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RADAR
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COMMUNICATIONS

A Report of the AAF Scientific Advisory Group

by
L. A. DUBRIDGE
E. M. PURCELL G. A. MORTON
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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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PART I

THE USE OF RADAR IN AIR FORCE OPERATIONS

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PART I

THE USE OF RADAR IN AIR FORCE OPERATIONS

INTRODUCTION

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

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

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

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

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

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

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

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

a few seconds for all objects in 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 ± 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.

PART II

RADAR

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

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PART II

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PULSED RADAR

INTRODUCTION

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

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

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

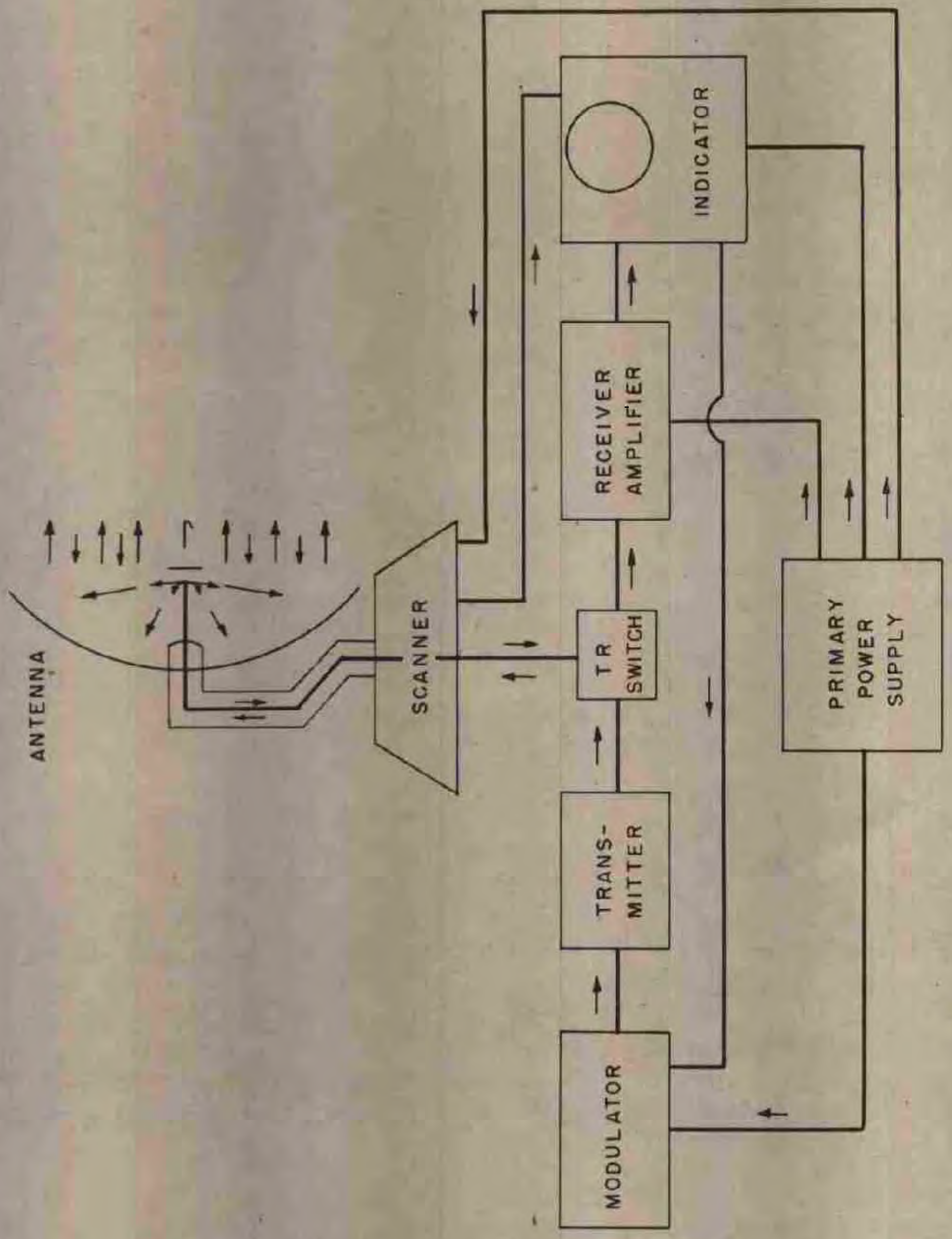
ANTENNA
SCANNER
TR SWITCH
TRANS-MITTER
MODULATOR
RECEIVER AMPLIFIER
INDICATOR
PRIMARY POWER SUPPLY

Figure 1

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

RANGE

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

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

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

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

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

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

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

where:

P_t = peak transmitted power

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

λ = wavelength

σ = scattering cross section of the target

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

Δf = bandwidth of the receiver

S = scanning and presentation loss factor.

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

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

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

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

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

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

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

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

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

Transmitter Power and Energy per Pulse.

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

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

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

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

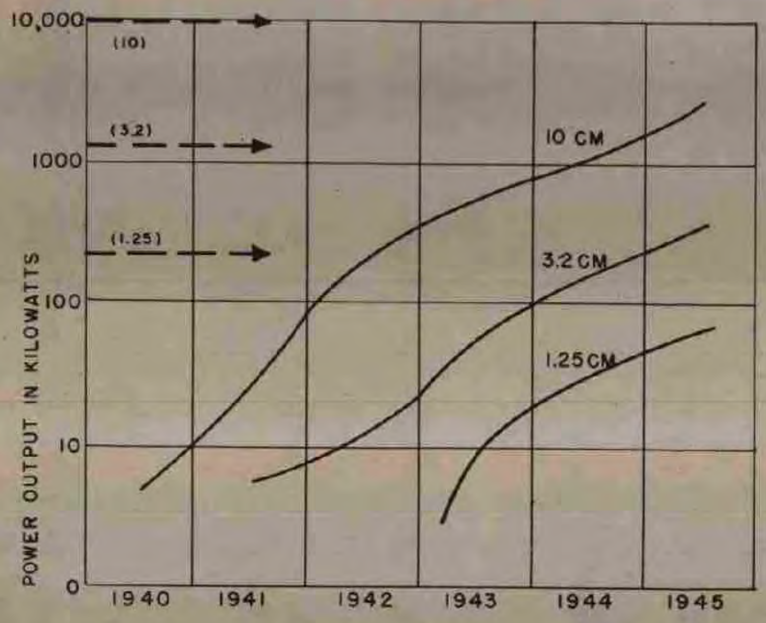


Figure 2

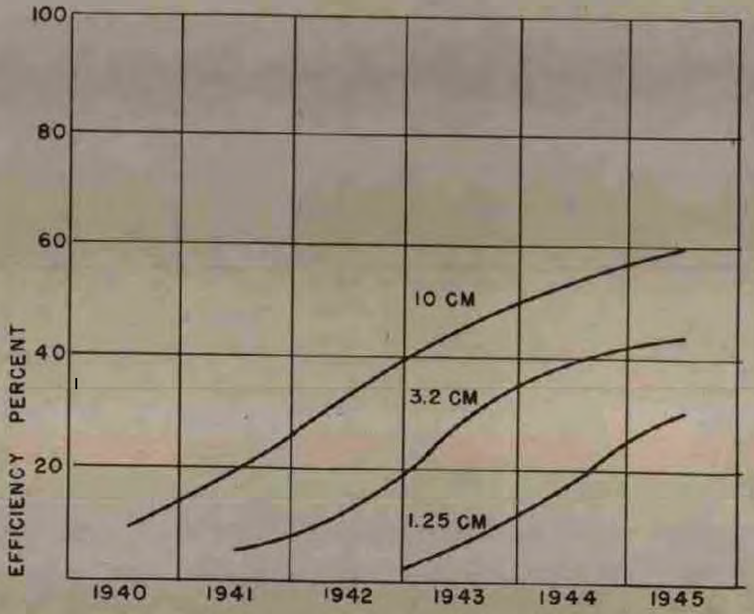


Figure 3

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

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

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

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

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

Antenna Gain.

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

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

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

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

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

Receiver Performance.

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

Scanning Loss.

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

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

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

RESOLVING POWER

Angular Resolution.

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

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

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

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

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

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

Range Resolution.

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

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

SCANNING AND COVERAGE

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

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

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

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

TARGET PROPERTIES

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

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

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

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

PROPAGATION

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

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

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

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

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

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

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

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

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

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

(1) Location and delineation of storm areas.

(2) Determination of winds aloft.

(3) Examination of storm structure in three dimensions.

(4) Measurement of degree of turbulence in storm.

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

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

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

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

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

CW DETECTION METHODS

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

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

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

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

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

MOVING TARGET DETECTION

INTRODUCTION

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

CW DOPPLER SYSTEMS

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

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

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

PULSE DOPPLER SYSTEMS

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

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

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

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

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

FUTURE USES FOR PULSE DOPPLER RADAR

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

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

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

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

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

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

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

COMPARISON OF DOPPLER METHODS

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

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

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

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

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

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

AIRCRAFT ELECTRIC POWER SUPPLIES

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

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

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

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

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

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

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

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

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

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

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

SUMMARY

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

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

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

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

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

ASSIMILATION OF RADAR INTO THE AIRPLANE

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

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

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

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

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

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

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

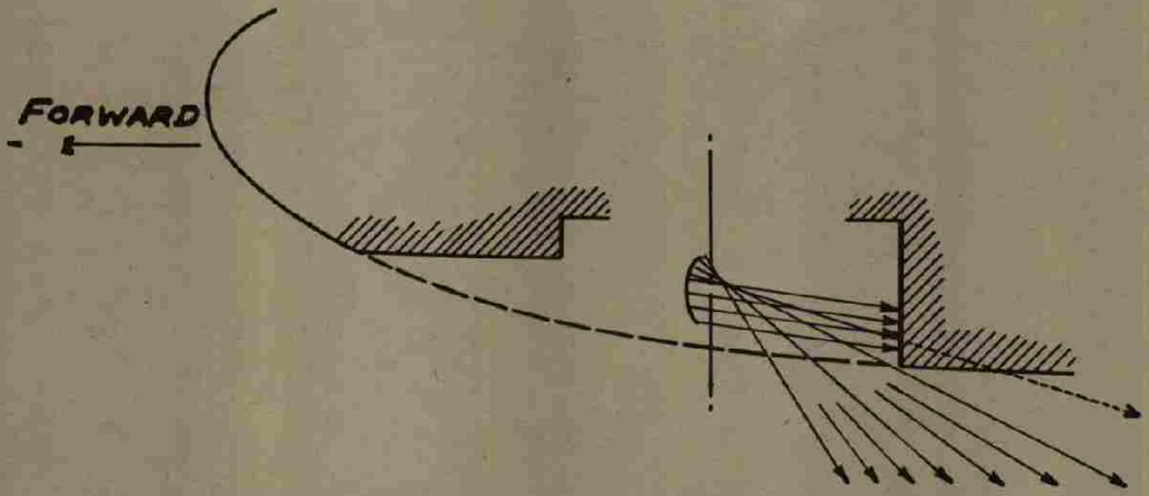


Figure 4

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

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

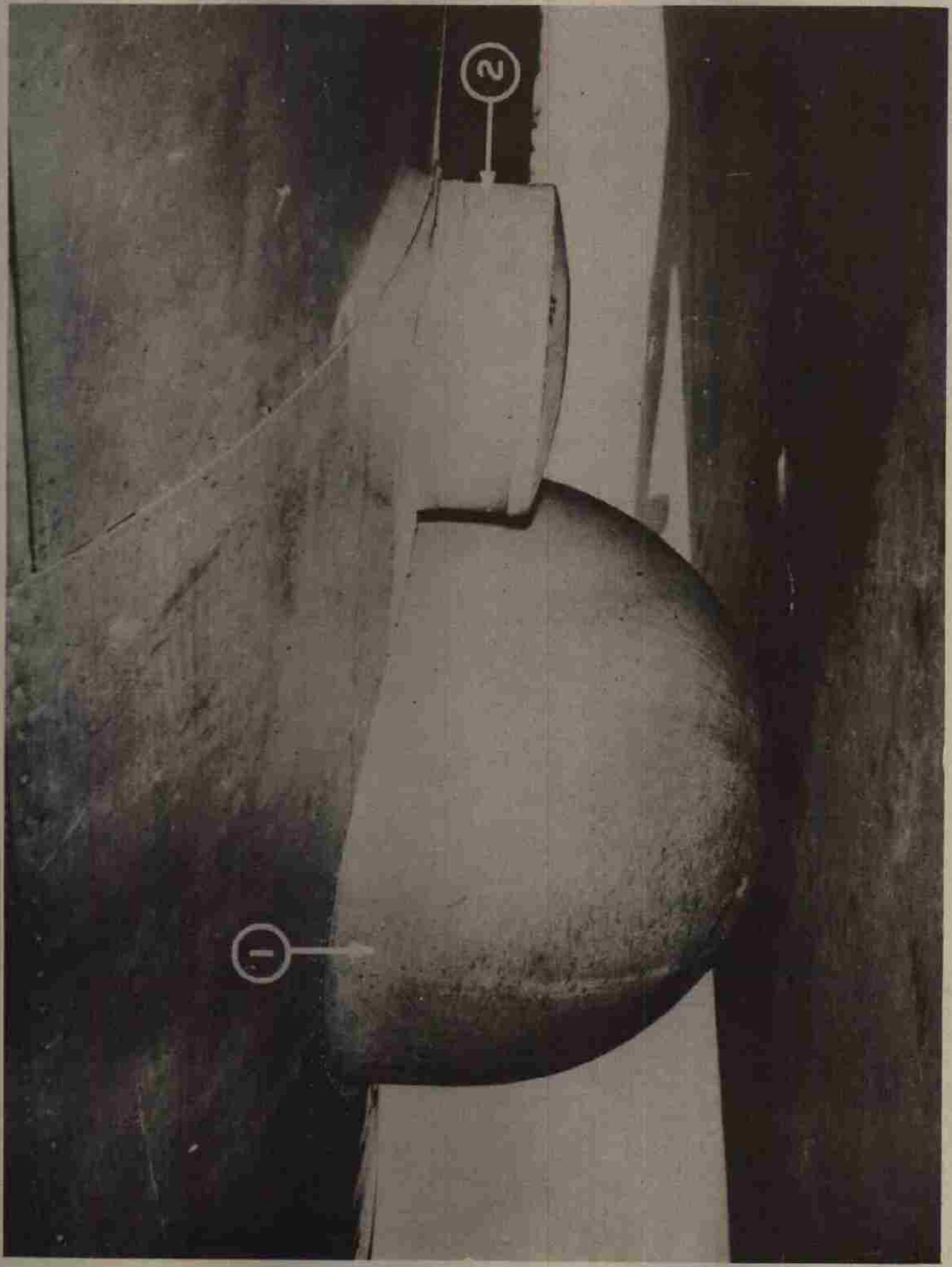


Figure 5

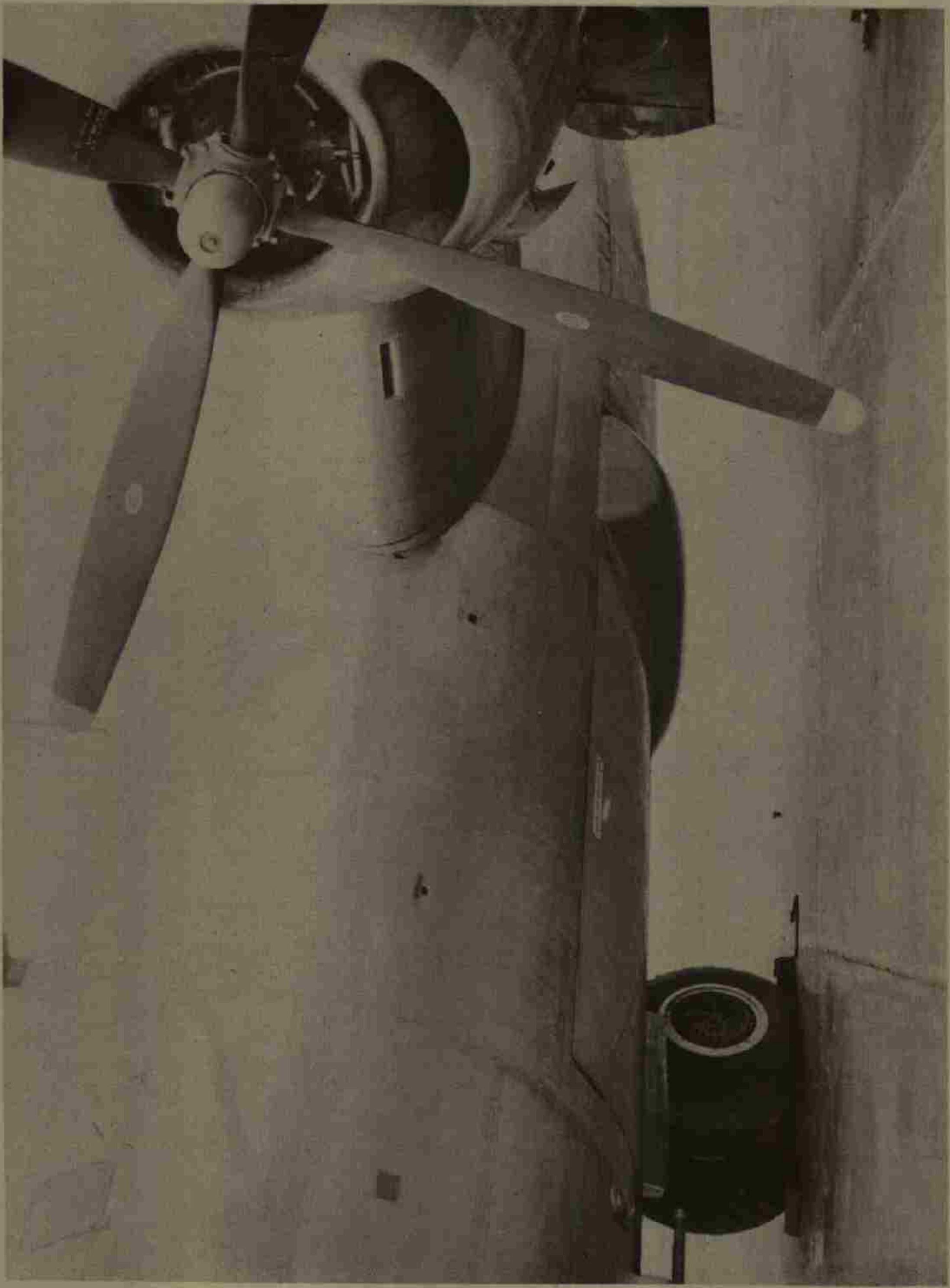


Figure 6

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

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

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

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

RELIABLE ELECTRONIC COMPONENTS

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

CONNECTORS

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

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

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

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

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

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

RESISTORS

Wire Wound.

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

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

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

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

Carbon.

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

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

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

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

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

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

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

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

BOMBSIGHTS AND COMPUTERS

REQUIREMENTS SET BY AIRCRAFT SPEED AND ALTITUDE

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

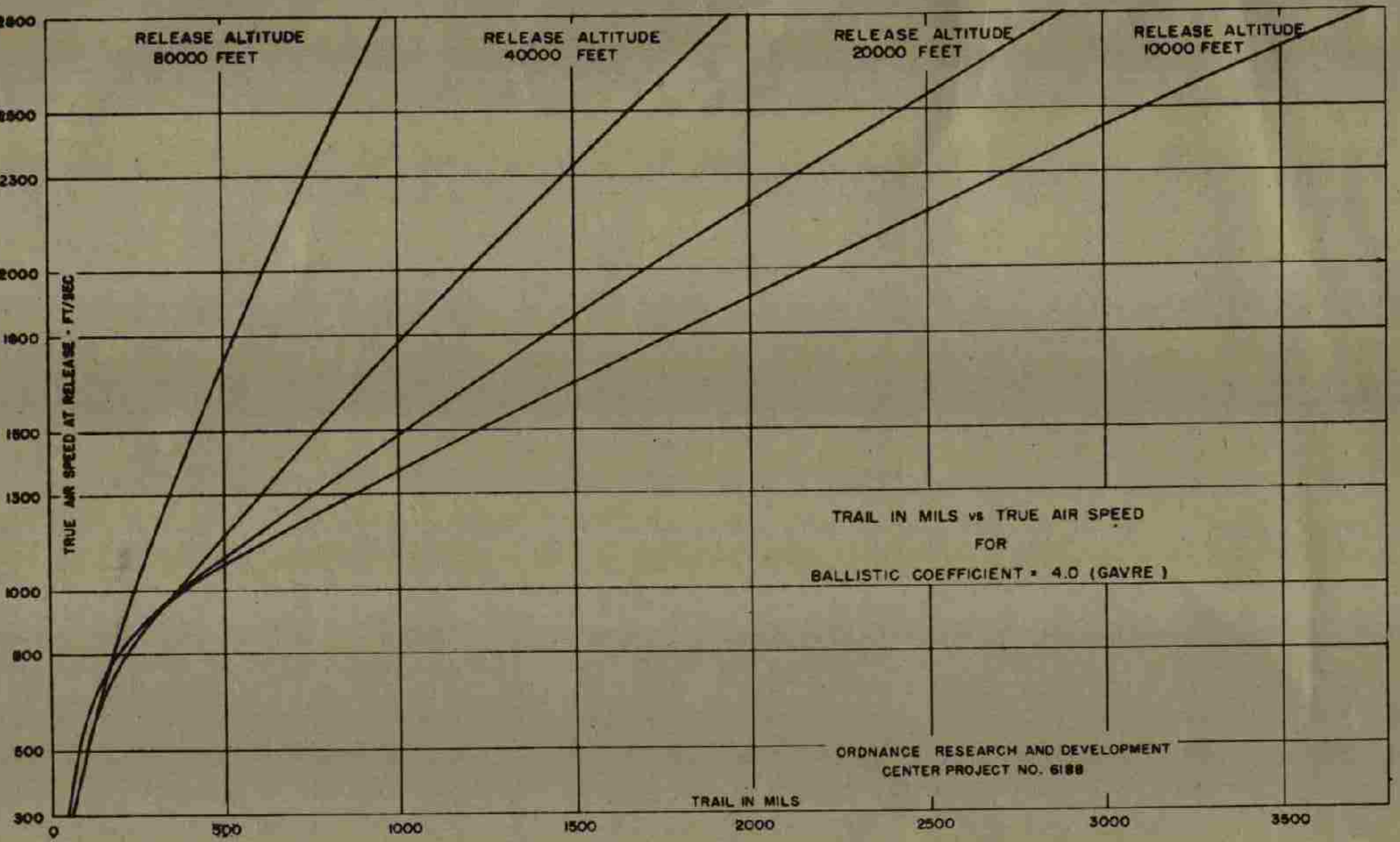

RELEASE ALTITUDE
80000 FEET
RELEASE ALTITUDE
40000 FEET
RELEASE ALTITUDE
20000 FEET
RELEASE ALTITUDE
10000 FEET
TRAIL IN MILS vs TRUE AIR SPEED
FOR
BALLISTIC COEFFICIENT = 4.0 (GAVRE)
ORDNANCE RESEARCH AND DEVELOPMENT
CENTER PROJECT NO. 6188
TRUE AIR SPEED AT RELEASE - FT/SEC
2800
2500
2300
2000
1800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

Figure 7

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

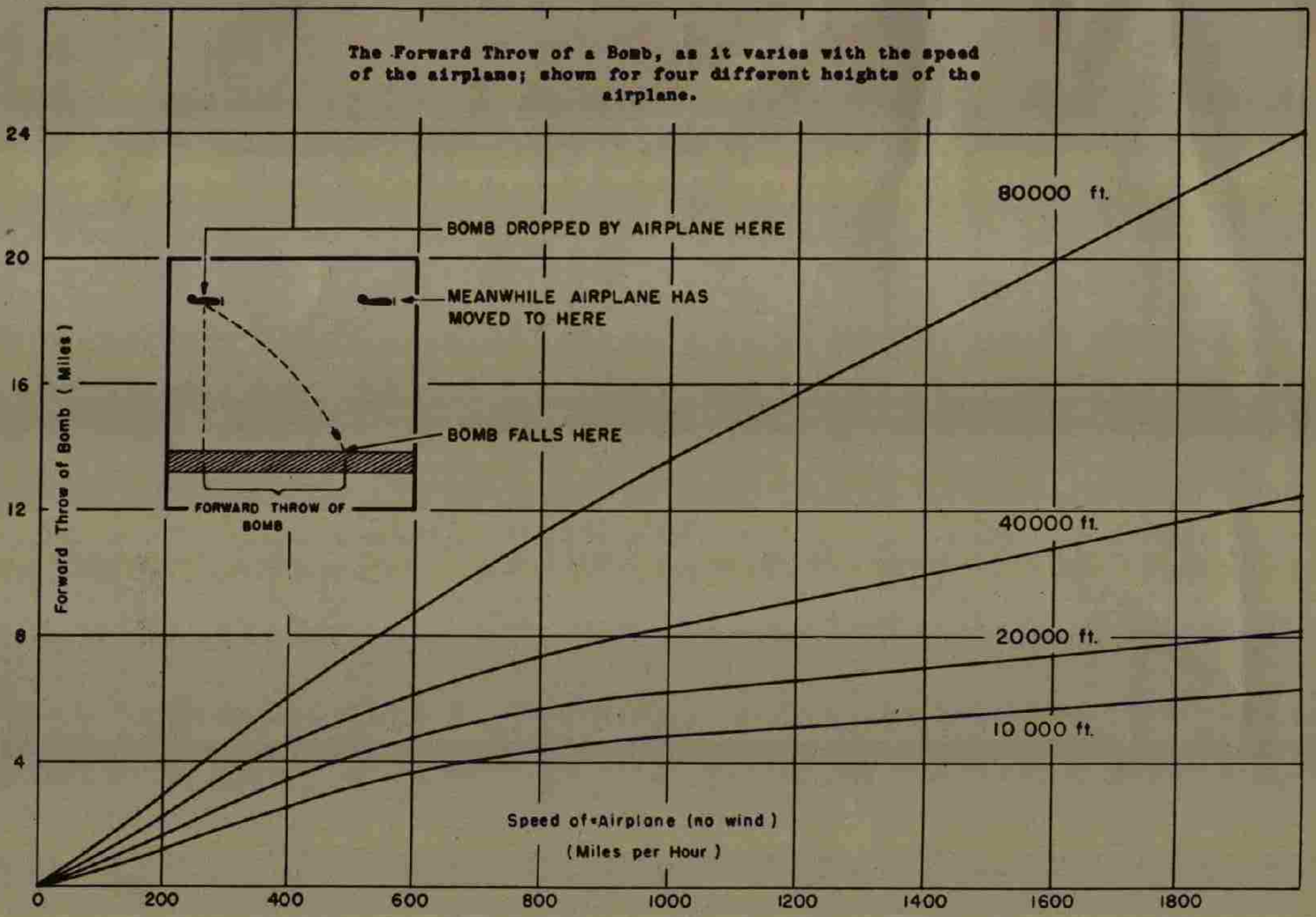
Bomb	*10,000-ft Alt*	*20,000-ft Alt*	*40,000-ft Alt*
GP, 1000 lb, AN-M65	3.87	3.74	3.65
S. A. P., 1000 lb, AN-M59	3.78	3.77	3.76
GP, 2000 lb, AN-M66	4.45	3.92	3.62
A. P., 1600 lb, AN-MK. 1	6.3	6.3	6.3

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

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

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

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



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

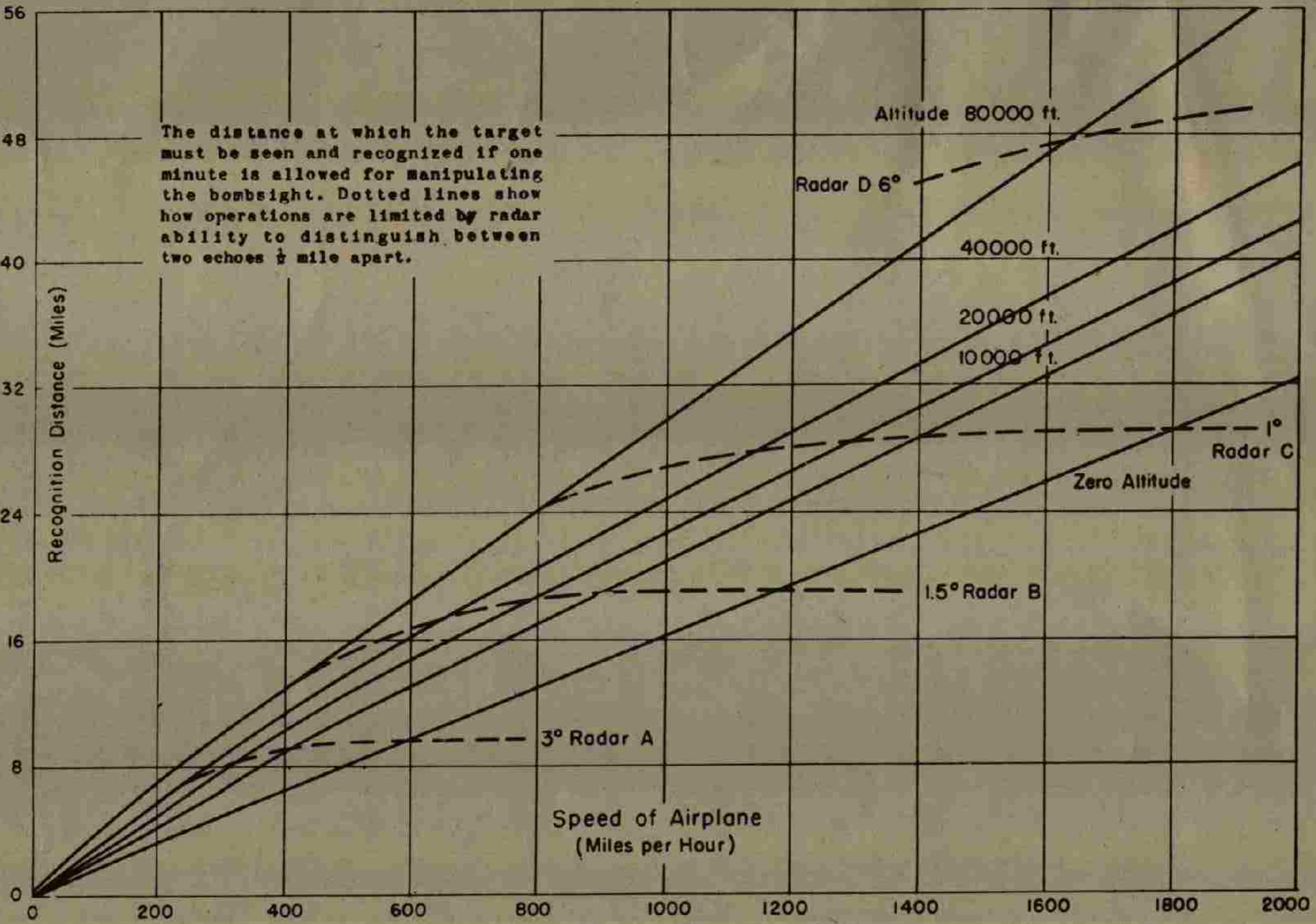
Figure 8

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

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

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

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



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

Figure 9

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

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

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

TABLE 1

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

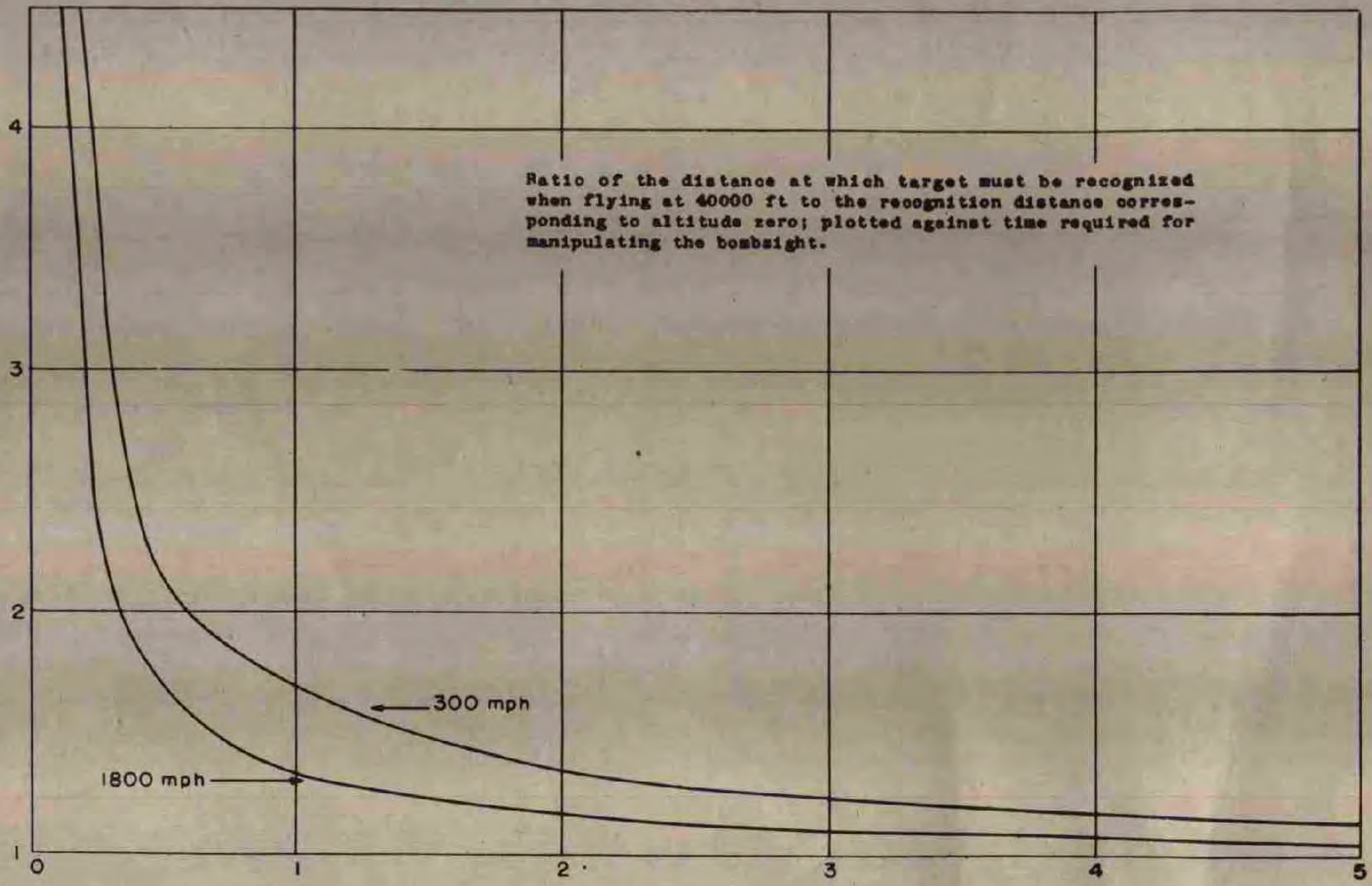
The numbers shown under slant range in the table above are the maximum distances as measured from the airplane to the mean between two point targets one-half mile apart on a line perpendicular to that of the line of sight, and such that the radar is just able to indicate these as two separate and distinct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

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

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

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

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



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

Figure 10

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

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

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

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

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

POSSIBILITIES OF SATISFYING THE REQUIREMENTS SET DOWN ABOVE

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

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

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

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

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

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

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

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

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

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

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

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

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

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

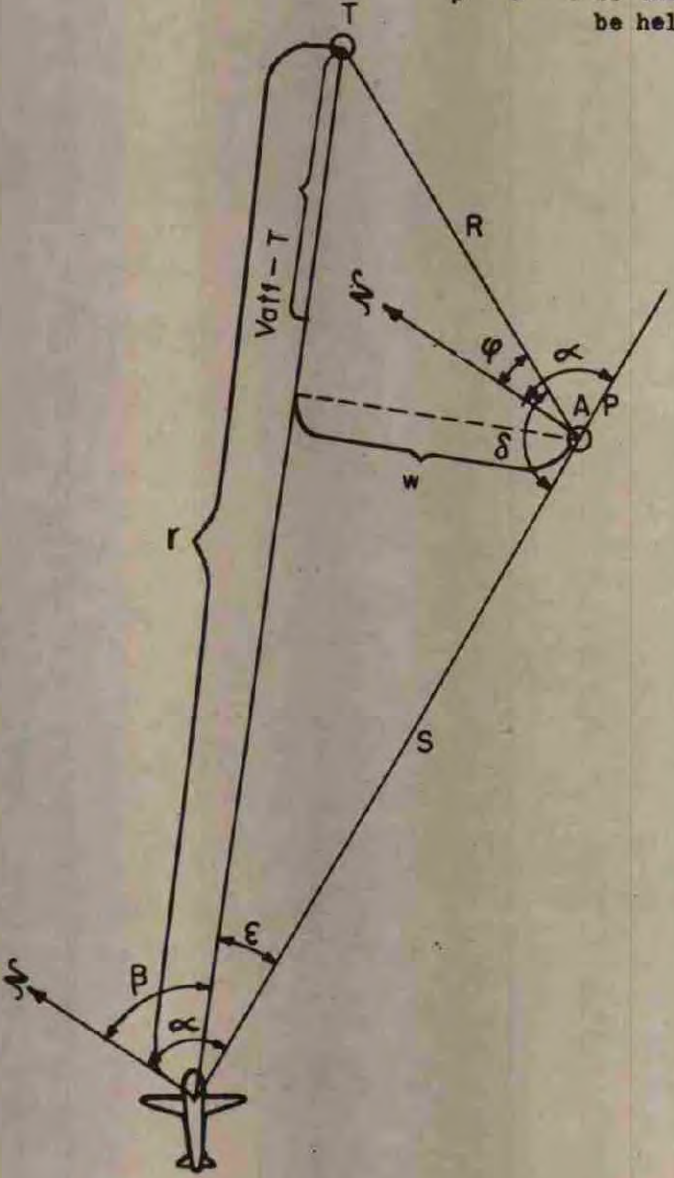


Figure 11 — Computations Necessary for Offset Sighting Computer

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

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

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

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

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

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

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

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

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

Conclusion.

The following recommendations are made:

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

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

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

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

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

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

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

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

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

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

THE MEANS FOR STRIKING EXACTLY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

GUNSIGHTS

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

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

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

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

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

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

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

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

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

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

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

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