PART II

RADAR

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

By

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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

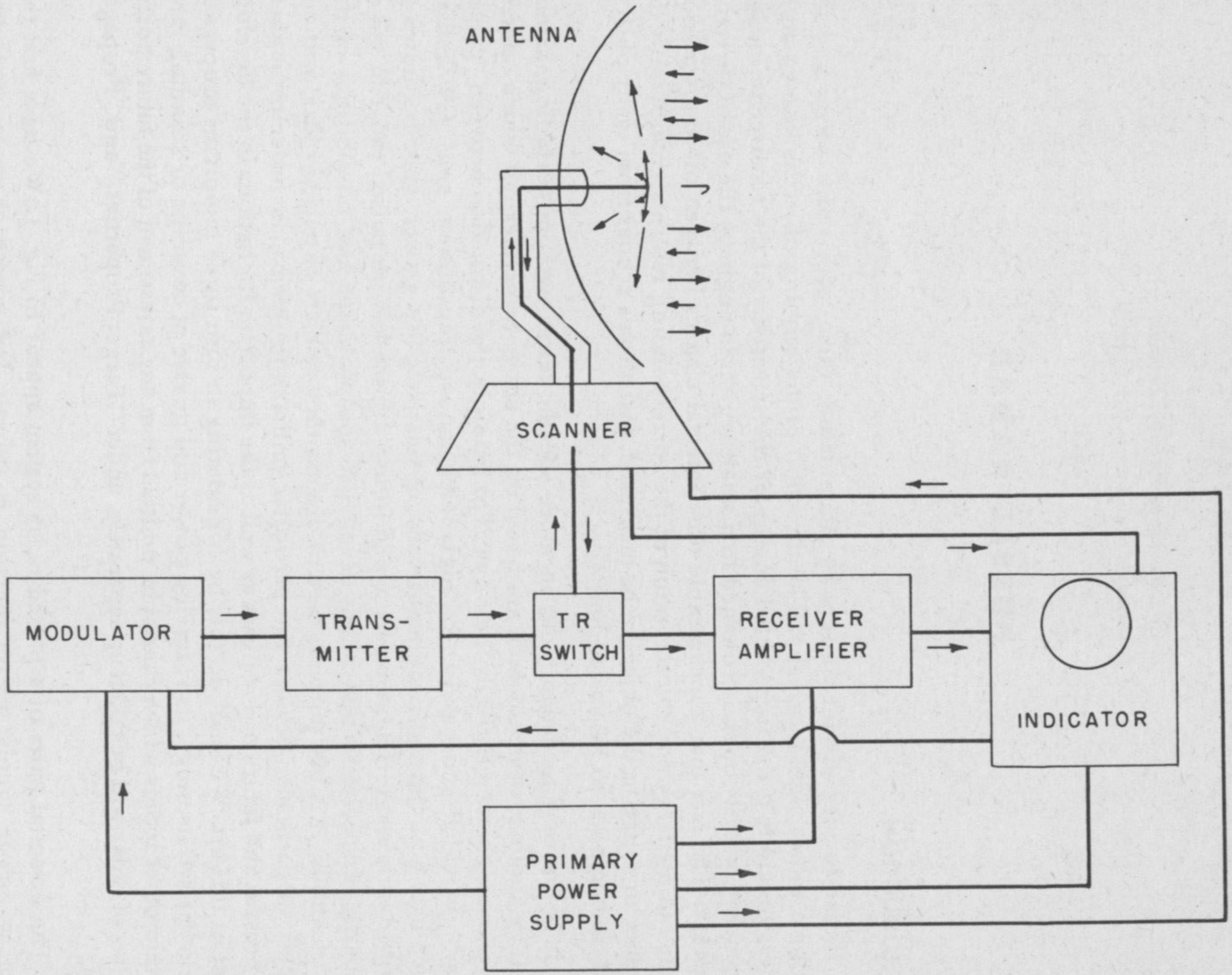
ANTENNA
SCANNER
MODULATOR
TRANS-
MITTER
TR
SWITCH
RECEIVER
AMPLIFIER
INDICATOR
PRIMARY
POWER
SUPPLY

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:

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

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

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

Transmitter Power and Energy per Pulse.

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

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

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

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

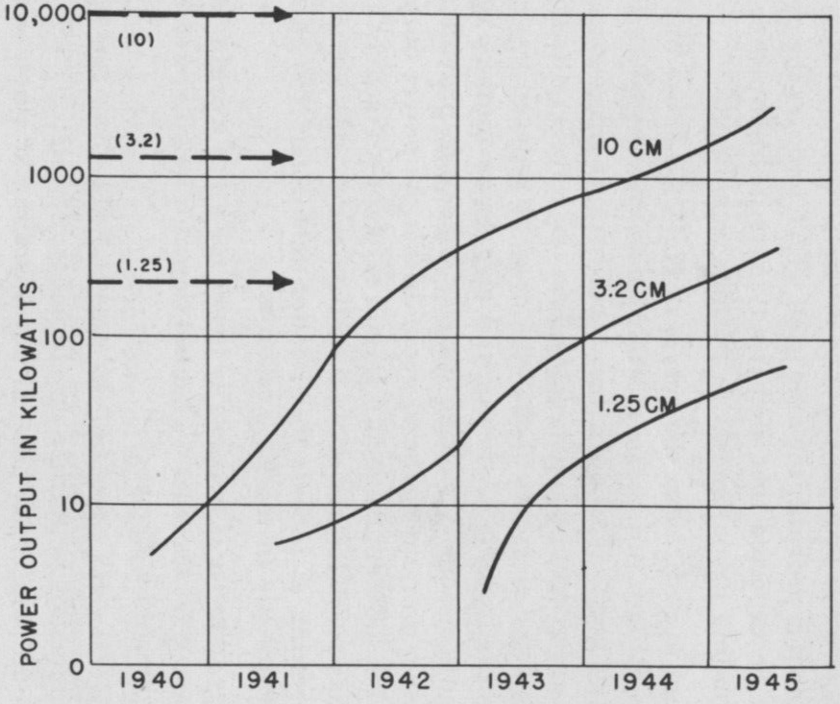


Figure 2

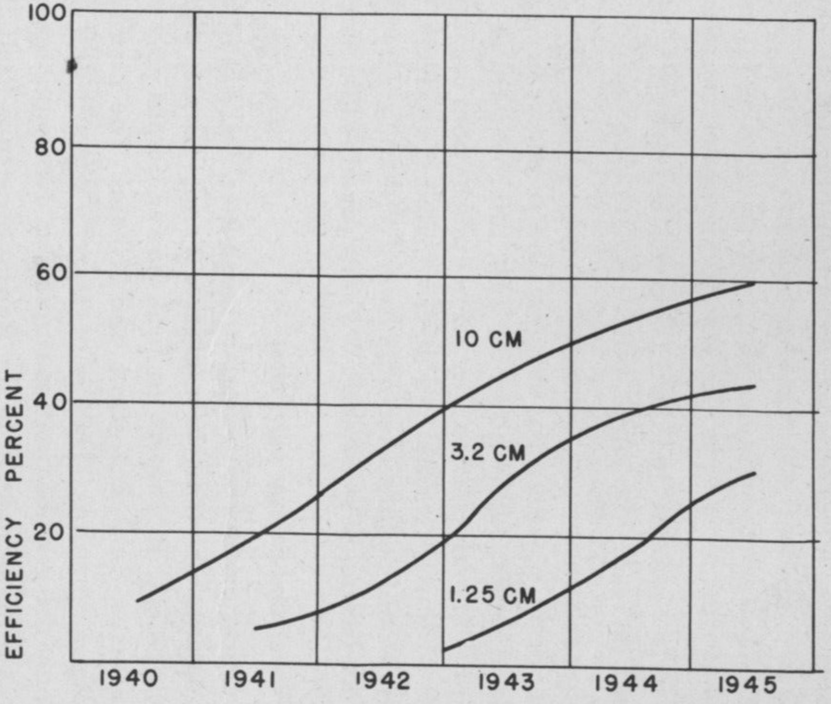


Figure 3

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

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

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

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

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

Antenna Gain.

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

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

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

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

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

Receiver Performance.

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

Scanning Loss.

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

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

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

RESOLVING POWER

Angular Resolution.

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

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

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

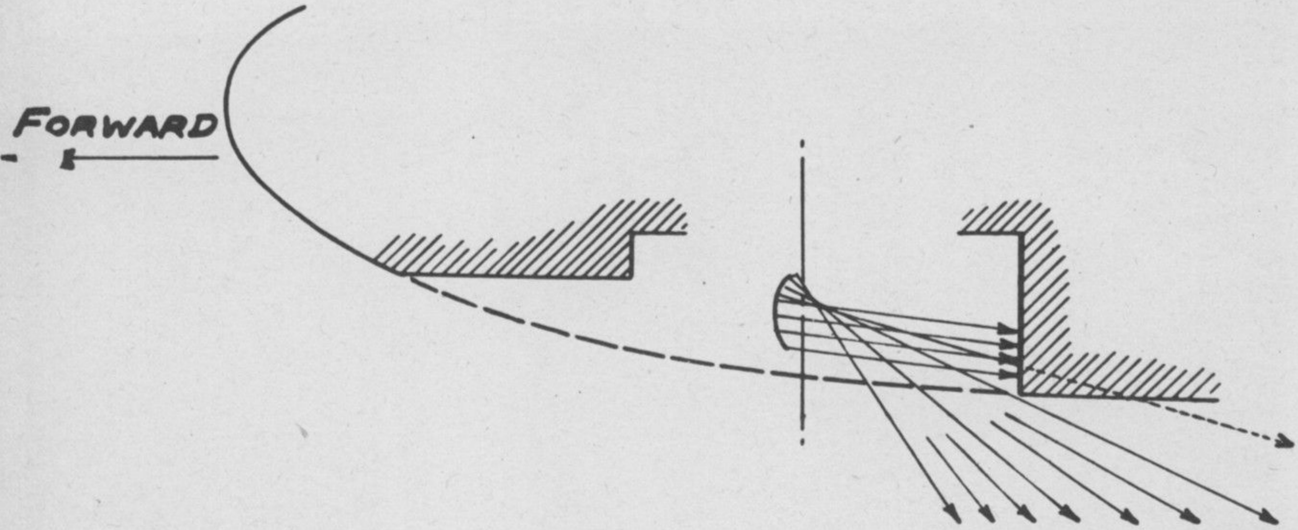


Figure 4

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

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

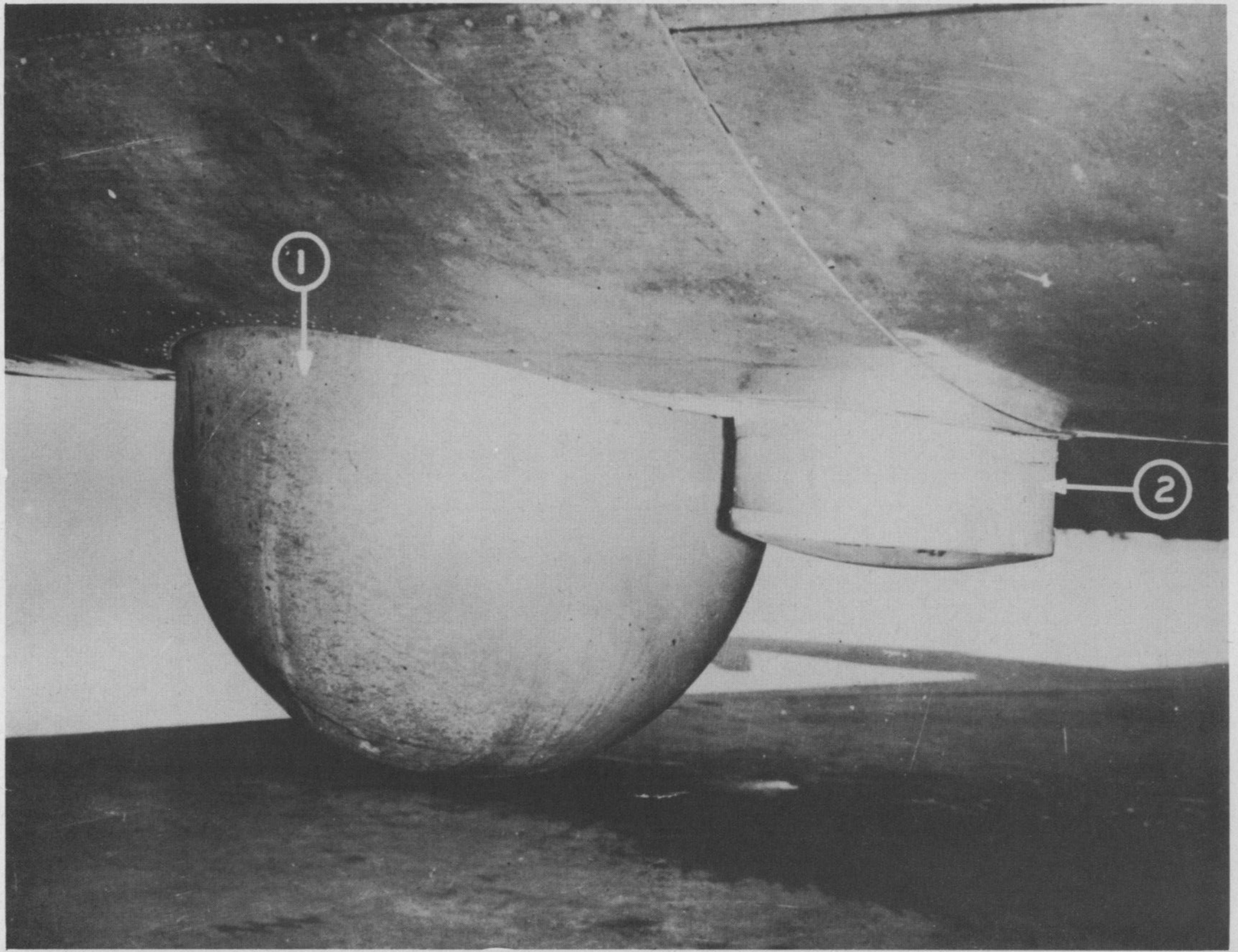


Figure 5

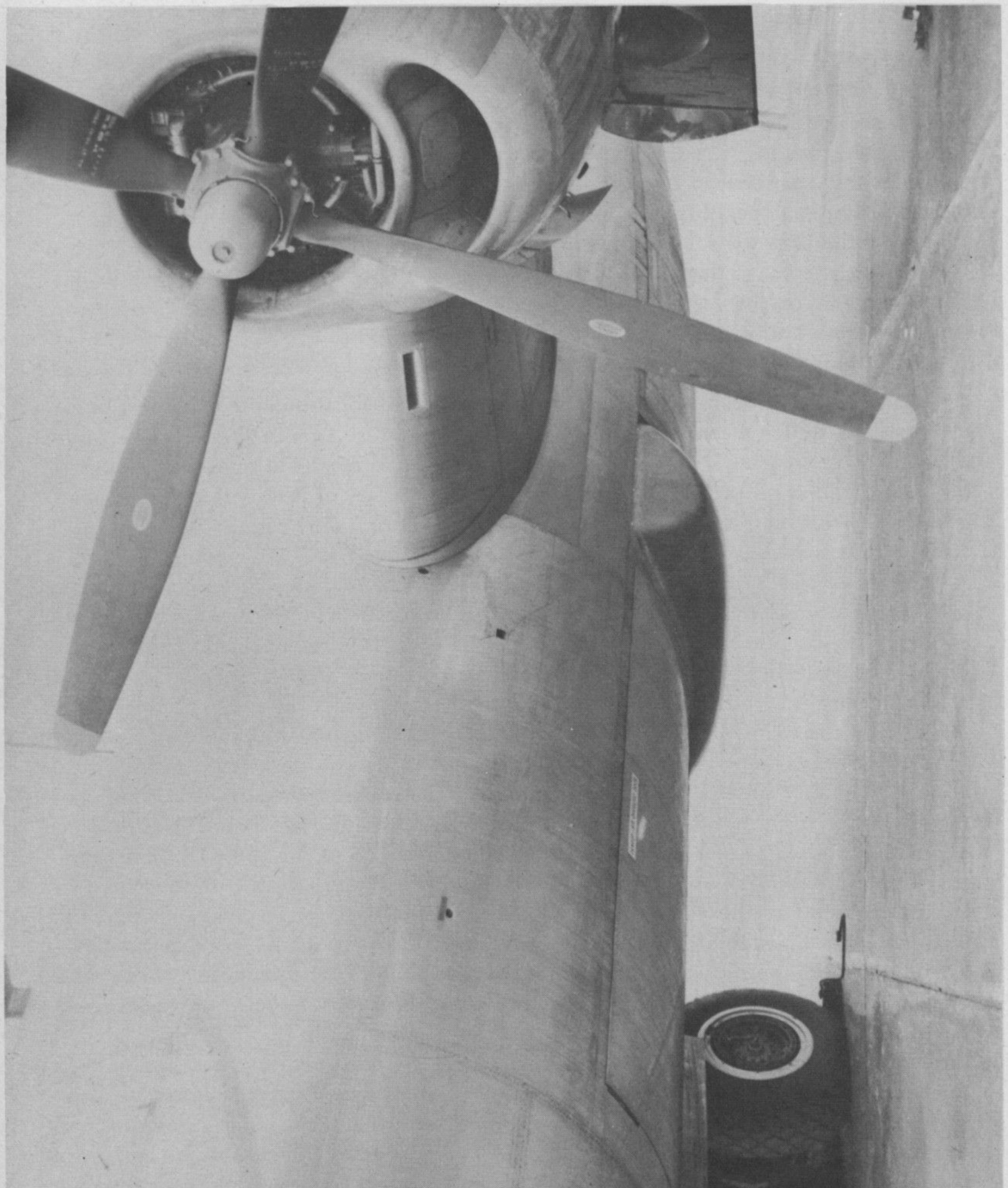


Figure 6

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

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

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

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

RELIABLE ELECTRONIC COMPONENTS

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

CONNECTORS

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

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

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

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

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

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

RESISTORS

Wire Wound.

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

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

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

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

Carbon.

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

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

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

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

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

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

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

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

BOMBSIGHTS AND COMPUTERS

REQUIREMENTS SET BY AIRCRAFT SPEED AND ALTITUDE

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

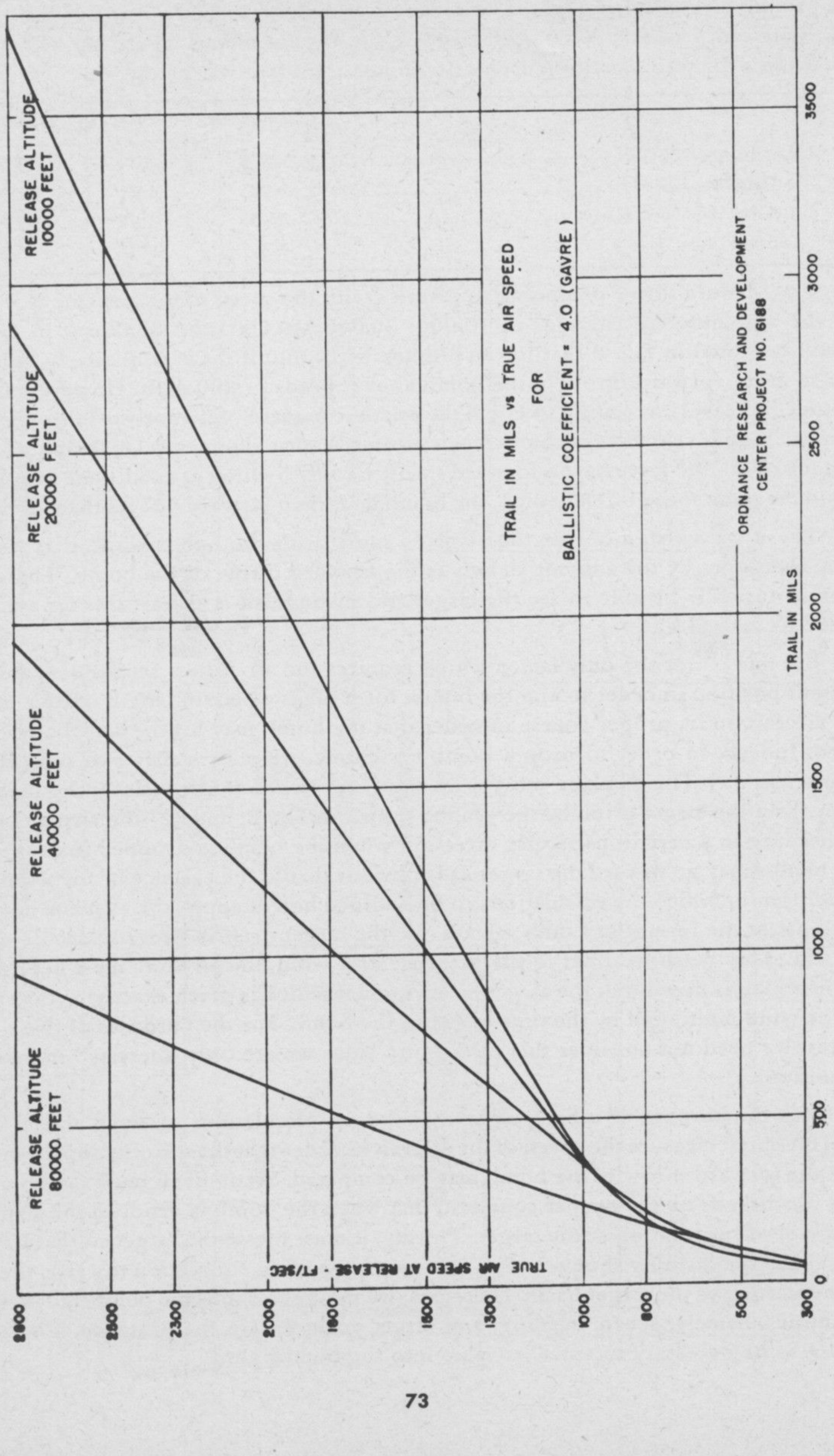

RELEASE ALTITUDE 10000 FEET
RELEASE ALTITUDE 20000 FEET
RELEASE ALTITUDE 40000 FEET
RELEASE ALTITUDE 80000 FEET
TRAIL IN MILS vs TRUE AIR SPEED
FOR
BALLISTIC COEFFICIENT = 4.0 (GAVRE)
ORDNANCE RESEARCH AND DEVELOPMENT
CENTER PROJECT NO. 6188
TRAIL IN MILS
0
500
1000
1500
2000
2500
3000
3500
TRUE AIR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

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."

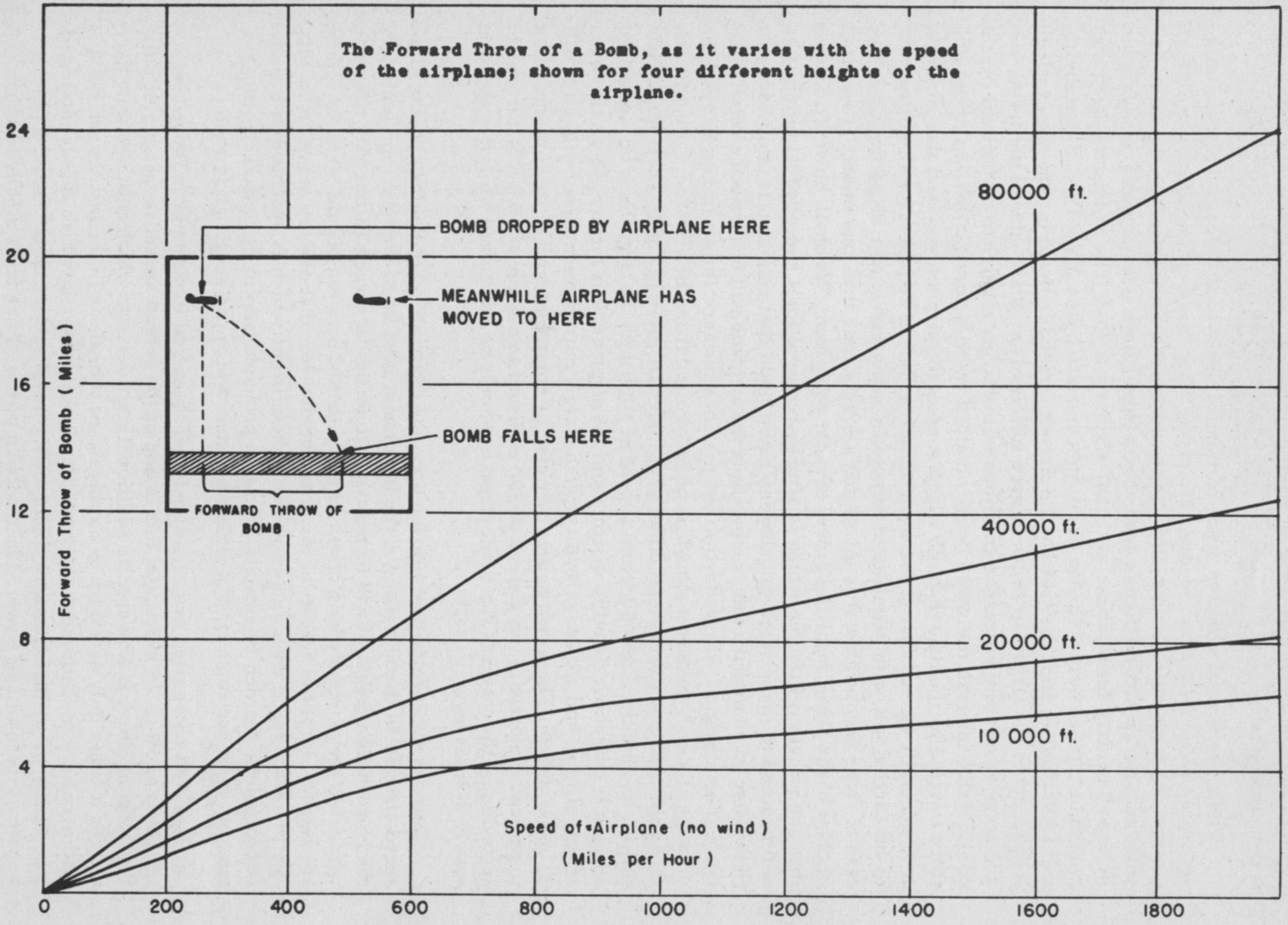
Bomb	*10,000-ft Alt*	*20,000-ft Alt*	*40,000-ft Alt*
GP, 1000 lb, AN-M65	3.87	3.74	3.65
S. A. P., 1000 lb, AN-M59	3.78	3.77	3.76
GP, 2000 lb, AN-M66	4.45	3.92	3.62
A. P., 1600 lb, AN-MK. 1	6.3	6.3	6.3

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

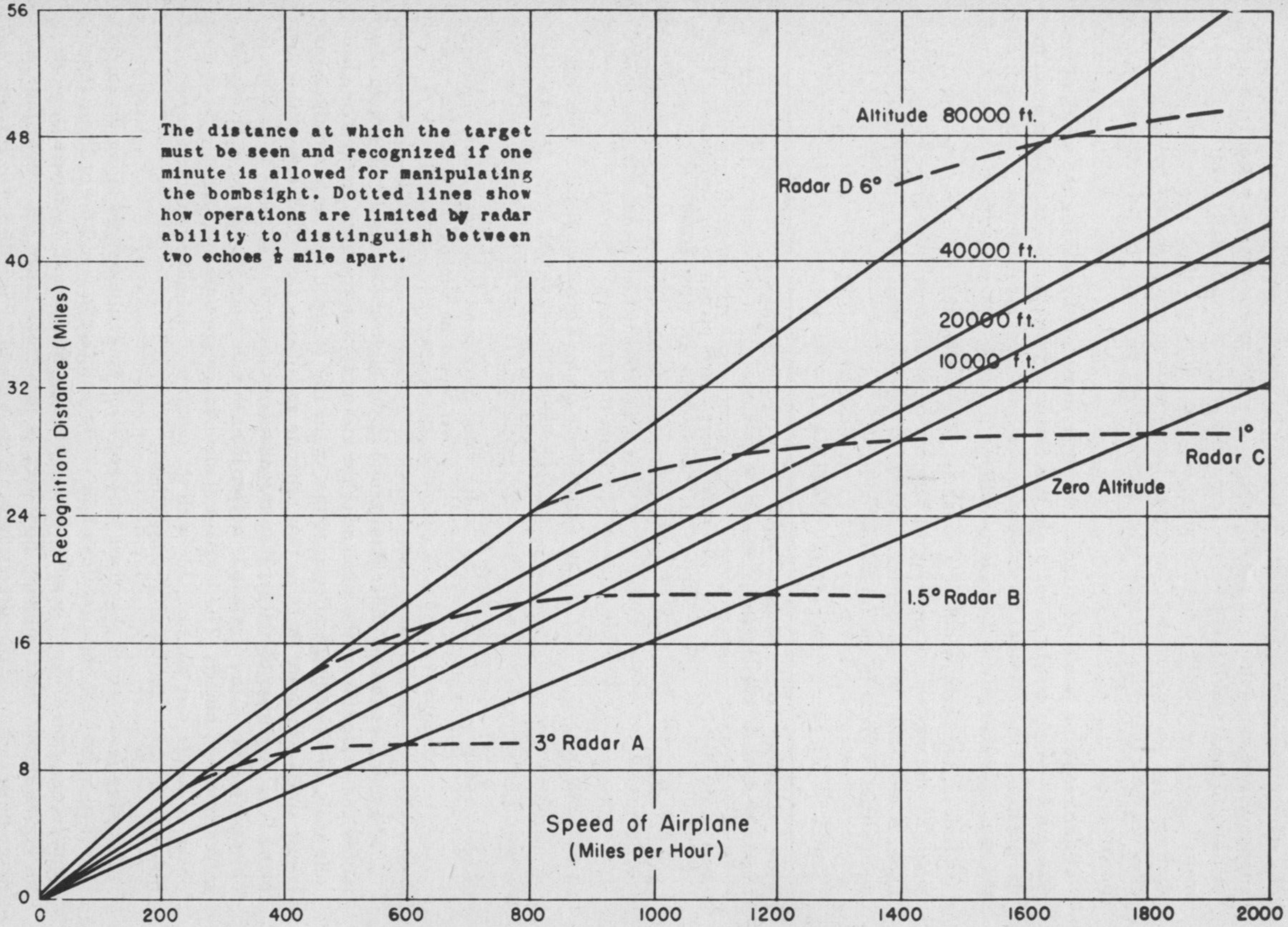

The distance at which the target must be seen and recognized if one minute is allowed for manipulating the bombsight. Dotted lines show how operations are limited by radar ability to distinguish between two echoes ½ mile apart.

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 wave-length, 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.

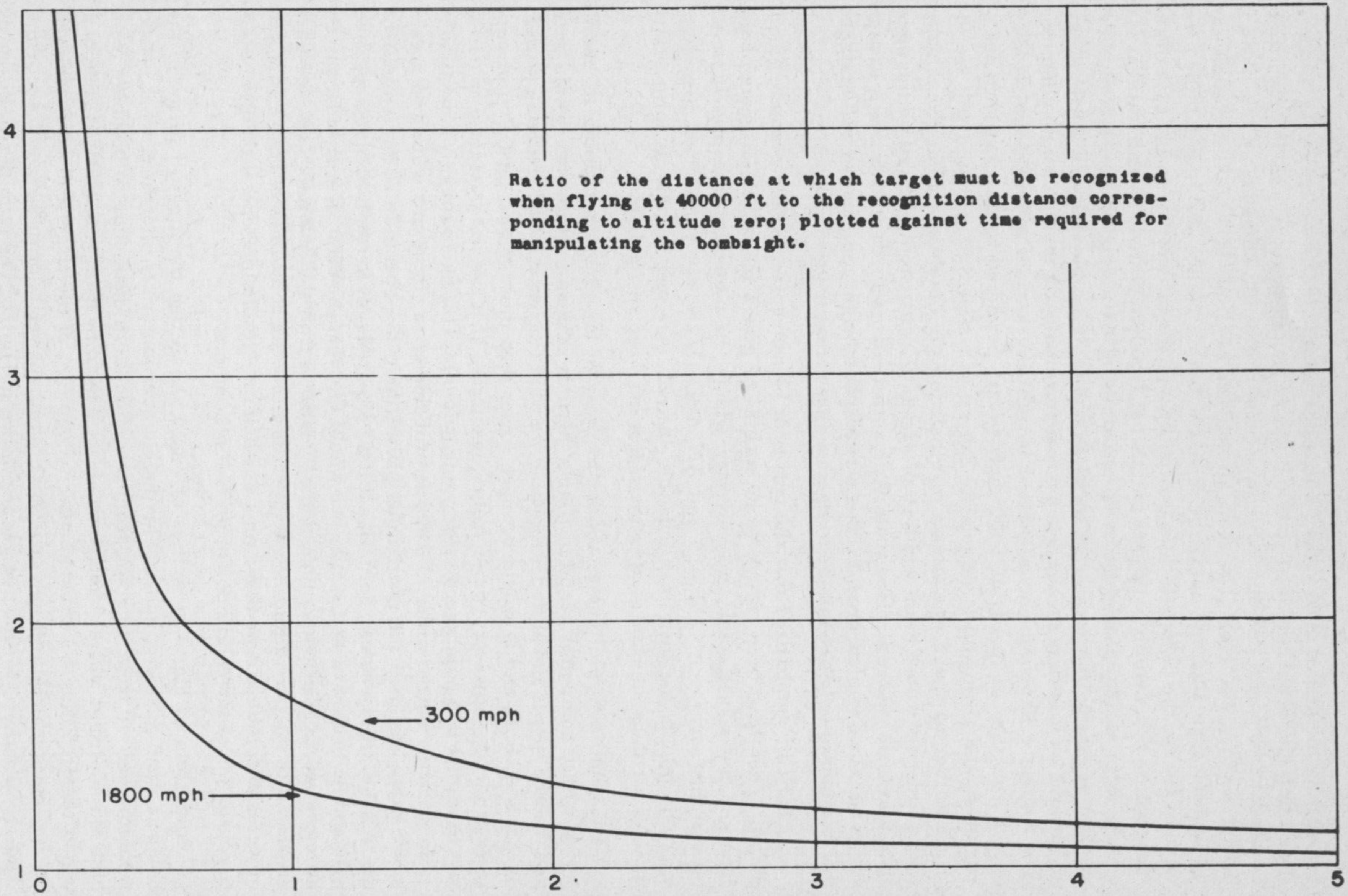
The numbers shown under slant range in the table above are the maximum distances as measured from the airplane to the mean between two point targets one-half mile apart on a line perpendicular to that of the line of sight, and such that the radar is just able to indicate these as two separate and distinct 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 airspeed 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

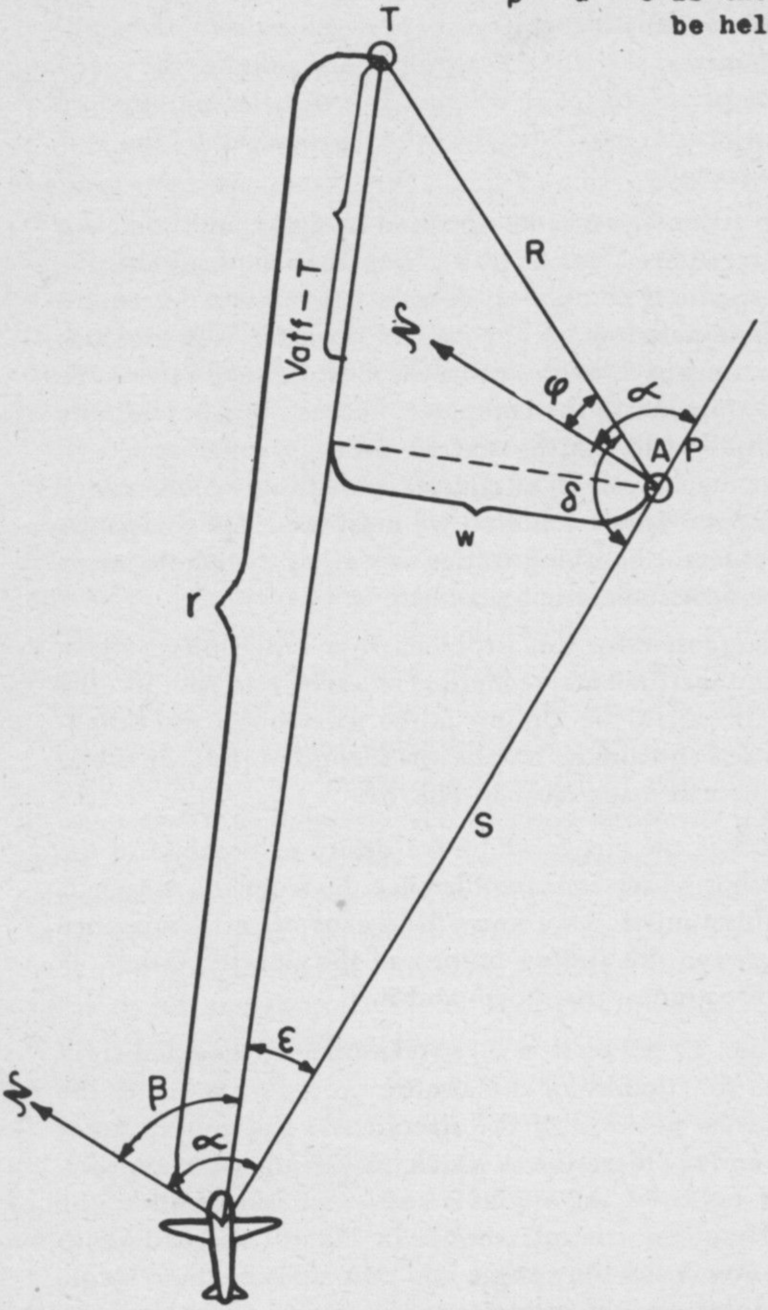


Figure 11 — Computations Necessary for Offset Sighting Computer

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 of a recently developed technique for measuring the thermal radiation from the atmosphere at microwave frequencies, it is possible to measure the total absorption of the atmosphere in any direction. One can thus determine the direction of minimum absorption which is straight up, providing there is horizontal uniformity in the distribution of oxygen in the atmosphere. How accurately the latter condition is fulfilled is not known. The operation is easily carried out automatically and the equipment required is neither bulky nor complicated, consisting essentially of a very small antenna and a microwave receiver. Further investigation of this method would appear desirable.

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

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

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

Conclusion.

The following recommendations are made:

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

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

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

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

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

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

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

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

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

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

THE MEANS FOR STRIKING EXACTLY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

GUNSIGHTS

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

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

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

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

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

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

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

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

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

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

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

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