of this suggestion is not known, but as early as 1942 the RAF, at the suggestion of Wing Commander Sidney Lugg, mounted in a Wellington a set derived from the CHL/GCI, with a rotating 200-megacycle antenna which made it very remarkable that the airplane was able to get off the ground. This equipment was on the face of it technically impracticable, and no particular operational experimentation with it was carried out. The notion of airborne aircraft control has been reinvented several times since, but it is interesting to observe that the equipment which is now under development for airborne tracking of distant aircraft is called AEW (standing for airborne early warning). While it may be thought that this is done in analogy with the set whose principal use is fighter control, but whose name in MEW (microwave early warning), the fact is that the AEW is essentially an equipment conceived to permit ship-based aircraft control. It happens to be installed in an airplane, but this is so only because a mast of the requisite height for the ranges demanded by the design would raise the center of gravity of the ship on which it was mounted to an intolerable degree.

It will be instructive in the present discussion to inquire as to the general conditions which make an airborne aircraft control system desirable. The basic circumstance, of course, is that the world is round. Only microwave radar has the property of permitting an antenna of a size which can be successfully carried by an operational airplane to give the performance necessary in a radar equipment which provides sufficiently detailed information for aircraft control. The beam of a microwave radar is propagated in a quasioptical fashion, and does not extend over the horizon to any substantial degree. This leaves two possibilities when control of air operations must be exercised in places over the horizon from friendly territory: Either an airborne control center, with the necessary radar and communications equipment, and personnel for plotting and control, must accompany the combat aircraft, or else such an airplane must carry with the combat aircraft the necessary radar equipment, and specialized communications equipment which permits the display of the radar to be relayed back to a control center located on a ship or a piece of friendly land. This, of course, assumes that the command communications are also so relayed; it is now commonplace that really satisfactory command radio can only be achieved at VHF and above, and this suffers from the same horizon limitation which affects the microwave radar.

The ultimate choice between these two possibilities has not been made, and can scarcely be made intelligently while neither has actually been tried out even under proof-test conditions, let alone in combat. It may be remarked in comparing them, however, that the chief disadvantages of the airborne control center is that the limited pay load and space afforded even by the largest aircraft now in use limits severely the layout and adequate manning of such a control airplane, especially considering the amount of electronic equipment which must be carried to look after the necessary information-gathering and control-communications services. A secondary drawback is the fact that the men operating as controllers in such an airplane are subjected to the same combat stress as the crews of the bombers and fighters they are controlling. While this may lead to a feeling of brotherhood between controllers and controlled which results in unquestioned obedience to directions, it will also lead to some deterioration in the performance of control personnel. The principal disadvantage of the scheme of relaying information is its cumbersome operational character. Successful control depends, in general, not alone upon the radar plane accompanying the combat aircraft staying in the air, but also upon a relay airplane near the control center staying in the air. The amount of electronic equipment which must all work at once to conduct an operation is considerably greater in this latter scheme. In so far as any *a priori* decision between these means is accessible, it will arise from the direction in which the development of combat aircraft is to proceed in the future. This matter is considered fully later in this paper, page 142.

There are two sorts of operation which require or benefit by over-the-horizon aircraft control; these are fighter control and bomber operations. The first is defensive, and has as its aim destruction of enemy aircraft bent on attack, at a sufficient distance from the target to provide plenty of room for friendly fighter maneuver. The second is primarily offensive, and any class of aircraft may be engaged. The bombers mentioned in the phrase "bomber operations" may be anything from very heavies to self-propelled bombs. The purpose of the control is partly navigational, partly to warn the bombers of imminent attack by enemy air units, and partly to control escort fighters, if any. It will be instructive to discuss the immediate future possibilities in these two types of operation.

The range at which fighter control can be successfully exercised by ground radar has always been marginal, because of the horizon limitation, and is now definitely too small. If the attacking aircraft fly at low altitude, the optimum detection range is very small and increasing speed of the attacking airplanes demands its increase not only because of the shorter time between radar pickup and hostile attack, but also because of the greatly increased difficulty of making an interception on a high-speed plane. A typical example which proved troublesome when this was written [May, 1945] was the problem of the Japanese suicide bombs. These had a range, from release at the mother plane, of some 50 miles, which made the interception and destruction of the loaded mother plane before it had released its bomb, almost impossible if the only radar information available must be obtained at the target with antennas no higher than the usual one of a ground or ship radar equipment. B-29's of the

Twentieth Air Force were used to bombard the airfields from which these aircraft operated; this was a somewhat inefficient use of the B-29, and suggests that greater returns might have been obtained by a contiuous picketing of these fields by radar-equipped B-29's capable of alerting friendly fighters when a raid takes off. It is conceivable that this could be done with the help of existing airborne radar, if it were skillfully used. In any case, it is clear that the only available answer to low-altitude attacks by fast aircraft is a warning service and aircraft-control facility whose coverage extends well beyond the optical horizon.

The problem, as it concerns bomber operations, is not nearly so clearly defined. This is so chiefly because the air offensive of the future is more difficult to predict than the defense. The backbone of the latter will always be destruction of the enemy's offensive machines, whatever shape they take, and this will always demand warning and information of position sufficient to permit control of the defensive agencies, whatever they may be. The design of offensive machines is something else again. There is an enormous range of choice, ranging from an extension of the escorted heavy-bomber attack familiar from European experience, through medium-bomber operations and the use of fighter-bombers, to an attack by entirely unmanned aircraft, which, in the extreme may themselves be projectiles. The usefulness of the detailed control which modern radar permits will be greatest for the escorted heavy bomber operation, and will decline through the list just given, with the important exception that unmanned aircraft may be controlled to their target entirely by means dependent on radar. This last is a somewhat speculative possibility. In the present war we have committed ourselves rather completely to the mass escorted heavy- or very-heavy-bomber operation as the chief weapon of long-range air attack, and further discussion of air-based control of offensive air operations will be made on the basis, principally, of this type of operation.

During the last months of operation of the Eighth Air Force, which was the cradle of the modern escorted heavy-bomber operation, control of escorting fighters and some degree of navigational facility to bomber formations were provided by a long-range high-definition radar set which was sited first in eastern England, and later on the Continent. Increasing reliance was placed on aircraft control exercised by this equipment, and it became clear that an extension of the facilities it provided to cover the entire area of operations of the Eighth Air Force could, in principle, cause a revolution in the character of the operations of that force. It was customary to lay out a proposed operation, down to the most minute detail, from 24 to 48 hours before it was actually to be carried out, and the numbers of aircraft involved were so huge that no enemy reaction, however unexpected or threatening, could be allowed to cause an alteration in the broad outlines of that operation. The ability of the MEW radar, within its range, to permit the fighter dispositions to be altered to deal with actual, not expected, enemy reaction suggested that the entire operation could, in principle, be controlled from such an installation if its range of coverage were sufficient. Such coverage can be provided, clearly, by air-based detection and control equipment.

THE EQUIPMENT

It will be our purpose in this section to discuss only the principal performance features of existing and proposed equipment for air-based control of air operations.

It will not be our aim to discuss this equipment exhaustively, nor to indicate its limitations arising from the present state of our technical development. We must, of course, discuss the limitations which are fundamental and cannot be escaped. Perhaps it will make this distinction clearer to say that the horizon range of microwaves is a fundamental limitation, which, there is good reason to think, cannot be avoided. On the other hand, the fact that there is presently no adequate three-dimensional radar indicator, showing a scale map of the air space with aircraft positions and past courses displayed upon it, is simply a confession of the fact that insufficient technical effort has been put on the development of such a device, which has not yet appeared sufficiently urgent. There are two basic types of equipment to be discussed: radar and communications. Communications includes as subtypes voice radio, IFF, and radar-relay equipment.

So far as the radar is concerned, there is presently under development and nearly ready for operational use a set which has been informally called the AEW (AN/APS-20). This equipment operates at 9 cm and has several operational drawbacks which must still be cured in order to provide a really satisfactory radar for airborne aircraft control. The two chief objections to the AEW as it is presently designed are that it does not provide any means of giving accurate height information, and that it suffers excessively from ground returns. A less significant drawback is that the AEW will not, in its first embodiment, give full horizon coverage on a single aircraft of any type; its performance falls short of this. Improved receiver performance is in sight as a consequence of the discovery of a process for making very much better mixer crystals than used to be thought possible, and the range limitation is very clearly a transitory one. Height-finding from a platform as unstable as an airplane is a considerably more important difficulty, but there is no reason to think that this will not yield to development effort. Perhaps the most difficult of all is the elimination of ground returns, but this has been successfully achieved for stationary ground radar stations, and there is no basic reason for supposing that this technique cannot be improved and extended even to a radar station in a moving airplane. The situation with regard to radar equipment for air-based control of air operations can be summarized by saying that all the necessary techniques are either in hand or in sight.

The same remarks apply to the equipment for the relaying of radar information. Perhaps because this has never been seriously done in military operations, it seems that there are no difficulties in principle, and the work in hand on this subject gives great promise of success. It may be, and probably will be, that the first embodiments of this equipment will have faults, but these should prove to be correctible.

There is a basic difference between the two types of equipment just mentioned and the voice radio and IFF gear demanded by a flexible control setup. While the technical difficulties of the former are considerable, they seem capable of solution and (this is the important point) a very small number of equipments will do the complete operational job even for a very large air force. Large-scale policy decisions do not have to be made, and the influence of political considerations on the technical problem is at a minimum. This is not true of voice radio and IFF. Whatever equipment is installed in aircraft for use by the air-based control facility will be expected to serve as voice radio and IFF for all possible purposes, and the resulting political arguments will be very formidable. While it is not realistic to ignore this fact, which arises from the circumstance that all aircraft carry the equipment concerned, this will have to be done to permit us to get on with the discussion.

With the foregoing remarks about the lack of realism involved in such a discussion, it is fair to say that the existing and proposed voice radio, operating at VHF and just above, is very nearly satisfactory (it can be somewhat improved by a system which has sufficient channels to provide a separate one for each aircraft; such a system has previously been described in detail). Existing and proposed schemes of IFF are entirely unsatisfactory. Not only is the directivity of the largest feasible antenna which can be carried on an airplane marginal for the precise separation of friend and foe needed for aircraft control, but also personal recognition is not provided by any system, not excepting the highly regarded Mark V, and personal recognition is the backbone and the basis of successful aircraft control. It is even likely that the height-finding on friendly aircraft could be done with the help of the IFF system, if one like that proposed in the foregoing article could be used. It is to be hoped that the very great advantages of such a system in all connections will result in its adoption. Its virtues from the standpoint of airborne control can scarcely be regarded as important enough alone to produce its adoption. It is important to recognize, however, that the lack of directivity and of personal recognition facilities in all IFF, including the Mark V, constitutes a fundamental limitation arising from the frequency range used, and is curable only by the adoption of a completely new system.

THE FUTURE

As has already been indicated, the importance and the detailed design of equipment for the air-based control of air operations will depend upon the character of these very air operations. It is difficult to foresee just what this character will be. There are basically two directions in which offensive air operations can go. The first is toward a Navy task force sort of arrangement, in which the present-day escorted heavy-bomber operation is elaborated to whatever degree the square-cube law permits. This contemplates giant fleets of large airplanes, capable of long-range performance, and protected by specialized fighters (which may be manned or not, as the nature of the opposition demands), flying in formation from base to target and dropping great loads of bombs. On the assumption that long-range escort fighters can always be provided with the ability to engage defending fighters on reasonably equal terms (this has so far been the case), the chief hazard to such future aircraft can be expected to come from antiaircraft fire. Such fire, as the speed and the operating altitude of the bombers increase, will probably not be gunfire because of the large times of flight and the consequent difficulty of accurate prediction, but will be composed of homing or ground-directed self-propelled missiles, such as rockets. The problem of defense against this fire can be reduced to that of the problem of defense against fighters if the offensive aircraft fly high enough to permit such missiles to be engaged by their defending escort fighters before the missiles reach the bombardment aircraft. Such an eventuality places an extremely great premium on the development of a swift and adequate facility for the air-based plotting of such attacks, and the marshalling of escort fighters in detail to meet them.

The second direction in which offensive air operations can go is diametrically opposed, and seems at first glance to offer a far smaller field for the air-based control of air operations. This is the development of extremely fast bombers (or self-propelled unmanned bombs) which would proceed without escort from base to target. They would rely on their speed alone, and the difficulty of interception which is creates, for security against both fighter attack and ground antiaircraft fire, by whatever type of weapon. At first sight, this seems to remove the necessity for detailed control of air operations, but only at first sight. Not only is the guidance of unmanned bombs to their target of the greatest importance, but also there is a type of defense against such attack which makes radar location and fighter control as important as ever.

This arises from the circumstance that the laws of motion followed by a bomb are equally known to both sides in a war. Consequently, if a fleet of bombs or of bombers, flying at supersonic speeds, is detected by the enemy to be flying in a given direction, he can make a shrewd guess as to the target, and he can tell at precisely what point in space a bomb must be released from each altitude to hit the target. It will then be possible to deploy defensive air mines, which may be ground-controlled helicopters without crew, in a space lattice so placed that the offensive machines must run through it if the target is to be attacked at all. This will almost certainly be a more feasible form of defense than attempted fighter interception of very fast aircraft can ever be, and it demands the sweeping of the mine barrage before a successful attack can be carried out. This can only be done on the basis of the same sort of highly detailed aircraft control which has been contemplated throughout this article.

Since any other direction of development for offensive air tactics lies between the poles of the great air fleet and the supersonic unmanned bomb, and since both of these demand control of aircraft to be exercised over the horizon from friendly bases, we can conclude that:

(1) Air-based control of aircraft will be an important technique in future air warfare.

(2) The necessary radar equipment and equipment for relaying radar indication to a ground or ship base are being developed in a form which gives promise of being satisfactory.

(3) A decision between the control of air operations from an actual airplane, or such control from a ground or ship base, receiving relayed radar signals, cannot be made without extended experiment, which has so far not been undertaken.

(4) The voice communication and IFF techniques afforded by the use of microwaves are far more promising than those offered by existing or contemplated equipment, and will be very helpful to air-based control of aircraft if the political difficulties of introducing them can be overcome.

LOCATION OF TARGETS

EXACT TARGET LOCATION

It will do very little good to provide elaborate and precise means of navigating aircraft, and other elaborate and precise means of dropping bombs, unless we know where targets are to be found in enemy territory. The navigation and bombing problems may possibly be entirely solved by the means of automatic machinery involving no men in the aircraft, but the problem of determining precisely where the target is located in the first place requires the judgment which can only be supplied by men. It may be divided into two parts, namely, (a) reconnaissance, to locate the target in the enemy territory in order that plans for its attack may be formulated, and (b) recognition, to distinguish and recognize the target immediately prior to its attack. Reconnaissance is the process initiated after intelligence has determined that the target actually exists.

RECONNAISSANCE

Unless accurate maps or geodetic surveys of the enemy's territory already exist, these must be provided by our own forces. One example in the present war has been the mapping of the Solomon Islands and other Pacific Islands rendered necessary by the inaccuracies of the charts which we had before the war. The prime purpose of such maps should be to give an accurate picture of the topography of the enemy territory. They may or may not show the actual location of all possible targets. They will, however, show the shape and location of cities, important rivers, coastlines, mountains and other natural features.

The most important method of finding out what the enemy territory looks like is by aerial photography. The methods of aerial photography have been highly developed, and there is no reason why they should not continue to be useful even if the speeds and flying altitudes of aircraft increase. For very high-altitude flying, however, it may often occur that photographic missions have to be carried out from such long distances that very few of them succeed in finding enemy territory unobscured by clouds. In such cases, useful maps can be made by photographing the indicator scope of an airborne radar set. It may be desirable to provide special reconnaissance radar whose express function is to provide large and clear map-like presentations of the terrain, suitable for photographing.

It will not, however, be desirable in all cases to furnish either the ordinary aerial photographs or the reconnaissance photographs taken of radar scopes to bombardiers and navigators for use during actual bombing missions. Rather, it may be desirable to make line-drawn maps from these photographs. Apparatus to assist in the preparation of detailed maps from aerial photographs is at present highly developed. The development of similar apparatus for reducing radar-scope or PPI photographs to maps should present no difficulties and would require only the initiation of a development program to get it under way.

Incidental to preparing maps from photographs it is necessary to know not only what the enemy territory looks like but where it is located with respect to our own territory. In order to provide this latter information, a means of geodetic survey must be provided. That is, we must know the exact latitude and longitude of prominent features of the enmy territory. In order to provide this information, it is necessary that there be some means of accurately locating the photographic aircraft with respect to our own territory while it is taking the photographs. Several methods may be used to furnish this information: (1) Astronomical navigation may be carried out by the photographic airplane. (2) Various types of electronic ground-based navigational equipment may be employed.

Because of the limited range of electronic equipment, the solution to this problem differs according to the distance which separates the nearest friendly base from the enemy territory. If the nearest friendly base is more than approximately 1000 miles from the enemy territory, we must rely upon astronomic navigational data in order to position accurately the photographing aircraft. At the present time astronomical methods of navigation are not as precise as several types of electronic methods. Therefore, if the enemy territory is not more than approximately 1000 miles from the nearest friendly base, the latter should be employed. For this purpose the Loran apparatus presents many attractive possibilities. By its use, position data may be continuously and automatically recorded and impressed directly upon the photographs. (The principles of the Loran system of navigation and its future possibilities are described in the section "The Future of Hyperbolic Navigation," pages 110 ff.).

Neither astronomical data nor even Loran data, with the possible exception of cycle-matching Loran, discussed on page 114, will be of sufficient accuracy to compare favorably with maps made according to the standard methods of geodetic survey. There is, however, another system of electronic navigation called Shoran which is capable of giving data for the location of the photographs which compares favorably in every way with standard methods. This system, however, possesses the disadvantage that it can only operate from bases which are on the order of 200 or 300 miles distant from the enemy territory. Therefore, it may not always be possible to use it, especially at the beginning of a war. This restriction on the range of our most accurate survey means is a fundamental one and is not likely to be greatly improved by future developments in the electronic art. It suggests that before wars are declared one should already be in possession of accurate maps of the enemy territory.

After we have provided ourselves with accurate and precise survey maps of the enemy territory, we must then spot on these mapsthe location of those enemy installations which we regard as targets. However, before we can spot the enemy's targets upon the map, we must first know that they exist. The first procedure will undoubtedly be to make factual surveys of the enemy industry to find out what targets and how many and approximately where they are likely to be. This can be done by the usual methods involving agents, the study of prewar economic data, and other studies such as are now carried out by the Board of Economic Warfare. This information can also be found from aerial photographs or even in some cases from photographs of the radar indicators of the reconnaissance aircraft. However, the enemy, knowing that we are desirous of locating his main factories and other installations may try to disguise their appearance either by camouflage or by providing simulated decoy targets, or he may try to jam our electronic equipment. We must, therefore, employ a variety of means to locate the targets, comparing the results of one against the others. There are also several electrical devices whereby the operation of our agents and the conveyance of their data may be expedited. Some of these will be discussed below.

In considering the use of each of the devices to be discussed, therefore, we must also consider what means the enemy may use in order to defeat them. We shall discuss here the provision of decoy targets and the concealment of the actual target, leaving the dicussion of jamming to another place. The means of concealment include natural cover (as by forests), camouflage, and the placing of major installations underground.

We shall first describe the means which may be used to locate accurately the position of cities and other targets which occpy a large area.

AERIAL PHOTOGRAPHY

There is very little that the enemy can do to conceal his cities or major factories. Efforts had been made during the recent war, especially by the Germans, to disguise the appearance of parts of cities, for example, by covering over main roadways with roofs of camouflage material. In another case, the enemy provided a decoy, complete in many details, of an important oil field. Such methods are, however, of more importance to the enemy in his efforts to defeat the recognition of his enterprises by bombardiers prior to a bombing mission than they are in defeating our reconnaissance efforts. The reason is that the long period of time which is available for the study of reconnaissance data usually enables decoys to be detected as such, since the actual target also appears on the photographs.

The concealment by camouflage of any target against aerial photography can generally be defeated by one of two methods. First is the employment of colored photography. There are very few pigments useful for optical camouflage which so carefully match the colors of the surrounding territory that by the proper applications of color photography and the use of carefully selected color filters they cannot be made to stand out in considerable contrast from the surroundings. This is regardless of the fact that they may appear indistinguishable to the eye. The second method involves the use of stereoscopic photography which has also been highly developed. This method provides photographs which when viewed through suitable devices show the height of the subject to be greatly exaggerated. The method is powerful because the height of a target such as a factory building cannot be made smaller by the application of camouflage paint.

In many cases, cities and large industrial installations may be located with sufficient accuracy from a study of radar-scope photographs taken by photographing the indicator tube of an airborne reconnaissance radar set. The ordinary methods of camouflage which are suitable against aerial photography do not at all accomplish their purpose when radar is employed to look at the target. The reason targets are seen in radar sets is because of their gross characteristics and in particular because the target contains many reflecting surfaces which would have to be covered over by means of a camouflage material in order to make the target invisible. However, most camouflage materials, such as nets and pieces of cloth as they are now commonly employed, are quite transparent to the radar beam, which would therefore look through them and see the target underneath. Moreover, were the camouflage itself sufficient to hide the target beneath it, it would be in turn very difficult to prevent the camouflage from being detected as an object or region on the PPI or radar indicator tube different from the surrounding terrain, and this in turn would be almost as satisfactory as seeing the target.

The use of decoys to defeat radar detection of targets has been tried in some cases. However, the installations required to make a radar decoy are very expensive in comparison to those required to make an optical decoy. Furthermore, the same considerations apply here that apply to optical decoys, namely, that since the actual target will also appear and time is available to study the photographs, there is little hope that the Intelligence personnel would be fooled by this measure. It is, therefore, not regarded as being practical to attempt to hide either cities or area targets from reconnaissance aircraft either by camouflageing them or by providing decoys.

The building of cities underground is not regarded as practical from the point of view of the ventilation required if the city includes power plants and large, heavy industries. In this respect reference is made to "Heat and Television Guided Missiles," (G. A. Morton) page 42 ff., of the SAG report *Guidance and Homing of Missiles and Pilotless Aircraft* which discusses the problems of ventilating and getting rid of the heat generated in large installations when they are built underground. There are, however, many special types of large industrial installations, in particular aircraft assembly plants, which can be placed underground with practicability. These underground installations can be detected neither by aerial photography nor by radar-scope photography, and other means must be sought. We must therefore consider how we may detect these underground factories.

One must first remember that all the power consumed by a factory of any sort is eventually turned into heat. This process involves the friction in the machines, the resistive losses in electric motors, the heat generated by lighting fixtures, by air compressors, and so on. Now, if the factory is to be kept at sufficiently low temperature as to be endurable by the workers, some means must be provided for getting rid of this heat. As is shown in the above-noted paper on the thermal detectability of underground factories, this heat may be dissipated by a sufficiently elaborate but quite practical ventilating system; it will not dissipate of its own accord. In this respect an underground building resembles a thermos bottle. The hot air taken from the factory must be conveyed to the surface of the earth, and unless special and very expensive means are taken, the hot-air exhaust pipes may be detected by sufficiently sensitive equipment carried in reconnaissance airplanes. The reference mentioned shows that there are only a certain limited group of plants which may be so treated and that in any practical case there is always going to be a possibility that the exhaust pipes may be detected. Of course, the detection of such exhaust pipes is very nearly as good as the detection of the plant itself. Therefore, one should seriously consider the installation in reconnaissance aircraft of equipment especially devised to detect the heat given off by industrial installations. Apparatus for this purpose is understood to be now under development at the RCA laboratories.

In the event that underground installations are undetectable by heat-sensitive equipment carried in reconnaissance aircraft, other means may be partially effective in detecting them. The chief of these is the employment of sound detectors. Just as all industrial installations give off heat so do they give off a good deal of noise. The direct detection of this noise by microphones carried in reconnaissance aircraft is not regarded as practical because of the noise of the aircraft itself, which will very easily shield any noise from the ground. However, as is shown in the reference, it is possible to drop radio transmitters, carrying microphones, to the ground which may then pick up the noise on the surface of the ground and retransmit it to the reconnaissance aircraft. Devices suitable for this purpose, called sonobuoys, have been employed in the recent war against submarines. These sonobuoys are dropped in the water in vicinities suspected of harboring submarines, and they pick up the submarine noise and radio it to the aircraft above. It is entirely practicable to employ similar devices against underground targets. Of course, a great many of them would need to be employed, but fortunately they are not very expensive to construct. The tactic would be to fly a considerable number of aircraft over the enmy territory and drop such a sound detector say for every square mile of territory. By suitably coding these detectors and marking the position in which they were dropped it would be entirely possible in some cases to locate the underground factory with a fair degree of accuracy.

Radio transmitting equipment, although it may be constructed underground, necessarily requires an antenna above the surface. Highly developed and rather simple equipment is already available for detecting enemy radio transmitters.

Atomic power plants, should they be developed, may be detected not only by the heat which they give off in common with other industrial establishments, but also they may be expected to give off types of radiation peculiar to themselves, which are able to penetrate considerable thicknesses of earth. It may be feasible to provide suitable airborne equipment for the detection of such radiation.

In the present war, equipment has been employed to detect submerged submarines by virtue of the irregularities which they produce by virtue of their iron construction in the earth's magnetic field. In principle, such devices should also be applicable to the detection of underground factories. However, because of the short range of detection, these devices are not regarded as highly practicable for this purpose.

We may divide all industrial installations into three classes. These are: (1) heavy industrial establishments, such as steel plants or entire cities which can neither be economically placed underground nor can be dispersed; (2) manufacturing enterprises which cannot be dispersed but which may be placed underground with a certain amount of immunity to detection; (3) small establishments and potential targets dispersed on the surface. Small factory buildings isolated from any surrounding establishments may be effectively comouflaged or hidden by natural cover assuming that they are not underground. They may be camouflaged or hidden either from detection by aerial photography or from detection by airborne radar. However, the type of camouflage which is required in the first case is not particularly effective in the second, and the type of camouflage which is required against radar may be definitely harmful from the point of view of detection by aerial photography. Even targets which are hidden by natural cover like forests may in some cases be detected by airborne radar because the forests are often transparent to the radar beam. They will also be detectable by virtue of the heat which they give off as has been previously pointed out. The best way of locating such small establishments accurately is by a repeated series of reconnaissance missions each employing all of the useful techniques simultaneously. By a study of the successive photographs taken on successive days over a considerable period of time, it will often be possible to detect imperfectons in the camouflage or other unnatural phenomena which will serve to expose the position of the target. Objects which are surrounded on two or more sides by water are particularly easy to detect by radar beams. This applies particularly to bridges. In some cases, however, in the present war the Germans succeeded in constructing bridges which were entirely submerged, their roadways being about a foot beneath the surface of the river. Such bridges are of course quite undetectable by radar and also in most cases by photography, or indeed by any other means. Their presence may be again detected, however, if a sufficient number of photographs are taken over a long interval of time, due to changes in the river height, eddies, and other chance phenomena.

Materials exist which are sufficiently nonreflecting to radar beams as to render the covered objects undetectable thereby. A building covered with such material and located in a dense forest might be expected to be completely undetectable by radar. In such cases, recourse must be had to the subsidiary methods mentioned in connection with underground establishments; in particular, the possibility of dropping of small sound detectors must be considered.

TACTICAL RECOGNITION

Tactical recognition is the procedure whereby the bombardier or gunner is enabled to find the target preparatory to aiming at it. In the case of large and extended targets, such as factories or major industrial installations which are located above ground, this presents no difficulty, the problem having already been solved by the reconnaissance. Small maneuvering targets (such as tanks) or targets which are stationary but of small size (such as small buildings) camouflaged or underground installations, gun batteries and the like may be marked by agents. This may be done by the use of beacons of various types which may be set up just prior to the raid. In a few restricted cases, the beacons may consist of flares. However, in most cases it would be preferable to use devices which are, temporarily at least, invisible to the enemy. In this category come portable radar beacons. Such beacons are being made, and in the future considerable effort should be made to make these devices smaller and lighter so that they may be more inconspicuously carried by a man. Use of such devices would require no special equipment to be attached to the sighting devices in the aircraft since radar bombsights are already equipped at the present time to detect corresponding beacons, and visual light flares would of course be detected in the usual manner.

A useful tactic for vehicle detection might also be to place small microphones and associated radio transmitters along the expected path of the enemy vehicles. Operational tests, however, would be required to tell whether such a procedure would be tactically successful. It might be more successful as a means of sentry duty available to ground troops than as a means of identification for air attack.

A number of special devices may be utilized in order to enable the attacking aircraft to recognize unmarked targets.

Special attachments are available to airborne radar sets which will enable them to detect small moving land targets such as motor cars and tanks. The development and application of such devices is highly recommended.

The use of airborne control information centers may be of importance in strategic bombing operations. A complete description of the operation of such airborne control centers has been given in "Air Based Control of Air Operations," page 138. Finally, the attacking airplane may be equipped with specific radiation detectors to detect radio and radar transmissions, and this apparatus may be used to identify targets. IFF equipment is a particular example of equipment which is widely used to identify enemy positions from friendly ones.

There are a number of devices, navigational in nature, which may be used on the ground in order to control aircraft to the exact vicinity of the target. These include the various types of ground-controlled radar (which had been previously discussed under bombsights), IFF equipment, and of course the various types of communication equipment.

CONCLUSION

The problem of exact target location may be divided into two parts: (1) the strategic reconnaissance problem which accurately maps the enemy territory and locates on these maps the exact positions of all targets; and (2) the tactical recognition problem, the solution of which enables the attacking aircraft actually to sight upon the target. Different devices for the different types of these problems have been outlined. It is considered that no one device will solve all of the problems but that the devices employed must be chosen according to the need. The problem of training and briefing of all personnel concerned should not be neglected. In particular, the selection of suitable operational personnel is of the utmost importance; simplification of the intelligence material which is presented to the operational personnel must be achieved; and it is recommended that methods of presenting and preparing intelligence material should be studied continually.

RADAR AIDS FOR THE ALL WEATHER AIR BASE

INTRODUCTION

It is best to begin this discussion by listing the various steps which an all-weather air base would face in handling the take-off or return of large numbers of aircraft under instrument conditions. The problems vary from the emergency landing of a single airplane to handling several squadrons of airplanes many of which may be foreign to that particular field. The facilities for the most complex cases will be considered here although it is recognized that emergency landing of small numbers of planes may require only a part of the equipment required for the full job. In the proper sequence these various steps are:

(1) Clearance for taxiing aircraft and blind take-off.

(2) The marshalling of aircraft after take-off into squadron formation and the relinquishing of control of the aircraft to whatever navigational system may be used to aid the flights in their mission.

(3) The identification and control of aircraft returning to the field. It is probable that this will include the spacing, stacking or any other method of separation of planes into desired intervals for landing, and the initial contact of the plane with the landing aid.

(4) The final approach using the landing aid.

(5) Speedy clearance of runways after landing.

In normal weather the air-base control tower has little concern with functions except within a very small area (approximately 5 miles radius) around its field. The control tower gives taxiing instructions for take-off and landing, and functions to control planes entering the traffic circuit. The prime responsibility for the actual position of the plane is the pilot's. There are many who believe that in blind landing, the pilot can be given instruments by which he can function much as in good weather and with the very minimum of control by the tower. It appears to many others, however, that the functions listed above will all have to be the prime concern and responsibility of ground personnel and equipment, functioning very much as a control tower. In fact, the development of satisfactory facilities for handling large numbers of aircraft in blind approaches, should lead to the adoption of part of the same methods for good weather control. There is much to be said for each of these viewpoints to make it appear that both are correct, that the two systems of operation are complementary and that both will be of future use.

GENERAL MILITARY REQUIREMENTS

It would be well to set down a summary of the military requirements of the problem outlined above. Some of these are general requirements for all instrument flying, and are doubly important here.

(1) The system must give satisfactory results with all types of pilots, with the inexperienced as well as the veterans, even when tired or wounded.

(2) It is desirable that the systems require as a maximum but a few hours of pilot training and but little long-term practice to enable satisfactory emergency use.

(3) Both ground and airborne equipment must give 100% reliability. This is not only necessary for safety but is required to hold the pilot's confidence. This means that constant monitoring facilities for presentation to the pilot should be provided on airborne receivers. If beam-approach systems are used, the beams must hold their position over long periods of time.

(4) The system must be capable of handling planes approaching at various speeds up to 1000 mph, and whose top landing speed may be of the order of 250 mph; landing speeds range from 70 to 250 mph.

(5) The system must handle nonscheduled emergencies such as disabled planes, crack-ups on the runways, etc.

(6) Provisions must be made for preventing collisions.

(7) The equipment must provide security against enemy intruders.

(8) The equipment must provide protection against jamming.

(9) The weight and bulk of the airborne equipment must be kept at a minimum.

(10) The ground equipment must not present a hazard to flying aircraft.

(11) Ground equipment on the airfield itself must be mobile. If possible, all equipment should be air-transportable.

(12) The equipment must indicate to the pilot how to clear any flight obstacles which may be required around the airfield.

(13) The final landing aid must give the pilot an accurate sense of position in both the horizontal and vertical planes. It is desirable that the heading of the aircraft with respect to the runway should be indicated.

(14) The equipment must be capable of handling successive planes of very different landing characteristics.

(15) Provision must be made for positive identification of all aircraft to be landed.

(16) If landing beams, homing beacons, etc., are used, positive identification of a particular field in congested areas is required.

(17) Interference between ground stations cannot be tolerated.

(18) In multiposition ships, the system should allow for another member of the crew (copilot, navigator, or radio or radar operator) to take some part in the landing operation.

(19) Provision should be made for landing on parallel runways. Landing aids for the two runways must not interfere.

(20) Adequate radio communication must be available in the plane.

(21) At every all-weather airport, there must be at least an emergency system, of sufficient flexibility to handle any type of aircraft or military pilot. This requires that

every plane to be used in all-weather operation be equipped with some emergency landing aid, or that the system used require only radio communications in the aircraft.

(22) The over-all system should be capable of handling planes on single runways at approximately the speed at which these planes can be landed under good visibility conditions. The minimum requirement is 60 planes per hour, the maximum not more than double this.

(23) The pilot's indication or presentation device must be as simple as possible and such that little or no mental computation or interpretation is needed.

(24) Last and perhaps most important is that the equipment must gain and hold pilot's confidence. The pilot is a human being who likes to stay alive; pilot apprehension and distrust have killed about as many landing systems as pilots. The psychological attitude of the pilot is of prime importance in bad-weather flying and landing. In order to convince him, the data presented to him has to be of highly reproducible accuracy. He should be able to make check flights in good weather to convince himself of their accuracy.

The preceding list of requirements hold for the most rigorous conditions; no one existing equipment, radio or radar, completely satisfies this list. Combinations of existing equipments can be made, however, which will approximately satisfy all the operational requirements.

The question is asked, "How do the requirements for permanent bases differ from temporary ones?" In the above list only item (11) seems to be affected if permanent installations are desired. At permanent bases it will be possible to make a much more elaborate installation of the ground equipment; the mobile features of the airport gear may be removed and duplicate landing equipments established for various runways. It is possible to lay down permanent connecting cables from tower to field installation, etc. The need for extremely rapid shifting of landing equipment from one runway to another is not generally considered a necessity.

EXISTING LANDING AIDS

The following is a list of the navigational and landing aids that are in operational use by USAAF, USN, or RAF; are in development by the services; are developed but not in operational use; or are obsolete.

1. Navigational aids to help aircraft back to base or systems that can function as such
    a. radio ranges
       direction-finding chains
       Loran
       Gee, H, etc.
       radio-homing beacons with coded sectors
       *racons (used with AI or ASV radars)
       *airborne radars such as H_2S, ASV
       *AN/CPS-1
       *GCL, etc.
    b. *AN/CPS-6

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*Indicates microwave systems.

2. Traffic control systems
   a. radio ranges, direction-finding chains, etc.
      *AN/MPN-1 (partially effective)
   b. *British ACR systems
      *AN/CPN-18 (AAF, NDRC development)

3. Approach systems
   a. Beam approach (localizers and glide paths)
      (1) SCS-51
          VHF-BA (British)
      (2) *PGP (X-band pulsed glide path NDRC)
          *Sperry (S-band CW localizer and glide path)
      (3) SBA (British Lorenz)
          Air Track (YB and YO)
          Bendix (93 mc)
          Lorenz (10 mc)
          CAA-MIT (600 mc)
          } all constant-intensity glide paths
   b. Beacon-beam approach system
      (1) Radar BA (BABS) or Lucero
          BA (British)
      (2) BUPS
          AN/CPN-7
      (3) AI-BABS, ASV-BABS
   c. Ground control of approach
      (1) AN/MPN-1
      (2) AN/MPN-3
          AN/CPN-4
          AN/GPN-2
      (3) Modified SCR-517 or SCR-717, or
          AN/APS-15

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*Indicates microwave systems.

TRAFFIC CONTROL

Let us now examine in more detail some of the landing functions required for an all-weather air base.

The problem of handling large numbers of planes (say 60 to 80 per hour) returning to the field under conditions of poor visibility is a rather hopeless one without radar facilities. Neither the planes nor the towers however, now possess the radar facilities to locate the planes individually in azimuth, elevation, and range with respect to the landing strip, nor to identify, space or stack them, nor to give proper order of landing, nor to feed them into a given final approach system.

The first and foremost requirement for the all-weather base is a ground search radar that is capable of giving to the control tower the necessary positional information of all the aircraft in space about it, including traffic passing through the control area, as well as that desiring to land. Ground radar can supply all the necessary information and control such planes if the necessary communication and personal idenitfication schemes are available to identify each individual plane, i.e., to identify positively, the plane desiring information or to be controlled, and to give instructions.

The GCA equipment developed at the Radiation Laboratory and now in operational use by the AAF, Navy, and RAF, although primarily an approach system, contains the first elements of traffic control in its S-band search radar. It has been used in a limited way to study some of the problems of aircraft traffic control on a PPI of 15- or 30-mile radius. Experiments were performed on stacking methods about the airport itself, stacking in angle, range, dog-leg path, etc., and the correlation of an approach system with blind vertical stack by the tower itself. These have led to the conclusion that in general a separate equipment must be made available with greater range, elevation coverage, indicator facilities, etc., than the present GCA to serve adequately the desired function. It has not been found possible for the one PPI operator available for traffic control to keep more than four or five single planes completely under his control at one time. Control schemes are now under study and test by the Air Forces whereby groups of planes such as fighter-bombers which can fly formations of two to four planes through cloud may be controlled by such facilities as are available in GCA itself. However, such procedures will be limited to highly maneuverable aircraft and must be looked on as only interim solutions.

The Army Air Forces together with the Radiation Laboratory began experimental studies of the equipment, operator, and operational requirements for such a separate ground radar set under the AN/CPN-18 development program for an airport search set.

This program proposes to study the following problems:

(1) The control of the spacing, course, and altitude of single or formation flights of planes over sufficient range so that the planes arrive over a marshalling point or "gate" at the proper interval be immediately handled by the final approach system. From the early experiments mentioned above it is believed possible to control the returning courses of a large number of planes with sufficient skill if planes are brought under control early enough, i.e., at sufficient range. Thus the aircraft will be stacked in a horizontal plane as they progress through the control area toward their field. It is realized that in a dense population of airfields it may be necessary to have such a system act as an area control, feeding planes into a number of fields; hence more than one such gate may be required.

(2) The control of these planes about such a gate, which may be a homing beacon, radio range station, etc., may be required since it may be found impossible to adjust arrival of planes at such gates with sufficient fineness in time as just to match the landing interval which the landing aid, whatever it might be, can handle. The gate, of course, can be the airfield itself, although it is generally felt that points eight to ten miles distant are more desirable. Provision must be made then for surveillance by radar of the control point so that planes may be stacked horizontally or vertically about them and their position in such a stack known at all times. It will then be possible to call the planes into the approach aid at the desired time so the desired landing rate can be maintained.

(3) The control of the descent of planes through overcast under sufficient ceiling (200 to 500 ft possibly) so that they may be brought in by the search radar itself. It has been found possible with the GCA search to bring airplanes in on the PPI alone so that singly or in small formations, they break out below the overcast and make their final approach visually.

(4) The final function of such a set is to feed planes into a final approach system so that, if a ground control system such as GCA is used, the plane is in proper position to be handled quickly and easily on the narrow sectors of vision of the approach system, or if other types of landing systems are used, so that time is not wasted in hunting localizer beams, etc.

It is recognized that the above aids fail unless proper facilities for communications with the planes and positive personal target identification methods are available.

In the experimental program outlined above, eight-channel HF and VHF communication facilities will be provided. It is hoped that communication channels necessary for the traffic control function will be found to be a maximum of two or three. Transmitting to any one plane under control need not be long, only a few seconds, so that many planes may be controlled in a short time. It may be required to separate the different functions into different channels.

The identification problem is recognized as perhaps the most difficult of all. It is recognized that, on a long-range program, a solution such as the proposed microwave communication system must be found to provide a very large number of communication frequencies and to provide personal recognition of aircraft. It is felt, however, that considerable success can be achieved by a combination of the several identification aids now available, namely, communication direction-finding, particularly if the direction-finding bearing can be added to cathode-ray tube presentation, height information, and beacon facility such as Rosebud. The combination of such information with maneuvering, such as the sending of a given plane out on a given heading from a given point, should be studied thoroughly.

Schemes will be devised in the future by which the information as to an airplane's range, azimuth, and elevation relative to a given control point may be fed to the plane's automatic pilot so that planes may be automatically controlled in the stack. In this vein, one should mention the experiments being conducted in England on orbiting control using Radar BA. The range indication from the interrogated ground beacon is used to feed voltages into the autopilot so as to hold the plane on a circular course around the beacon at constant range from it. Planes could be fed into such a system and given different ranges, say at half-mile intervals, in which to stay until called out to land. The spacing of such planes to obtain very high landing rates does not at the moment look too promising. These experiments are in their infancy and will be watched with a great deal of interest.

LANDING AIDS

The development of usable radio aids to landing has been along three general lines. The first, beam-approach devices (localizers for azimuth and glide paths for elevation), is the field in which most of the development has been concentrated. These systems are called air-indicated systems, i.e., airborne receiver systems and indicators such as cross-pointer meters or cathode-ray tubes. These are used to detect and indicate single or multilobe beams generated on the ground and pointed in the desired directions in azimuth and elevation out from the runway. The second general class, beacon-beam approach systems, involves the use of airborne interrogators in addition to the airborne receiving and indicating gear. The ground equipments are essentially beacons which only radiate their beams when interrogated by the airborne equipment; the positional information furnished by the plane's interception of the beam is presented to the pilot or navigator on CRT's or on meters. The third general class is ground-controlled approach systems which in general are ground installations of scanning systems that obtain on the ground all the information as to a plane's position relative to a desired glide path in azimuth, elevation and range from the runway and then relay such information by voice or aural tone to the plane through normal radio communications.

A fourth classification which is in its early experimental stages might be added. This involves the use of the information available in the plane from any one of the other three general types as data to be fed into an automatic pilot to accomplish automatic approaches and landings.

Radar, particularly microwave, equipment has made valuable contributions in all three of the general types. Some of its peculiar properties such as the ability to produce very narrow beams (less than one degree half-widths) with reasonably sized antennas, the relative freedom from atmospheric effects, etc., over the short distances involved, the relative security from jamming and interference afforded by such narrow beams can materially aid in the elimination of many of the faults experienced with the lower frequency CW systems.

In discussing landing aids it is generally admitted that the systems in existence today are primarily approach systems. They are, in general, designed to handle a plane to within a certain altitude above the runway from which point the pilot lands his plane visually.

This does not mean that they cannot be used all the way to the ground and blind landings made on them. Practically all the systems that have been devised (those that have died as well as those adopted for general use) have recorded numerous "hooded" or blind touchdowns with expert instrument pilots; most of these systems are, however, incapable of achieving such results time after time under zero-zero emergency conditions with the ordinary AAF pilot and hence are not entitled to be considered as truly blind-landing devices. A true blind-landing device must provide for guiding the plane straight down the runway after touchdown until the plane has rolled to a stop. It must solve the problem of the change in the plane's direction after touchdown from its direction of flight while crabbing in the approach due to the cross wind.

Although conditions of ceiling and visibility which necessitate using instrument landing aids vary widely and hence require varying degrees of proficiency of the aid, a satisfactory definition of an approach aid may be the following: A satisfactory approach aid is one which is capable of repeatedly bringing the plane to within an elevation of 50 ft above the runway over its end, in azimuth to within the center half of a narrow runway of 150-ft width, and on such a heading, in such an altitude, forward speed, and rate of descent as to be able to make a visual landing from that point. The fulfillment of such conditions will take care of the vast majority of instrument landings. Since worse conditions down to zero-zero emergencies do arise and since pilots will attempt by necessity to fly an approach system all the way to the ground, a successful approach system will find itself used in zero-zero, and may, if a sufficient number of such emergency landings are made, become to be regarded by pilots as actual blind-landing devices.

The development of the intensity-type system involving radio-beam localizer and glide path has followed along natural lines in first the use of single-lobe beams and then multilobe (two to eight in azimuth and dual lobe in elevation). Most of the early type 1929-1939 glide paths were single-lobe constant intensity paths. All such systems, such as the Air Track and British SBA Lorenz, have now been abandoned in favor of the dual-lobe, straight-line glide path such as utilized in the IT&T development, now a part of the SCS-51 equipment. The constant-intensity systems, besides requiring the airplane to fly a curved path in the elevation plane, suffered severely from false and bent courses with bad bumps due to reflections from buildings, etc., and, since they involved ground reflections, were susceptible to ground, moisture conditions, and roughness of terrain immediately in front of them and other difficult sighting problems. They failed to meet almost all the requirements listed and hence died.

The surviving CW system, which the Army has adopted as its standard beam-approach device, is the SCS-51. This is considered by all service, including the British, to be the best CW beam system yet devised. The decision to adopt this was made in 1943 after some trials in conjunction with two microwave glide paths, the PGP, an X-band pulsed glide-path system developed by NDRC, and the S-band CW system developed by Sperry. This decision was based partly on the feeling that greater reliability would be realized with the standard type tubes, receivers, and antennas that were used in the 110-megacycle localizer and the 330-megacycle glide path than with the untried specialized gear of the microwave equipment. A development contract, later cancelled, was let to continue the improvement of the pulsed glide path and to devise a pulsed microwave localizer.

The difficulties now being experienced with many of the SCS-51 installations suggest that it might be well for the proponents of the intensity-type beam systems to reconsider carefully the advantages which microwave equipment have to offer. These troubles involve maintenance of the ground gear, problems of sighting both localizer and glide path (where normal obstructions on the airfield or hills, etc., have to be carefully balanced out by screens or shields), effects of moisture both on the ground and on the antennas on beam position, and unreliability of the airborne gear. The glide path uses the perpendicular-type aerial system which necessitates the use of ground reflections in order to be produced.

Both the microwave systems are tiltable glide paths which do not require ground reflections to form their beams and which in fact attempt to adjust their beams above such ground objects. The state of the radar art is now sufficiently advanced that an X-band glide path such as PGP can reliably reach out to ranges of 15 miles or more and can be built into compact airborne installations and fairly reliable ground gear. The pulsed glide path is favored over the CW microwave system in the much simpler, less bulky and weighty, airborne and ground installations. It is felt that an adequate microwave localizer could likewise be developed. Considerable work in the airborne instrument-presentation problem might likewise produce more satisfactory results.

This general approach to the problem, however, when examined in the light of the conditions set forth in the section on "General Military Requirements," page 151 is incapable of meeting the majority of them and appears to be ultimately hopeless in providing a general, flexible system sufficiently accurate and reliable for emergency use by all pilots to be considered as the required all-weather aid. All such systems require long and careful pilot instrument training and continued practice. They do not provide sufficient safety factors in the lack of pilot warning of danger of collision with other planes or ground objects, etc. Such systems will no doubt prove useful in certain limited installations, in carefully chosen sites, with careful maintenance and continuous human monitoring of both ground and airborne gear, and with long and continuous practice by expert pilots. However, their use is restricted to those planes which presumably can afford to carry the weight of the airborne components and hence offers no general solution. Past and present experience suggest that all systems which depend for their positional information on the relative intensities of two or more lobes will fail ultimately in achieving wide-spread pilot confidence and will eventually meet the fate of their predecessors.

The case for the beacon-beam approach system has been presented primarily by the British who contemplate using the Radar BA system in Bomber Command. Only the localizer system has reached experimentation. Its chief advantages over the type just discussed are: greater security, because the ground gear is not continuously radiating but only when interrogated by the correct frequencies; less subject to interference unreliability; much more stable in beam position; more readable presentation (at present presented to navigator who talks pilot in); narrow azimuth pattern to minimize sighting difficulties; and continuous range information.

The 200-300 megacycle BABS system, however, will suffer from some airport sighting problems as the beams are subject to reflections from hangars, etc.; higher frequency equipment would be less susceptible to such effects although they are not completely eliminated on S- or X-band. The present Radar BA airborne equipment is very heavy (150 pounds, although it is thought that 60-pound equipment can be attained). The present equipment is designed to be used with the Eureka or Lucero interrogator and later with SCR-720, etc.; thus it is limited in application to those planes so equipped.

The use of microwave ground beacons such as BUPS or BUPX has been tried as a localizer facility with the plane carrying the appropriate S- or X-band radar to interrogate. Skilled pilots or navigators observing PPI presentation can achieve moderate success in aligning themselves with the runway under conditions of small cross wind and when the terrain surrounding the airport is completely familiar to the pilot. The problem of finding the correct heading to counter cross-wind appears a fairly difficult task.

It is extremely doubtful that such systems can hope for any widespread use; certainly those planes without the necessary interrogating radars will not add them specifically for this use.

Suggestions have been made that there might be a possibility in the future of utilizing time-measuring schemes. The time difference between the reception by the plane of beacon responses from two interrogated beacons placed on a base line perpendicular to the runway could be used in indicating the azimuthal error left or right of the extended runway line. The time intervals for practical base-line distances between the two beacons are so small, however, that a considerable advance in interval measuring methods and steepness of transmitted pulses will have to be made before such a possibility could be considered. For example, for beacons one-half mile apart, differences of 0.1 microsec would occur for an airplane 50 ft off course at one mile range and approximately 0.01 microsec for same error at ten miles range.

The development of the ground control of approach (GCA) equipment by NDRC and the operational use of the gear (AN/MPN-1) in the past few months by the services has made available an entirely different approach to the instrument-landing problem. For a number of years attempts have been made to talk a pilot down first by listening for him over the airport and attempting to direct him from such meager data as could be obtained from the sound of his motors and later by the use of direction-finding fixes on his radio transmission.

The success of the GCA equipment during the first few months of its operational use in achieving numerous emergency landings under operational conditions and with pilots who have never previously made an approach on the equipment suggests that the system possesses a number of desirable attributes.

(1) First and foremost, since it feeds information to the pilot over his normal radio communications, the system requires no additional specialized gear in the plane. It, therefore, can be considered a universal system if the proper communication channels are made available for use.

(2) The radar information obtained by the narrow-beam scanning antennas covering the plane's position continuously in range, azimuth, and elevation is of very high accuracy (order of two mils in elevation and four mils in azimuth) and is not subject to error because of reflection of the beams from the ground, hangars, other aircraft, etc. Likewise such microwave beams suffer very little distortion from atmospheric effects over the short distances used in the system. Sighting difficulties in relation to the equipment's position to other airport objects are therefore minimized.

(3) Reflections from objects close to the desired azimuth or elevation landing path instead of being harmful provide positional information to the ground crew of the proximity of the plane to these objects so that the plane can be warned when it is too close and can be given direction of course to fly to avoid them. This includes other planes in or crossing the approach path.

(4) The verbal information presented to the pilot is in such form that the amount of data interpretation is greatly minimized. It is fed to him through the sense least in use by him during the approach, his ears. Thus the pilot is relieved of part of the additional burden placed upon him by the instrument-flying condition instead of having the strain increased by requiring his close attention to additional meters or CRT's as is necessary in most other systems. Some of this strain is shifted to the ground crew

who are, for the moment, better equipped to accept the responsibility for the plane's safety.

(5) It has shown itself capable of handling all types of aircraft. In general it has been found possible to use glide paths of approximately 3° angle with all types although the desired glide angle can be changed quickly from one angle to another within the range 2° to 5°.

(6) The radar-scope presentations allow the operators themselves constantly to monitor the system so that they are immediately aware of any shift in the radar picture due to instability in electronic circuitry, etc., which may cause the positional data given to the pilot to be incorrect. This constant human monitoring is a tremendous safety factor which cannot help but increase pilot confidence if demonstrated to him.

(7) Its mobility about the airport from runway to runway is unusual for such ground equipment.

(8) It has demonstrated that it can be used by tired and inexperienced pilots with little or no previous contact with the equipment although it is recognized that pilot indoctrination and a few training flights are useful in dispelling fears and increasing the willingness to use the equipment when the necessity demands it.

(9) It is felt that a strong virtue of the ground-control approach system is its great versatility in handling the many unforeseen emergencies that arise in instrument weather flying.

The traffic handling capacity of GCA was overemphasized in the early experimental period. The proponents of the system are fully aware that it cannot serve as a traffic-control set in itself. It, however, has been repeatedly demonstrated that if planes are fed into it at proper intervals it can handle planes in the approach at two- to three-minute intervals which is better than any other existing system can do. It has in addition a partial traffic handling capacity of four or five single planes or groups at a time, which is a feature no other system can at present claim. The potentialities of high-density traffic handling on the approach are only now being considered with multi-positional-approach indicators, etc. A rate of 60 planes per hour is being aimed at in new Army-developed GCA's.

OTHER PROBLEMS

The question of aids to instrument take-off should perhaps be mentioned. It would be perfectly feasible to provide any of the discussed landing aids to view the take-off and give the pilot positional information. Inasmuch as hooded take-offs are common practice in service flying experiments, it is felt that the chief problem comes after take-off in maneuvering away from the field. Obviously the traffic control radar search set or the GCA search could aid materially in marshalling after take-off, in avoiding collisions with planes and hills, etc.

Finally there is the problem of clearing the runway after landing. The control tower of the future will no doubt wish to have accurate information as to where his taxiing planes are, and the planes will want information as to how to taxi. The British have experimented with a short-range high-resolution X-band set to show the position of ground objects on the field with indicator presentation in the tower. Such aids could certainly be provided although it is hoped that the use of high-powered light or infrared systems might be easier solutions.

CONCLUSION

The all-weather air-base problem has two important aspects, traffic control and blind landing. Related subjects of less importance include blind take-off and ground-traffic control of aircraft taxiing along the runways. A complete system should solve all of these.

Air-traffic control may best be achieved by means of microwave radar, based on the ground and used by the control-tower officials together with the requisite communicating facilities, etc.

Two types of blind-landing equipment are outstanding, namely: the talk-down system as typified by GCA, and the glide path localizer system typified by SCS–51, and systems designed by the Sperry Corporation and by NDRC (PGP system).

The former of these types is noted for its operational flexibility and ability to cope with emergencies. The latter type is regarded as being particularly suited for heavy traffic. It would appear that this type of equipment is desirable under such conditions but that an airport equipped with it should also possess GCA. However, there will be some airports where only GCA is needed.

When assessing the relative ease of training and maintenance of these two types of equipment it should not be overlooked that one of them requires a good deal of equipment to be operated and maintained in the airplanes.

RADAR COUNTERMEASURES

In this section we shall try to estimate the influence of countermeasures upon the future usefulness of radar. One occasionally hears the view expressed that every radar system has its counterpart in a jamming device to which it will sooner or later fall victim. The picture suggested is one of an eventual undeclared truce in radar warfare, in which neither side can profitably use radar, because the other side could promptly annul its effectiveness. This view is not supported by a critical study of the problem and of the trends in radar development.

Action which can be taken against a radar-equipped enemy may be, roughly speaking, of three sorts:

(1) Jamming, that is, causing extraneous signals to appear in his radar set which confuses, obliterates, or falsifies the information he seeks.

(2) Concealment, that is, reducing the visibility to radar of his targets (for example, the Germans at last succeeded in rather effectively hiding their submarines from radar by submerging everything but the "Schnorkel," and by applying to the top of that a special coating of low-reflecting power).

(3) Listening or detection of radar transmission leading either to early avoiding action or to direct offensive action against the radar station itself.

JAMMING

The radar-jamming methods which have been used or at least developed in this war can be conveniently classified in four categories.

(1) Electronic Blanket Jamming. In this type of jamming, the aim is to obliterate the radar echo by jamming signals. The most effective type of jamming signal so far devised has been a CW carrier which has been either amplitude- or frequency-modulated by resistor noise. Two cases must be distinguished, however, one in which the main jamming signal energy is confined to a frequency range about equal to the radar receiver bandwidth (to be called "spot-frequency jamming"), and the other in which the jamming energy is distributed over a broad band (to be called "barrage jamming").

(2) Electronic Spoof Jamming. In this form of electronic jamming the idea is not to obliterate the radar echo, but to provide several additional synthetic echoes which will confuse the radar operator so that he will not know the exact position of the true echo.

(3) Reflector Jamming (Window, Angels, etc.). In this form of jamming, material is disseminated whose radar reflection is made either to cover up the target signal or to provide many similar echoes for confusion purposes. This form of jamming has been very widely used because it is inherently broad band.

(4) Special Forms of Jamming. In this category fall many special jamming tricks, generally utilizing some vulnerable feature of the radar set. As an example,

"Peter" may be mentioned; this is a jamming scheme utilizing the lobe switching rates of automatic tracking radar sets.

Certain problems are common to all methods. In the first place, one must know something about the particular enemy equipment to be jammed. If the jammer is electronic, it must be set on the proper frequency. In many cases this requires continual monitoring of the enemy transmissions in order that any changes in frequency may be followed. The problem is made more difficult when there are many enemy stations in the vicinity and more difficult still when these sets scan with narrow beams, so that the transmission is heard only during brief, widely separated intervals. Uniformity of jamming cover must be sought, for complete protection, and it is usually harder to protect many targets than to protect a single target.

The above requirement can be discussed quantitatively only in particular cases. The important question of the power required for jamming, however, deserves to be examined quantitatively. Suppose we are required to jam a radar set operating at a single known frequency. If the jammer is located at the target to be protected, and if the jamming power is radiated from a nondirectional antenna, the power required is at least equal to the radar-scattering cross section, σ, of the target. Using the same symbols which we used in writing the radar equations, page 42, with P_j meaning minimum jamming power,

$$P_j = \frac{P_t G \sigma}{4 \pi R^2} \tag{4}$$

For example, consider a target of radar cross-section 1000 sq ft (about that of a large bomber) 20 miles from an MEW (AN/CPS–1) set. P_j in this case is about 60 w, for a nondirectional jammer located at the target.

The power output of present jamming transmitters is indicated below. The numbers in the last column suggest what might be done with present techniques, and are, of course, only guessed. The important trend to note is the decrease of available power with decreasing wavelength. This can be traced to causes closely related to those responsible for the decrease at shorter wavelengths of the peak power of radar transmitters, already mentioned in the section on "Pulsed Radar". Thus in respect to power output alone, the jammer and the radar compete on more or less even terms at different wavelengths. However, at shorter wavelengths, with a given antenna size, the radar beam is concentrated more strongly on the target, G, equation (4), being proportional to $1/\lambda^2$. This factor tips the balance heavily in favor of the radar. The disadvantage to the jammer can only be overcome by providing the jammer itself with a highly-directional antenna. But this drastically limits the usefulness of the jammer. If either the jammer or the radar is moving, the jamming beam must accurately track on the radar at all times.

The following is a comparison of the present and possible power outputs for jamming transmitters.

Wavelength	*Present Power Output*	*Possible with Further Improvement*
50 cm	20 kw	100 kw
10 cm	1 kw	10 kw
3 cm	250 w	1 kw

The jamming operation implied in the preceding discussion conceals targets only near a line through radar and jammer. It is self-screening jamming. When the radar is looking in some other direction, to mask its signals, much more power is required, by a factor of the order of the gain of the radar antenna. This gives an additional and enormous advantage to short-wavelength, high-gain radar.

Spot-frequency jamming requires that the jammer monitor the frequency of the radar transmitter in order to be able to set the jamming transmitter on the right frequency and to follow any changes in radar transmitter frequency. Now the bandwidth of the radar receiver is determined essentially by the pulse length and in most applications is of the same order (a few megacycles) independent of the carrier frequency. But the band over which a given type of radar can operate is usually limited to some fraction of the carrier frequency, which fraction includes more megacycles the higher the frequency. Thus it is usually more difficult to discover the exact frequency of a high-frequency transmitter, and to follow arbitrary changes in frequency.

In barrage jamming, the monitoring problem is avoided by causing the jamming transmitter to emit radiation over a broad frequency band. This is much more expensive in power by just the ratio of barrage bandwidth to radar receiver bandwidth, a ratio which in general is larger the higher the radar frequency, as explained in the previous paragraph.

Electronic spoof jamming, which seeks to create confusing artificial echoes is less effective against short-wave radar because of the higher resolving power of which such equipment is capable. It is hard to inject spoofs which cannot be recognized as such.

Because of its broad band, window jamming has been most successful. Microwaves have not been the answer to it, although it is still true that they are by far the hardest frequencies to jam with window. The actual weight of window material needed to give an echo approximately that of a bomber is not critically dependent on λ, but depends on cutting methods, packing, materials, etc. At present about four ounces of material will give one B-17 echo although at X-band slightly more than this is required. However, to lay a lane of window to cover a flight of bombers requires one such bundle dropped in every radar "pulse packet." This will last only a given time (usually about five minutes), then needs replacing. Thus the amount needed per hour for the lane will be approximately inversely proportional to pulse length and to θ (beam width). Since both of these quantities go down with λ, the microwaves are far more difficult to jam with window. As an example the new 584-X set, designed to withstand window at X-band has a pulse length of 0.1×10^{-6} sec and a beam width of about 2°. It has successfully tracked an aircraft through window laid by a preceding aircraft at the rate of 600,000 dipoles per sec.

It will be possible, however, to devise new materials and reflection methods so that even our best microwave sets will be greatly hampered. Our best technical answer to it appears to be MTI which should virtually remove the threat of window.

ANTIJAMMING DEVICES

It will never be possible to claim that a given radar set is jamproof. However, it may be uneconomical to carry out effective jamming tactics. As we have seen, microwave sets are generally much more difficult to jam for several fundamental reasons. In spite of this it is believed that an active antijamming program is an essential part of future radar development. The most important lines of research appear to be (1) the development of tunable systems, (2) moving target indication (also tunable), and (3) further improvement in discrimination. If this research is coordinated with systems design and development, there is every reason to believe that the jamming of future sets will never be as successful as the early jamming of both our own and the enemy's long-wave radar.

CONCEALMENT AND CAMOUFLAGE

If a target exposed to radar beam is to be hidden from detection, it must be prevented from reflecting radiation, or it must be located in the midst of other objects which return similar signals. The problem of reflection elimination has been discussed previously. It is possible, with existing means to reduce the reflection coefficient of a large, smooth metal surface to a few percent of its normal value. It is much more difficult to do this for an object of complicated shape. The blacking-out of aircraft by this means is not practical with present techniques, since the coating required would be prohibitively heavy. In any case, the external shape of the aircraft would not permit a very great reduction in scattering cross section. For submarines, for small vessels, perhaps also for long-range rockets, antireflection coatings may prove to have some value.

The best concealment for objects on the ground is natural cover, in the form of rough terrain, trees, or other highly reflective objects. This may not suffice to conceal a moving target, if the radar uses MTI. In general, the higher the resolution of the radar the more densely distributed the cover must be.

A countermeasure which can be classed either as deception or camouflage consists of making a fake target or otherwise altering the picture seen by the radar, by man-made reflectors. This was tried by the Germans in some cities with little success. A more economical and effective measure was the use of single reflectors to confuse sea-search radar.

It is occasionally suggested that the radar echo could be eliminated by a device on the target which would receive, amplify, and retransmit with suitable phase and amplitude, the incident wave, so as precisely to cancel the reflected wave. This might be possible in certain very special cases, but an extended target such as an airplane reflects short radar waves in a complicated way. The net amount of reflection depends critically on the direction from which the incident wave arrives. The cancelling device would have to measure this angle instantaneously with a precision which could be achieved only by the use of an antenna as large as the airplane. On many other grounds, as well, such a scheme is utterly impractical in the microwave region.

In general one must conclude that *we cannot foresee any means by which aircraft can be made invisible to radar.*

LISTENING

The detection of radar transmissions is an extremely simple problem technically. If a target is to be detected by radar, there is no way of preventing an observer at the target from detecting the incident.

The radiation arriving at the target is necessarily intense, and the most rudimentary equipment suffices to detect it. Because of this advantage in power, it is not difficult to make the detection device sensitive over a very broad band of frequencies. The assumption that the enemy does not know that he is being looked at with radar will never again be justified. It can almost be said that one temporary advantage of radar over the searchlight, its invisibility, has vanished.

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DEFENSE AGAINST THE ATOMIC BOMB

(Supplement to Radiation Laboratory Contribution to the AAF SAG Report)

By

G. E. VALLEY

FOREWORD

The effect of the atomic bomb on military tactics and weapons will be far-reaching. At the present time, detailed analyses of what all of these effects may be cannot be given. The following notes seek only, therefore, to present some thoughts and speculations on this subject by members of the Radiation Laboratory. They are presented here more as a basis for discussion of the necessary research policies, than as definite suggestions of what those policies should indeed be.

DEFENSE AGAINST THE ATOMIC BOMB

INTRODUCTION

The atomic bomb renders obsolete a number of tactics and weapons newly developed during the war. Among these are even some which were so new as not yet to have been put into operation. Since it would be folly to continue to develop outmoded weapons, this supplementary note is written to indicate what some of these may be.

The atomic bomb is fantastic; its advent means that we must think boldly if our future efforts are indeed to be aimed at future needs. We must not hesitate to scrap our present weapons regardless of their novelty, it they cannot be employed in a war of atomic bombs. It would be better to have no weapons at all, and to know it, than to place our faith in obsolete devices of imposing size and number.

We should not let the fact that such outlawed weapons as poison gas and bacteria were not used during the past few years convince us that the atomic bomb can similarly be outlawed. The ease by which enemy material can be destroyed by this weapon and the simplicity of its associated tactics indicate forcefully that it will be used.

LESSONS FROM THE WAR

It has been demonstrated that bomber fleets of at least 1000 aircraft can be produced and operated at one time. It has also been shown that one atomic bomb can wipe out a city of 300,000 inhabitants. Therefore, in one raid, it is in principle possible according to present conditions to wipe out a city of 300,000,000 inhabitants or its equivalent. If we assume that half the pouplation of this country inhabits the cities, it has an urban population of 70,000,000. Assuming that a fleet of 1000 aircraft were to be individually directed against the different cities inhabited by these 70,000,000, they and their works could be wiped out four times over.

We must assume that this possibility will dominate the offensive plans of any power contemplating war.

From this, one must conclude that massive multiplane raids against individual targets are things of the past. This means that formation flying and everything that it connotes to the aircraft and radar designer must be most carefully considered to determine whether or not it is obsolete. If this tactic is found to be obsolete, then it follows that the tactic of saturating the enemy's antibomber defenses is also obsolete, for all practical purposes.

The situation then becomes tactically very like the Battle of the Buzz Bombs, in that individual bombers (manned or pilotless, airborne or rocket) will seek individually to penetrate a massive defense. This battle is also of interest because it represents a nearly automatic defense (SCR-584 plus the M-9 director, plus the servo-driven 90-

mm guns) against robot-controlled aircraft. It may, therefore, be regarded as setting the pattern for the future.

We are informed in the Radar Press Release that "one Sunday late in August, 105 buzz bombs crossed the British Coast, headed for London. Only three of them arrived." Now this was the best figure attained; London would certainly have been wiped out had the V-1's carried atomic bombs even against such superlative defense measures.

But the fact that a defense which let through as few as 3% of the attacking aircraft would be inadequate if these carried atomic bombs is not the most important lesson to be derived. What is most important to realize is that this defense required at least six weeks to reach its maximum efficiency, and this in spite of the fact that all the defense weapons were at hand, all the operators trained, and the whole country experienced and forewarned in war of this particular means of attack. In spite of all the training and availability of weapons and military experience the first attackers suffered little loss.

This is not an indictment, therefore, of the defensive instruments, since after all 97% of the attackers were eventually shot down; what it means is that the people who manned the defense were incapable of instantaneous reaction. Therefore, the pre-eminent problem of defense with which we are now faced is: "How can the defense be made to react to the first blow with all its potential efficiency?"

Combining the known capabilities of the atomic bomb with the experience of the past war, we can state three requirements for any defense against it:

(1) The defense must be capable of defending all our potential targets simultaneously.

(2) The defense must closely approximate 100% efficiency.

(3) The defense must function with its maximum efficiency against the first raid.

POSSIBLE METHODS OF DEFENSE

There are three general classes of defensive measures which may be considered:

(1) Prevent any potential enemy from setting an atomic bomb attack in motion.

(2) Destroy the bombs before they reach their targets.

(3) Render all our potential targets impregnable to the atomic bomb.

The most general remark about these possibilities is that we should not try them all if this means that no one of them is developed to perfection. Three methods of defense, each 50% effective, when used together do not necessarily yield a defense which is 150% effective.

Class 1.

In order to prevent anyone from setting off an atomic-bomb raid against us we need to police the world, either as a member of an international organization or independently thereof. It means that we must prevent anyone else from manufacturing atomic bombs. Since the manufacture of these bombs is intimately connected with the peaceful utilization of atomic energy, this may mean that we must be prepared to use forceful measures to restrain anyone else from manufacturing atomic fuel. This might mean that the world-wide utilization of atomic energy must be placed under our control, the fuel being prepared here and carefully rationed to the rest of the world, to be used under our surveillance or that of an international organization.

Barring such an arrangement we must be prepared immediately to start reconnoitering all places where atomic fuel can be manufactured, and be prepared to destroy such manufacturing establishments.

Aircraft such as the B-36 should be equipped for reconnaissance with neutron and heat detectors since large amounts of either or both of these types of radiation are known to be emitted by the most important method of manufacturing atomic fuel (the uranium-pile method for manufacturing element 94). Such aircraft must also take aerial photographs. The use of radar photography should not be omitted; since great range is not nearly as important as high resolution and 360° "looking," 1-cm PPI equipment should be used. It is recommended that an effort be made to equip a B-36 with at least a 12-foot antenna suitable for PPI use, and operating in the 1-cm region of wavelength. A special modification of AN/APQ–34 or AN/APS–30 could probably be prepared in six months time.

Since none of the detecting devices mentioned can be regarded as infallible, we must depend upon repeated reconnaissance and constant interpretation and comparison of the results for certainty.

In order to destroy any atomic-fuel factories we discover, the atomic bomb used in conjunction with the present bombsights will be sufficient. It does not seem very worth while to improve the accuracy of bombsights over that now attainable; on the other hand, considerable bombsight research will be needed to make instruments at all suitable for supersonic aircraft. However, in comparison with other technical problems posed by the atomic bomb, it might be unwise to continue an elaborate bombsight development program. The development of guided bombs probably falls in the same category.

The above police measures are useful right now; they will only remain useful if we retain control of the situation. If we lose control of the international atomic-energy situation, then fairly fantastic measures must be adopted.

Suppose we are denied reconnaissance by aircraft. We may then try the German suggestion of an observation post established in a free orbit beyond the atmosphere. Corresponding to this, the development of V-2 missiles with ranges of several thousands of miles is also important. Probably the easiest way to start such developments is to try to send a remote-controlled rocket to the moon, since the direct line-of-sight control problem is simplest.

If one discards the suicide-pilot method of control, two methods of control suitable for distances reaching far beyond the horizon are available: (1) automatic celestial navigation such as was worked on by the Eastman Kodak Co., and (2) radio control. It will be difficult to get the required accuracy with either of these methods and in addition the second may be easily jammed.

The missiles may in addition be fitted with homing devices sensitive to light, heat, electrical and nuclear radiation. Their use would relax the accuracy requirements placed upon the control system considerably; unfortunately, the high speeds likely to be attained by such rockets may require the homing devices to have impossibly long ranges of action in order to be effectual. The ideal solution would thus seem to be to control the rocket for somewhat more than half its journey by microwave radio (governed by an elaborate ground-based computer) and to have a homing device in the rocket guide it the rest of the way. The development of the ground-based control radio is relatively straightforward; the development of suitable homing devices cannot be regarded so optimistically.

Class 2.

If we elect to defend ourselves by destroying all the missiles launched against us, the defensive measures must be as nearly automatic as can be conceived. They must locate, recognize, load and fire their missiles automatically. Regardless of the size and excellence of training of our forces, there are enough equivalents of the Pearl Harbor attack in history to teach us that the human part of the defense force is not likely to be ready. Since only one attack will be necessary we cannot take the chance that the lessons of the past plus future good intentions will preserve us.

The defense will almost certainly employ radar-guided missiles. Probably these will be launched from the air, since the attackers, if airborne, will likely fly low; if the attack is by long-range rocket; then either air- or ground-launched counter rockets may be employed.

Since it will be desirable to destroy the attackers some distance away from the target, a combination of guided and homing missile will be likely to be employed. It would be sensible to coordinate the Army and Navy antiaircraft guided-missiles programs, in order to use the available effort more efficiently. Only one problem should be attacked; there is now sufficient technical knowledge to choose the correct method of attack. In order to get warning of attack, radar of much longer range than is now available should be designed. A free-space range of several thousands of miles is attainable and would be useful. Possibly long-wavelength nondirective sets such as the British CH Stations which were so useful in tracking V-2 will be needed. In any event, a chain of such stations should be set up on the far sides of both oceans.

The possibility of the previously mentioned space-ship observation post should not be neglected.

Class 3.

In order to render all our installations impregnable to atomic-bomb attack, they must either be placed underground or be dispersed in units so small as to make prohibitive the price of knocking out any sizeable number of them.

The technological problems associated with a thing like an underground steel mill are probably as difficult to solve as those associated with building a space ship or any of the other defensive measures.

The economic and social consequences of such a program would certainly reduce our standard of living and thus weaken us militarily in an indirect way. This is particularly true since one cannot single out any particular industry for such treatment: all are interconnected. However, the continuing popular use of automobiles and air transport will cause, according to many, a certain amount of natural decentralization of the economy. This process can be aided by a wise tax program, and should be viewed with satisfaction as long as adequate transportation is available.

CONCLUSION

The foregoing indicates that technologically, economically, and sociologically the simplest defense against atomic bombing is a world-wide police system whose purpose would be to prevent the manufacture of atomic bombs.

PART III

AIRCRAFT RADIO COMMUNICATION EQUIPMENT

By

G. A. MORTON

PART III

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4 DECEMBER 1945

SUMMARY

A reliable and adequate radio-communication system is essential to integrated aerial tactics. Basically a long-range liaison and short-range command system is necessary. Other special systems may be employed to supplement these. ①

At the outset of World War II, the Army and Navy liaison systems were BC348, BC191, RU, RAX, GO and the command units SCR274N, ATA, ATR. Because of obvious deficiencies a new series including liaison systems ART13, XANRB3, ARR15, ARB, BC348 and command systems SCR522, ARC1 were put into production and widely used.

Currently new transmitters and receivers are being developed which include such features as receiver-controlled transmitter frequency, Autotune and automatic tuning mechanisms. For the immediate future at least, the development of liaison systems will continue to make use of present frequency bands because of propagation considerations. New developments will take place in antenna design, in band-switching methods and in numerous individual components. Teletype, recording and voice-coding systems may also be worked out for this service.

Command systems will probably move to higher frequency bands (200 to 500 mc) to obtain more channels, smaller components, a wider choice of modulation methods, etc. Much work remains to be done on suitable switching mechanisms for multichannel communication, on oscillator stability, component development and practical antenna design.

Progress is being made and should be encouraged in the future toward adapting the very high frequency portions of the radio spectrum for communication systems. This should make possible highly directional channels, limited range systems and also systems which are difficult to intercept or jam.

Radio relays will be of considerable importance, both for the transmission of radar and television pictures and for multichannel speech systems. Much work remains to be done in this field and it should have a prominent place in an aviation radio research program.

INTRODUCTION

Aircraft radio communication is an essential and critical part of integrated aerial warfare. The transition from individual combat methods to integrated group tactics, although predicted at the close of World War I, did not occur in fact until fairly recently. It has placed demands upon existing radio-communication equipment which the latter is scarcely able to meet. Frequently, it has been necessary to use rather crude improvisation which has been far from satisfactory. As the development of integrated and coordinated aerial warfare progresses, even greater demands will be placed upon the radio-communication system. Therefore, particular attention must be paid to laying out a program for the development of adequate aircraft radio equipment as part of the major program of developing an air force sufficient to meet the requirements of security.

In laying out such a program full cognizance should be taken of the "systems engineering" as part of the problem as well as the equipment design, and production. The essential requirement is not for the communication between two planes, or a plane and a ground station but for the intercommunication within a group of planes which may number hundreds or even thousands. The integration of the system as a whole is fully as important as the design of the individual units.

It is extremely important that care be taken not to impose excessive technical demands upon the designer, in the type of equipment demanded. The gap is very great between the performance that can be expected from equipment in the laboratory in the hands of engineers or skilled technicians and equipment which is simplified to the point where it can be reliably operated by unskilled personnel, and rugged enough so it will stand the type of handling it must meet in actual service. Because of this gap, it may be necessary to divide the communication equipment into two classes, the first representing an essential minimum of absolutely reliable devices, the second, those which are desirable and useful but whose failure does not jeopardize the performance of the combat group as a whole.

For the next decade or perhaps longer, the first group of equipment will probably be represented by apparatus which is fairly similar to the type now in use both in military and commercial aviation. Aircraft experience to date indicates that it is almost essential to use a dual radio communication system comprising a liaison system and a command system. The liaison system operates at relatively long wavelengths and is capable of ranges from a few hundred to several thousand miles. The command system operates at a much higher frequency in order to permit a great many communication channels, and is limited to ranges up to one or two hundred miles, in other words, line-of-sight communications. These two systems constitute an irreducible minimum for coordinated air activity. With them, it is possible for one or more flights of airplanes to take off from several bases, fly to an assembly point and thence to the target and return, while at all times maintaining sufficient communication so that the required instructions and information can be reliably communicated.

The second classification will consist of equipment employing some of the newer radio techniques. For example, microwave transmission to give high directionality, special modulation systems to reduce probability of jamming and static interference, and special coding systems to reduce bandwidth and to prevent interception. In addition, it would be highly desirable to have an extremely short-range microwave communication system which could be used between planes in a formation instead of the high-frequency command system. By using a high enough frequency for this short-range communication system, it would be possible to restrict its communication distance to a predetermined range, and thus allow communication between planes while in effect maintaining radio silence as far as enemy ground defenses are concerned. Furthermore, indicator or recording systems are also extremely useful in controlling operations. Such systems may take the form of teletype recorders, reproducing written messages, facsimile recorders for the transmission of maps and diagrams as well as written material, or, to go to the other extreme, simply indicating equipment for the transmission of a half-dozen or more simple symbols designating prearranged maneuvers and instructions.

To make possible all-weather flying, the major air bases should maintain the equivalent of a "Teleran" system. This system locates all planes in the neighborhood of the base by radar and transmits the information back to the approaching planes in visual presentation; thus each plane receives a television image of a map giving not only its own location, meteorologic and other pertinent information, but also the location of all other planes flying at the same level. Furthermore, the system provides for the blind landing and take off of planes.

CURRENT COMMUNICATION PRACTICE

Before discussing future trends of aircraft-radio development, it would be well to review the development of radio-communication technique during the last four or five years, that is, since the onset of World War II. At the start of the war, the military aircraft radio equipment was far behind that used by the commercial aircraft companies. In fact, most of the equipment followed design practice that was at least ten years old.

The command set used by the Army at the beginning of the war was the SCR-274N system and the corresponding Navy equipment was the Navy ATA transmitter and ARA receiver. These sets operated in the neighborhood of two megacycles and were designed for communication between squadrons, and to control towers. They were pilot-operated and were carried in fighters, small bombers, etc. The first receivers of this series were tuned radio-frequency receivers. Later on, superheterodyne receivers were used. The transmitter followed more-or-less conventional design but employed master oscillator which was not crystal-controlled. The weight of the combination was approximately 100 lb. A basic production of 100,000 units of this type equipment was set up.

The liaison equipment of this period consisted, in the case of the Army, of a general purpose receiver (BC-348) physically resembling the Hallicrafter, which was carried in airplanes of the two-engine bomber class and larger. This receiver was a superheterodyne with two continuously tunable bands, one extending from 200 to 500 kc and the other from 1500 to 18,000 kc. The weight of this receiver was about 30 lb. The transmitter in this series for heavy bombers of the four-engine class and up consisted of 125-w CW and MCW units tunable over two ranges, namely, 300 to 600 kc and 3000 to 26,500 kc. An intermediate transmitter, BC-191 and BC-275, was used for twin-engine medium bombers. This was a CW and phone transmitter with plug-in units to change frequency in bands between 1500 and 12,500 kc. At the same time the Navy was using the RU (tuned radio frequency) and RAX (superheterodyne) receivers. These sets were narrow and deep in shape and each set had a rather limited band range so in order to obtain large coverage several units were used. In other words, instead of band switching which is now common practice, different receivers were employed. The Navy transmitter GO was similar to the Army long-range transmitter described above.

As the war progressed, it became increasingly evident that this radio equipment was entirely inadequate. In the first place, it was both Army and Navy practice to transmit and receive on the same wavelength. However, the stability of the sets described above was such that it was extremely difficult to maintain communication on this basis. Furthermore, if two planes from different bases were required to meet and to continue together in a combined operation, it was virtually impossible to arrange to adjust their receivers and transmitters beforehand so that they could establish immediate communication when they arrived at the assembly point. Therefore, much time was wasted in adjusting instruments after the rendezvous. Finally, because of the poor stability of the transmitter, the bandwidth that was necessary to carry on communication was so large that the number of channels available was entirely inadequate.

Because of the obvious inadequacy of these systems, new types of both command and liaison systems were put into production and are now in use. The command systems of the new Army series operate in the VHF region of the radio spectrum (i.e., 100 to 156 megacycles), and both transmitter and receiver are crystal controlled. These units have four operating bands which are selected by push-button controls. The receiver bandwidth is 50 to 60 kc in order to take care of the instability of the transmitter and receiver crystal oscillators. This system was designated as the SCR-522 system.

The Navy lagged behind the Army by two years in moving into the VHF region for its command equipment and then adopted the ARC1 system. This is similar to the Army unit in that both the transmitter and the receiver were crystal controlled, but has eight bands instead of four. The weight of the Navy unit is 50 lb and it was a nominal 10-w output.

The difficulty with these systems is that they have required enormous pools of accurately calibrated crystals distributed all over the world. There are now over a million special crystals in these pools and this is still not an adequate supply.

For liaison communication, the Army and Navy adopted the ART-13 transmitter. This is a 100-w crystal-controlled unit, weighing about 110 lb. It has 11 spot frequencies, one band being in the region of 200 to 600 kc, the other ten in the 2 to 18 megacycle band. Experience has shown that the 200 to 600 kc band which was designed for communication with naval vessels, etc., is rarely used and will probably be abandoned. In addition to its increased stability as a result of being crystal controlled, this transmitter marks a great advance over those previously used in that it employs the Autotune or automatic tuning mechanism for changing bands. This consists of a series of preset notched cams mounted on a shaft which is motor driven. The cams make it possible to stop the shaft rotation at the position of exact tuning from a remote point.

A number of attempts were made to design special receivers for this transmitter but so far they have not been wholly successful. The XANRB3 was designed for this purpose but was rejected for lack of frequency stability. Recently the ARR-15 has been developed to take its place but as yet the acceptance tests are not complete.

In the meantime, the Army has been using the BC-348 receiver which was described above. The Navy is using the ARB general purpose receiver which is very similar to the BC-348. These receivers, when their application makes remote tuning necessary, must employ the expedient of a flexible shaft from the operating point to the appropriate dial on the receiver. Block diagrams showing the tube components in the transmitter ART-13 and BC-348 are given in Fig. 1.

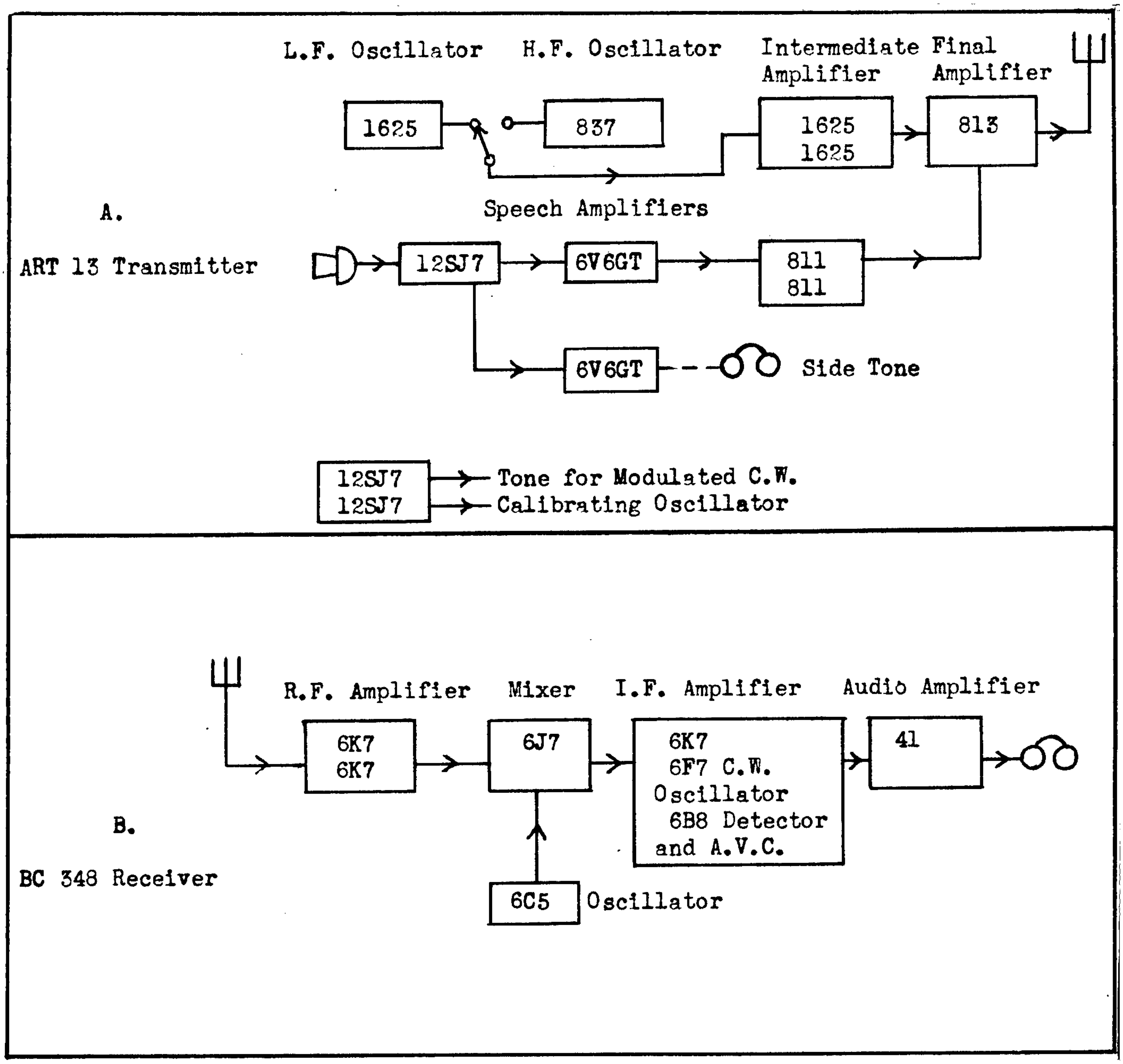

Figure 1 — Block Diagrams of Equipment

RECENT DEVELOPMENTS

A dual liaison receiver has been designed and has been accepted for production by the Navy which eliminates a good many of the difficulties enumerated, in particular, that of making contact between two parties from different bases. A block diagram of this transmitter-receiver system is shown in Fig. 2. The receiver is a superheterodyne with a main oscillator which is variably tuned over a narrow range of frequency, for example, one octave. However, the oscillator is arranged so that its output has a large harmonic content. Therefore, the second harmonic can be used to cover the octave beyond the fundamental frequency band and the fourth harmonic, the octave beyond that. This method is employed to give continuous tuning over a range from 1500 to 12,000 kc. An oscillator which has as narrow a tuning band as this can be made to have a reasonably high degree of stability even though not crystal controlled. Since the set is push button actuated with spot bands of predetermined frequencies, it is necessary to have a fine tuning adjustment. This is done by adjusting the intermediate frequency against a calibrating standard. A second oscillator (D) is arranged to tune with the IF adjustment so that the frequency that it generates is always identical with the output of the IF frequency. This is hetrodyned with the output of the local oscillator (B) and after going through the detector (E) generates a frequency identical with the frequency to which the receiver is tuned. This frequency is used to control the transmitter, consequently the receiver and transmitter always operate on exactly the same frequency. If the operator tunes his receiver until he hears a transmitter, he will know that his transmitter is tuned exactly to transmit his receiver frequency. Furthermore, assuming that the operator communicating with him is using the same type of system, he can be sure that the latter's receiver is also on this frequency. This greatly simplifies the problem of making contact.

Another type of receiver-transmitter which is in the design stage and may be in production in the immediate future is shown in Fig. 3. This system is similar to the one described above in that the transmitter frequency is controlled by the system's receiver so that the transmitter always operates on exactly the same frequency that is being used for reception. It differs from the previous unit in that the main oscillator is crystal controlled and, therefore, has higher stability. Furthermore, the IF amplifier and second oscillator is tunable rather than merely being adjustable. This means that the frequency is continuously controllable over a certain bandwidth. In order to facilitate remote control, this outfit uses Autotune or automatic tuning mechanisms throughout.

So far, radio equipment has been discussed in terms of the requirements for fighters and bombers. The communication equipment needed for transports is very similar to that required for large bombers and, in general, the same types of liaison and command radio equipment are employed. Artillery liaison flying, which is generally done in small planes operating close to the ground, places somewhat different

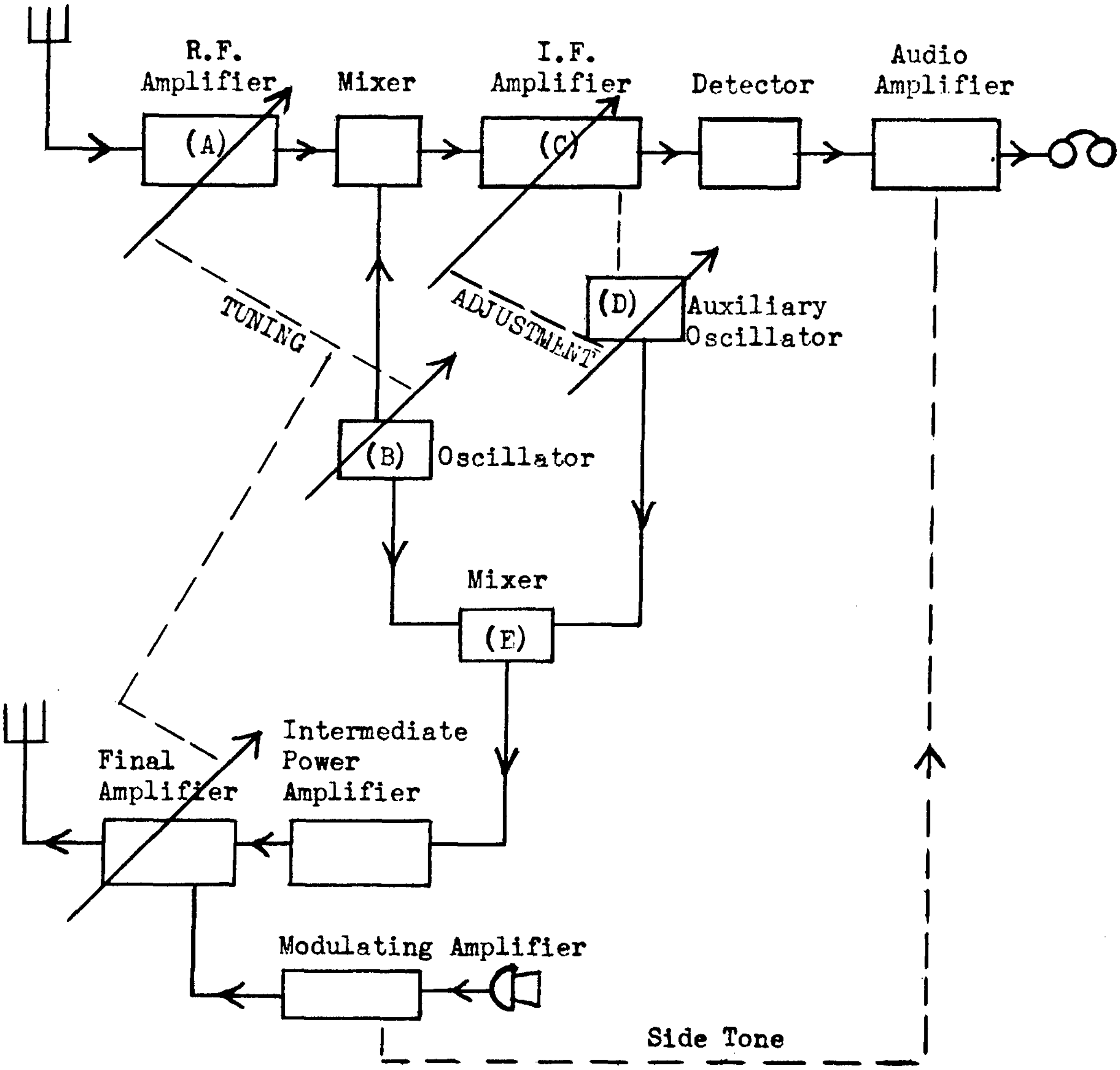
R.F. Amplifier
(A)
Mixer
I.F. Amplifier
(C)
Detector
Audio Amplifier
TUNING
ADJUSTMENT
(D)
Auxiliary Oscillator
(B)
Oscillator
Mixer
(E)
Final Amplifier
Intermediate Power Amplifier
Modulating Amplifier
Side Tone

Figure 2

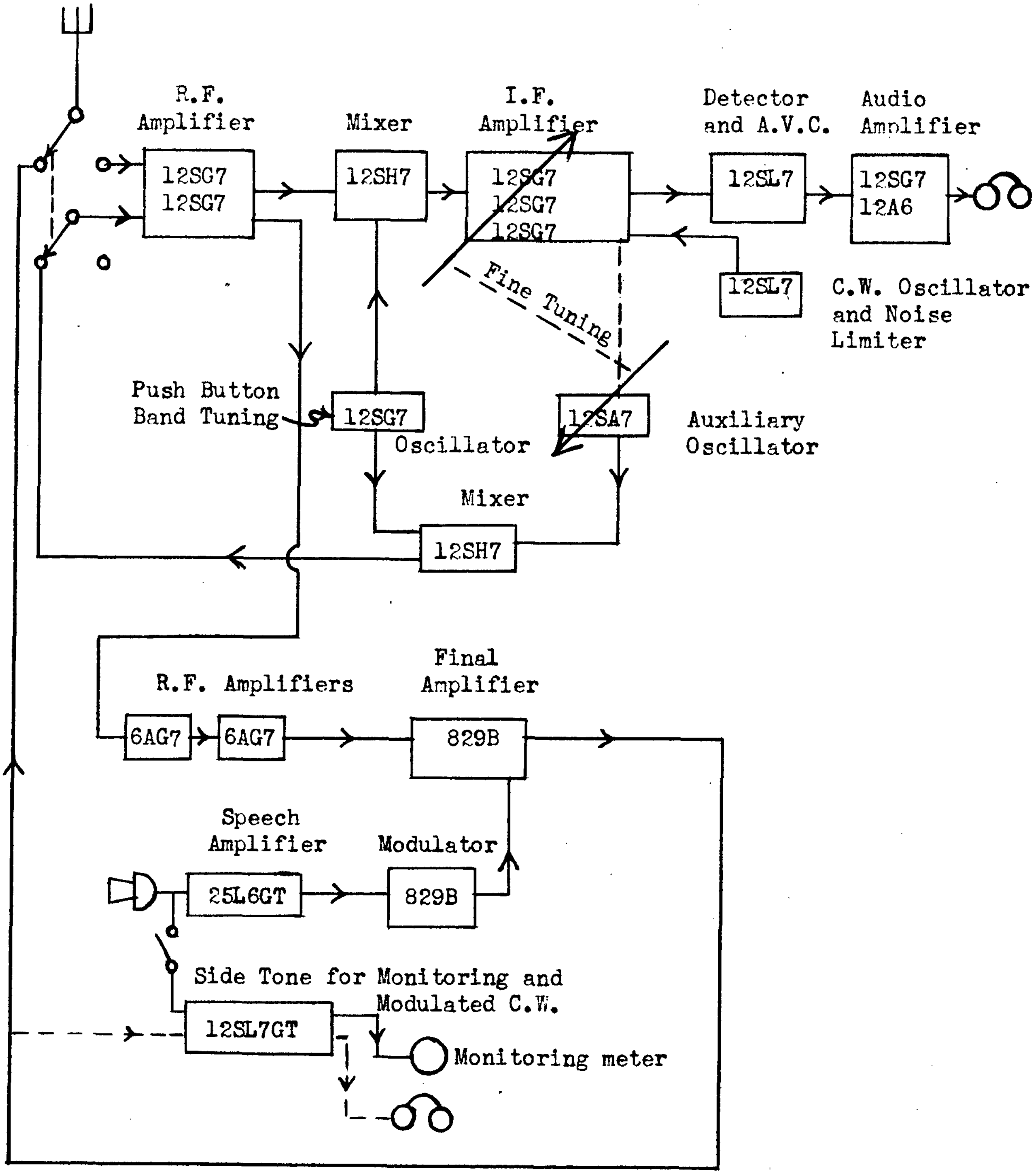
R.F. Amplifier
12SG7
12SG7
Mixer
12SH7
I.F. Amplifier
12SG7
12SG7
12SG7
Detector and A.V.C.
12SL7
Audio Amplifier
12SG7
12A6
12SL7
C.W. Oscillator and Noise Limiter
Fine Tuning
Push Button Band Tuning
12SG7
Oscillator
12SA7
Auxiliary Oscillator
Mixer
12SH7
R.F. Amplifiers
6AG7
6AG7
Final Amplifier
829B
Speech Amplifier
25L6GT
Modulator
829B
Side Tone for Monitoring and Modulated C.W.
12SL7GT
Monitoring meter

Figure 3

requirements on its radio equipment. In spite of the relatively small distances over which communication must be maintained, it cannot employ the very high frequency which characterizes command communication sets. This is because the airplane must stay close to the ground so that line of sight is quite limited. Almost all sets used for this purpose are medium high frequency, operating in the two to six megacycle band. In general, these sets consist of a one channel crystal-controlled transmitter and a tunable receiver.

The communication equipment described above represents the principle types of units used by the Army and Navy Air Forces. Many other receivers and transmitters have been used on a small scale, particularly for test purposes and to meet special problems. However, the types enumerated above constitute the great bulk of the equipment used.

FUTURE TRENDS

With this background of existing communication equipment as a guide, it should be possible to formulate a reasonable program for the future development of a system adequate to meet the increasing demands placed upon it. Such a system will include liaison and command instruments as well as certain special transmitters which will be discussed later.

LIAISON COMMUNICATION

Perhaps the most difficult problem of aircraft communication is that of the liaison system. The primary requirement of the liaison system is reliable communication over large distances. Ordinarily to obtain great distances in radio communication, the longer wavelengths of the radio spectrum are used. The relationship between range and wavelength and the reason for the selection of long wavelengths for this purpose is illustrated in Fig. 4. Thus transoceanic radio communication is frequently carried on at 100 or 200 kc. However, in order to obtain moderately efficient coupling between the medium of radio propagation and the transmitter, it is necessary to have a transmitting antenna which is the order of 3/8 to 1/4 of a wavelength. At 200 kc, this means that the antenna must be more than 1000 ft long. Obviously, such antennas are not practical for aircraft. From the standpoint of antenna lengths, the minimum frequencies that can efficiently be used with aircraft equipment is in the neighborhood of one or two megacycles. When frequencies as high as this are employed, transmission at a distance can be obtained only by relying on the reflection of the radio waves from the various ionized layers of the upper atmosphere as illustrated in Fig. 5. Since for any one frequency these reflections are quite variable, it is not possible to depend on a single frequency where absolutely reliability of communications is essential. It has been found that if the receiver and transmitter are capable of selecting one out of eight or ten different frequencies in the band between two and

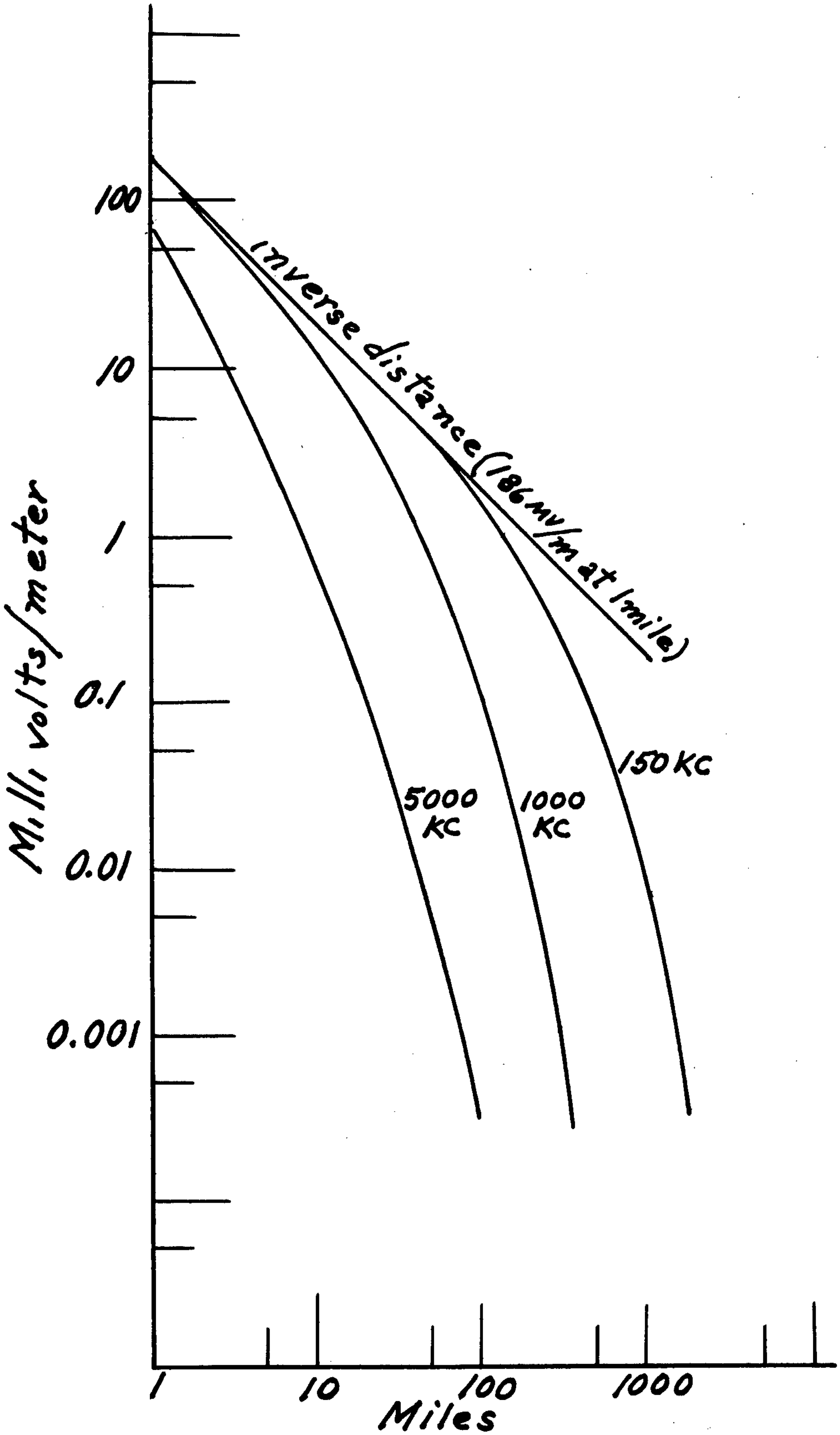

Figure 4 — Dependence of Ground Wave on Distance & Frequency (good ground)

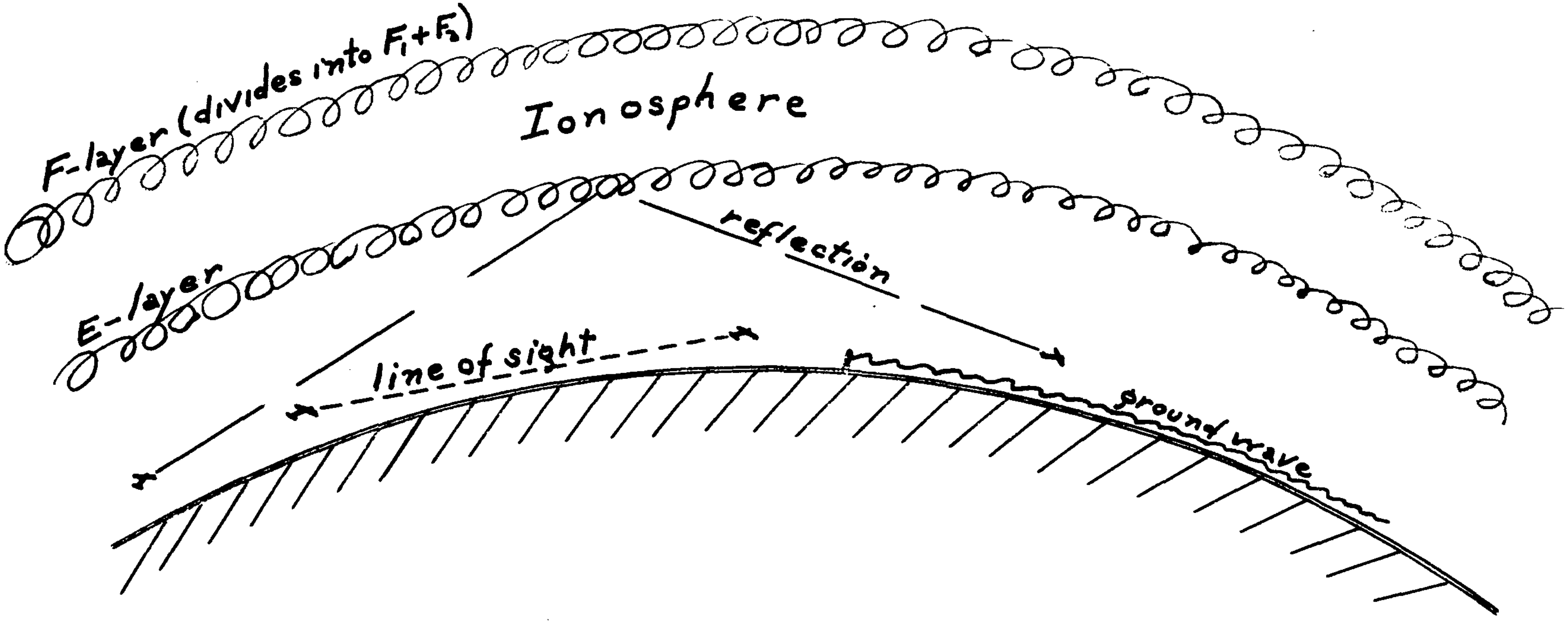

Figure 5 — Radio Transmission

thirty megacycles, reliable communication in general is obtained. Even when this is done, communication may occasionally be interrupted during periods of violent magnetic storms and sunspot activity. At present, no means is apparent for overcoming this difficulty in long-range transmission and the liaison equipment of the future will probably operate in the same region of the radio spectrum as at present. However, improvements will be made in the method of shifting from one band to the next in order to find a channel over which satisfactory communication can be established. It is possible that automatic tuning systems can be devised for making this selection so that the operator does not have to pick out the channel himself.

Even in the two to thirty megacycle bands, the antenna presents a formidable aerodynamic problem. In order to obtain efficiency it should be about 100 ft long. According to present practice, it consists of a wire stretched between the nose of the plane and the tail fin. However, as airplane speeds increase, such a wire and its supports cannot be tolerated, and other types of antenna construction must be found. Some interesting experiments have been carried on, using the wings of an airplane as the antenna. Figure 6 illustrates the way these tests were conducted. The wing of the airplane from the engine nacelle to the tip was made of plastic. The radiator was an internal conductor stretched from the engine to the wing tip. The wing tip itself was metalized to form a capacity cap. The conductor was fed from a matching tuner located close to the engine. This tuner was in turn supplied by coaxial cable from the transmitter. As different frequency bands are selected it is necessary, of course, to reset the tuner. This was done by means of Autotune mechanisms from a remote control point in the cabin. In the test described, only one wing was used as the antenna because of phasing difficulties when both wings were tried. However, this phasing difficulty can be overcome by further developmental work, thus making it possible to employ the full length of both wings for the radiator. This should constitute a very efficient radiator and present no serious aerodynamic obstacles. In this connection, it is interesting to note that some very promising experimental work on bonded glass as a structural material for airplanes has been carried out at Wright Field. Bonded-glass wing structures would be admirably suitable to carry the liaison antenna wire.

Because the nature of the propagation characteristics makes it necessary to use one of a number of rather narrow bands at different frequencies, the problem of maintaining several communication channels is difficult. Since intelligible speech requires a bandwidth of about 2000 c, if double side-band transmission is employed only four or five channels at the most can be maintained. By going to single side-band transmission, it may be possible to double this number. If more than this number of channels become necessary, recourse will have to be made to teletype communications or a speech-coding system, along the lines investigated by the Bell Telephone Company in their work with the Vocoder. At present, little would be gained by going to these systems because practical oscillator stabilities are not better than about 0.02% which means that stability alone will require some six kilocycles band width at the high-frequency end of this communication band. However, oscillator stabilities are almost certain to improve as the radio art continues to develop.

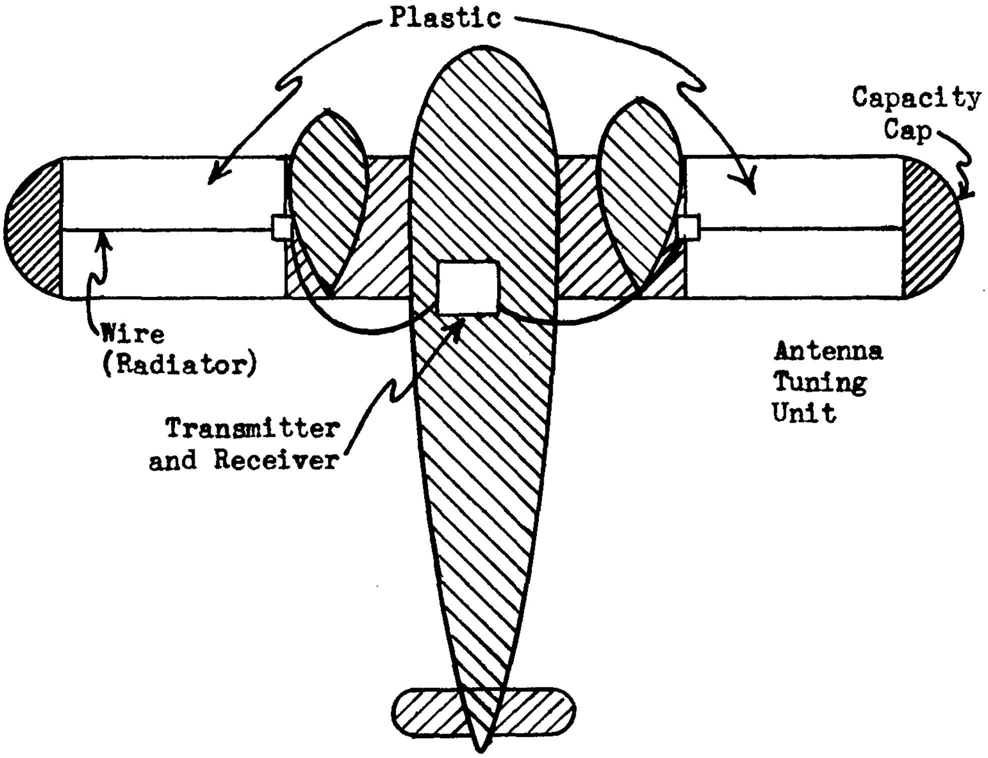

Figure 6 — Antenna System with Plastic Wing Sections

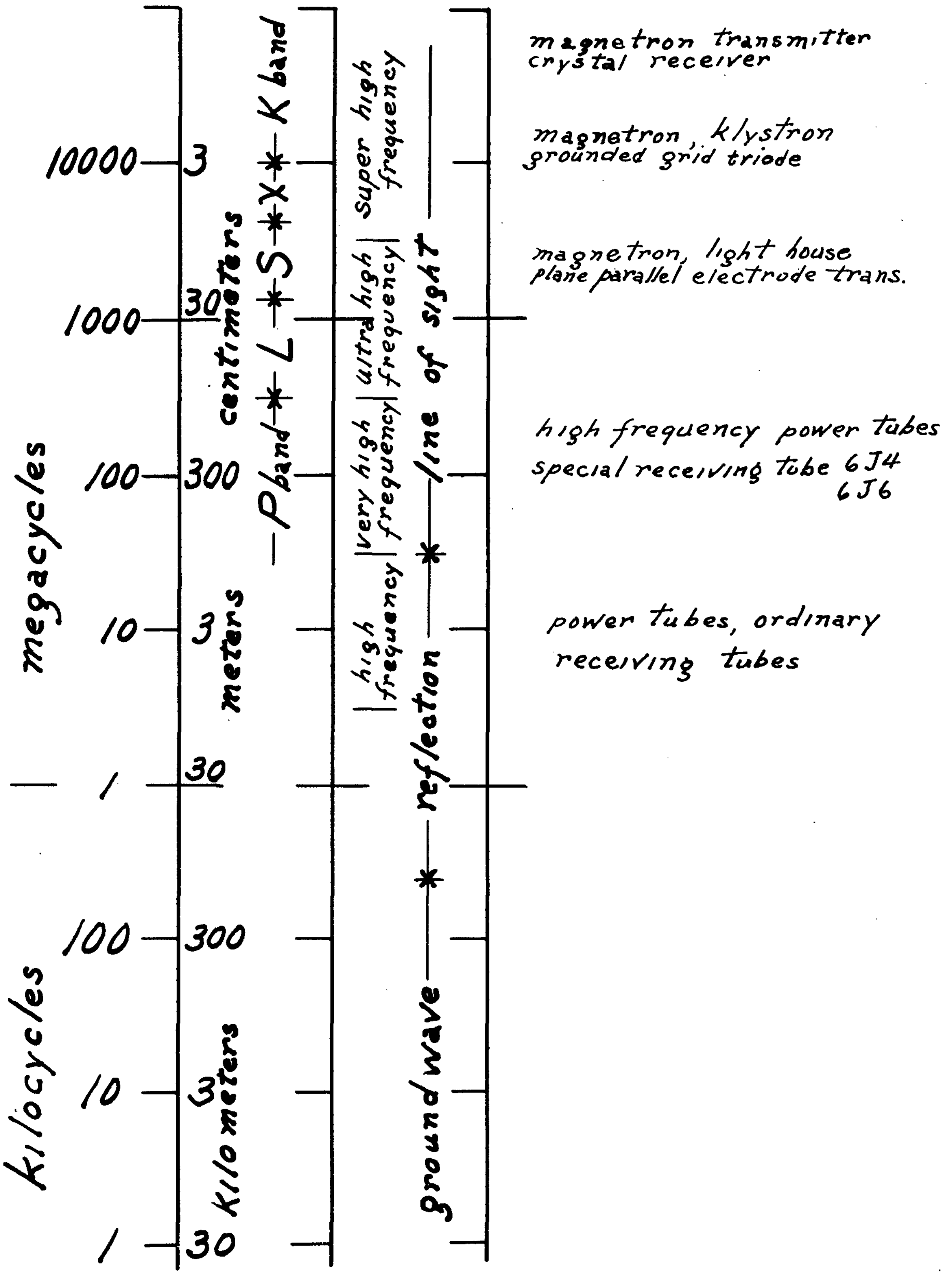

Figure 7 — Radio Spectrum

The radio transmitter and receiver itself will not differ basically from those used at present. Improvements will be made in tubes and circuits which will allow more efficient power utilization and in particular, as has already been pointed out, tuning mechanism will be made simpler to operate and more reliable. Other improvements in the liaison communication equipment may be made possible by virtue of new discoveries. However, these cannot be included in plans formulated at this time.

COMMAND SYSTEMS

Command communication equipment at present operates in the 100-156 megacycle band. However, undoubtedly the frequency for this application will be raised in the immediate future. By moving into the region of 200 to 500 megacycles, more channels become available, antenna design becomes somewhat easier, and there will be less interference with bands already allocated for commercial postwar aviation. Tube and circuit methods for this region of the spectrum are quite well developed so that it is possible to design and produce absolutely reliable receivers and transmitters. Furthermore the essential parts of the unit can be made very small and lightweight.

The antenna for these frequencies is small enough so that it can be contained within the aerodynamic members of the airplane and consequently, offers no additional drag. Antenna design presents some difficulty where uniformity of response in all directions is a requisite. However, the problems are straight forward and can be solved by adequate engineering studies.

Much higher frequencies may eventually be used for command communication. This includes the ultrahigh-frequency band 300 to 3000 megacycles and the superhigh-frequency region above 3000 megacycles. However, at present, techniques in this portion of the radio spectrum are in their infancy. It will be some time before accumulated engineering experience compares with that which exists for the lower frequencies. Nevertheless the feasibility of communications in the centimeter (1000 megacycles) and microwave (10,000) regions has been indisputably demonstrated and any long term planning should not neglect these possibilities.

There are a number of advantages to be gained by going to the higher frequencies. Since transmission of speech intelligence requires a fixed channel width the number of channels in a region representing a certain percentage of the frequency used increases with the frequency. For example at 1 megacycle a 10% region would contain 10 channels 10 kc wide, while a 10% region at 1000 megacycles would contain 1000 such channels and at 30,000 megacycles the region could contain 30,000 channels. Thus a great many more channels become available for a multiphone system.

Wider channels can also be employed in greater frequency spread available in the centimeter and microwave regions. This permits the choice of special forms of modulation which might render the system less susceptible to jamming and interception. Some work has been done in the study of such special forms of modulation including pulse, phase and frequency modulation, but much remains to be done in the future to determine their possible advantage for command communication. A program for radio development should include more extensive tests on these various types of modulation, particularly with regard to their susceptibility to jamming and interference and ease of enemy interception. Except for their less economical use of communication bandwidths and certain other minor objections, in general such modulation systems may prove to have important advantages.

Greater directivity can be obtained as the radio carrier frequency is increased. This may be important in connection with certain types of operations. In general, however, this is an undesirable feature since most frequently an omnidirectional system is desired. Antennas giving a uniform pattern in all directions are more difficult to attain at very high frequencies and the power utilization is less efficient.

Under wartime pressure, research in the ultrahigh-frequency regions has led to major advances in technique. The introduction of the lighthouse tube and other plane parallel-electrode ring-seal tubes represent an important step. Great improvement has been made in wave guide and coaxial systems. When certain problems of frequency stability have been overcome and the engineering design problems worked out ultrahigh-frequency radio systems will become very important. It is quite possible that equipment working in the 1000 to5000 megacycle region will come into extensive use supplementing the command systems discussed above working at the lower frequencies, or possibly it may replace them entirely. Microwave systems may have important application for military aviation communication. They are characterized by certain unique advantages as well as disadvantages. Most prominent among the advantages is the extreme directionality that can be achieved; also in this region of the spectrum there is practically no natural static.

While microwave techniques are still very new, nevertheless enough work has already been done to lay the ground work for future systems. A good deal of valuable experience has been gained with S-, X- and K-band radars which can be applied to communication systems. Tests also have been made on phone transmitters and receivers operating in this portion of the radio spectrum.

As illustrative of microwave communication possibilities a system proposed and described in reports from the Radiation Laboratory at M.I.T. will be discussed.*

The system is to provide transmitter-receiver combinations on a large number of airplanes in such a way that communication can be effected between any pair independent of all the others. Thus it would provide what amounts to a telephone exchange between planes; calling another plane would simply be a matter of dialing the appropriate number. By the response of his own receiver, the individual calling can tell immediately whether the party called is within range and is receiving his signal.

Like the systems illustrated in Figs. 2 and 3 there would be a single oscillator which would serve as master oscillator for both the transmitter and receiver. However, unlike these systems transmission and reception would not be on the same frequency but on frequencies differing by the intermediate frequency.

In order to make such a system feasible it is necessary to use very stable oscillators. Ordinarily neither klystrons nor magnetrons operating at these frequencies provide anything like the required stability. However, the units in question can be stabilized against an accurately made, temperature-compensated resonant cavity by means of a feed-back loop. The cavity serves as the master frequency-determining

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*Radiation Laboratory Reports #815 and #830 by R. V. Pound.

element of the transmitter-receiver unit. Normally this cavity will be set at the frequency assigned to the particular station. In making a call the operator adjusts the frequency of the cavity until it has the required value for the station he is calling. The adjustment will probably be made by means of some dial system similar to those currently in use for ordinary telephones. Proper contact will be indicated by a light or meter on his receiver. At the same time the receiver at the station being called will flash an indication.

A schematic diagram of a transmitter-receiver combination for such a system is shown in Fig. 8. In the absence of incoming signal, energy from oscillator B is divided by "magic tee", C, into two equal portions, one of which is radiated from the antenna A and the other is fed to the stabilizing cavity D. The cavity D and two crystals E and E′ act as a discriminator and generate a voltage when the oscillator differs from the resonant frequency of the cavity. This voltage is amplified and supplied to the frequency-control element of the oscillator. When the frequency is too high this voltage is in the direction to decrease the frequency, and conversely, the voltage tends to increase the frequency if it is too low. The degree of stabilization that can be achieved depends upon the stability of the cavity and the properties of the feed-back loop. Preliminary experimental oscillators have been stabilized to 10 kc and better in this way.

The oscillator output can be frequency modulated simply by introducing the modulation voltage into the feed-back loop as shown in the figure.

When used as a receiver the incoming signal enters the same antenna used for transmission. The signal is divided at the "magic tee" and the useful portion goes through a wave guide to the balanced discriminator F, F′ where it beats with the signal from the local master oscillator B. Since the incoming signal has a carrier frequency which differs from that of the oscillator B by the IF the output from F, F′ leads to a frequency-modulated signal on a carrier of the correct intermediate frequency. In general the intermediate frequency cannot be low enough so that it represents the spacing between channels. Practical considerations suggest that the IF might be in the neighborhood of 30 megacycles. With an elaborate system of switching and image rejection one half the total number of channels available could be used for communication. A more practical and straight forward arrangement would permit one-third of the total number of channels to be used. This arrangement is shown in Fig. 9.

Group A in the figure is the distribution of transmitter (master oscillator) frequencies, the receiving frequencies and the image frequencies. A calling station adjusts its master oscillator to the receiving frequency of the station being called. This is seen in Group B. The calling station will receive the station called on his image frequency. Since his normal receiving frequency will be over a group of image-response channels no interference will result.

Even with this reduction to one-third of the total number of channels available there are still a large number which can be used. Assume the band to be used to be that at 10,000 megacycles and that the tuning range be 10% or 1000 megacycles. Then if 100 kc is allowed for each channel the total number is 10,000 and the useful number over 3000. This figure is conservative and it is certain that practical stabilities of better than the 100 kc can be achieved, thus increasing the number of useful channels.

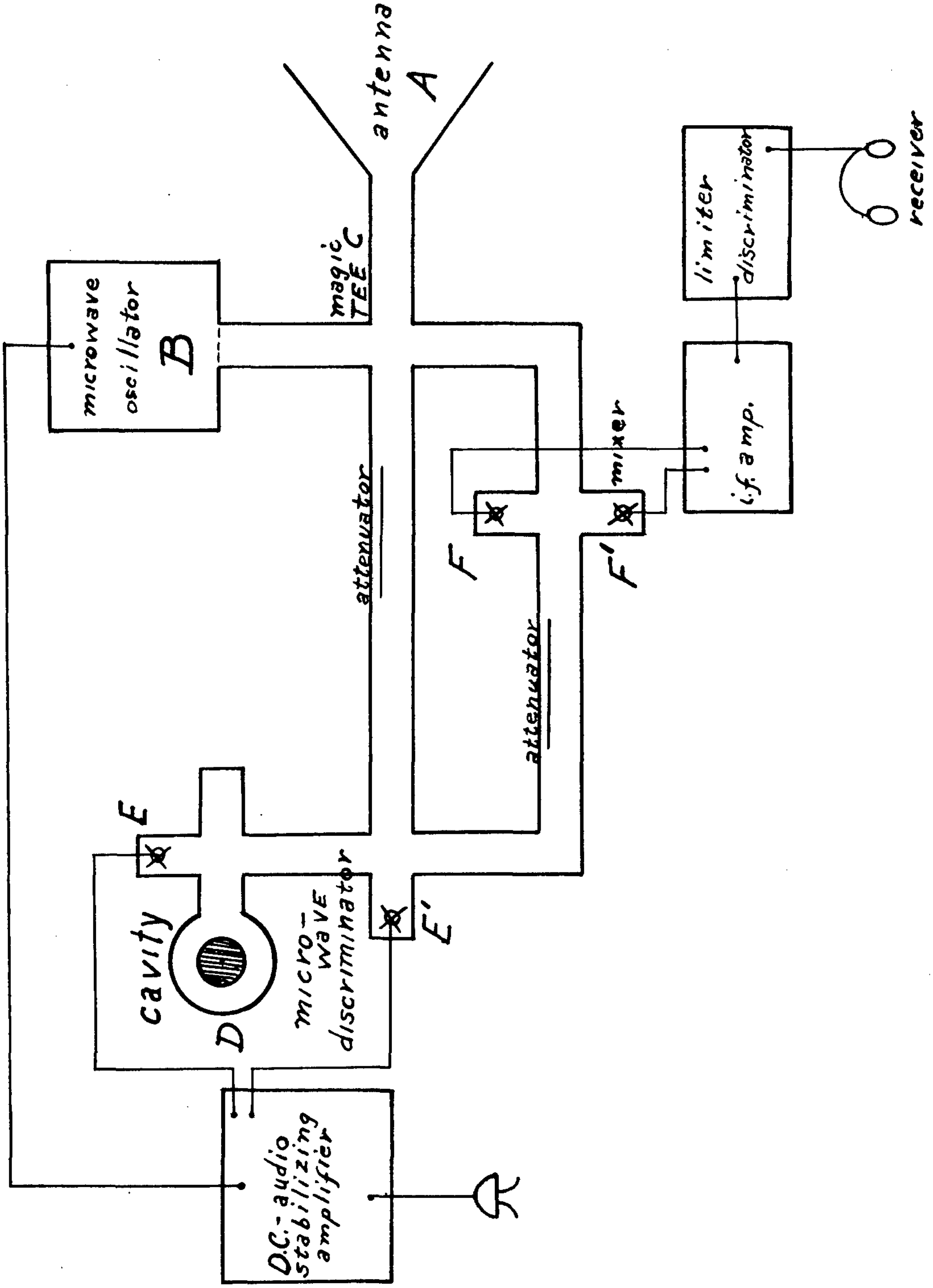

Figure 8 — Stabilized Microwave System

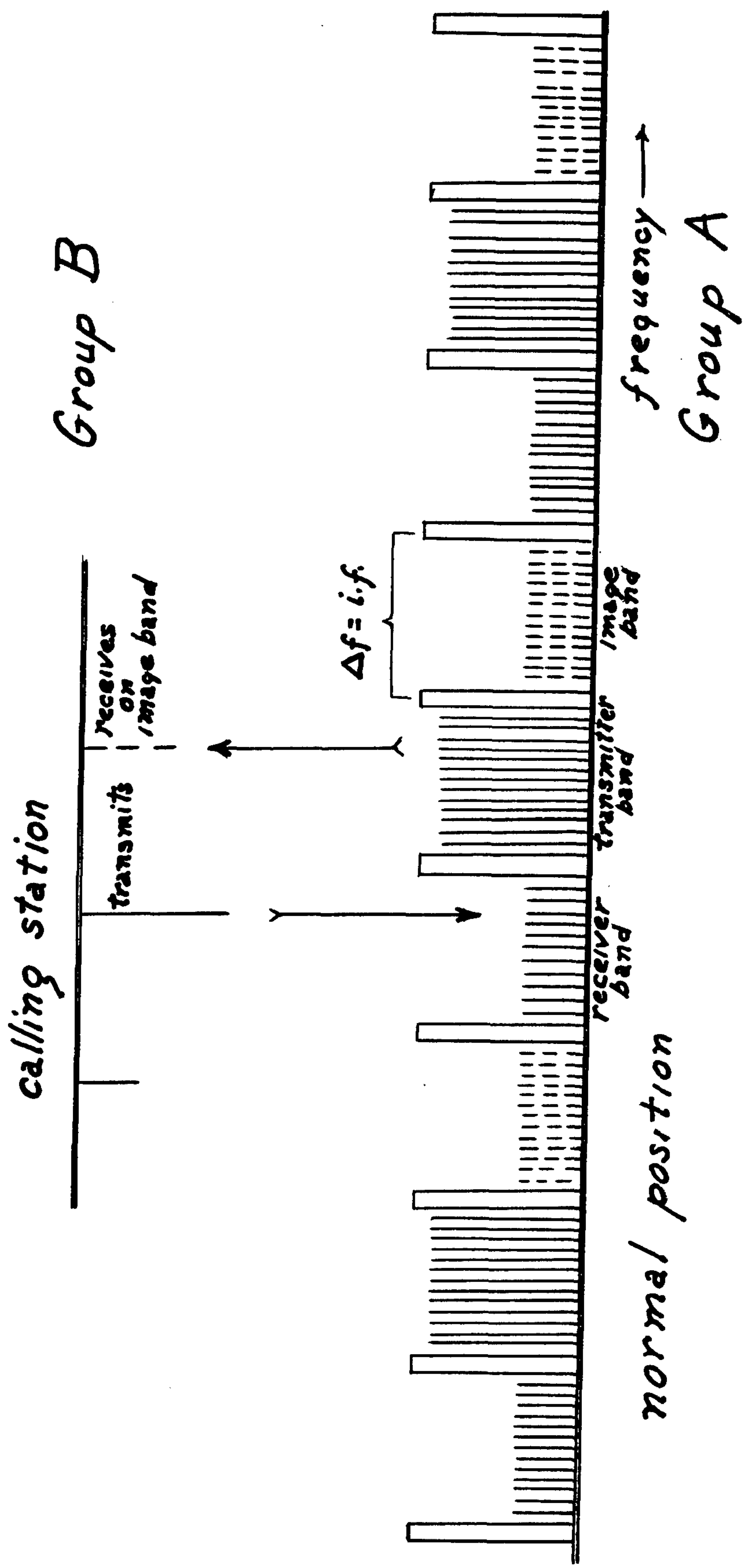
Group B
calling station
transmits
receives on image band
Δf = i.f.
image band
transmitter band
receiver band
normal position
frequency ⟶
Group A

Figure 9

An experimental transmitter-receiver combination of this type has already been experimentally tested and shown to be entirely feasible. In view of the rapidity with which the microwave field is advancing, the technical availability of the system is assured.

Going to still higher frequencies, 60,000 megacycles or more, the portion of the spectrum is reached where molecular absorption of the gases in the atmosphere is of consequence. Employing these frequencies, it should be possible to design short-range radio communication systems which would allow the transfer of intelligence between planes in a formation and yet have the signal strength attenuated so rapidly that the enemy at a slightly greater distance could not intercept or even detect radiation. Furthermore, it would be virtually impossible to jam the communications between the planes in the formation, short of sending jamming transmitters actually into the formation itself.

CHANNEL CONTROL AND SPECIAL SYSTEM

Much developmental work remains to be done as to methods of selecting and switching communication channels within the command-frequency spectrum. A command system designed to obtain the maximum performance from a large formation of aircraft may require individual channels for each of the airplanes involved plus additional channels for various groups of these planes and a master channel for the entire formation. If such a system is used, the switching and selecting must be made as easy as ordinary telephone dialing. Already work is being done to develop such a system. An experimental British receiver has been built which incorporates some 300 channels. These channels are slected by means of two dials, each having positions designated by letters of the alphabet. To tune the receiver and transmitter to any channel, one merely dials the two letters designating that channel. There is no fundamental reason why this system cannot be extended to include a thousand or more channels and the dial be simplified to a single telephone dial with the ten digits marked on it, on which one dials three or four numbers just as one does in the case of using the conventional telephone. Where this system is used, each plane could be assigned a channel so that any other airplane wishing to communicate with it would simply dial the appropriate number which tunes the calling transmitter and receiver to a channel which the plane being called keeps continuously open for the reception of such messages. Submaster and master channels also kept continuously open would be reserved for the use of the formation leaders. Some channels would also be reserved for emergency work. Such a system would require two or three transmitter-receiver sets per plane. However, with the short distances involved the power required would be small and each set could be made very compact. The switching system required could readily be evolved from present day telephone technique.

Mention has already been made of the possibility of reducing jamming and interference by the use of various modulated systems. There is also the problem of minimizing enemy interception of messages. This may make it necessary to use speech-scrambling systems in order to render the messages unintelligible. It would be relatively simple to develop scrambling systems whose coding could be changed at predetermined intervals in such a way as to make enemy interception virtually impossible. Intelligence transmitted by teletype or facsimile may possibly play some role in command communication system. However, this appears to be less likely than in the case of the liaison communication. Both teletype and facisimile methods are so well developed that they need no further comment.

For some aircraft work, it is desirable to have a system which gives a permanent or semipermanent indication of the command being transmitted. This is particularly important in the case of a fighter pilot as there is a considerable probability of his being occupied at the moment the message is being sent, and if it is not recorded he may lose the information. Work has already been done along these lines in connection with a British system named "Beechnut" and a corresponding American system designated as "Voflag."

In the "Voflag" system the message, consisting of six units of intelligence, is preset into the transmitter together with the calling signal code. An electromechanical scanner surveys the preset message and directs subcarrier frequency modulation keying of an amplitude-modulated ultrahigh-frequency radio transmitter.

At the aircraft receiving the message, the "Voflag" signal is intercepted by a voice communication receiver and converted to an electrical audio output. The audio output is fed to discriminator circuits with very high selectivity which separate out the keying signals. These operate a small synchronous motor which distributes the code signals to a teleselector mechanism. The output of the teleselector controls the annunciator messages display box or can be used to control a printer.

The system is equipped with an automatic repeat-back which informs the transmitting station of the correct delivery of the message.

Because of the high selectivity of the receiving circuits and the protective feature of the balanced equal-length signalling code used, the system is very difficult to jam.

The systems discussed in the preceding paragraphs are still only in the research stage. It will be many years before they are brought to a point of development where they can be considered part of the absolutely essential minimum. However, long before this stage is reached, they may serve as important adjuncts to the fundamental communication system.

All radio communication above 50 or 100 megacycles is essentially limited to line-of-sight transmission. If radar patterns or television pictures requiring the transmission of bandwidths of several megacycles becomes an important part of the aircraft communication system, it will become necessary to develop airborne radio relay links in order to maintain communication over great distances. This will be particularly important if the transmitters are part of remote-controlled missiles. A good deal of work has already been done in developing automatic relay systems for television and multichannel telephone communication. The present equipment is, in general, too bulky for airborne use but it can be said with considerable assurance that the bulk and weight of this equipment can be reduced by a large factor without going beyond present technical knowledge. Operation at 3000 megacycles or more it will undoubtedly be possible to design a relay unit which will give several hundred miles line-sight communication range, with a nominal output power of 50 w or less. Equipment of this type could be carried in either pilot operated airplanes or remote-controlled ships and could serve to retransmit either pictures or multichannel voice communications. A number of such airborne repeater stations spaced at intervals between the aircraft formation and its operational control point may in the future serve to maintain liaison communications as a supplement to a long-wave transmitter. This would have the advantage of permitting a great number of communication channels, of being virtually free from static and atmospheric interference and of being less susceptible to jamming. Probably the long-wave transmitter would be retained only to be used in event that the relay chain was broken.

Control of the landing, take-off and flight formation of planes from a ground station or base becomes very difficult when large numbers of planes are involved, particularly under the black-out conditions imposed by war. The presence of fog, heavy rain or other unfavorable meterological circumstances greatly increases the hazard and makes accurate control essential. The employment of a "Teleran" system or its equivalent will expedite these operations and to a large extent reduce the danger associated with them.

The "Teleran" system includes the radar location of all planes in the neighborhood of the base and transmitting this information together with other data to the planes in the form of a television picture. It also provides for the blind-landing of planes as ordered.

For this system the space above the air base is divided into levels. The planes as they come in are assigned to the various levels. At the ground station all the planes are located by radar and the location of the planes in the different levels are plotted electronically. A map of the air-base terrain, including meteorological indications, with all of the positions of planes in a level is transmitted by television to all the planes in that level. Thus every pilot not only is informed of his own location but also knows the location of all other planes at his level and can thus avoid the possibility of collision.

A complete blind-landing system, with guide beams and indicators is provided in the lowest level.

Such a system gives the air base complete control of incoming and outgoing planes and should greatly increase the safety of what is now a very hazardous operation.

COMPONENTS

In addition to the development of systems and equipment outlined above, a good deal of effort should be spent on perfecting components which go into making up the communication equipment. Industrial engineering has developed excellent components, tubes, inductors, capacitors, resistors, and insulators for commercial radio equipment. However, the demands placed on components, and reliability required is very different for military aviation radio than for ordinary commercial practice, even commercial aviation.

The development of components should be carried out in collaboration with parts manufacturers to ensure an eventual adequate supply of these elements. Attention should be focused on such factors as stability, resistance to shock, insulation under extremes of pressure, temperature, humidity, etc.

It is certain the components with the required characteristics can be produced, and the only reason they are not at present is that they are uneconomical to use in commercial equipment.

* * * * * *

Other developments in the technique of radio communication undoubtedly will occur and obviously will make it necessary to alter the program. However, the program as outlined can be considered to represent the minimum realizable communication system and any deviations from it will necessarily be in the direction of improvement.

RECOMMENDATIONS

The discussion above outlines a course of radio-communication equipment development which would meet the basic needs of an effective air force. It also suggests special lines along which research should be directed. These are the following:

Liaison Systems (2 to 30 megacycles)

1. Antenna research in collaboration with aeronautical designers.
2. Improvement of oscillator stability.
3. New tuning methods, with an aim to obtaining automatic band selection if possible.
4. Investigation of voice coding systems for reducing the band widths required per channel.

Command Systems (200 to 500 megacycles)

1. Antenna design.
2. Stability of oscillators and other components.
3. Development of multichannel switching and selector mechanisms.
4. Study of antijamming and anti-interception methods.
5. Modulation methods.

Components

1. Development of suitable tubes.
2. Development and production of insulators, resistors, capacitors, etc.

[redacted]

Special Systems

1. The study of centimeter, microwave, and millimeter wavelength systems. This includes the investigation of all components including antennas.
2. Highly directional transmission and reception.
3. Pulse modulation.
4. Application of facsimile, teletype and indicator systems to aircraft needs.
5. Television and radar picture transmission.
6. Airborne radio relay links.
7. "Teleran" air base control systems.

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Summaries are given of radar and communication development up to nineteen hundred and forty six. Use of radar in navigation, all weather flying, and guided missiles in air force operation is discussed. Future trends of pulsed radar, target properties, propagation, CW detection methods, radar countermeasures, bombsights and computers beacons, electronic components, etc., are considered. Current communication practice and recent developments in aircraft radio communication equipment are outlined.

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Some of the present and future possibilities of radar and related techniques in various types of air operations are briefly outlined. These include all-weather air operations, increased accuracy in bombing, gunfire, and navigation, provision of information and controls to relieve the overburdened pilot both in navigation and combat, and the remote control of pilotless aircraft. The basic art of pulsed radar is discussed by considering the range, resolving power, and the rate of coverage or scanning rate so as to suggest the present and future possibilities and the limitations of radar developments. Aircraft radio communication is an essential and critical part of integrated aerial warfare. The development of radio-communication techniques since the onset of World War II is reviewed, and the future trends of aircraft-radio development are discussed.

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