BEACONS

BEACONS AS AIDS TO NAVIGATION

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

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

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

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

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

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

Beacon Policy: Universal vs. Ad Hoc Beacons.

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

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

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

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

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

The Design of Navigational Beacons.

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

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

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

Design of Radar Sets for Beacon Operation.

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

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

Radar sets should have the following facilities on beacon operation:

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

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

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

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

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

TACTICAL EMPLOYMENT OF BEACONS

Beacons for Paratroop Use.

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

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

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

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

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

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

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

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

Beacons for Air-Ground Cooperation.

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

Airborne Beacons for Air-to-Air Use.

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

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

Miscellaneous Uses of Beacons.

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

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

THE USE OF BEACONS FOR BOMBING

Ground Beacons.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Bombing by the Use of Airborne Beacons.

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

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

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

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

THE FUTURE OF HYPERBOLIC NAVIGATION

HYPERBOLIC SYSTEMS

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

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

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

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

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

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

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

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

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

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

GEE

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

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

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

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

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

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

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

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

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

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

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

LORAN

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

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

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

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

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

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

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

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

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

The chief disadvantages of Loran are:

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

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

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

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

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

SS LORAN

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

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

LOW-FREQUENCY LORAN

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

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

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

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

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

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

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

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

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

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

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

DECCA

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

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

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

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

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

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

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

POTENTIAL ACCURACY AND RANGE

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

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

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

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

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

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

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

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

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

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

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

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

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

AUTOMATIC DATA ANALYSIS

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

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

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

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

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

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

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

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

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

AUTOMATIC PILOTING

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

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

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

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

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

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

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

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

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

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

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

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

RELAYED FIXES

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

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

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

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

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

GUIDANCE OF PILOTLESS AIRCRAFT

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

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

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

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

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

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

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

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

HYPERBOLIC SURVEYING

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

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

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

GROUND CONTROL OF AIRCRAFT

TECHNICAL ASPECTS OF THE CONTROL AND AIRCRAFT LOCATION PROBLEM

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

TACTICAL EMPLOYMENT

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

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

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

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

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

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

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

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

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

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

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

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

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

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

V-Beam.

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

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

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

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

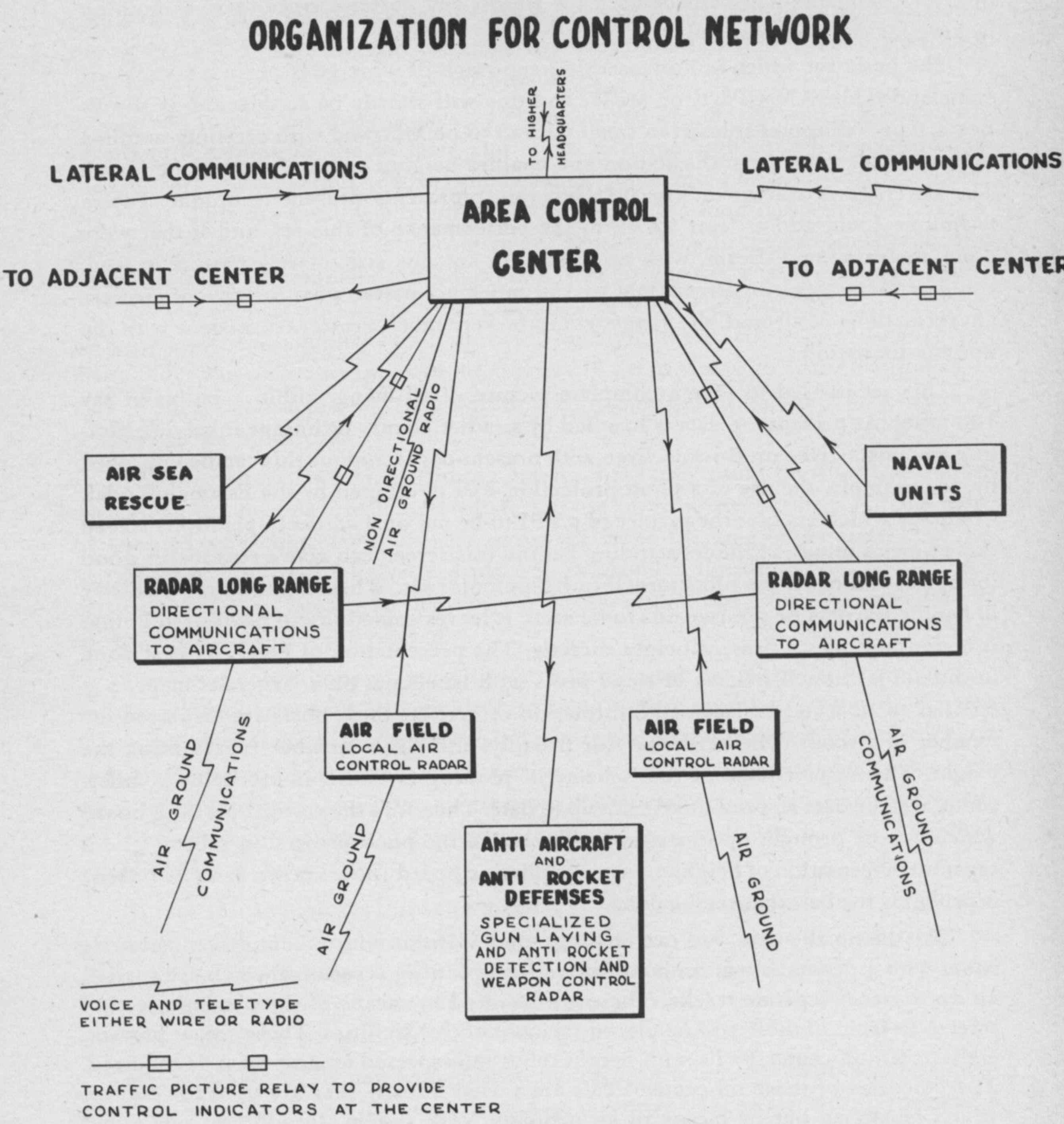

Figure 12 — Organization for Control Network