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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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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 view over an enormous 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;

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.

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 equipmnet. 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.

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 $\pm$ 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 factory 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.

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 automtically 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.

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 stisfactory 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.