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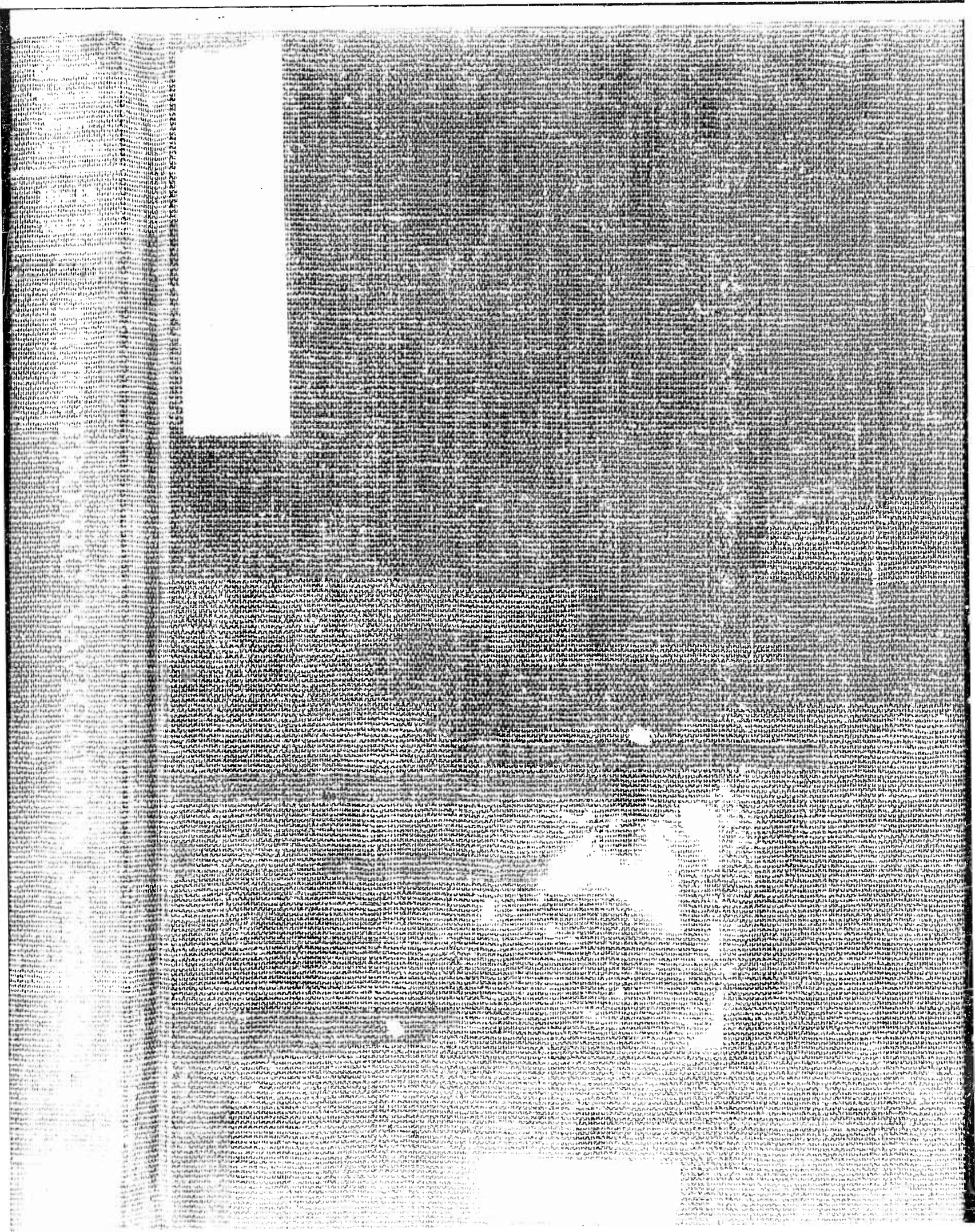
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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 13, NDRC

VOLUME 2B

ELECTRONIC NAVIGATION SYSTEMS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 13
HARADEN PRATT, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A — Armor and Ordnance
Division B — Bombs, Fuels, Gases, & Chemical Problems
Division C — Communication and Transportation
Division D — Detection, Controls, and Instruments
Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1 — Ballistic Research
Division 2 — Effects of Impact and Explosion
Division 3 — Rocket Ordnance
Division 4 — Ordnance Accessories
Division 5 — New Missiles
Division 6 — Sub-Surface Warfare
Division 7 — Fire Control
Division 8 — Explosives
Division 9 — Chemistry
Division 10 — Absorbents and Aerosols
Division 11 — Chemical Engineering
Division 12 — Transportation
Division 13 — Electrical Communication
Division 14 — Radar
Division 15 — Radio Coordination
Division 16 — Optics and Camouflage
Division 17 — Physics
Division 18 — War Metallurgy
Division 19 — Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Of all the NDRC Divisions, few were larger or charged with more diverse responsibilities than Division 13. Under the urgent pressure of wartime requirements, the staff of the Division developed navigation and communications devices and systems which not only contributed to the successful Allied war effort, but which will continue to be of value in time of peace in the fields of transportation and communications. The work of the Division, under the direction first of C. B. Jolliffe and later of Haraden Pratt, furnishes a foundation for what promises to be even more radical developments than those of the war — for one example, direction finders which will operate at all elevations and azimuth angles, in other words, hemispherically.

The Summary Technical Report of Division 13 was prepared under the direction of the Division Chief and authorized by him for publication. The report presents the methods and results of the widely varied research and development program, and, in the case of work with speech scrambling and decoding, it presents for the first time a comprehensive review of the state of the art. The report is also a notable record of the skill and integrity of the scientists and engineers, who, with the cooperation of the Army and Navy and Division contractors, contributed brilliantly to the defense of the nation. To all of these we express our sincere appreciation

Vannevar Bush, Director
Office of Scientific Research and Development
J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

THE PRESENT volume, Volume 2B of Division 13, NDRC, was originally prepared by Central Communications Research, Cruft Laboratory, Harvard University, as Part II of the final report on Contract OEMsr-1441, Service Project AN 31. It is included in this series as a supplement to Volume 2A of the Summary Technical Report of Division 13, NDRC. It presents a descriptive and critical survey of a number of the electronic navigation systems developed during the war, both in this country and in Europe. Some of the systems described are now or were operational during the war. Others are merely proposed. Pin-point bombing and blind landing techniques are excluded.

Section 1 represents an analysis of the principles underlying the three basic types of navigation systems together with notes on the accuracies and limitations inherent in them.

Sections 2 through 30 embody descriptions more or less detailed of the various systems. Section 31 contains comparisons of the several systems, conclusions as to their characteristics, a table summarizing numerical and other data, and recommendations for further research.

The report (OSRD Report No. 6279) of which this volume is a reprint was dated December 1, 1945, and, necessarily, the survey work leading to this report was completed sometime before that date. Thus, systems proposed after the end of 1945 are not included.

HARADEN PRATT
Chief, Division 13

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Introduction

Under the pressure of wartime requirements a great many new and useful navigational methods have been developed, planned, or suggested. The purpose of this survey is to make a basic study of all known radio aids to navigation in order to set up fair and useful bases of comparison, and in order to provide a common background for further developmental programs. Conveniently, all known systems may be analyzed in terms of three basic types, which are described and criticized in Section 1 of this report.

In Sections 2 to 30 inclusive, we have attempted to summarize available knowledge regarding specific systems, showing how each system is built up by dressing one or more of the three basic types with instruments appropriate to the occasion. In part, this instrumentation is determined by the particular navigational problems which the designers of the system have attempted to meet. In part, the choice of particular instruments and expedients seems arbitrary, depending upon individual preferences and previous achievements of the system engineers. In some such instances, we have mentioned alternative methods or devices, especially when the alternative procedure seems to offer certain advantages. However, the authors of this report specifically disclaim any personal experience or specialized background in electronic navigation, other than that which they have acquired in this research by analyzing all available documents, visiting a number of research laboratories, and conferring repeatedly with the various Army, Navy, and Coast Guard groups in charge of such developments and applications. This fresh approach to the problem has permitted a strictly impartial consideration of all systems. If any personal preferences occasionally are implied in the text, it should, therefore, be understood that such thoughts have developed in the course of this survey, and now represent the consensus of opinion of an unbiased five-man jury.

The authors consider an important part of their contribution to be the collection and presentation of descriptions of the numerous systems, existing or proposed. If these systems are to be critically compared, such a collection of descriptive material would in any case have to be made, and this report therefore presents both the conclusions reached and an outline of the knowledge on which they are based. Collection of these data proved to be a major enterprise, requiring the selection and analysis of several hundred documents, picked out from thousands of abstracts of related material. Where possible these documents were supplemented and brought up-to-date by personal inquiries and by inspection trips. After "threshing out" each system at some meeting of our research group, individual authors have described the several systems assigned to them, attempting to observe a reasonably uniform practice in text and diagrams. Such descriptions normally begin with a brief summary in a standardized tabular form, intelligible to any scientifically-minded reader. This introduction is followed by a presentation of such technical features of each system as are deemed likely to interest persons who are reasonably familiar with electronic circuitry in general. Familiar items such as conventional transmitters and receivers have been treated very lightly, in order to conserve space for a fuller presentation of important novelties in electronic timing devices, phasing networks, etc. Particular attention has been paid to those technical assets and liabilities of each system which seem likely to determine its ultimate precision and coverage. The descriptive sections are intentionally very unequal in length. Considerable detail has been included in treating systems which have been placed in actual operation. Some of the proposed systems are very interesting and may later prove to be valuable, but their components are somewhat nebulous at this stage in the design and can be treated adequately in a few sentences.

With one very minor exception we have had complete access to all pertinent information available in the United States and England. This information naturally included data regarding a considerable number of enemy systems, though we have had to describe some of these in outline form only, lacking details of instrumentation (in October 1945) at the time our survey closed. The gaps are probably not important, as the one outstanding German system is covered in considerable detail, partly on the basis of post-war inspection of significant components. On account of the classification assigned to most of our source material at the time when such information was obtained, we find it obligatory to assign the initial classification of "Secret" to this survey. However, we hope and expect that our initial classification may soon be reduced or deleted by competent governmental authority. Such action would release the information to a larger group of engineers at a time when it should be particularly useful in planning a coordinated world-wide navigation system. At the specific suggestion of the Army and Navy, we have always included the post-war aspects of the problem in our debates, in addition to the closely-related military tasks. In our own judgment the descriptions and diagrams here included are suitable for declassification at this time.

In order to conserve space we have excluded from our descriptions certain highly specialized problems which the term "navigation" might otherwise include. The specific exclusions are:

1. Pin-point bombing
2. Blind landing
3. Electronic Altimeters.

Accordingly, our treatment of "navigation" includes the location of military vehicles and troops on land, the navigation of ships at sea, and the guidance of aircraft over long distances and in the neighborhood of airports. Pilotage of ships under difficult conditions is included in our field of interest, but our problem is suspended while an aircraft is making its "bombing run" in the immediate vicinity of a hostile objective and terminates when an aircraft arrives at the "stacking space" over a friendly airport. These restrictions accord with the original directives in which the survey was requested.

One additional comment on the word "navigation" may be useful by way of introduction to our subject. In the broad sense "navigation" is typified by the problem of the tramp steamer, which should be able to follow any arbitrary route, anywhere on the high seas. We do not speak of "navigation" when referring to the locomotive engineer, who follows a steel track and is governed by block signals, warning torpedoes, etc. Commercial airlines, especially over land, present an intermediate case, lying between these two extremes. Normally the pilot follows an electronic track, equipped with radio beacons and equivalent milestones. However, he may inadvertently become a "navigator" in the broader sense, in case he is driven "off-the-beam" by severe storms or other emergencies. Modern versions of the "beam" system are strongly favored by the airlines and are included in this report, though our main interest attaches to the more difficult problems of general unrestricted navigation.

Following the numerous descriptions of specific systems we have included a few final remarks (Section 31) on comparisons, evaluations, conclusions, and suggestions for continued research and development. For the most part, these are the natural and almost inevitable comparisons and suggestions which germinate automatically when a small discussion group submerges itself in such a welter of related systems for a number of weeks. Constant restraint has been necessary in order to keep individual members of the group from inventing a dozen or more new variants of the species already on display. Scattered at appropriate places throughout the descriptive sections will be found a few minor researches, of a theoretical

nature, aimed at evaluation of the capabilities and limitations of the general principles appearing in the context.

We wish to acknowledge the cordial cooperation of the Army and Navy Liaison Officers associated with the project and with our laboratory. Great assistance has been rendered by the OSRD Liaison Office in Washington which assisted in the procurement of the majority of the foreign and domestic documents employed in the survey. Exchange of information with the Watson Laboratories and the Wright Field research group of the Army Air Force, and with Division 14 of OSRD has been particularly valuable. Provided with suitable credentials, we have been hospitably received by a number of the industrial laboratories that are represented in sections which follow. If exception be taken to any of our evaluations of the industrial proposals, we are confident that our sincerity and good faith will not be questioned, however much we may be criticized on scientific principles and applications.

In some cases, diagrams and descriptive material have been freely borrowed from the appropriate documents, which are listed in the bibliography at the end of each section. In other cases, where the wealth of available material made considerable condensation necessary, a new approach has been used. The documents listed in each bibliography do not, of course, represent all the available references, but rather those which we have found to be of greatest value for our purpose.

Space does not permit a complete description of the detailed circuitry in each of the radar systems contained in this report. The circuits of one radar system (AN/APS-15) are described in detail. Descriptions of the other radar systems omit detailed circuitry and consider only the general characteristics, important features, and special techniques involved. The circuit details may be found in various references listed under each system.

Table 1.01 serves as an outline for Section 1. It will also be repeated, with appropriate insertions, at the beginning of each of the descriptions of individual systems; the table containing a summary of the characteristics of the particular system under examination. Finally these individual tables are collected on a single sheet (pages 31.06, 31.07).

Table 1.01

1. Type of System (How the information is obtained)

   (a) Pure range system (circular lines of position)
   (b) Differential range system (hyperbolic lines of position)
   (c) Azimuth system (radial lines of position)

2. Useful Range (Over what coverage area the information is obtainable)

   (a) Dependence on transmitter power
   (b) Other considerations

3. Accuracy and Precision (Errors in the results obtained)

   (a) The time measurement. Maximum theoretical precision obtainable with equipment
   (b) The propagation path. Uncertainties due to propagation
   (c) Ambiguities
   (d) Geometrical considerations in obtaining a "fix" from two or more lines of position

4. Presentation or Use of Data (How the information is presented to the navigator)

   (a) Aural
   (b) Visual
   (c) Automatic control

5. Operating Skills Required (Training and experience)

   (a) At ground or fixed installation
   (b) In the navigated craft
   (c) Time required to obtain a line of position or a fix

6. Equipment Required (Weight, complexity, service and maintenance requirements)

   (a) At ground or fixed installation
   (b) In the navigated craft

7. Radio-frequency Spectrum Allotments Required (Frequency, wavelength, bandwidth)

8. Present Status of Development

I. Types of Navigation Systems

a. Pure range systems

All systems depend on the constancy of the velocity of electromagnetic waves. This quantity relates the measurement of a time or an electrical phase angle to the determination of a distance or an angle in space. Consider first the determination of a distance which is measured by measuring the time of travel of an electro-magnetic disturbance over the distance. The simplest application of this fundamental idea is that of radar "ranging" or distance measuring. (The word "simplest" used above does not refer to the equipment used to make the measurement but rather to the simplicity of the governing principle). The radar transmitter sends out a signal which may be a pulse-modulated or otherwise modulated radio frequency carrier. This transmission travels outward from the transmitter with a spherical wave front. Aircraft, surface vessels, obstructions, and geographical or tropospheric discontinuities and variations in the dielectric constant all reflect as "echoes" a small part of the transmitted energy. A sensitive receiver located at or near the transmitter receives and amplifies these "echoes". By suitable circuitry the elapsed time between the sending of the signal and its return as an echo is measured and the distance to the reflector of the echo is then known. Suppose for example that such a measurement has been made and turns out to be twenty miles and that the reflector in this case is a surface vessel. The radar operator would then know that somewhere at a distance of twenty miles from his set (the position of which is assumed known) there is a surface vessel. (The operator may also get some measurement of the azimuth angle to the particular vessel but that is another part of the story, so let us suppose for the moment that all he knows is the distance). He could then draw a circle of twenty-mile radius on his chart, and thus establish one line of position for the surface vessel. A similar determination on the same vessel from a radar set at a different location would establish a second circular line of position. These two circular lines of position drawn on a chart about their respective transmitter locations will intersect at two points, one of which corresponds to the location of the surface vessel. The "fix" might equally well be determined by taking radar range measurements from a craft to two or more known fixed reflectors or responding beacons. In any case this pure range type of system is characterized by circular lines of position. The responding beacons referred to above are simply receiver-transmitters which send back an amplified "echo" or response, thus extending the useful range of the system and perhaps identifying the point from which the response was returned.

It is implicit in the pure range or distance measurement type of system that the position of the navigated craft is disclosed in the general case where the craft is to have its "fix" determined. Either it must radiate a signal to man-made reflectors or beacons or to geographical reflectors. Or if its position is determined by radar methods from fixed stations it must be informed of its fix. This information may be coded or returned on a narrow beam communication system, televised, or otherwise kept secret. It is however possible to "vector" or direct a craft by ground radar determinations without exposing the position of the craft. The direct range system has the inherent property of being saturable. A system is said to be saturable when the number of craft which may navigate with the aid of a given fixed installation is limited. Thus the number of aircraft or surface vessels which may be "tracked" by a single radar set is limited, as is the number of craft which can interrogate a given beacon at any one time without overloading it. If the radar set is on the craft, then the number of such craft which can radiate signals in a given band is limited by interference. Either each craft must send out pulses at his particular frequency so that he can distinguish them in echo, or each must interrogate a beacon at the beacon receiving frequency and match his own characteristic pulse rate in order to select his own response. In the first case more craft mean more channels

in the spectrum, in the second the number of responses which a beacon can put out is limited by overlapping. Practically, the theoretical condition of overlapping is not approached since average power output for present day beacons limits the permissible number of responses per unit time for a given pulse energy. If one attempts to shorten pulses to avoid overlapping, the result is increased band width of the spectrum required for the transmission. The fundamental reason for the saturation effect is the "round trip" nature of the transmission. This in turn is necessary if one is to measure total time of travel. There is at present no sufficiently accurate absolute time clock with a microsecond "hand". If one had such a clock aboard the craft and knew that a certain station transmitted a pulse every second on the even second on precise Greenwich time, he could then measure the time that the pulse required to travel from the fixed station to his position, and hence have a direct measure of distance with one way transmission, and hence no saturation effect or disclosure of position.

At the present time it is possible to build crystal oscillators which under proper operating conditions, temperature, voltage control, etc., will run with an uncertainty not exceeding 1 part in a thousand million. 1 part in 10^9 is equivalent to 1 microsecond in 17 minutes or 5.37 microseconds in 1.5 hours which is an uncertainty of 1 mile in 1.5 hours. (5.37 microseconds is the time required for light or radio waves to travel one mile.) Thus having set the high precision clock described above, a navigator could determine his position with an uncertainty of one mile or less for a time of one hour and a half from the setting of his clock. This means that at the present state of the art one might navigate by pure range measurement up to 450 miles at a speed of 300 miles per hour, without saturation or disclosure of his position with a maximum error of 1 mile in the determination of his line of position, assuming of course that the above accuracy could be maintained with airborne equipment as well as at the ground station. This hypothetical pure range system requires the accurate measurement of very long time intervals which is not yet practicable. Shorter intervals of time can be measured more exactly, that is to say an extremely accurate clock is required to measure with a precision of one microsecond in 1000 seconds but it is easily possible to measure time with a precision of one microsecond in one second. The microsecond is a very convenient unit of time and because of the constancy of the velocity of light it is quite common to speak of distances in terms of microseconds, i.e. one statute mile is equivalent to 5.37 microseconds for a one-way trip, or to 10.74 microseconds if a round-trip path is considered as in radar echoes. A number of useful conversions from distance to time and corresponding wave lengths and frequencies are given in Appendix B at the end of this document.

b. Differential range systems

In the differential range systems, a shorter time interval is measured to determine a line of position. This is accomplished by transmitting signals from two fixed antennas, these signals having a known time or phase difference as they leave the transmitting antennas. If the signals are pulses, these are separated by a time interval known to the navigator who is to use the system. If they are modulated or keyed then the modulation envelopes or radio frequency cycles have a known phase relationship. Suppose for example, that two transmitting stations are located at points A and B in Figure 1-01 where the distance A to B is known as the base, and is in this example 111.72 miles long, that distance being chosen since it corresponds to six hundred microseconds time of travel of a radio wave from A to B. Suppose that pulses are sent out simultaneously from A and B so that a navigator with proper measuring equipment could determine the difference in the time of arrival of these pulses at his craft. If the craft were at any point on the line which bisects the base line at right angles, then the two pulses would arrive simultaneously, or conversely if the navigator received the pulses simultaneously he would know that he was somewhere on the perpendicular bisector of the base line. If he received the pulse from B 100 microseconds before the pulse from A he would know that he was 18.62 miles

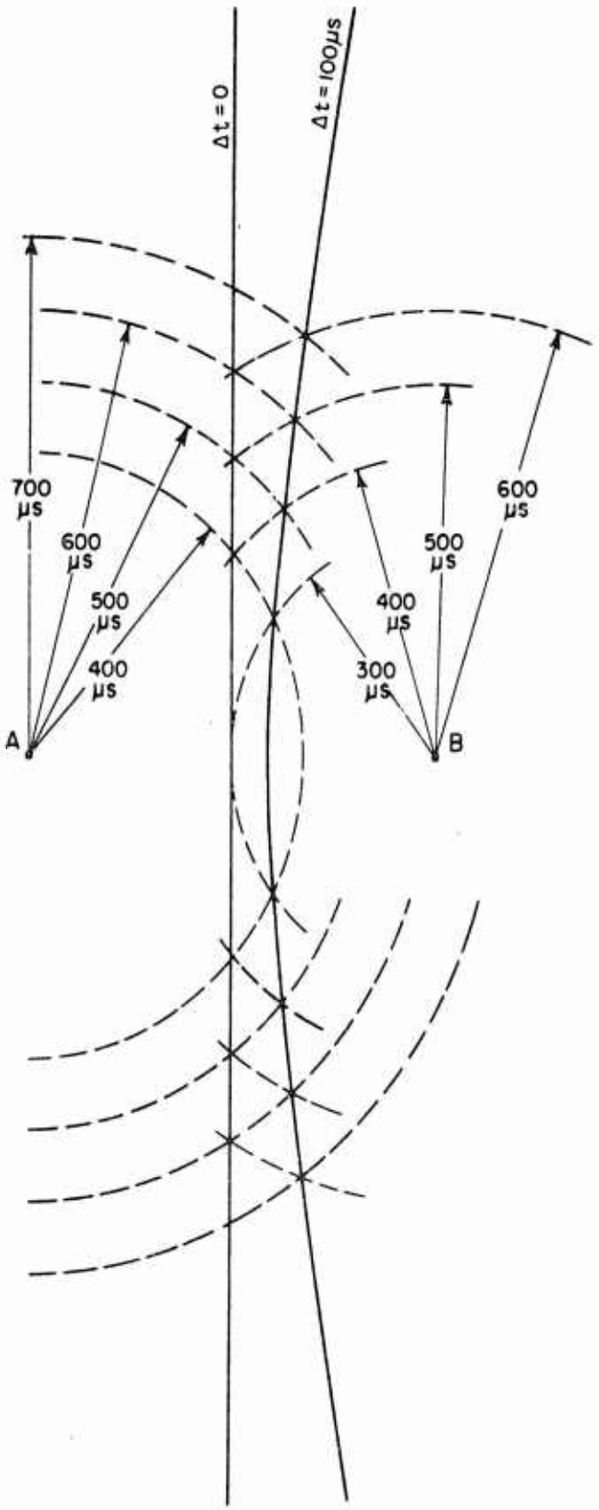


Fig. 1-01 Construction of hyperbolic lines of position

nearer B than A. The locus of points which are 18.62 miles nearer B than A may be found by arbitrarily selecting a distance and drawing a circle of this arbitrary radius about point B; and then drawing a circle about A which has a radius 18.62 miles greater than that about B. The locus of points thus determined is the curve shown in Figure 1-01, (solid line), which is the line of position for the craft when the measurement indicates that the pulse from B arrives 100 microseconds before the pulse from A. Figure 1-02 shows two families of concentric circles drawn (dashed lines) about points A and B, the successive radii of the circles being 18.62 miles or 100 microseconds apart. Connecting successive inter-

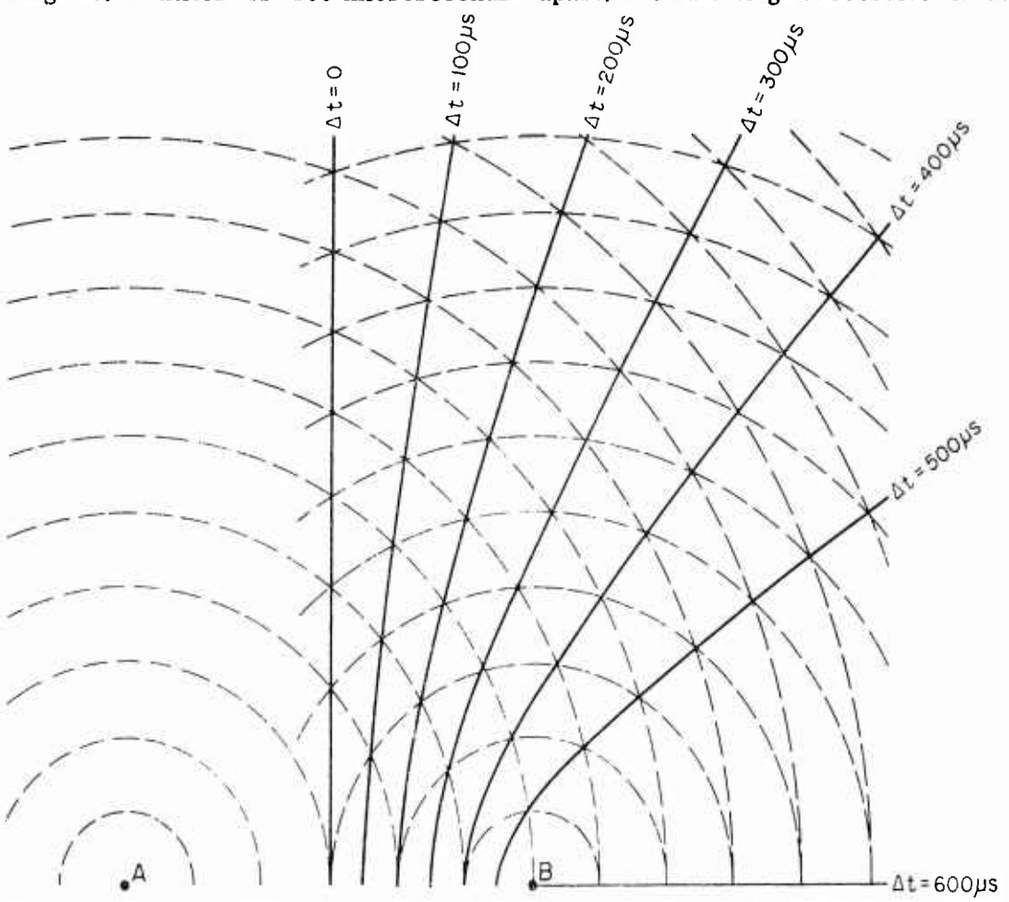


Fig. 1-02 Family of hyperbolic position lines, showing the relationship to an optical interference pattern

sections of circles (solid lines) gives lines of position corresponding to time differences of 100 up to 600 microseconds difference in time of arrival of the two pulses. These lines of position are hyperbolae (if one assumes that the earth is flat, which is very approximately true for coverage areas not more than 500 miles across) since they are the loci of points whose distances to A are greater than their corresponding distances to B by a constant amount. Navigation systems of this type are called hyperbolic or differential range systems. In the region to the left of the base-line bisector in Figure 1-01 and 1-02 the pulse from A will arrive first and one could draw a similar family of lines of position. The navigator must be able to distinguish the A pulse from the B pulse in order to tell whether he is to the right or left of the bisector. If the pulses are indistinguishable there will be an ambiguity. This is avoided in certain systems by delaying the pulse from one station by a time greater than the time to traverse the base line length. If pulse A is so delayed then the pulse from B will arrive first at all points in the diagram, there will be no ambiguity. Suppose that pulse A is delayed 700 microseconds behind pulse B . Figure 1-03 then shows the same diagram as Figure 1-02 without

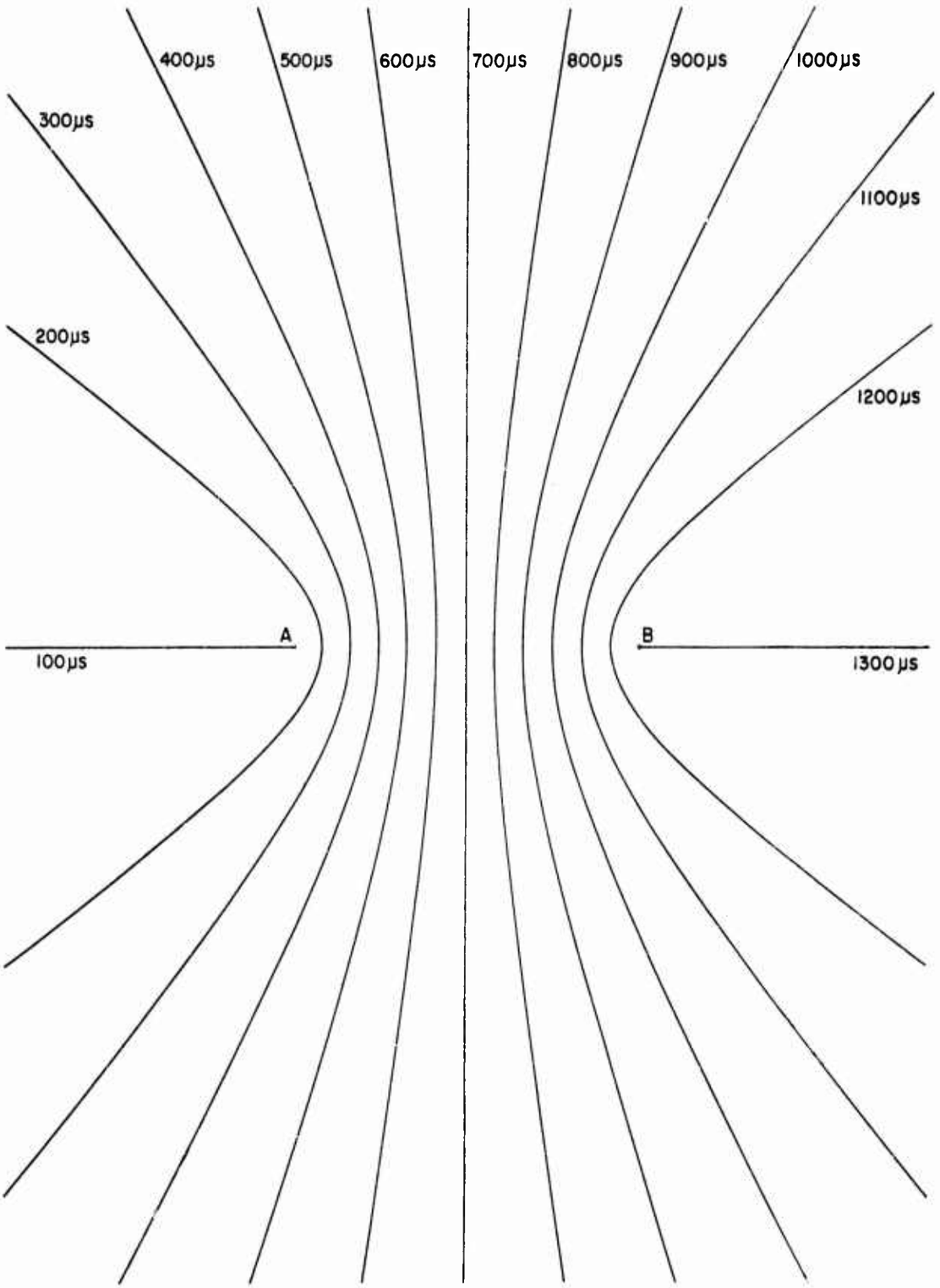


Fig. 1-03 Family of hyperbolic lines of position, with the A pulse delayed 700 microseconds behind the B pulse

the construction circles and with the hyperbolae marked with appropriate delay times in microseconds. Two or more such sets of hyperbolic lines of position will be necessary for determination of a "fix". Note that with direct range measurement one transmitting antenna could define a family of circular lines of position, whereas with the differential range system at least two transmitting antennas are necessary to define a family of hyperbolic lines of position. With the differential range system the craft emits no signals of its own and hence does not disclose its position, and furthermore the system is not saturable. The longest total time which the navigator must be able to measure is the total delay time between the sending out of pulses plus the time-length of base line. Since the time-length of the base line entered into the delay time as a necessary minimum value when there is to be no ambiguity, the total time to be measured may be somewhat longer than twice the length of the base line expressed as a time. In Figure 1-03 this is 1300 microseconds for points at the extreme right of the diagram. Thus in general the greater the length of the base line the longer the time interval which the system must be capable of measuring. The only serious limitation on the length of the base line is that synchronism must be maintained between stations whose pulses are to bear a fixed relation to one another, and this in turn means that the pulse from one must be receivable at the other under all propagation conditions. Very long base lines are desirable for hyperbolic systems, since the lines of position will then be more or less straight and parallel over a large area; this in turn means a large area over which the maximum precision of the system is attainable. As pointed out earlier, the lines of position of a hyperbolic system are hyperbolae if the curvature of the earth can be neglected. However, as a number of people have pointed out, if one could use the longest possible base line, which is half the circumference of the earth, and set up transmitters at each pole, then the lines of position would be circular and would in fact be parallels of latitude. Hyperbolic systems lend themselves to fixed course navigation where the fixed course is a hyperbola. It is interesting to note that when navigating on a hyperbolic course the tangent to the course at the position of the craft always bisects the angle made by lines drawn from the position of the craft to each of the two stations which define the hyperbola. This in turn means that the vector components of velocity towards each station are equal in magnitude.

Pulse transmissions have to be repeated with a known repetition pattern, usually at a constant repetition rate. As long as the repetition period is somewhat greater than twice the longest time to be measured there will be no ambiguity. On the other hand it is desirable to keep repetition rates fast enough so that the navigated craft does not move too far between measurements. If the measurement of time is made visually on an oscilloscope then it is desirable to have the repetition rate fast enough to avoid flicker. In the example of a pulse-modulated system just considered a delay time of 100 microseconds was added to the time length of the base to make up the total delay time of the A pulse. This delay time has two useful functions. First, it avoids the need of measuring very short time intervals which may be difficult in a system designed for measuring long intervals. Second, it may be varied in a predetermined manner for denying the effective use of the system to the enemy.

As a second example of a hyperbolic system suppose that the transmissions from stations A and B of Figure 1-04 are sinusoidally modulated at 833 cycles per second, so chosen because the wavelength corresponding to 833 cycles per second is twice the base length which is 600 microseconds, and that the radio frequency of stations A and B is different so that the transmissions from the two stations are recognizable. Suppose further that the modulation envelopes are 180^{0} out of phase as they leave the transmitting antennas. On the craft being navigated there are two receiving circuits tuned to the transmissions from A and B, and a suitable means of phase comparison (it is assumed that equal phase-shifts are introduced by the two receivers). On the bisector of the base line the two modulation envelopes from A and

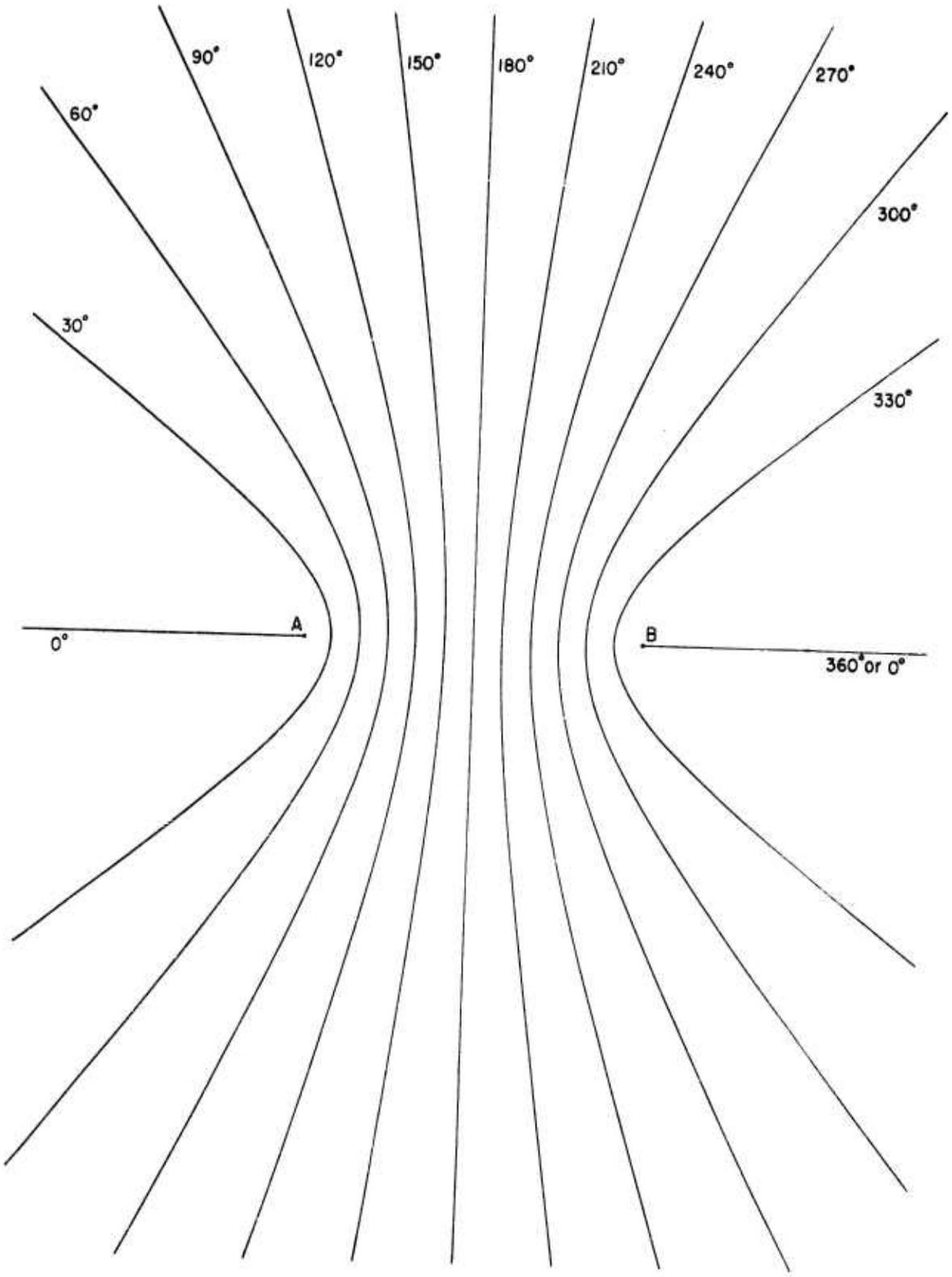


Fig. 1-04 Hyperbolic position lines, similar to Fig. 1-03, but with delay times defined in terms of phase differences between the A and B signals. Base line = $\lambda/2$

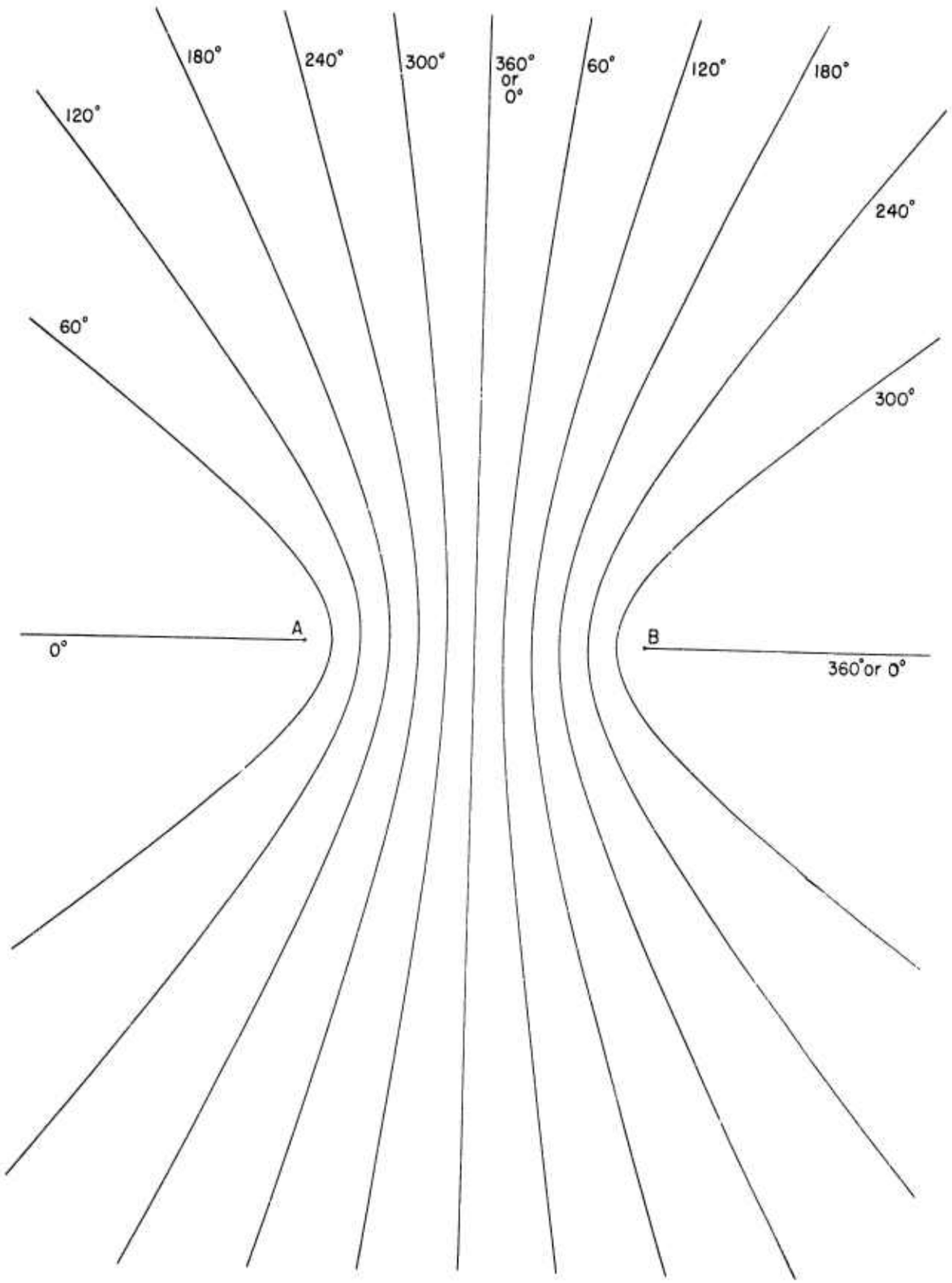


Fig. 1-05 Similar to Fig. 1-04, but with base line = λ

B will be delayed in transmission by the same amount and will arrive, as they were transmitted, 180° out of phase. Along the base-line extension from the A station the phase difference between the two envelopes will be zero, if one uses the A transmission as phase zero, and the position lines are lines of constant time difference as they were in Figures 1-02 and 1-03 except that the time is measured in terms of phase angles of the 833-cycle modulation envelope. The period corresponding to 833 cycles is $\frac{10^6}{833}$ = 1200 microseconds, and a phase difference of 30° at 833 cps corresponds to a time-difference of 100 microseconds. Note that for this choice of modulation frequency there is no ambiguity and also that 360 electrical degrees of phase shift corresponds to 180° of azimuth angle about the center of the base line. If a higher modulation frequency is used, the ratio of electrical to azimuthal degrees is increased, but ambiguities arise. For instance, suppose the modulation frequency is 1666 cps so that the wavelength of the modulation cycle is equal to the base line length, and that the modulation envelopes are in phase as they leave the transmitting stations. Figure 1-05 then shows the resultant phase relationship between the received A and B modulation envelopes. It is evident that there are two lines of position corresponding to any measured phase angle between 0 and 360° and hence an ambiguity. However, if the phase control of the transmitted modulation envelopes and the precision of phase measurement at the craft in terms of degrees of electrical phase angle is the same at 1666 cps as it was at 833 cps, the precision of a line of position will be twice as high at the higher frequency. In general, for a constant base line length, and constant precision of phase output and measurement, higher frequency means higher precision of a line of position and more ambiguities. Lengthening the base line and keeping modulation frequency and phase precision constant does not improve the line of position precision at points near the baseline, although as will be pointed out in the discussion of azimuthal systems the precision at points away from the base line is improved. This is simply saying that longer base lines give larger coverage areas for a given precision of result. The number of ambiguities is in general twice the number of wave lengths of the comparison frequency in the base line, the number of ambiguities being the number of lines of position along which the same phase or time difference will be measured. Another possibility is to transmit two different unmodulated radio frequencies from the two ends of the base line, and then to convert these to the same frequency at the craft for the phase comparison measurement. Here again the phase shifts introduced at the craft must be proportional to the frequency and constant in time. One might transmit unmodulated radio-frequency carriers at the same frequency for each antenna except that it would be impossible to distinguish the transmissions from the two antennas, and hence compare their phase. Since radio frequencies are much higher than the 833 cps used in the previous example the number of wave-lengths in the base line would be large as would the number of ambiguities in the pattern if the base length were kept the same. Furthermore the problem of maintaining radio frequency phase synchronism at the two ends of a long base line is difficult. Hence systems using phase comparison at radio frequencies usually employ shorter base lines. A shorter base line implies a smaller region where the lines of position are approximately parallel. If the lines of position of any hyperbolic system are extended far enough out from the base they asymptotically approach straight lines radiating from the center of the base.

c. Azimuthal or radial systems

A hyperbolic system becomes an azimuthal system when the base line is a small fraction of the useful range of the system. At distances from the center of the base line greater than five times the length of the base the hyperbolae are essentially straight lines radiating out from the center of the base line. The hyperbola which is the bisector of the base is exactly a straight line at all ranges. On the earth these radial lines of position are approximately great circles for all ranges greater than five times the base length. (The approximation is due to the possibility of mul-

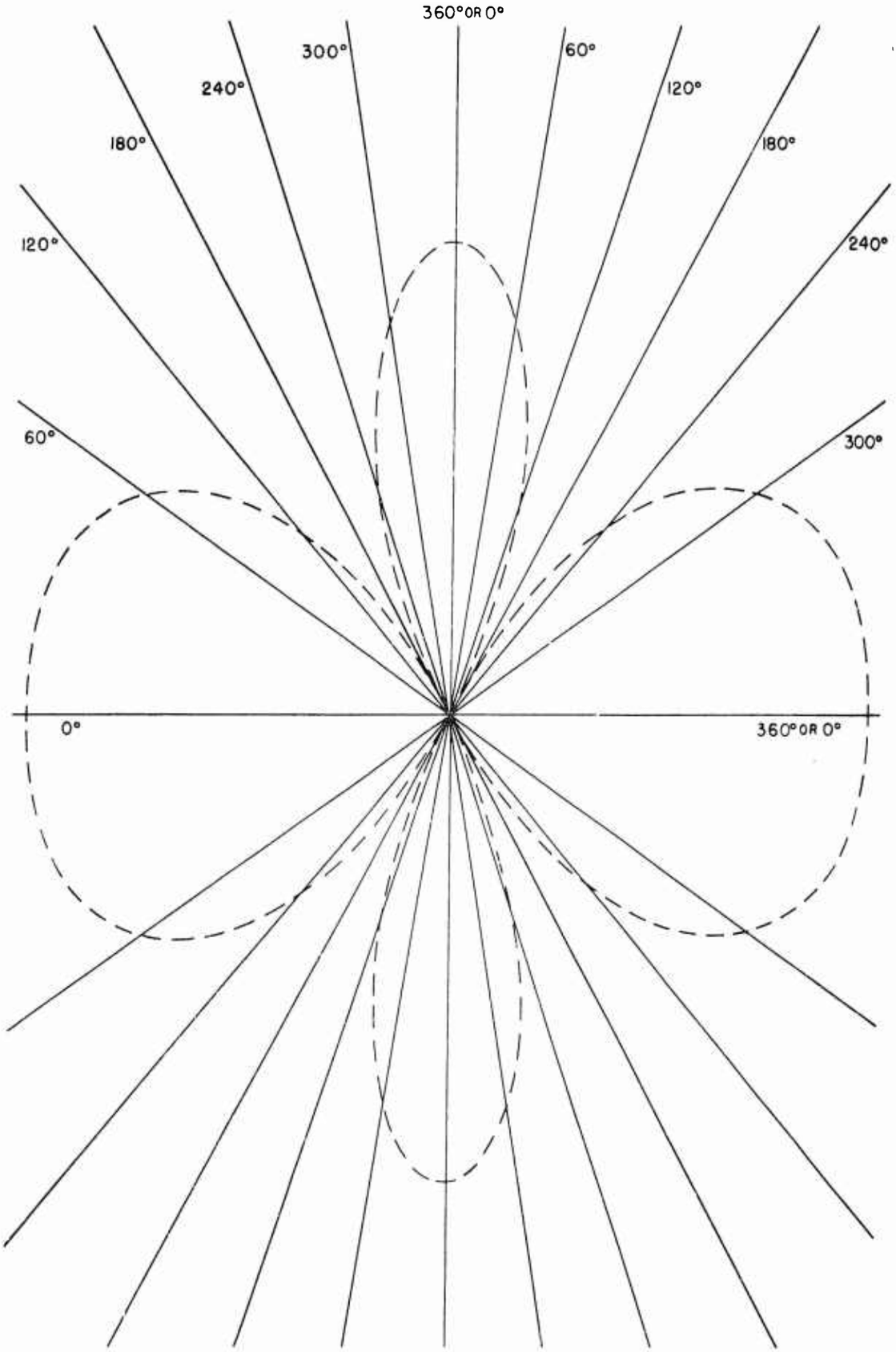


Fig. 1-06 Azimuthal lines of position, derived from Fig. 1-05, showing effect of radio-frequency phase addition and cancellation, resulting in horizontal radiation pattern. Spacing = λ, transmissions in phase

tiple transmission paths). As an example of an azimuthal system, suppose that the base line is 1.862 miles long and that the antennas at each end of the base line are driven in phase at a frequency of 100 kcps, the frequency whose corresponding wave length is 1.862 miles, so that the base line is one wave-length long. Figure 1-06 is simply an extension of Figure 1-05 which was for a case where the base was one wave-length long. The base line length is so small compared to the useful range that the points A and B are very close together and are not shown on the diagram although their line of centers is assumed horizontal as it was in Figure 1-05. The relative phase between the transmissions from the two antennas is given alongside the lines of position. Now however, the frequency is the same from each transmitting antenna and along the lines marked 180^{o} there will be phase cancellation so that no radio frequency signals from A and B will be detected. Along the lines marked 0^{o} or 360^{o} there will be phase addition and a maximum intensity of 100 kcps signal will be received. The result of this is an interference pattern where the intensity of the received signal varies as the cosine of half the angle of phase difference. The dotted curved lines in Figure 1-06 are a polar plot of this function and are called the horizontal pattern of the antenna arrangement of Figure 1-06.

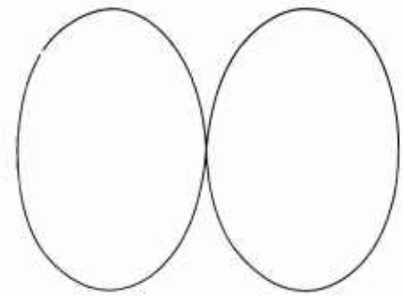
Figure 1-07 shows typical antenna patterns for various spacings and phase relationships of the A and B signals. In azimuth systems the lines of position define bearing angles on the base line of the system, so that the uncertainty of a line of position expressed in miles is directly proportional to the distance out from the center of the base line. The angular precision is highest near the bisector of the base and poorest along the base line extensions. If with a given system it is possible to control and measure phase to an uncertainty of ten degrees of electric phase angle then the geometric angular precision will depend on the number of wavelengths in the base line and on the angle between the particular line of position under consideration and the bisector of the base. Consider points near the bisector of the base line and assume the base line to be one-half wavelength long. The differential phase angles are the same as those in Figure 1-04 and one has 30 electrical degrees compressed into less than 10 azimuthal degrees. So that if there were an uncertainty of ten electrical degrees, the geometrical line of position uncertainty would only be 3.33 degrees. If the base line is a whole wavelength then 60 electrical degrees correspond to less than 10 geometric degrees so that the same uncertainty of ten electrical degrees gives only 1.66 azimuthal degrees of uncertainty. As the base line is increased in length, the precision and also the number of ambiguities increase in direct proportion. In general, the maximum precision in a radial line of position attainable with a two-antenna azimuthal system near the base line bisector is given by a simple equation.

$$\frac{\text{Uncertainty in miles}}{\text{Distance to center of base in miles}} = \frac{\text{Overall uncertainty in electrical degrees}}{\text{Number of electrical degrees in base}}$$

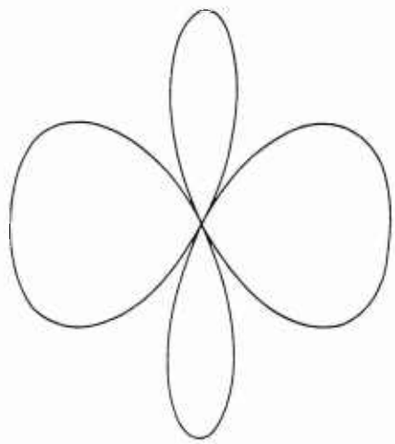
Thus if the system is capable of transmitting and measuring with an overall uncertainty of 3.6 degress and if the base is 360 degrees (one wavelength) long the uncertainty in distance will be one mile at 100 miles from the center of the base or 10 miles at 1000 miles. If the uncertainty of electric phase angle can be held constant while raising the frequency and keeping the base length constant, or while lengthening the base and holding the same frequency, the effect will be to increase the precision in direct proportion. For a two-antenna azimuthal system the more general equation for any given line of position is given on page 1.22. This equation assumes that the base line length is much less than the distance from the observer to the center of the base, which is true for azimuthal systems by definition. The number of ambiguities is twice the number of wavelengths in the base.



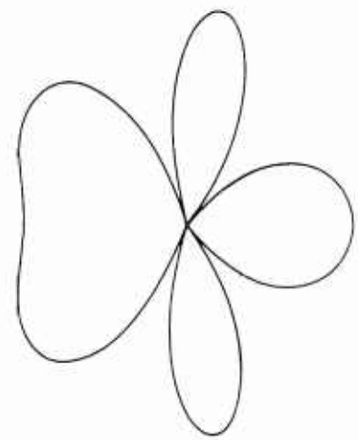
(a) Spacing $\lambda/2$, phasing 0^{o}



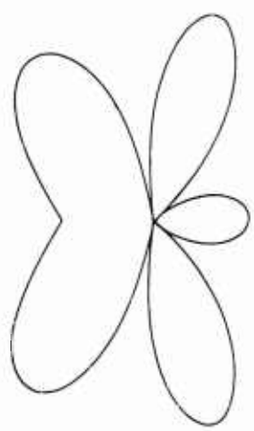
(b) Spacing $\lambda/2$, phasing 180^{o}



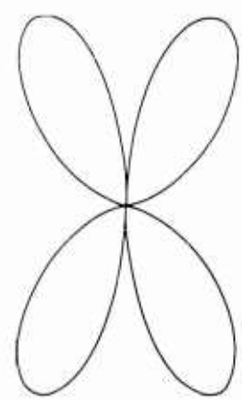
(c) Spacing λ, phasing 0^{o}



(d) Spacing λ, phasing 60^{o}



(e) Spacing λ, phasing 120^{o}



(f) Spacing λ, phasing 180^{o}

Fig. 1-07 Horizontal radiation patterns, line of antennas horizontal

All the discussion so far has been concerned with systems employing two antennas. Many azimuthal systems use more elaborate antenna arrays and variable phase control circuits to produce rotation or oscillation of antenna patterns. Others rotate the entire antenna array to produce the same effect. At the super high frequencies these antenna arrays take the form of reflectors and lenses having very sharp directional antenna patterns. With multiple antenna arrays the number of ambiguities increases, for a given spacing, but since the array intensity pattern becomes more directional the side lobes are less pronounced and not as likely to give rise to ambiguities. Systems which can be rotated have the advantage that the only line of position actually intended for use is the base line bisector which is the most accurate line defined by the system. An example of a horizontal radiation pattern produced by three antennas is shown in Figure 17-03.

Composite Systems

A number of radar systems using such sharply defined antenna patterns yield both range and azimuth data and hence serve to locate the craft from one fixed installation. The range data define circular lines of position about the radar set and the azimuth data define radial lines of position which intersect the circles at right angles and give a "fix". The accuracy is constant for varying azimuth at a given range, in contrast with other systems in which the two position lines defining a fix do not always intersect at right-angles. Also the radial line of position is always the base bisector.

II. Useful Range

(a) Dependence on transmitter power

Coverage implies that the navigation system is capable of maintaining continuity in the supply of navigational information. Twenty-four-hour continuity is implied unless otherwise stated in a specific application.

The signal strength necessary for satisfactory reception depends on local noise conditions at the receiver and on the noise generated within the receiver itself as well as on the type of transmission and the method of presentation. Local noise varies with the geographical location, the season of the year, the time of day, and other factors many of which are unpredictable. Coverage areas often may be extended by increasing the transmitted power, but the increase of useful range at long ranges is very small even for large increases of power. For instance, referring to Figure 1-11, at 125 kcps, doubling the output power would extend the range for 10 microvolts per meter signal strength of ground wave from 1530 to 1610 miles. And increasing the power by a factor of one hundred would only increase the 10-microvolt ground-wave range to 2110 miles. The useful coverage area of a navigation system is further determined by several factors.

(b) Other considerations

(1) The maximum range from fixed stations is governed by the same considerations that affect any radio transmission, fading and irregular or uncertain reception.

(2) Interference between sky-wave and ground-wave transmission may prevent use of the system in certain parts of the coverage area and there may be skip regions.

(3) The angle between lines of position may be so oblique as to make the precision of a fix too low.

(4) The coverage area by day will in general be different from that at night,

due to changes in the average noise level and to ionospheric conditions (see page 1.26).

(5) The useful range for aircraft using line of sight transmissions is extended at high altitudes, and is subject to correction near the transmitting station, since range measurements are actually slant range and since the phase aspect (see Appendix A) of the transmitting towers changes rapidly as the elevation angle becomes large. Also atmospheric refraction affects maximum range slightly.

(6) Under certain conditions tropospheric effects, "ducting", etc. may greatly affect the coverage area.

Since in many cases coverage areas are limited by the precision attainable with a given system, most of the discussion of the above factors will be found under the heading of accuracy.

III. Accuracy

The accuracy of a "fix" depends on the precision of the line of position established by a navigation system and on the geometrical relationship of the two or more lines used to obtain the "fix".

All electronic navigation systems depend on the measurement of a time interval, which in turn defines a distance (through the velocity of light). The spread of recent determinations of the velocity of light in a vacuum is shown in Figure 1-08. There is an uncertainty based on the above determinations of approximately 5 parts in 100,000 in the value of this quantity. The velocity of light in air is reduced from the value in a vacuum in the ratio $1/n$, where n is the index of refraction of light in air, and is equal to 1.000294 for standard pressure and temperature conditions. For extreme ranges (p = 82 cm of Hg, $t = -50^{\circ}C$; to p = 70 cm of Hg, $t = +50^{\circ}C$) of temperature and pressure on the surface of the earth, the velocity of light could vary by as much as one part in ten thousand. Thus there may be a maximum uncertainty on the surface of the earth of 1.5 parts in 10,000; converted to actual distance this means, that without temperature and pressure corrections, there is an uncertainty of 80 feet in 100 miles or 800 feet in 1000 miles. It is evident that for most systems this is a negligible uncertainty compared to others which arise. Since atmospheric conditions may be quite accurately known, it is possible to correct for errors caused by them if extreme precision is necessary. The uncertainty could thus be reduced to approximately 0.5 parts in 10,000. The index of refraction at high altitudes approaches its free-space value which is unity.

Since all navigation systems yield lines of position relative to fixed installations, the geographical location of these fixed stations, beacons, reflectors, and natural reflecting or absorbing surfaces, must be accurately known. This constitutes a serious problem in parts of the world where surveys have not been accurate.

The uncertainties in velocity of propagation, and in the location of geographical points on the earth, must be taken into account, but they are not peculiar to a particular electronic system of navigation.

There are three general categories of errors which depend on the design and operation of the navigational devices.

(1) Errors arising in the measurement of time intervals. These intervals may be as long as several thousand microseconds or shorter than 1/1000 microsecond (10^{-9} seconds). These very short intervals are usually called phase differences. Errors in time or phase measurements may occur both at the fixed installations and in the navigated craft.

(2) Errors caused by variations in the path taken by the transmission in get-

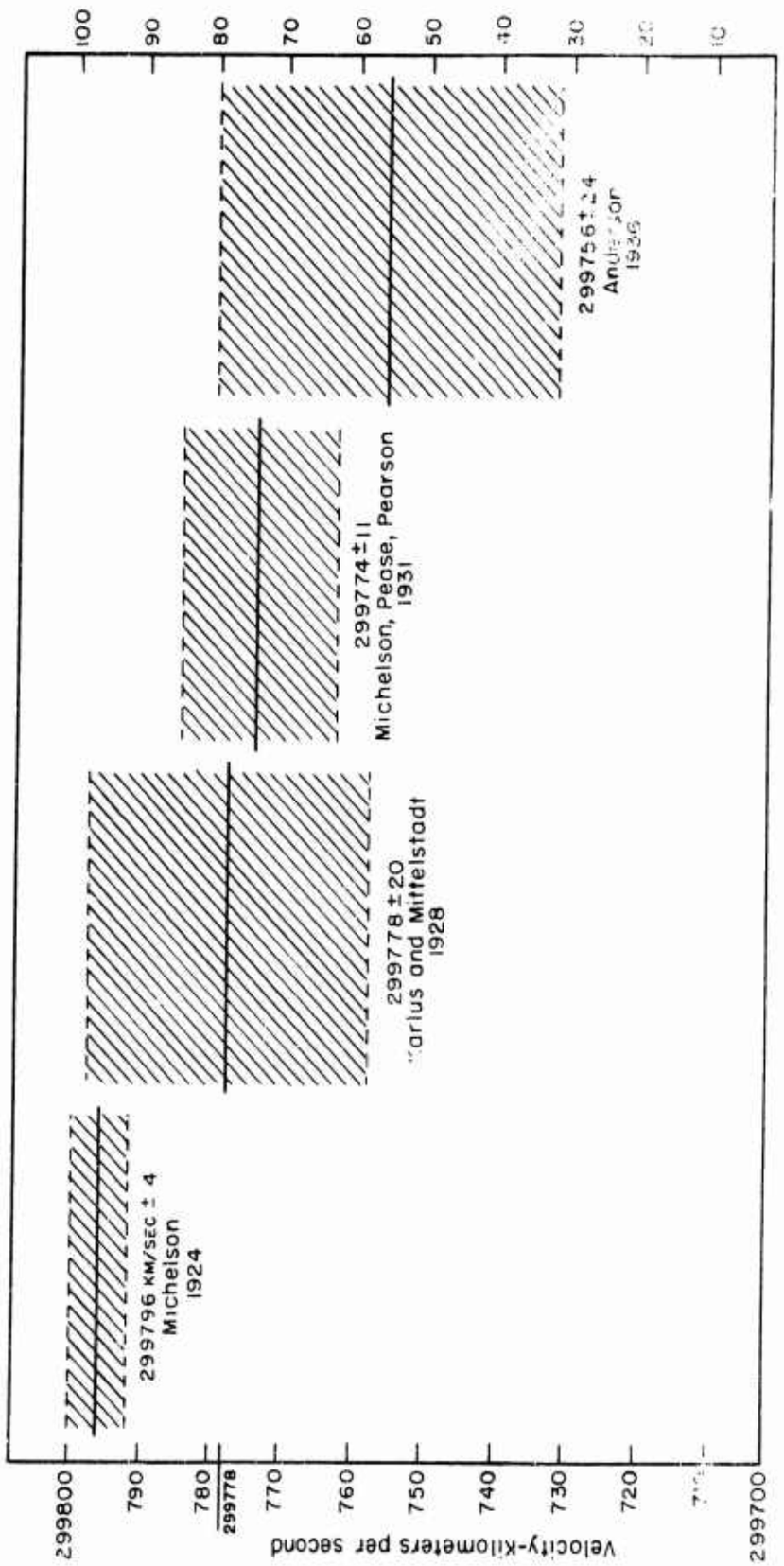


Fig. 1-08 Spread of recent determinations of the velocity of light in a vacuum

ting from fixed station to craft, and vice versa. For ground-wave propagations the path is usually quite predictable, and the errors are smaller than those which arise in sky-wave propagations where the path includes one or more ionospheric reflections.

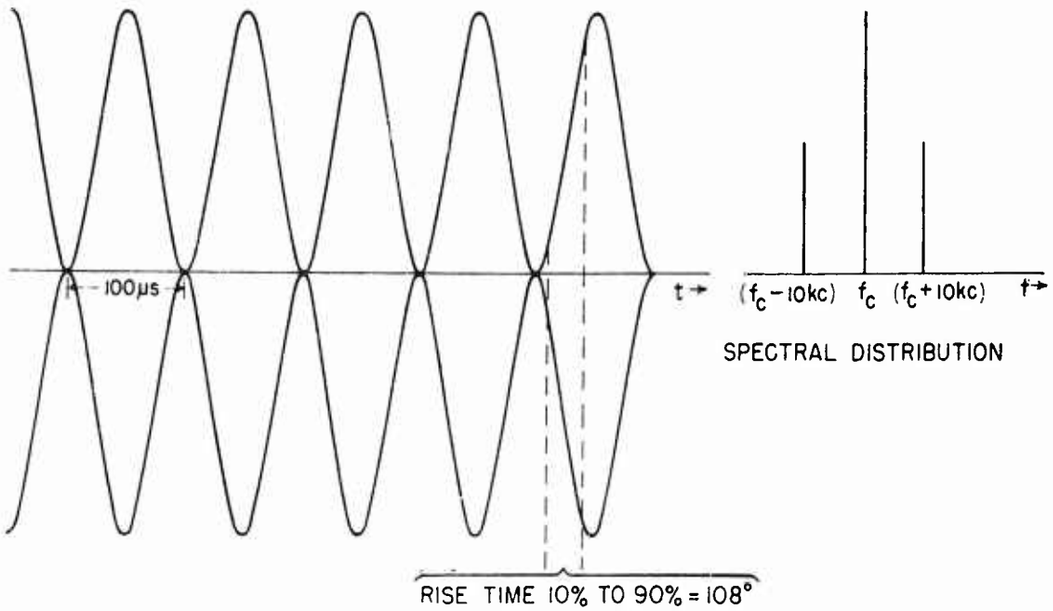
(3) Errors due to ambiguities which the navigator fails to resolve In many systems the navigator of the craft receives the same signal along more than one line of position and should be able to distinguish these by a fore-knowledge of his approximate position or by other means.

The Time Measurement

The generation of voltages defining standard time intervals, and the processes used to compare such standards with the time intervals to be measured, are possible sources of error in all types of system. In a direct range, or circular system, the total time of travel of an electromagnetic disturbance is measured and converted to a distance by multiplying by the velocity of propagation. In differential range, or hyperbolic systems, the differential time is measured and converted to differential distance or directly to a line of position. In azimuth systems the differential time is in the form of an electrical phase angle which may be measured directly or obtained by measuring relative intensity of radiation patterns where the intensity is a function of transmitted radio-frequency phase, and also of the transmitter phase aspect as seen from the receiver.

The measurement of an interval of time depends first, on the generation of a standard frequency which furnishes a continuous series of equal time intervals (cycles) and is the time "measuring stick"; and second, on some means of comparison so that the time interval to be measured may be compared with a number of cycles or a fraction of a cycle of the controlled frequency. The precision of crystal-controlled oscillators is easily of the order of one part in a million, and may be as good as one part in 10^9 if extreme care is taken with temperature control and so forth. For direct range measurement one part in a million corresponds to a precision of 0.528 feet in 100 miles which is a negligible error. High-"Q" ringing circuits and other timing devices may be used where a lower order of accuracy is sufficient. Unless very long time intervals must be measured, the precision of a crystal-controlled frequency is likely to be much better than that of the comparison operation. The problem is not unlike the measurement of time intervals with a clock. Assume that the clock runs at a uniform and accurate rate: this is equivalent to saying above that the oscillator operates at a constant frequency. If the clock has a second hand, which revolves at one revolution per minute, one could measure an interval of one hour to an approximate precision of 1 part in 3600 by measuring time intervals to the nearest second. To measure the same time to a higher precision one would have to divide the distance moved by the second hand in one second into smaller intervals. Since the number of angular subdivisions on the face would have to be increased, it would be necessary to use a narrower pointer or one whose alignment with fixed marks on the clock face is accurately discernible. This requires both a narrow or sharp edged pointer and sharply defined marks on the face. It may be necessary to mount a hand on the clock which moves around ten times a minute or even faster, in order to spread out the time scale. The various electronic timing and indicating circuits make possible a precise measurement of much shorter time intervals than ordinary clocks but have the same basic limitations. The electronic measurement of phase differences is a typical time measurement. In making a phase comparison it is easily possible to measure relative phase with uncertainties of the order of five or ten degrees. It is much more difficult to measure phase angles with maximum uncertainties of the order of one half degree. One one-hundredth of a cycle, or 3.6 degrees, represents a typical uncertainty for phase angle measurements. At 100 cps, 3.6 degrees of phase angle corresponds to 100 microseconds, so that with such a coarse "measuring stick" it would be extremely difficult to measure times with uncertainties of the order of one microsecond. Using a comparison of 100-cps

(This page is inserted as the simplest means of correcting the inadvertent omission of Figure 1-09.)



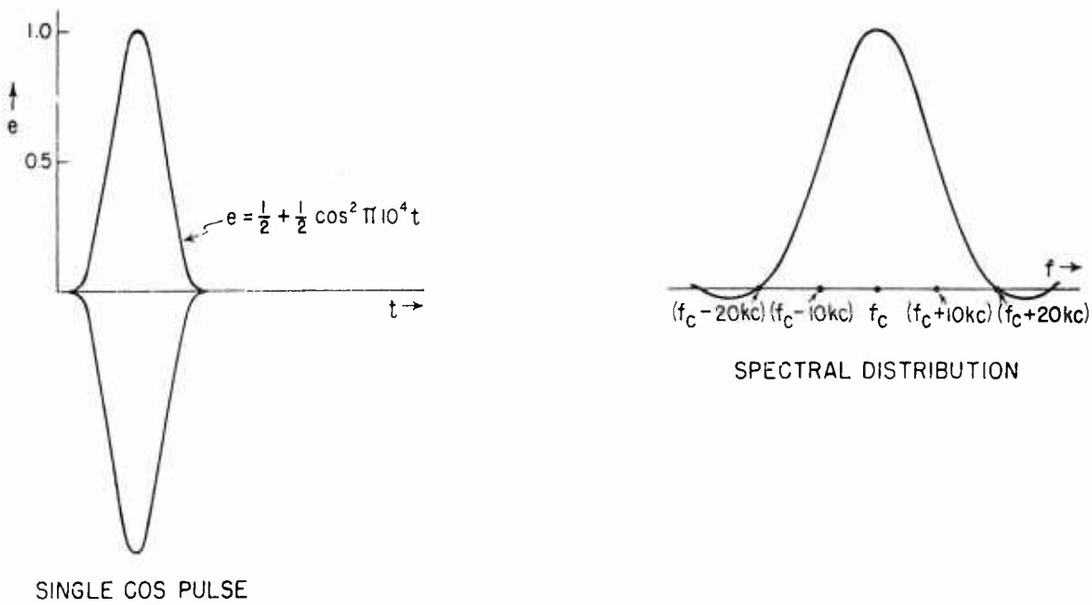


Fig. 1-09 Comparison of continuous 10 kcps modulation envelope with a single pulse shaped like one full cycle of the modulation envelope as shown. Periodograms showing the spectral distribution for each type of transmission are shown on the right. (Note that the 10 kcps side band amplitudes for the continuous wave case have the same value as the distribution curve for the pulse at carrier frequency plus or minus 10 kcps.)

modulation envelopes for a system such as that discussed on page 1.10, one could measure times up to 10,000 microseconds (assuming that the transmissions from the two stations are distinguishable), corresponding to base-line lengths of the order of 1,000 miles, with an uncertainty of the order of 100 microseconds, and have no ambiguities. If higher accuracy were necessary it would be better to use a 1,000-cps modulating frequency for the phase comparison. This would give uncertainties of the order of 10 microseconds for the same precision of phase angle measurement, but would give rise to 10 ambiguities or 10 lines of position along which the same phase difference is measured. In order to reduce uncertainties to values of the order of 1 microsecond it would be desirable to use a modulating frequency of the order of 10,000 cps, which would in turn give 100 ambiguities. An expedient for resolving the ambiguity in this case is to omit 99 out of every 100 cycles, transmitting a single complete 10,000-cps cycle every 10,000 microseconds. This cycle begins and ends at the zeros of output voltage in the modulated output assuming 100% modulation. The equation for the amplitude (e) of the upper envelope of such a pulse is $e = \frac{1}{2} + \frac{1}{2}\cos 2\pi 10^4 t$. The modulation envelope becomes in this case a pulse having a length of 50 microseconds at the half-amplitude value. Fig. 1-09 shows such a pulse for comparison with the 10-kcps modulation. On the right are shown the spectral distributions of transmitted frequencies for the two types of transmission. It is evident that receiver band width requirements will be similar for the two transmissions; this point is further discussed under frequency and bandwidth.

Phase comparisons are simplest and usually most accurate when the comparison is between waveforms having 0^o or 180^o phase difference. Many direction finders can detect phase deviations as small as one-half a degree from zero. In this case the phases of a wave arriving from a distant transmitter at two parts of a receiving antenna array are compared and the array is turned physically until the phase difference is zero, indicating that the array is parallel to the arriving wavefront. The final measurement is always made at zero phase difference. In other systems, a voltage corresponding to one of the two waveforms whose phase difference is to be measured, is the input to a calibrated, continuously-adjustable phase shifter, which is adjusted for zero phase-difference between its output and a voltage corresponding to the other wave. The comparison is thus made at zero phase difference and the actual phase difference is read off the dial of the phase shifter. This procedure adds the possible errors in the phase shifter to those of the recognition of zero difference. Certain other types of phase measuring devices have larger errors near zero difference than elsewhere. Systems which define lines of position as lines of constant radio-frequency phase difference must transmit accurately phase-controlled carriers from each transmitting antenna, and at the receiver the circuits must not introduce different phase shifts into the two transmissions. Furthermore, it is necessary to identify transmissions from the different antennas. This is done in the POPI system by a keying sequence, transmissions from different antennas occurring successively at a single frequency. In this case the receiver circuits will not give rise to differential phase shifts. However, it is necessary to have a phase "memory" circuit in order to compare phases of voltages produced at the reception point by the different transmitting antennas, since they do not occur simultaneously. The Decca system transmits simultaneously at different frequencies from the two or more antennas of the fixed station. These carriers are converted to a common frequency at the craft and compared. Assuming accurate phase control at fixed stations, the phase shifts in the receiver's radio frequency and converter stages must be accurately controlled, since the two transmissions come through different amplifier channels. This requirement in turn precludes the very sharply tuned circuits which might at first seem desirable for continuous-wave reception and noise exclusion. Any variation in the time delay between transmitted pulses in a pulse system, or any shift in phase of a modulation envelope, or radio frequency carrier, will

shift the whole pattern of lines of position, and hence must be accurately controlled. Many azimuthal systems define lines of position which are rotated either by rotating the entire antenna assembly, as in various radar systems, or by systematically and continuously shifting the phase of different antennas of the transmitting array, as in the Sonne system or the various omni-"ranges". In either case the phase control is a possible source of error in the resultant lines of position. In certain azimuth systems the time measurement, or rather time definition, is entirely done at the transmitter.

A system of the AN type of radio beacon defines a line of position as a line along which two overlapping patterns have the same intensity. These patterns might be produced by keying antenna currents to produce the two patterns shown in Fig. 1-07 (a) and (b). The pattern of Fig. 1-07 (a) is keyed as an A (·–) and the pattern of Fig. 1-07 (b) is keyed as an N (–·) which interlocks in time with the A to produce a continuous tone along the lines where the two patterns have the same intensity, which is known as the equisignal. Electra operates on a similar principle except that the keying of the patterns is by interlocking dots and dashes, and the pattern used is multilobed, giving higher precision but more ambiguities. These systems only define exact position along a finite number of lines. Sonne rotates the Electra pattern and thus enables the navigator to find his line of position over the entire coverage area. In the Federal long-range system, lines of position are defined by relative intensity measurements on four overlapping patterns. All these systems depend on accurately phased antenna currents, which constitute a timing problem. The numerical relationship between phase angle uncertainty and azimuth angle uncertainty is given by

$$\Delta\theta = \frac{\Delta\phi}{2\pi n \cos\theta} = \frac{\Delta S}{R} .$$

Where $\Delta\theta$ is the uncertainty in azimuth angle
$\Delta\phi$ is the overall uncertainty of electric phase angle
n is the number of wavelengths in the base
θ is the azimuth angle measured from the perpendicular bisector of the base
ΔS is the lateral uncertainty in line of position in miles
R is the distance to the center of the base in miles.
A numerical example for the Sonne system is worked out on page 17.24.

Whether the time comparison is between radio frequency cycles, or sinusoidal or pulse modulation envelopes, the real criterion for time uncertainty is the steepness of slope of the wave form at the point of comparison. The rise time for a pulse is usually taken as the time required to get from 10 to 90 percent of the peak pulse amplitude. For a pulse form like that of Fig. 1-09, this time corresponds to 108 degrees of phase angle or about thirty times the typical maximum phase uncertainty of 3.6 degrees used above. For pulses, a rise time of 25 or 30 times the maximum allowable uncertainty is a reasonable engineering choice. Since rise time is inversely proportional to band width of transmitted pulse waveforms, one attempts to keep rise times as long as possible. This question is discussed further under frequency and bandwidth. The relation of rise time for pulses to maximum time uncertainty also depends on the type of presentation.

If the pulses are being displayed and compared on a PPI scope, where the pulse modulates the beam intensity, it is necessary to have the duration of the pulse of the same order of magnitude as, or somewhat shorter than, the maximum tolerable uncertainty. Thus to measure times with an uncertainty not greater than one microsecond, the pulse rise time should be somewhat less than a microsecond. On the other hand where the pulse is displayed as a vertical displacement (as in Loran) or horizontal or radial displacement (as in Shoran) against time as the other coordinate, the pulse may be of considerably longer duration than the maximum tolerable uncer-

tainty. In these cases the relative sizes of CRO spot, and the total spread of the pulse determine the minimum uncertainty. With the latter presentation, it is usually desirable to have the entire pulse on the screen for monitoring of amplitude so that pulses of similar forms may be compared. Thus if the total trace length is 200 microseconds (as in Loran) it is quite possible to make pulse comparisons with uncertainties of the order of one microsecond. In all cases small, sharply focused spots are necessary for such measurements and the noise level must not be too high. In Loran or Shoran noise tends to make a multiple or broadened trace which is not capable of fine resolution. In PPI presentations noise clutters the screen and tends to reduce the sharpness of the picture. No general statement can be made as to the effects of noise on oscilloscopic presentations since noise wave forms may have any of an infinite number of possible shapes. No noise is assumed here in the horizontal or time base signal. If the pulse is modulating a low frequency carrier whose period is a substantial fraction of the rise time then the position in time of the front edge will flutter by the amount of the carrier period unless the phase of the carrier bears a constant time relationship to the pulse envelope.

The Propagation Path

The second general class of errors in navigational systems are those arising from deviations from the expected transmission path or paths. Radio transmissions in free space travel straight outward from a source, like other electromagnetic radiations. Radiations starting from sources near the surface of the earth will encounter various obstacles, and will travel through the earth's atmosphere. The radiations may be reflected or absorbed by obstacles. In general, diffraction will occur, so that obstacles of small dimensions relative to the wave length will not cast clearly defined radio shadows. Since the atmospheric density decreases with height there will be refraction, tending to bend the radiation path towards the earth. Radiations originating near the surface of the earth tend to bend around the curvature of the earth by a combination of refraction and diffraction. Since the earth is an imperfect conductor there will be ohmic losses associated with the passage of an electromagnetic wave over the earth's surface. These losses will tend to attenuate the radiation intensity near the surface. If the earth were a flat, perfect conductor the radiation would decrease in intensity inversely as the distance from the source. This is practically the case for transmissions well above the surface of the earth, as in line of sight transmission from plane to plane. Actually the attenuation along the surface is greater than that predicted by the inverse first power of distance due both to the curvature and the poor conductivity. Norton's Formula* takes account of these factors and its reliability has been experimentally verified down to a frequency of 180 kcps, and there is no reason to doubt it at frequencies below this value. Figures 1-10 and 1-11 are graphs of Norton's formula for a range of low and medium frequencies, transmitter and receiver being at the earth's surface and transmission occurring over sea water. The inverse first power of distance law is plotted on each graph for reference. At high frequencies ground losses are high and diffraction bending is less pronounced. This direct transmission is known as ground-wave propagation. Under certain conditions, the expected ground-wave range may be greatly increased by "ducting" or "trapping" of a wave between the earth's surface and inversion layers in the atmosphere above the earth. This phenomenon is particularly common over sea water.

The other important radio transmissions between points on the earth's surface are known as sky-waves, since they are propagated by means of reflections from ionized layers of gas in the upper atmosphere. The free electrons in the rarefied gases of the outer atmosphere behave like any free electrons in that they move in response to electromagnetic radiation. The motions of free electrons in a metal are re-

* K. A. Norton, "The Calculation of Ground-Wave Field Intensity Over a Finitely Conducting Spherical Earth", Proceedings of the I.R.E., December, 1941.

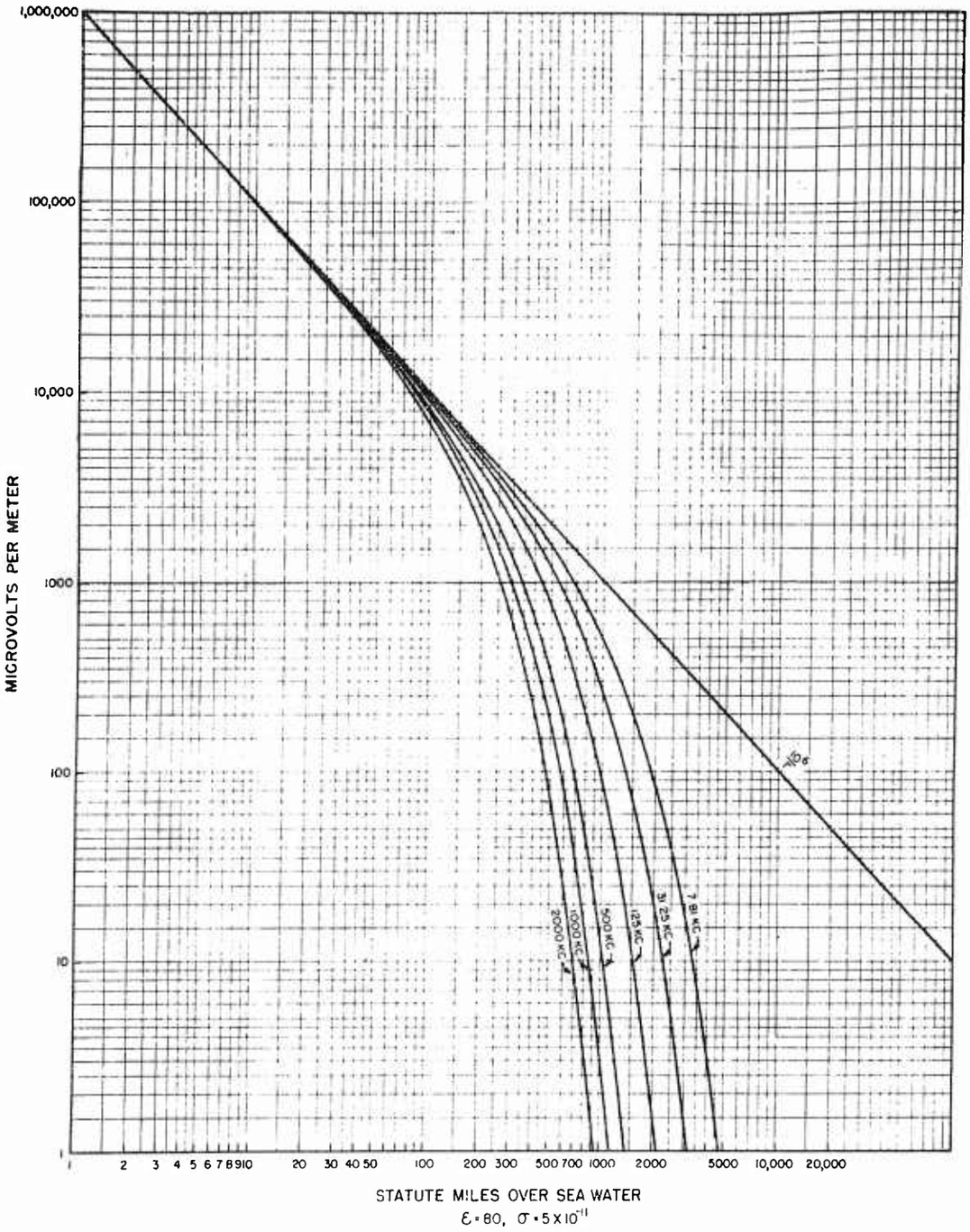


Fig. 1-10 Graph of Norton's formula for transmission over sea water, both scales logarithmic

sponsible for its reflecting properties. Free electrons in the ionosphere will reflect impinging radiation if the electron density is sufficient. The motions of the free electrons may be hampered by collisions with gas molecules. This process will involve loss of energy and therefore absorption of energy from the radiation which originally caused the motion. The ionizing of layers of gas is caused mainly by ultraviolet, and partly by corpuscular radiations from the sun, so that the electron density in a given layer is governed by a balance between the arrival of ionizing energy from the sun and the continual loss of free electrons due to attachment to atoms and molecules, and to recombination with positive ions. Since the ultra-violet and corpuscular radiations from the sun may fluctuate greatly in intensity, the re-

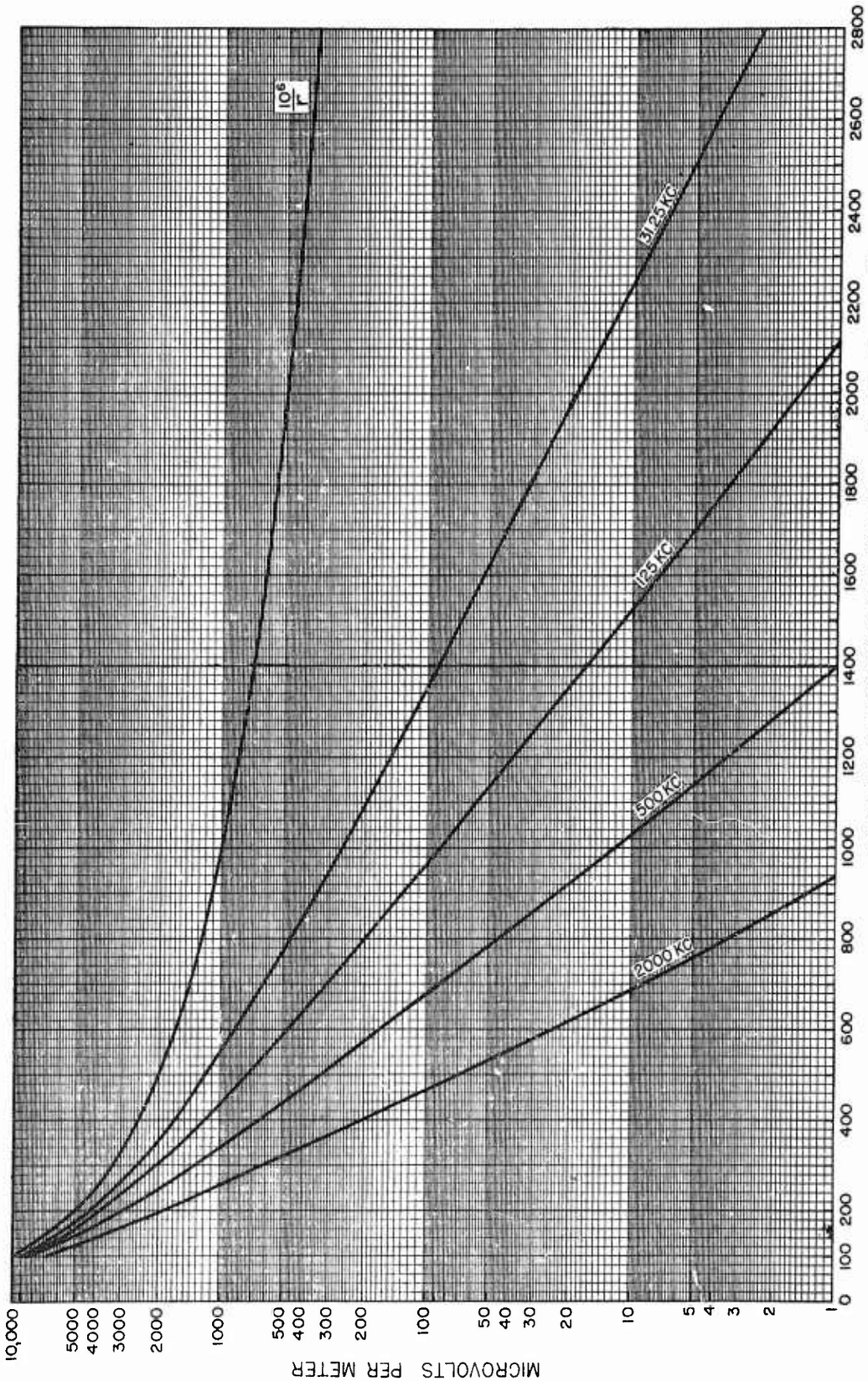


Fig. 1-11 Graph of Norton's formula as in Fig. 1-10 but with linear distance scale

sulting density of ionization will also fluctuate. The ionized layers are diffuse in structure and hence do not present a sharply-defined reflecting layer. For this reason the apparent height of the reflecting layer depends on the angle on incidence of the radiation as well as on the frequency. For vertical incidence the apparent height of the reflecting layer is greater than at grazing incidence. At grazing incidence the radiation travels for a longer distance through the lower fringes of the layer and is therefore subject to greater absorption losses due to collisions. The lower important layer is known as the "E" layer, which has an approximate effective height of seventy miles for a vertical incidence reflection. The upper layer is known as the "F" layer and is approximately 190 miles high. The "F" layer is a relatively thick layer, of greater electron density, having boundaries in which this density tapers off gradually. It often exhibits two maxima of electron density at different levels. The "E" is at present the more important layer for systems using pulse transmissions. For grazing incidence the effective height is lower, being approximately fifty-four miles for two-megacycle transmissions leaving the earth tangent to the earth's surface. There is evidence that this effective height for grazing incidence reflection is lower than fifty-four miles at frequencies below two megacycles. At the present time, data on ionospheric reflections for other than vertical incidence are systematically predicted from measured vertical-incidence data. However, there are practically no ionospheric data of any sort at low frequencies. Although the ultraviolet radiation from the sun is cut off at night, the recombination of molecular oxygen takes place slowly and a sufficient electron density persists through the night to give good reflection at the lower frequencies. In fact, although the "E" layer is denser in daytime than at night, it also extends to lower levels where the atmospheric gases are more dense, and hence where energy absorbing collisions are more likely to occur. At night, the "E" layer is more tenuous but also more sharply defined, and reflected radiations are subject to less attenuation due to passage through regions where the collision rate is high. Since the higher-frequency radiations require a greater electron density for reflection, there are practical limitations to the usefulness of sky-waves at various frequencies. At frequencies above 60 mcps ionospheric reflections are very rare. Between 60 and 30 mcps reflections may occur but are not reliably predictable, and hence not useful for transmission purposes although they may give rise to undesirable interference. Below 30 mcps fairly reliable predictions are available. In general, at frequencies below 20 mcps transmission from one point to another on the surface of the earth will be both by ground-wave and by one or more sky-wave types of propagation. (Sky-waves embrace one-hop or multiple-hop "E"-layer paths and one or more "F"-layer transmissions.)

Variations in lines of position in navigation systems which are directly or indirectly caused by sky-wave transmissions fall into two categories. First, those which arise from the fact that sky-waves exist as a mode of propagation in addition to ground waves. The second sort of errors are those arising from abnormal variations in the behavior of the reflecting ionospheric layers. Consider the first type of error. The sky-wave path between two points on the surface of the earth will always be longer than the ground-wave path. Speaking in terms of time, for points near the transmitter the one hop "E"-layer sky-wave will require approximately 600 microseconds longer time for transmission than the ground wave. As the receiving point is moved away from the transmitter, the amount by which the sky-wave path is longer than the ground-wave path approaches a nearly constant value which, in terms of time, is approximately sixty-five microseconds at extreme one-hop ranges for two-megacycle transmissions. This time difference between sky-wave and ground-wave transmissions, having common transmitting and receiving points, is known as the sky-wave delay-time and has important bearing on navigation-system design. Since this delay time decreases with increasing distance, the phase of a radio wave coming by sky-wave propagation will differ from that of the ground wave by a variable amount depending on the distance traversed. And furthermore, since the

received radiation is the instantaneous sum of ground-wave and one or more sky-wave components, its resultant phase and amplitude may vary with distance quite differently from the phase and amplitude variations of the ground wave alone.

A second source of error in systems using spaced antenna arrays may be present even with perfectly normal sky-wave reflections. Sky-wave transmissions may leave an antenna array at substantial elevation angles. When this occurs, the phase aspect of the transmitting antennas is different for sky-wave and ground-wave propagation. This is equivalent to saying that the differential distance to two antennas by the sky-wave route is in general different from the differential distance by the ground-wave path. The result is that in hyperbolic and azimuthal systems, the lines of position defined by the system are different for sky- and ground-wave propagations. Figure 1-12 shows in solid lines a typical set of ground-wave position lines for an azimuthal system and in dotted lines the pure one-hop sky-wave position lines for the same phasing of the antenna currents and the same antenna array. The dotted lines in this case are calculated for a uniform ionospheric height of fifty-four miles. A similar situation exists for hyperbolic lines of position. Note that the effect is not present along the base-line bisector (vertical line in Figure 1-12) and is largest as one approaches the base-line extension (horizontal line in Figure 1-12). The dotted lines converge toward the solid lines as the range increases, since the one-hop sky-wave leaves the antenna array at nearly zero elevation angle for extreme ranges, so that the transmitting array has the same phase aspect as for the ground wave, and therefore produces the same radiation pattern. However, two-hop "E"-layer and "F"-layer transmissions may predominate, and in this case the sky-wave correction may have to be applied even at extreme ranges. All the above effects can be compensated for if it is possible to separate sky-wave from ground-wave propagation, and if one has available a reasonably good prediction of seasonal and diurnal variations in the effective height of the ionosphere or expected sky-wave delay time. There are several possible methods of separating ground waves from sky waves. First, by being so near the transmitter that ground waves are strongly predominant, or far enough away that ground waves are reduced to negligible relative value. (There is in this latter case the strong possibility that the sky-wave may consist of both one-hop and multiple-hop transmissions which may be inseparable.) Second, by controlling the elevation angle of transmitted and received radiations so as to utilize only one path at a time. This is only practical at the higher frequencies, where sharply directional antenna systems are feasible. Third, by transmitting intermittently so that the first radiation received after a period of no transmission is that which traveled by the shortest route, which is the ground wave. The various pulse-modulated systems make use of this method of separation of ground and sky waves. If the pulse is substantially shorter than the minimum delay time of sixty-five microseconds, then ground-wave and sky-wave pulses will be distinguishable at all ranges, and either may be used for measurement purposes. Fourth, by transmitting at higher frequencies, so that ionospheric reflection does not occur.

With pure ground waves there is no need to be able to predict sky-wave propagation conditions, but in order to use sky waves it is necessary to know what to expect for delay times and usable frequencies.

Since sky waves must travel a distance at least twice the effective height of the ionosphere, roughly one hundred and ten miles for 2-mcps transmissions, the sky-wave intensity will normally be a small fraction of the ground-wave intensity at points near the transmitter; but, at ranges of the order of one hundred miles and more, the sky wave may be much stronger than the ground wave, especially over land. This is particularly noticeable at frequencies from ten to thirty megacycles where the ground-wave attenuation is high and where ionospheric reflection may be good. As the frequency is lowered, the distance out to points where ground- and sky-wave field strengths are comparable, increases. With present available data it

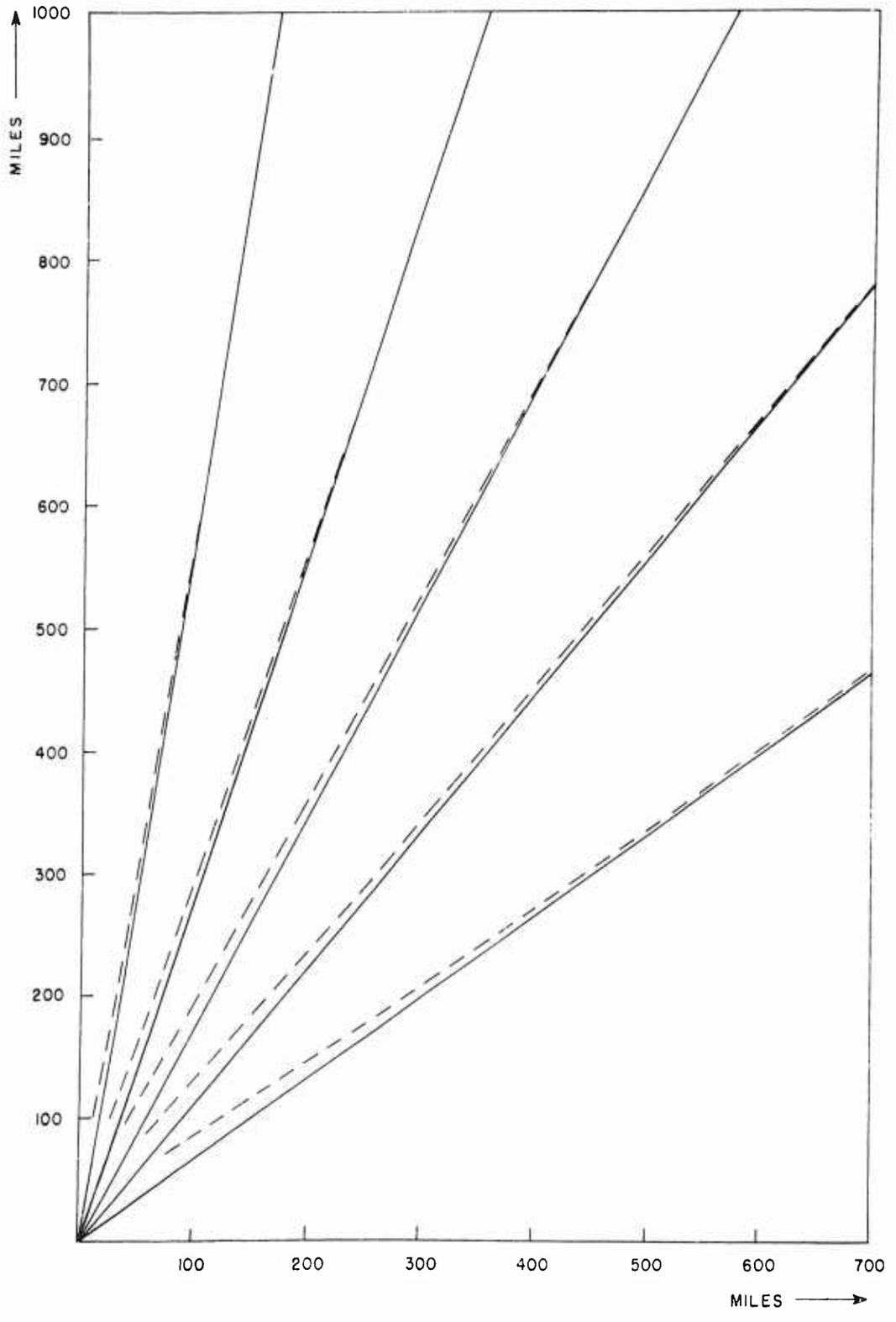


Fig. 1-12 Relative location of azimuthal lines of position for ground wave (solid lines) and one-hop E-layer sky wave (dashed lines). Base line horizontal, first quadrant only shown
Note: lines of position determined by two-hop E-layer sky wave and one-hop F-layer sky wave will deviate from ground-wave lines by larger amounts

is not possible to give numerical figures in this connection. Such data would be very useful in evaluating the potentialities of low frequencies for navigation systems. Several things need to be known in this connection for very low and low frequencies. First, what will be the sky-wave delay time for oblique-incidence ionospheric reflections. Second, how serious will sky-wave attenuation be, and will two-hop transmissions be of comparable field strength to one-hop transmission, since the one-hop propagation has a longer path through the lower attenuating fringe of the "E" layer. For a given range, an "F"-layer or a two-hop "E"-layer transmission takes off from the transmitting array at steeper elevation angles than for the one-hop "E"-layer path.

Systems using sky-wave transmission use a chart designed for ground-wave transmission by applying corrections based on a certain expected delay of sky waves. The correction may be equivalent to as much as 50-60 microseconds. Whether or not sky-wave corrections are necessary depends on whether the ground wave reception zone extends out to regions where the single-hop "E"-layer reflection paths leave the transmitter system at low elevation angles. Since the effect depends on the cosine of the elevation angle of the propagation path from the horizontal, elevation angles less than eight degrees will give rise to corrections which are less than 1% of the phase aspect at the point in question. If one assumes an "E"-layer 60 miles high, the ground-wave range would have to be approximately 700 miles in order to avoid appreciable corrections. This fact in turn will have a bearing on the choice of frequencies for systems depending on both sky- and ground-wave propagations. In general it is not desirable to use ground-wave propagation from one station of a transmitting pair and sky-waves from the other. This procedure is not at all impossible, but since sky-wave corrections would involve total sky-wave delay time and not the difference of two such times, the precision would be lower.

All the possible sources of error so far discussed arose out of a consideration of normal predictable ionospheric conditions, the uncertainties being as to which paths the radiation actually followed. There are also the types of errors which are due to unpredictable fluctuations. These fluctuations in sky-wave field strength are probably due to motions and density variations of the electrons in the reflecting layer. These motions give rise to a variation in the sky-wave delay time which has an experimental value ranging up to more than forty microseconds, and has a twenty-minute average which may vary by twenty microseconds from one twenty-minute interval to the next. Variations in sky-wave delay time may be thought of as variations in the effective height of the ionosphere. Because of this variation in delay time, any use of sky-waves for direct-range systems would involve rather large uncertainties. The same consideration has a bearing on the possibility of maintaining synchronism between a pair of hyperbolic-system transmitters. If it is possible to separate sky-wave from ground-wave transmission, it is possible to maintain synchronism with ground-wave signals, with correspondingly good precision, up to the limit set by the ground-wave intensity and local noise conditions. It is further possible to synchronize by single-hop "E"-layer sky-waves provided that there are means of separating this sky-wave component, and of maintaining watch to effect an intelligent smoothing of the fluctuations, and provided that a lower order of accuracy can be tolerated. In differential-range and azimuth systems, the difference between two sky-wave arrival times is the measured quantity, and if the variations in delay time are the same for each sky-wave then they will cancel out in the difference. This will be the case at points along the base line bisector where the distance to each transmitting antenna is the same (assuming changes in the effective height of the reflecting layer to be identical all over the coverage area). For points near the base line extension, the difference in ground-wave distance to the transmitting antennas has a maximum value, and even though the effective ionospheric height is the same at each reflecting point the variations in this height give rise to variations in the measured difference between times of

arrival of sky-waves. For azimuthal systems which have relatively short base lines (two or three miles), the reflecting points are near together and hence more likely to be at the same effective height, and to vary in effective height together. On the other hand with long base lines it is much less likely that the effective ionospheric height is the same at both reflecting points or that it will vary in the same way at the same time. Thus with continuous-wave systems using sky-waves or composite transmissions, the shorter base lines are better from the point of view of propagation uncertainties. Ionospheric tilt or "patchiness" may interfere seriously with the precision of a line of position from azimuth systems and its effect may be to displace any of the lines of position of the system. Tilt is equivalent to horizontal electron-density gradient.

Pulse-modulated systems offer the possibility of separating ground wave from sky wave and hence of making measurements on one component of the signal at a time. For instance, suppose that transmitted pulses have a duration substantially shorter than sixty-five microseconds. Then the ground-wave pulse would always be completely over before the same transmitted pulse travelling by the sky-wave route arrived at the receiver. There would be no interference and one could measure difference in times of arrival of ground waves or sky waves independently. However, as will be pointed out in the discussion of frequency and bandwidth, the length of a pulse is not a quantity which may be chosen at random for any frequency of transmission. As the frequency is reduced, the difficulties in the way of producing and using short pulses increase. This usually means longer pulses and hence overlapping of sky wave and ground wave. The technique of cycle-matching (suggested for LF Loran) on the early parts of two pulses whose time-difference is to be measured has some attractive possibilities.

The leading edge of a received pulse is unique in that for the first sixty-odd microseconds of its build-up time it will consist of pure ground-wave transmission, uncontaminated by sky-waves, provided that the receiver is within ground-wave range. If one could perform a phase match between radio-frequency cycles of two pulses during this early part of the pulse it would be possible to achieve the high time-precision which is obtainable with a phase measurement at the radio-frequency. This possibility hinges on certain identification of the first few cycles so that the right pair are matched. This identification in turn requires a rapid rise of the front edge of the pulse and therefore relatively wide band-width allotments.

Errors due to ambiguities

Two circles or two hyperbolae may intersect at two points. Either of these two points may be the actual position of the craft. Unless some third line of position exists, or unless the navigator knows his approximate position by other means, there is an ambiguity of position.

Azimuth systems having multilobed antenna patterns have sector ambiguity. That is, the signal received from the system is the same along several radial or hyperbolic lines. There are two factors which influence original design in these cases. If a system has few lobes, the number of sector ambiguities is less but the precision within a sector is also reduced for the same phase or amplitude discrimination. Many multilobe systems use a large number of lobes for high angular precision, and require an addition direction-finding equipment to locate which sector the craft is in, or a second "coarse" radiation pattern for the same purpose. It is essential that if the navigation system has ambiguities there be some means of resolving them. Furthermore, the sectors of ambiguity must be sufficiently broad that the craft cannot move across a sector in less than two or three times the time required to obtain a fix. If for instance a system has a ten-degree sector, then at a distance of 100 miles from the antenna array, the sector is approximately seventeen and one half miles across. Flying at 300 miles per hour at right

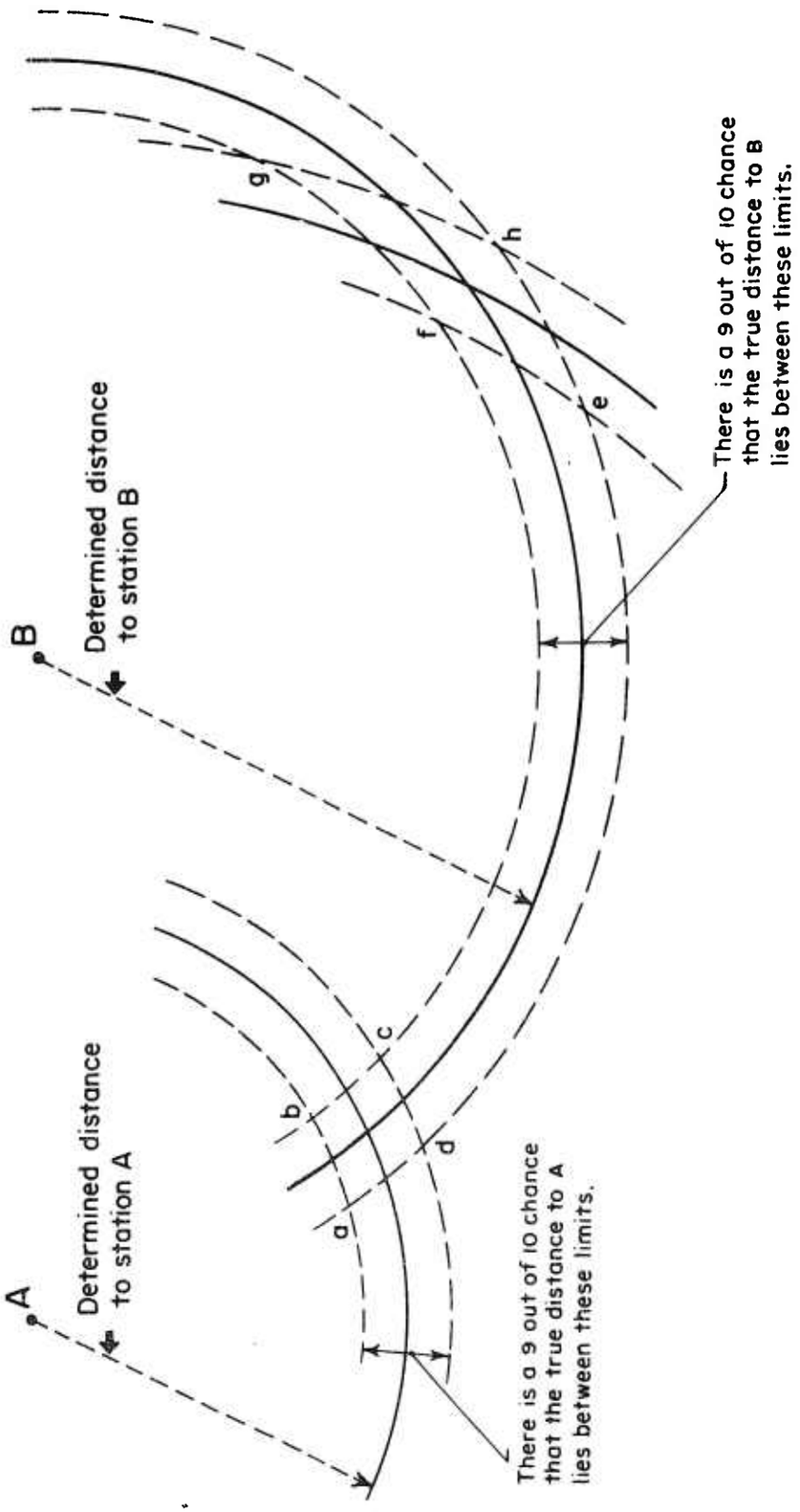


Fig. 1-13 Areas of uncertainty in a fix, range-type system

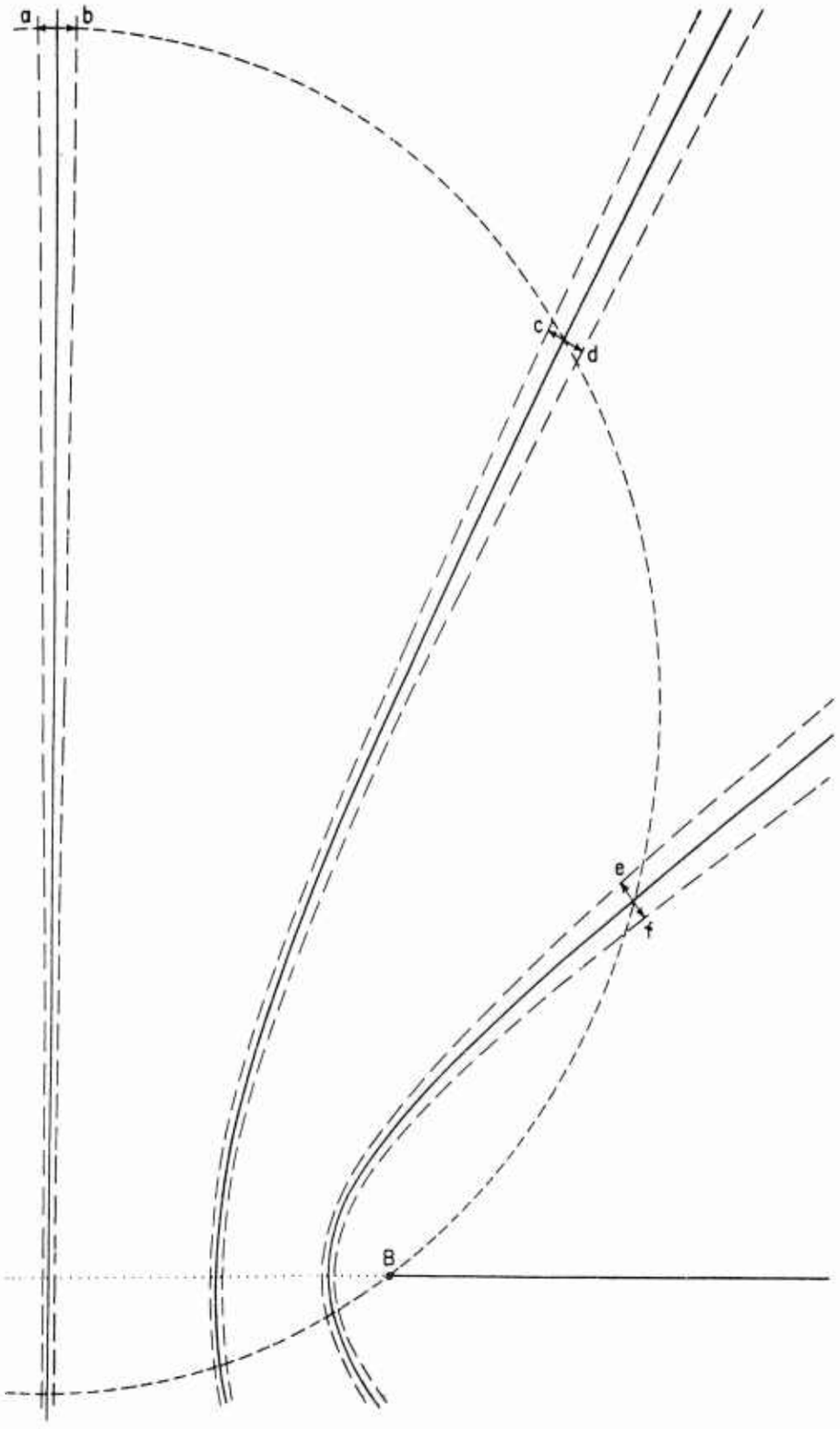


Fig. 1-14 Uncertainty in line of position, hyperbolic system

angles to the radial lines, a plane would cross the sector in three and one-half minutes. If the time required to obtain a fix is of the order of two minutes, it is obvious that the system would not be useful at ranges so close to the transmitter. It is evident that for regions sufficiently distant from the transmitting station, sector ambiguities fall into the category of gross errors which would only be a serious problem for craft which are completely lost.

Geometrical considerations in the use of two or more lines of position for a fix

Since time measurements and propagation path predictions are subject to error, a "line" of position established by the system has a degree of uncertainty. Suppose the navigator knows his exact position by other means, then a series of measurements using a navigation system which has no systematic errors will yield readings which on the average will form a statistical ensemble about the true value. It is then possible to draw two lines of position which form boundaries to a region within which 90% of a large number of position-line measurements will fall. These lines will straddle the true line of position. If the navigator wishes to determine his position, assuming that he does not know where he is, he can take a measurement and know that there are nine chances out of ten that his true position line is within a similar zone about his measured value. The geometrical shape of such a zone depends on the type of system and on the timing and path uncertainty. Figure 1-13 shows such zones for two circular systems. When a "fix" is taken using circular position "zones" from two stations such as A and B of Figure 1-13, there is an 8.1 out of 10 chance that the true position of the craft lies in the quadrangular area a, b, c, d. The quadrangular area e, f, g, h, in Figure 1-13 represents similar "zones" intersecting at a less favorable angle; there is still an 8.1 out of 10 chance of including the true position in the area but the area is larger and the true position therefore less accurately known. Figure 1-14 shows the shape of the zone of uncertainty about a hyperbolic line of position. Note that in Figures 1-13 and 1-14 the assumption is made that the measure of distance or time has the same uncertainty regardless of total distance or time measured. This will be true for all errors due to incorrect phase comparison or pulse alignment, but will not be true for errors arising from frequency drift or variations in either the velocity or the path of propagation. In Figure 1-14, the zone of uncertainty approaches a sector of constant angular width as the hyperbolae approach radial asymptotes. Figures 1-15 and 1-16 show similar constructions for zones of uncertainty in azimuthal systems. It is assumed that 90% of bearing measurements will fall within 1^{o} of the true value. Then at a distance of 100 miles from station A there are nine out of ten chances that the true line of position lies within 1.75 miles of the measured value, 0.0175 being the tangent of 1^{o}. If then two measured lines of position intersect at an angle near 90^{o} at a point not more than 100 miles from either station, the position of the craft is somewhere in the diamond shaped area shown shaded in Figure 1-15. In this case, the maximum probable distance between the actual position of the craft and its calculated position is of the order of two and one-half miles for the case assumed. If the angle of intersection of the two lines of position is for example 15 degrees, the result is shown in Figure 1-16, where the maximum probable error is approximately 16 miles at 100 miles from the fixed station. If one plots the region within which the angle of intersection of two lines of position is equal to or greater than any given value, the boundary of that region is found to be a circle passing through the two fixed stations. This is illustrated in Figure 1-17, where the circle passing through the two stations encloses a region where the angle of intersection of azimuthal lines of position is always equal to or greater than 30^{o}. At any point on such a circle, the angle of intersection of azimuthal lines of position is the same. At any point on a similar circle drawn for two stations constituting a hyperbolic system pair, the zone of uncertainty will be approximately the same width measured perpendicular to the hyperbolae as in Figure 1-14 where ab = cd = ef. Such a circle may be used to delineate regions of coverage having a precision equal to or better than a given value. If in range systems it is also possible to measure differential range, then the area

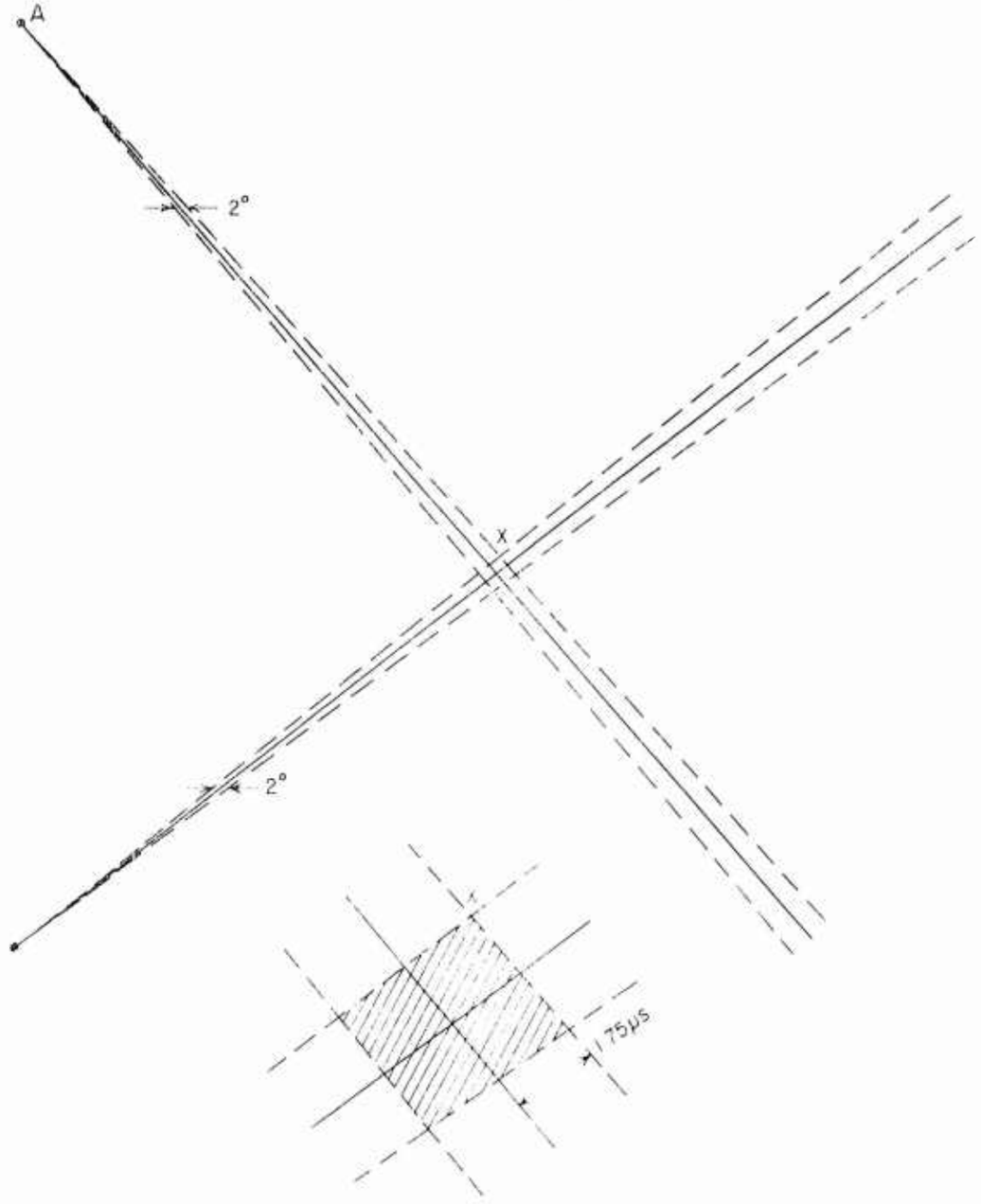


Fig. 1-15 Uncertainty in a fix determined from azimuthal lines of position, angle of cut near 90°

of uncertainty may be reduced by a substantial factor as shown in Figure 1-18. The diamond shaped area in black dashed lines is reduced to a hexagonal region between the dotted lines. In this case it is assumed that the precision of the differential range measurement is the same as that of the direct range measurement.

IV. Type of Presentation

The presentation refers to the manner in which the navigator is made aware of the navigational information. In certain cases it may be desirable to by-pass the navigator or pilot and feed the course data directly to the steering control mechanism. Aside from this "automatic" operation, the navigational data reaches the con-

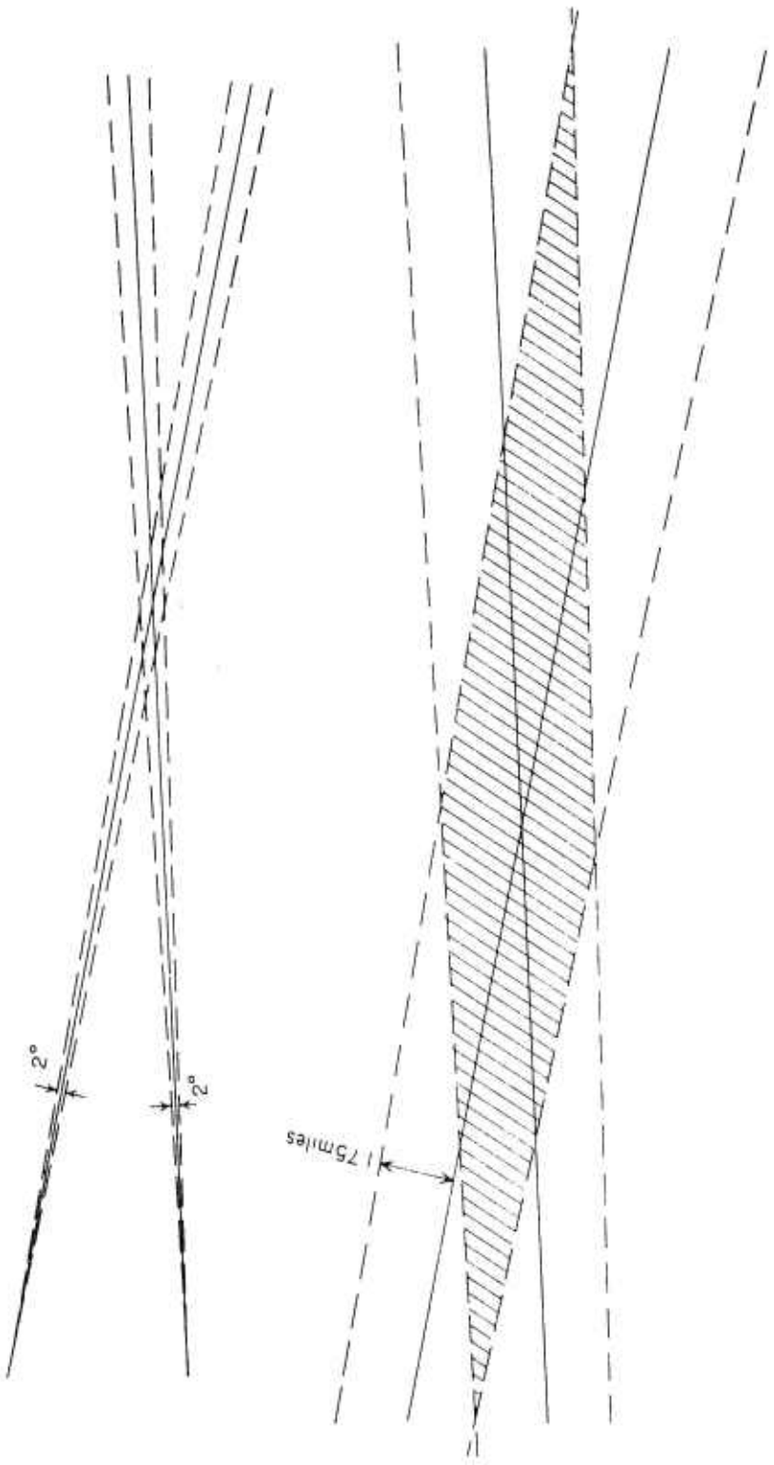


Fig. 1-16 Same as Fig. 1-15, but with angle of cut 15°

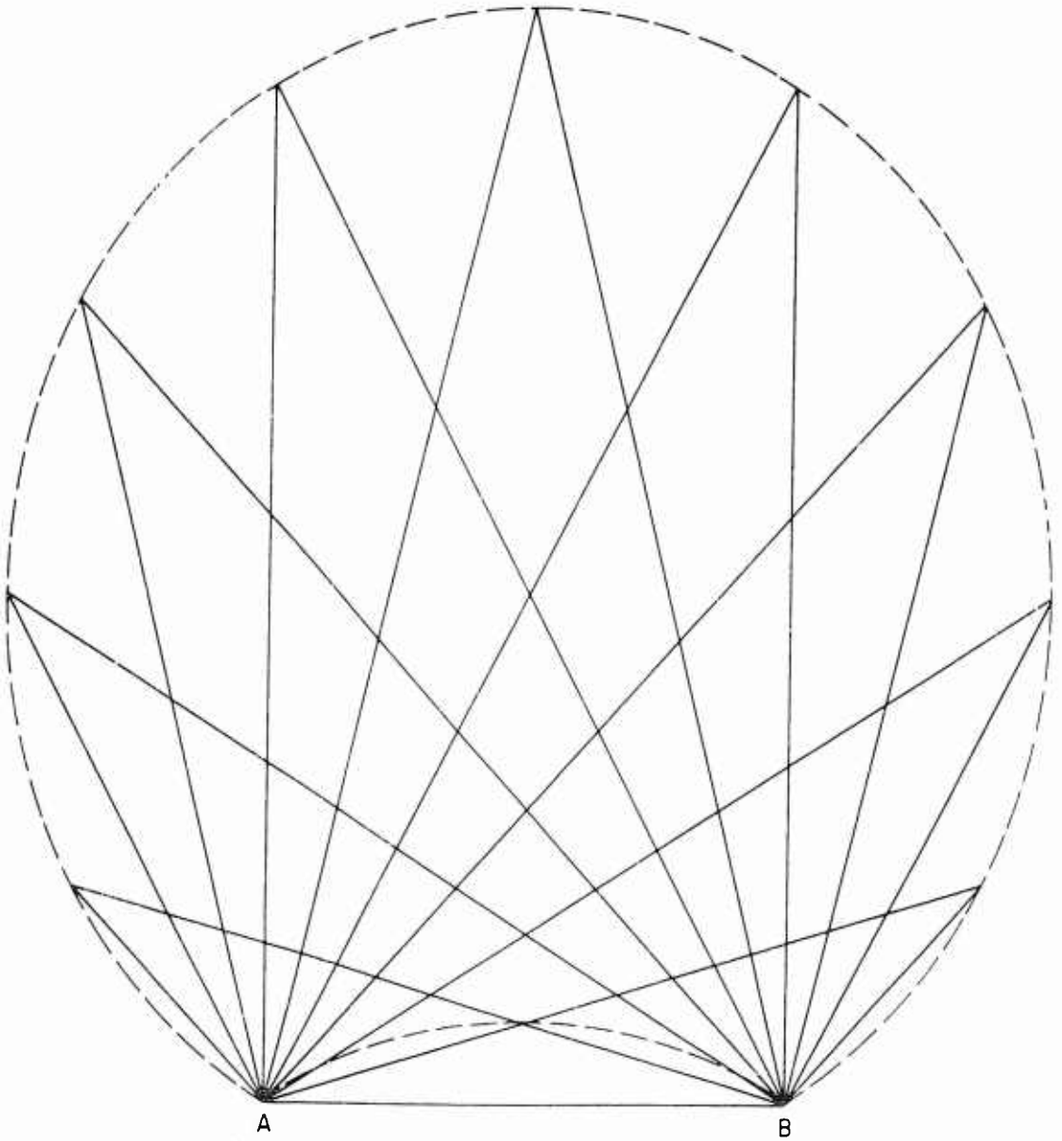


Fig. 1-17 Boundary of a region within which the angle of cut is equal to or greater than a given value

sciousness of the navigator by either visual or aural means. It is in general true that it is possible to present more information in a given time by visual means than by aural means. However, a glance at the various instruments visible from the pilot's position on an aircraft, and the recognition that he has to see objects outside the plane also, will indicate that in most cases of aircraft navigation, the pilot's visual channels for the reception of information are pretty well saturated. Whatever reaches the pilot by aural means arrives by way of a set of earphones which, in some cases, may be switched to several circuits (interphone, various radio communication channels, etc.).

For single-place fighter craft it is desirable to have navigational information presented in as simple a manner as possible. Homing information or preselected course flying lends itself easily to simple presentations such as right-left visual or aural indications. In this case accuracy is subordinate to simplicity. For aircraft direction or "vectoring" from ground stations, such as in radar fighter-dir-

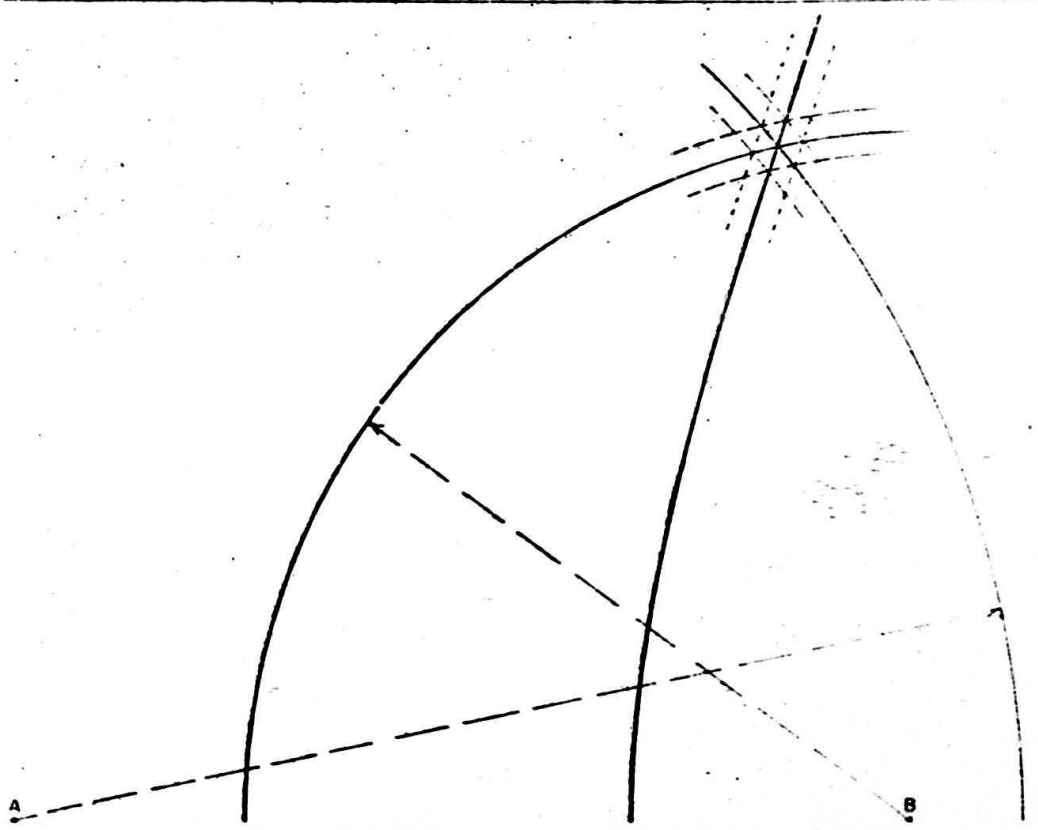


Fig. 1-18 Illustrating the reduction in uncertainty of position by combination of circular and hyperbolic lines of position

ection, the presentation is via voice communication channels from the control point, and high precision is possible since it is determined by the ground installations. A similar system is useful for airport traffic control. For general navigation of fighter craft the problem is more difficult. Suppose a fighter craft after a several minutes "dog fight" or evasive action is completely lost. Assuming that he has a compass, he then needs to be able to obtain a "fix" in order to proceed with his assignment. This implies that he must be able to take some sort of a chart of the region where he is and put a dot, labeled with a time, on it to represent his position. It may also be desirable to plot a series of fixes thus defining his course. While the presentation of general navigational data in a useful form to a fighter pilot is a very serious problem, it is relatively much easier to do for the navigators of large aircraft and ships since in these cases the navigator usually does not have extensive other activities.

Aural Indication

Under aural types of presentation there are three useful subdivisions:

(a) Direct verbal or code instruction via radio communication circuits from fixed stations or other craft. This is sometimes called "vectoring".
(b) Homing or other preselected course navigation by "dot-dash" or A-N direct error indication.
(c) General navigation by aural recognition of some form of identification of lines of position.

Direct verbal instructions are used in radar fighter or bomber control and in airport control systems. The ground or ship radar controller "sees" the craft

in its relation to other craft and fixed objects, and directs the navigation. This implies that some means of recognition must be used so that the controller knows which of several craft in his radar or optical field of vision is in fact the one which he is talking to. This is an extremely serious problem when many craft are using the system at the same time.

Homing or preselected course navigation often makes use of coded signals to indicate deviation from the preselected course. When the craft is off course on one side, the navigator hears coded "dots", when he is off on the other, he hears "dashes". Similar indication is used in the radio "range" navigation system where the coded letter A (·–) is heard when off course on one side, and N (–·) is heard on the other side. A system of this type may have a two or four or multilobe pattern so that there are several lines along which one could navigate towards or away from the beacon.

A truly general navigation system must enable the navigator to draw his line of position on a chart no matter where he is in relation to the station, provided of course that he is within range. Various systems do this by rotation or angular oscillation of a pattern such as the preselected course type. The navigator gets his line of position by aural recognition of the instant when an equisignal or otherwise designated line crosses his position, as in the Sonne system.

Visual Indication

The visual presentations of information fall into two natural classifications:
(a) Mechanical indication, dials, pointers, or switching of lights.
(b) Oscilloscope presentation.

The mechanical indicators include meters of the pointer-on-scale type and dial indications of various sorts. They are simple and direct and have the enormous advantage of not presenting too much information. Zero-center meters may be used to indicate deviation from prescribed course or from line towards home. The fact that deviations right or left from course may be made to appear as right or left deflections of a pointer is of great importance in that it contributes to the naturalness of a pilot's corrective reaction, a result not obtainable with aural presentations unless some binaural device is used. Furthermore, the exact course is more sharply indicated and the actual extent of deviation is quantitatively displayed. This is a desirable feature since it tends to prevent hunting back and forth across the course. Certain systems use automatic dial reading to indicate actual lines of position; others depend on coincidence alignment of some type on an oscilloscope followed by a reading of mechanical indicators attached to the phase shifters or potentiometers used in adjusting the coincidence.

Oscilloscope indicators are certainly the most versatile tools yet devised to present information that can be reduced to electrical or magnetic variations. The presentations may be of any sort from simple right-left steering directions to complete PPI maps of the surrounding geographical features as well as of other craft in the neighborhood. In general the oscilloscope presentation allows of the use of weaker signals than direct reading mechanical systems. Furthermore, anomalous propagation conditions, reflections from tropospheric or geographic discontinuities, and enemy jamming or meaconing may completely upset the operation of automatic mechanical indicators. A skilled operator on the other hand, using an oscilloscope presentation may recognize and discount the spurious signals and still be able to determine his line of position. An oscilloscope presentation is particularly adapted to monitoring sky-wave pulses in order to select times when conditions are stable and hence readings are more reliable. The same might be said for any instantaneous mechanical type of indicator except that the oscilloscope shows not only the ampli-

tude but the changes in form of the pulse which is indicative of the stability of propagation conditions. In general it will be easier to meacon continuous-wave transmissions than pulse types where the presentation is on a "scope". Suppose for instance that one is using a system in which lines of position are lines of constant radio-frequency phase difference between two carriers. A meaconing station could transmit one of the carrier frequencies and shift actual phase of the system locally or even over the entire coverage area if sufficient power were available. This could be done without the knowledge of navigators using the system. Also in the case of a system which establishes a line of position by comparison of modulation envelope phases, a continuous wave transmitter correctly phased could bring about a phase shift of the modulation envelope by any desired amount. Since meaconing cannot ordinarily be done from points near the system transmitter, the phase shifts produced will vary from point to point within the coverage area. Meaconing of pulse systems requires the generation of a false pulse. Theoretically at least it would not be impossible to generate a pulse which would cancel out one of the system pulses along an arbitrary line across the coverage area. Practically, this would be very difficult and the general effect would be to broaden the resultant pulse or display two pulses. This effect might not be observed by the navigator using a mechanical type of indicator but would certainly warn him of the malicious intent of the enemy if he were using an oscilloscope presentation. As previously pointed out, with pulse transmissions the front edge of a pulse is unique in that it arrives by the most direct route and is not composite. If the pulse is of short duration the signals arriving by the different paths do not overlap and hence may be easily recognized on an oscilloscope.

Oscilloscopic presentation of data has been criticized for displaying too much data at one instant and hence confusing the navigator. It is true that in the case of an inexperienced navigator, his first reactions to the indications on his "scope" might be total bewilderment, but so would the first reactions of almost any intelligent being to the array of instruments visible from the pilot's seat of a modern plane. Pilots become familiar with the utility of the instruments in front of them, and navigators come to depend on their "scopes".

In general, the mechanical indicators are best adapted to continuous-wave and modulated continuous-wave systems where ground-wave propagation predominates and where the transmissions are free from the effects of enemy machinations. Oscilloscope indicators are ideal for pulse types of systems where they may extend the useful coverage to longer ranges and enable the system to be used under less favorable transmission conditions.

V. Operating Skill Required

There is a tendency among many people to deprecate any piece of equipment which requires any skill on the part of the operator. If these people actually controlled the design of navigational equipment everything would have to be "foolproof" and new ideas would never get a trial. On the other hand, this tendency is a necessary and beneficial counter-balance to the imaginative genius of other people who would multiply and extend the intricacy of modern radar and navigational gear until only they themselves could operate it. The fact is that neither pilots or navigators are morons; they are people of well above average intelligence. They may be too busy under certain circumstances to be able to make careful and precise measurements, but given time and training, they could operate and maintain any reasonable creation of the electronic genius. Under the stimulation of wartime necessity, the number of ships and aircraft which must be navigated has multiplied enormously. The training of navigators must be carried out in as short a time as possible. The U. S. Navy allows a sixteen-week basic training period to train a man in the necessary mathematics, astronomy, geography, and navigation. As a part of this training, the navi-

gator learns to take a three-line celestrial "fix" in from twenty to forty minutes, which is no mean accomplishment and involves the skilful use of a modern sextant, an instrument fully as delicate to use as an oscilloscope or other ordinary electronic gear.

Since all navigation systems have a relatively small number of fixed transmitting stations compared to numbers of craft using the system, the training of relatively small numbers of operators and maintenance personnel for fixed installations is not as serious a problem as that of training the large numbers of navigators who will use the system in the navigation of various craft, even though the operators of fixed installations will in general require more extensive training than the navigators. The present trend in training programs is to allow as much as thirty or forty hours out of the sixteen-week basic training course for training in the practical operation of electronic navigational gear. Almost any intelligent person could learn to go through the motions of taking a "fix" by electronic means given sufficient time; but the skill and proficiency developed by training and practice enable the experienced navigator to get an accurate "fix" in a short time, and to be aware of faulty operation of the gear, or anomalous propagation conditions, or enemy "tampering" with the signal. As previously indicated, the time for getting a "fix" must be short compared to the maximum rate at which the craft passes from one sector of a pattern having ambiguities to another. Another important reason for insisting on a short time to take a "fix" is because when an aircraft is forced down or a surface vessel is damaged, life or death may depend on being able to get a "fix" quickly and radio out the craft's position with sufficient accuracy to enable rescue to be effected or at least to bring rescue craft within range of a "squawker" or other portable marker beacon.

VI. Equipment Required

At the relatively few fixed stations of a navigational system such factors as weight, power requirements, complexity, skills required of operating and maintenance personnel, etc., are comparatively easy to account for. A consideration of these same factors poses a serious design problem for equipment on the navigated craft. For large surface vessels the weight and bulk of the equipment is less critical than for small vessels and aircraft. On single-place fighter aircraft the weight and size become extremely critical factors in the design, and only the simplest types of presentation and lightest possible equipment can be tolerated. High precision and long range become less important than lightness and simplicity. On the other hand, shipborne and large aircraft navigational aids will tend to stress precision and long range usefulness. For aircraft where the fuel load is a large percentage of total load there is a three-way balance to be achieved between weight of navigational equipment, accuracy of the equipment, and fuel load saved by accurate navigation. In other words, cutting the weight at the expense of navigational precision may mean that due to flying a less accurate (and hence longer) course, the weight of fuel required increases more than the weight saved in navigational equipment.

Fixed Station Equipment

Since the best sites for fixed stations are usually remote from electric power facilities, a reliable and well-regulated power plant is the first requisite of a fixed station. Except for small battery-operated beacons the power supplies are usually generators driven by fuel-burning engines. Since the continuity and reliability of navigational coverage is of extreme importance, the power supply may need to have standby units.

The design of radio-frequency circuits in general will be conditioned by the same need for continuity and reliability, and in addition must include accurate frequency generation and phase-control circuits.

The transmitting antenna array is a critical element in many systems. Care in the choice of sites, adequate design of grounding networks, precision of spacing and angular orientation of antenna arrays all contribute materially to the accuracy and reliability of the system. As a rule it is impractical to build a low-frequency vertical antenna a quarter wavelength high (this would be 1093 feet at 300 kcps and 3280 feet at 100 kcps). Certain systems use barrage balloons to hold up a very long antenna but these have a foul-weather unreliability which precludes their use in a permanent installation. It is usually necessary to use an antenna which is a small fraction of a wavelength high, and then to "top load" it to increase the current at the base and to have the whole antenna carry a larger current, thereby increasing its effectiveness as a radiator. Whether the top is loaded or not, there is usually some type of matching circuit at the base to match the antenna to a transmission line or transmitter output. The whole combination constitutes a circuit with a fairly high effective "Q" when the actual radiating part of the antenna is short compared to a quarter wave length, and as a result the possible rate of rise of the front edge of a pulse output is limited. This is saying that the band width of the antenna and its associated circuits is narrow, perhaps undesirably so. Narrow-band circuits are used to limit transmitted radiation to a desired band width, but it is preferable to do such limiting and pulse shaping with more tractable circuits than antennas. Furthermore the radiation-resistance of antennas which are a small fraction of a quarter wave length (90°) is very small, being only 6.5 ohms for a 45° antenna (1/8 wave length) and 1.5 ohms for a 22.5° antenna. It is necessary to keep ohmic resistance of antennas and ground systems much lower than these values for any reasonable power efficiency. This in turn requires extensive radial grounding systems.* Since any form of sharply directive array involves a number of antennas, it is impractical to build them for low frequency systems. At higher frequencies, the antenna problem is much less difficult and it is quite possible to construct antenna arrays, reflectors (dishes), and lenses which give sharply defined beams, if these are desired.

VII. Frequency and Bandwidth

A general consideration of frequency and bandwidth requirements for tronic navigation systems involves both engineering and political aspects. The operating frequency for a particular system and its bandwidth requirement engineering problems. The availability of a given bandwidth at a particular lo in the frequency spectrum is a political question. The possibility of accura long-range navigation by electronic means has been amply demonstrated during the war, and the desirability of post-war maintenance of such services is obvious. A chart showing the present uses of various parts of the radio-frequency spectrum and the frequencies which the several navigation systems now use is shown on page 31.05. Since in most cases the exact transmitting frequency is not critical from an engineering point of view, it may be chosen to fit available ranges in the spectrum. Those parts of the radio spectrum which have been used for a fixed purpose for many years and for which large capital sums have been invested in transmitting and receiving equipment, as in the case of the broadcasting band from 535 to 1605 kcps, are practically untouchable even for a worldwide navigation system. On the other hand amateur bands are notoriously likely to be taken over for other purposes when their usefulness becomes evident. Many present navigational uses for parts of the spectrum are obsolescent or would be if more general use were made of present Loran coverage or that of any other successful long range system.

* An excellent study of the low-frequency antenna problem under steady-state condi- [illegible] reported in OSS - P - 22-2; [illegible] C 392

There is plenty of room in the spectrum for a good, well-integrated navigation system, but there is not room for all the possible systems covering the same territory at the same time. However, in view of the importance of the problem it is highly desirable to save available spectrum space for further experimentation with navigation systems and hence more rapid evolution towards better ultimate systems.

In considering the bandwidth of a given system it is necessary to take account of the bandwidth required for the complete chain of transmitting stations which are required to provide coverage over an ocean or a large land area such as North America or Europe. Thus a pulse system like Loran requires a relatively large bandwidth allotment, but one can operate many fixed transmitters on the same frequency since the various stations may be distinguished by their repetition rates. A system like Sonne on the other hand can operate with a much narrower bandwidth allotment per station, but cannot stack stations too closely together, and must not use the same frequency for any two stations which can be received simultaneously at any point in the coverage area. The present Loran receiver (AN/APN-4) is designed for receiving sixteen possible pairs (sixteen repetition rates) on each of four frequency channels. Complete coverage of the North Atlantic would probably require the use of all the rates on one channel. The range of Sonne is of the same order of magnitude as that of Loran, and sixteen Sonne stations spaced 3 kcps apart would require approximately 50 kcps of bandwidth for a complete system. This figure of 50 kcps bandwidth is of the same order of magnitude as that of an ideal Loran pulse transmission. Actual Loran transmissions are somewhat wider. It might be possible to stack Sonne transmissions as close together as 1 kcps apart, but sharp receiver circuits tend to broaden the equisignal and reduce the precision of a line of position. In general, the Germans used wider spacing than 1 kcps for their operating Sonne stations. The transmitted power from German Sonne stations was of the order of 1.5 kw which is to be compared with 100 kw of peak transmitted power from a typical Loran station. However, the equivalent ratio of signal strengths is 0.123 to 1.0. This value is indicated in relation to other signal strengths in Figure 1-17. The average power of a Loran transmission is much less than 1.5 kw.

Figure 1-19 shows the frequency spectra of a probability pulse like that of Figure 1-20 (solid line), a cosine pulse like that of Figure 1-09 and a rectangular pulse, all having a nominal duration of 50 microseconds. While it may be easy to decide what an ideal pulse should look like, it is not easy to generate such a pulse, modulating a radio-frequency carrier at the power levels which are necessary. The problem reduces to the fact that while the expenditure of considerably more money in engineering and operating costs might produce a better pulse from the point of view of reduced bandwidth of transmission, in most cases the interference produced in a narrow band receiver tuned 100 kcps off the center of the pulse spectrum will be negligible at points located at some distance from the transmitter. The distances at which pulses cease to be a serious source of interference depend both on the shape of the pulse as indicated, on the peak transmitted power, and on the local noise level and the noise generated in the receiver. The fact that radio noise conditions vary greatly with the location, time of day, and time of year, etc., make numerical assessments meaningless except in average terms. Nevertheless the truth remains that while pulse forms should be improved, there is a diminishing gain to be achieved by carrying out extreme refinements. Beyond a certain point the only benefits which result are confined to very limited areas near transmitting stations.

The design of practical pulse shapes is, like so many other engineering problems, a compromise between a number of conflicting requirements. As pointed out earlier, the shorter the allowable timing uncertainty the shorter the rise time of the pulse must be, and again for high resolution in PPI presentations the rise

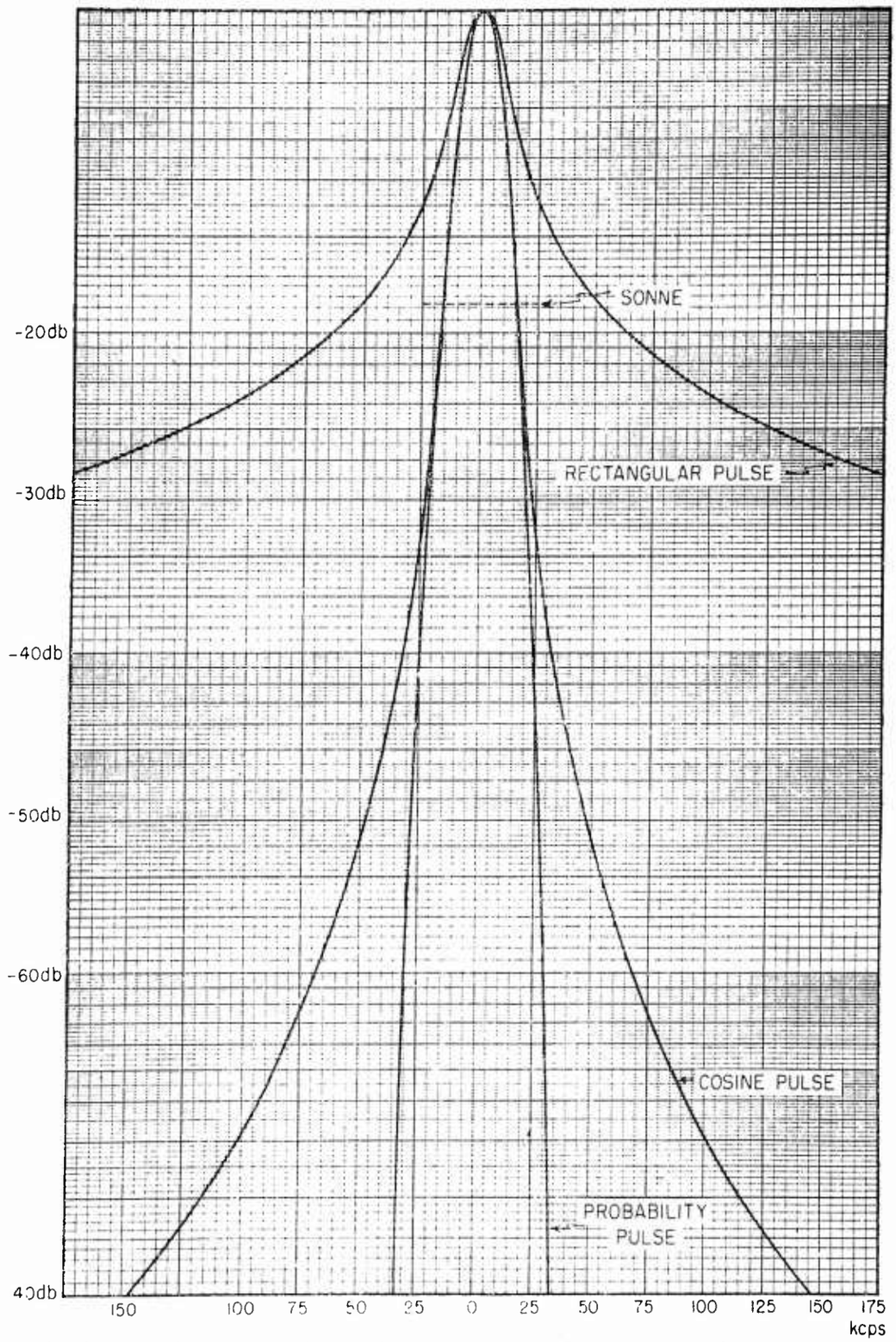


Fig. 1-19 Periodogram envelopes of rectangular, cosine, and probability pulses all having the same nominal duration and the same peak value. The rectangular and cosine pulses have harmonic terms in their periodograms which are not shown in the above curves since the point of interest is the rate at which the envelope decreases with frequency away from the carrier. If one assumes the peak power radiated during the pulses is 100 kw then the relative field strength of a (50 kc wide) group of Sonne stations radiating 1.5 kw is shown for comparison.

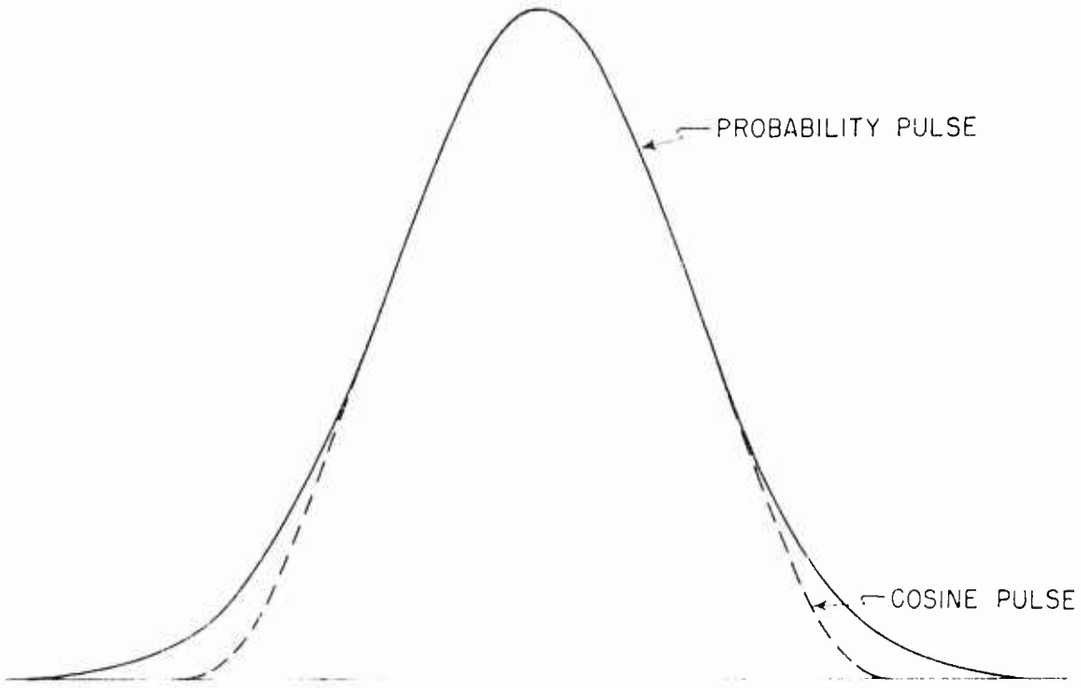
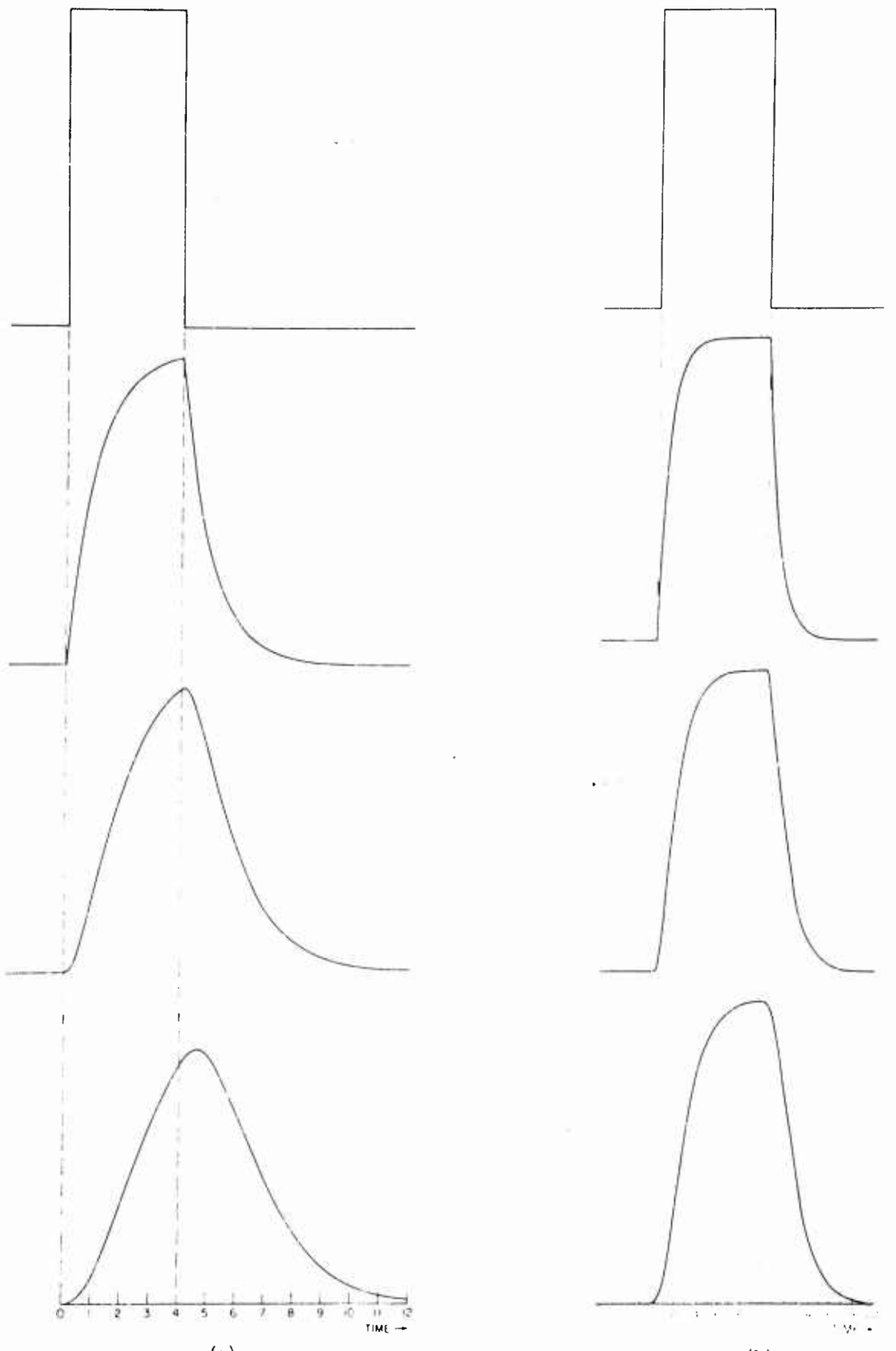


Fig. 1-20 Comparison of a probability pulse ($e = Ee^{-\alpha t^2}$) and a cosine pulse $e = E\left(\frac{1}{2} + \frac{1}{2}\cos \beta t\right)$ from $\beta t = -\pi$ to $\beta t = +\pi$

time and total duration of pulses must be short. The ideal pulse shape from the point of view of minimum bandwidth required for transmission is one having the equation of an error function, $e = Ee^{-\alpha t^2}$. However, all actual pulses have to reach their maximum value in a finite time whereas probability pulses have infinite duration measured along the time axis. The cosine pulse of Figure 1-09 is a simple mathematical form of finite time duration, and it has a reasonably narrow bandwidth as is evident from Figure 1-19. Many actual pulses have leading edges closely approximating this cosine form, although the trailing edges are more nearly of an exponential form. For a given pulse shape such as a half-sine or a cosine as in Figure 1-09, the shorter its duration in time the wider will be its spectrum and vice versa. However, one must be careful in interpreting the meaning of this statement. Consider for instance a comparison of rectangular pulses modulating a carrier and all having the same amplitude but different lengths in time. A receiver tuned a few kcps off the carrier will receive a click when the pulse begins and another when it stops. These clicks will have the same intensity whatever the pulse duration as long as it is very much longer than the period of a single RF cycle. The periodogram of such a pulse of amplitude E and having a duration $2t_n$ is

$$A(f) = 2Et_n \frac{\sin\left(\frac{\pi}{2} \cdot \frac{f}{f_n}\right)}{\frac{\pi}{2} \cdot \frac{f}{f_n}}$$

where f is the frequency measured from the carrier value, and $f_n = \frac{1}{4t_n}$. When the frequency is near the carrier value, f is near zero and A(f) reduces to $2Et_n$, so that the periodogram amplitude at carrier frequency will increase with the pulse duration. On the other hand for f>fn, and considering the values of the periodogram at the maximum points where the sine function is unity, the periodogram is given by



(a) (b)

Fig. 1-21 Modification of a rectangular 50 microsecond pulse at the end of each of three stages of video amplification. The upper half power frequency is 12,700 cps for a single stage and 6,500 cps for 3 stages in case (a); and 31,850 cps per stage or 16,200 cps for the three stages in case (b). The time scale is given in terms of the time constant of a single video stage in each case.

$$A(f) = \frac{2Et_n}{\pi \frac{f}{2f_n}} = \frac{E}{\pi f} \quad , \qquad \text{since } 2f_n = \frac{1}{2t_n}$$

showing that the amplitude of the periodogram is an inverse function of frequency off the center of the band for this particular pulse form, and is independent of the duration. In terms of energy, the energy in sidebands remote from the carrier frequency depends on the shape of the leading and trailing edges of the pulse, and is independent of pulse duration if the top of the pulse is flat, whereas the carrier energy is a function of pulse duration. The relative amount of sideband energy radiated goes down as the pulse is lengthened, since it is diluted by more and more carrier energy, but the actual sideband energy is independent of duration and the "clicks" produced are just as annoying. One solves the key "click" problem for code transmitters by simple delay circuits which round the corners of the otherwise rectangular modulation envelope. With pulses the problem is more difficult, since the steep front edge of the pulse is for many uses its most important feature and one which must be preserved if accurate time measurements are to be made. The problem is to have the leading edge of the pulse arrive at its steepest portion by a gradual increase of slope. The probability pulse accomplishes this to the highest possible degree but it spends too long a time reaching its steepest part, as shown in Figure 1-20 (solid line). The simple rule of leading and trailing edges is that if the function of time which describes the leading or the trailing edge has a discontinuity of value, as in a rectangular pulse (step function), then the sideband intensities diminish as the inverse first power of the frequency difference between sideband and carrier. If the derivative of the mathematical form of the pulse has discontinuities, as in the case of triangular or half-sine pulses, the law is inverse square, etc. In the case of the cosine pulse of Figure 1-69 the first derivative is continuous but the second is not, so the governing function is an inverse cube. All the derivatives of a probability pulse are continuous.

One might approach the problem from the point of view of physically generating a desirable pulse by modifying a convenient initial form until it has the desired shape. This modification may be thought of as a trimming off of the higher frequency components of the pulse. Figure 1-21 (*a*) and (*b*) shows the appearance of the initially rectangular pulse after each of three similar successive stages of video amplification for two different bandwidths. The vertical dimension of the pulse is kept nearly constant to bring out the essential change of shape corresponding to the reduction in intensity of the higher frequency components of the pulse spectrum. The last pulse shown in Figure 1-21 for each amplifier bandwidth is approaching the ideal probability pulse shown in Figure 1-20 (solid line). Although having the same initial width, the final pulse produced by the narrower amplifier will be broader than that produced in the wider amplifier. A similar effect is produced in the envelope of a pulse-modulated radio-frequency signal when it is passed through successive tuned circuits, as in a receiver or transmitter. This is shown in Figure 1-22. Here again the change in shape of a rectangular pulse-modulated radio wave "packet" may be thought of as due to clipping the higher frequency side bands of the signal. After detection, this pulse-modulated signal has the appearance of the last pulse in Figure 1-21. Any measurement of the time interval between two pulses, or the recognition of coincidence of two pulses, will be most accurate if it can be made at the steepest part of the pulse. Consider the alignment of two similar pulses which are to be exactly superimposed as in a Loran indicator, where the pulse amplitude is vertical and the time base is horizontal. The lateral separation of two pulses which are nearly superimposed is greatest at the steepest part of the pulse, as shown in Figure 1-23. As pointed out earlier, noise tends to broaden the trace and thus reduce the precision of such a measurement or alignment by causing the two pulses

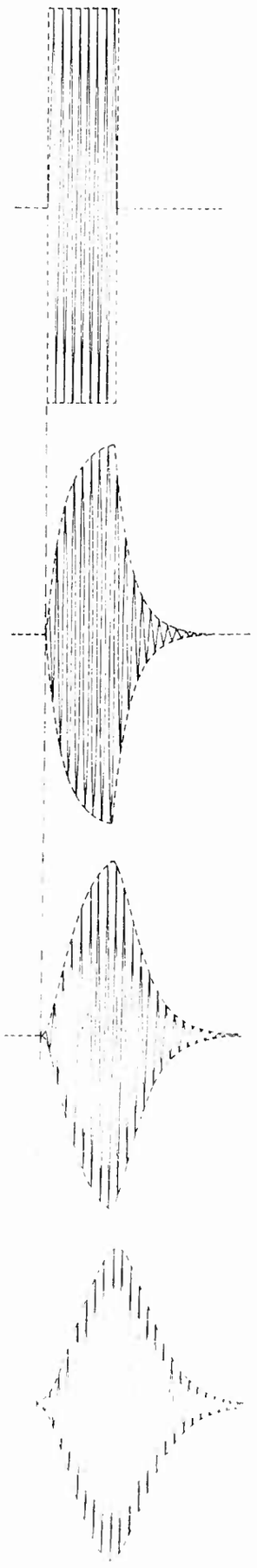


Fig. 1-22 Modification of a rectangular radio-frequency pulse in a radio-frequency amplifier having an overall bandwidth (for the three stages) of 13,000 cps (pulse length 50 microseconds).

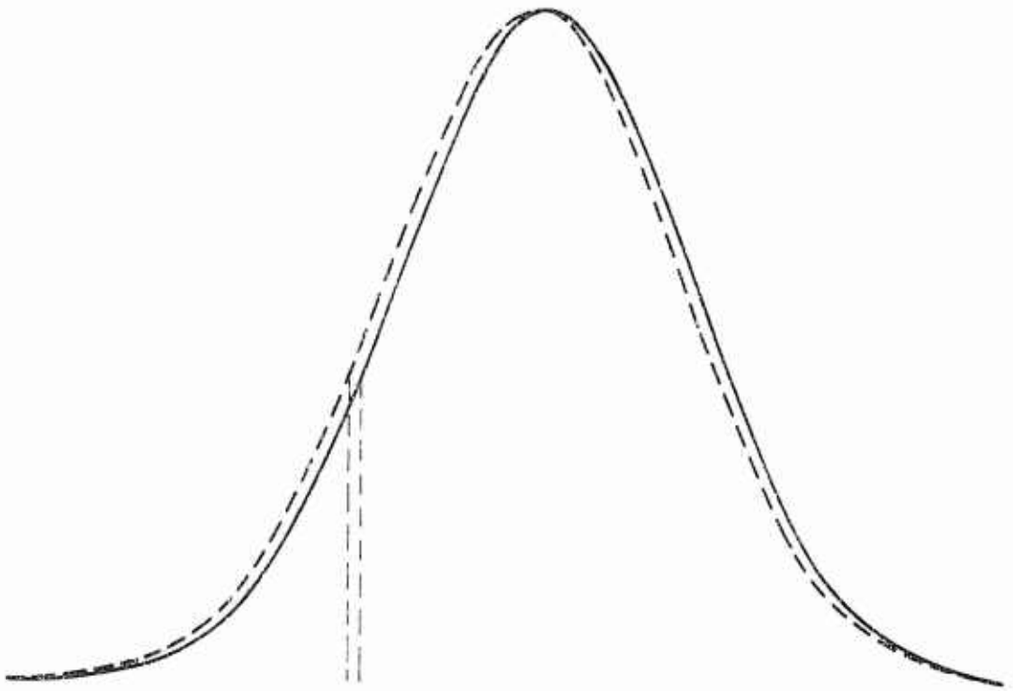


Fig. 1-23 Showing the lateral separation of two nearly superimposed pulses

being compared to merge into a single broad trace. As each trace is broadened the two pulses merge together where their slopes are small, but the last part of the pulses to become unresolvable is the steepest part.

From the point of view of propagation uncertainties, the earlier in time that one can use the front edge of a ground-wave pulse, the less contaminated it will be with other modes of propagation, hence the desirability of getting up to the steep part as rapidly as possible. If one is using sky-wave pulses there is the further requirement that the ground-wave pulse must not be so long that its trailing edge contaminates the leading edge of the desired sky-wave pulse. Thus both the steep front edge and the short tail are necessary attributes of practical pulses for such comparisons as are made in a Loran indicator. For any required steepness, which is usually numerically given in terms of rise time, one could stipulate the necessary duration of a pulse for any choice of pulse form (such as cosine or probability) and hence the band width required for transmission. Since the pulse which is finally displayed on the receiver scope is shaped by all the circuits through which it passes, a natural question arises as to relative bandwidths of transmitted pulse and receiver response. It is fairly obvious that there is no reason for having the receiver bandwidth much broader than that of the pulse being received, since the pulse shape is not improved (made steeper or shorter) by this procedure and the broader receiver picks up more noise. For any received pulse, the receiver will always increase the rise time and broaden the pulse by an amount inversely proportional to the overall receiver bandwidth. Figure 1-24 shows the effect on a cosine pulse, of the form used in Figure 1-09 and having a duration of 50 microseconds at half amplitude, produced by single-stage video amplifiers of three different bandwidths (30 kcps, 20 kcps, and 15 kcps). After passing through the 30-kcps amplifier, the pulse is broadened somewhat, but if one used a broader amplifier than 30 kcps the improvement in pulse form would be slight for the added cost and increased noise reception. On the other hand the pulse after the 15-kcps amplifier has nearly twice its original base length of 100 microseconds. There is an approximate relationship between the

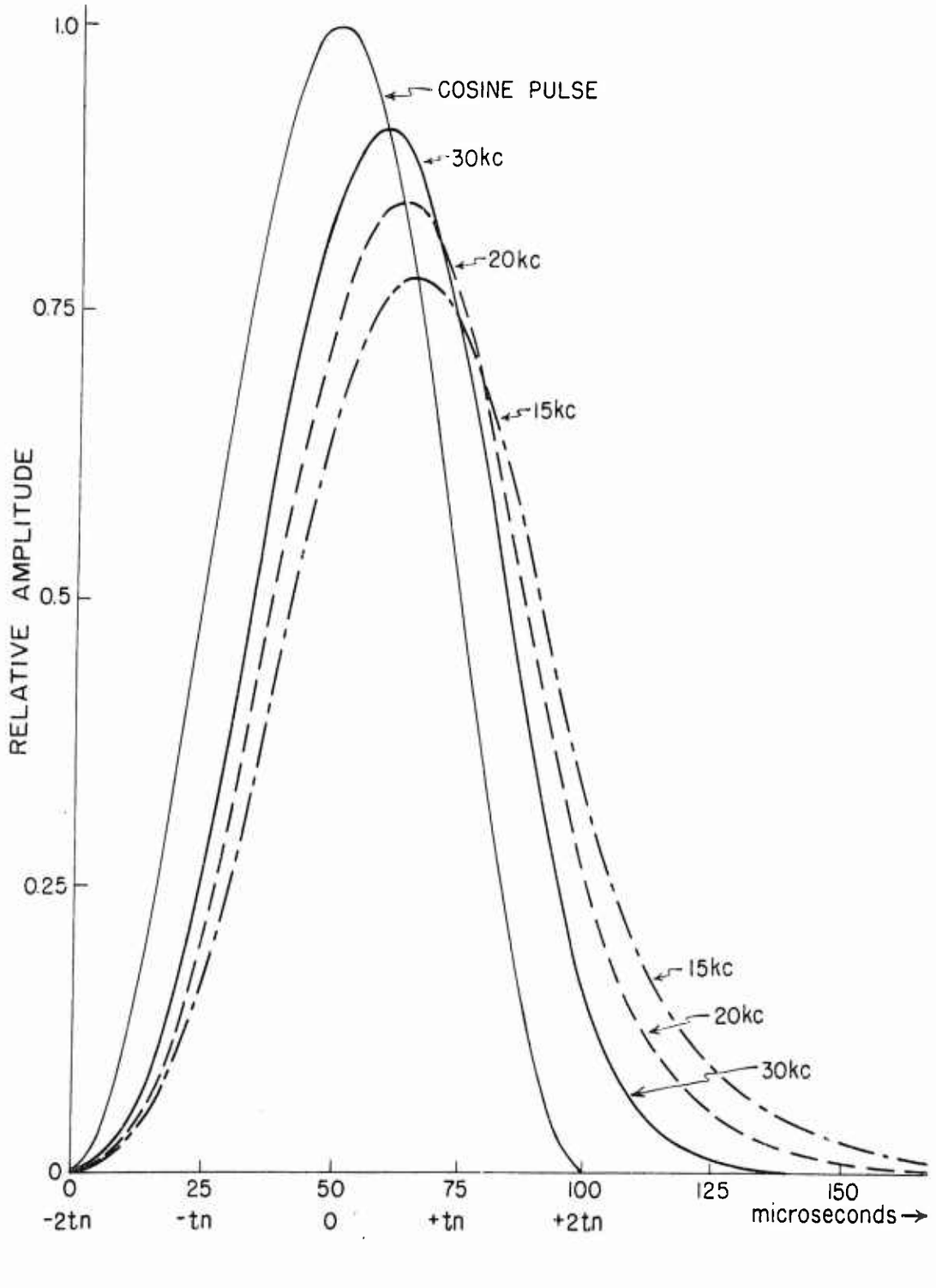


Fig. 1-24 Distortion of a cosine-shaped pulse in a single-stage amplifier, for three different bandwidths, showing the upper envelope of the pulse only.

rise time of a pulse and the upper half-power frequency of a video amplifier which is capable of transmitting the pulse with negligible distortion; i.e.,

$$\text{the rise time (seconds)} = \frac{0.35}{\text{upper half power frequency (cps)}}$$

A similar relation holds for a radio-frequency amplifier transmitting a pulse-modulated radio-frequency signal; here

$$\text{the rise time (seconds)} = \frac{0.7}{\text{bandwidth (cps)}}$$

where the bandwidth is the frequency difference between upper and lower half-power frequencies for the amplifier. The approximations are due to the fact that video and RF amplifiers may be compensated or aligned in various ways and the numerical factor depends on the amplifier circuits as well as on the particular pulse shape and the definition of negligible distortion. The ability of a receiver to follow a rapidly changing modulation envelope, whether it be a pulse modulation or a sinusoidal modulation, is the basic property which is measured numerically in terms of bandwidth. A similar statement holds for the ability of a video amplifier to follow a rapidly varying signal. The word "follow" used here refers both to following up the rise and down on the trailing edge. There is a tendency in present equipment to have the overall receiver bandwidth rather narrower than that of the transmitted signal, in order to improve the signal-to-noise ratio. If such a receiver operates satisfactorily from the point of view of precision of result, the implication is that the transmitted signal is broader than it needs to be and it should be tailored to reduce the required bandwidth for transmission. The whole question of ideal signal-to-noise ratios depends on the type of transmission, and the presentation and use of the received signal. In search radar applications, where the primary object is to detect the presence of craft at extreme ranges, it is desirable to use long pulses and narrow receivers. The presentation will show relatively large blobs for targets, incapable of fine resolution, but easier to spot above the noise which clutters the screen and hides the target whose location is unknown. On the other hand a broader receiver and shorter pulse could be used in the case of a target which has been located and enclosed within a narrow "gate" so that only those noise pulses which arrive within the time duration of the "gate" are seen along with the desired signal.

In the matter of signal-to-noise ratio, the various continuous-wave systems have the advantage of being able to use quite narrow band receivers. Changes in craft position are so slow, even at airspeeds contemplated, compared to the rapid changes of instantaneous radio-frequency voltage in a cycle or a modulation envelope, that one received cycle is almost identical to the next or to the next hundred cycles, and as a result the bandwidth required is small. However, it must be borne in mind that if radio-frequency phase is the information-bearing variable, then the amplifier must be stable against phase shifts. The narrower the band width, the more sensitive a receiver is to slight frequency drift. The angular phase shift caused by a slight frequency change in received radiation or drift of receiver resonant frequency is given for a single-stage single-tuned receiver by

$$\Delta\theta = \frac{2\Delta f}{\text{Bandwidth (cps)}}$$

where $\Delta\theta$ is the uncertainty in phase angle, Δf (cps) is the maximum deviation of receiver frequency from signal frequency. This difference is assumed small in comparison to the bandwidth and constitutes the frequency uncertainty. For several stages, the total phase shift is the sum of the phase shifts for each individual

stage. The overall bandwidth diminishes as the number of like stages increases, but not in simple inverse proportion. So that in general this formula gives too small a value for phase angle uncertainty in terms of overall bandwidth for a number of single-tuned stages. It is possible to design double-tuned stages and combinations of double- and single-tuned stages which are more stable against phase shifts. In general the more specialized the receiver the more difficult is its operation, service, and maintenance. As an example, suppose the bandwidth is 100 cycles per second and that it is required to keep uncertainties in phase below 3.6 degrees, or 0.0628 radians, then the maximum allowable frequency drift will be 3.14 cycles per second which is one part in 10^5 at 300 kcps. This would be relatively easy at the transmitting station where accurate crystal control of frequency is possible but would be more difficult in a receiver where thermal drift of the inductance and capacitance elements in the tuned circuits is not easily controlled under operating conditions which involve large temperature variations and require light weight and small physical dimensions. The Decca system requires phase-stable amplifiers and on the assumption that Decca has a range as great as Sonne or Loran, it would need 32 phase-stable amplifier channels for a receiver to use a chain of stations covering the North Atlantic for instance. There is the further difficulty that these 32 frequencies must all be submultiples of some higher frequency and it might be rather difficult to find space in the spectrum for a group of frequencies covering such a large overall band spread, even though the individual channels are very narrow. For a system like the Federal long-range system, the relative amplitude of received signals is the quantity which bears the information. Here the very narrow amplifier must be stable and linear with respect to input signal amplitude, since signals of different strengths have to be compared.

VIII. Present Status

There is a wide difference between an operational system and a proposal. When a system has been proposed, there is a temptation to dismiss the working out of practical details as if the success of such a process were a foregone conclusion. When one examines the detail of some of the operational systems it is obvious that more than one stroke of genius has gone into the working out of this detail.

On the other hand the operational systems have not reached their ultimate state of perfection and systems still require integration into unified navigational utilities.

Part I General Information

Introduction

A radio beacon is an installation of radio transmitting, or receiving and transmitting apparatus which supplies suitable information for use in the determination of one or more of the following: range, azimuth, identification. The following discussion is concerned mainly with radar beacons or racons of the so-called responder type which automatically transmit a reply signal only upon the reception of an interrogating signal consisting of a radar pulse of a length specially reserved for this function alone. This feature adds a measure of security to the operation of the racons. Responder beacons may be interrogated either by regular search radar sets (using a special pulse length of from 2 to 5 microseconds during beacon operation) or by so-called interrogator-responser installations designed especially for the purpose of interrogating beacons and receiving the beacon response signals. Responder beacons used for purposes of IFF, are commonly referred to as transponders. Interrogator-responsers are often referred to simply as interrogators; and these installations may or may not be synchronized with a local radar set. Interrogator-responsers which are synchronized with local radar sets usually operate at a submultiple of the radar pulse repetition rate in order to reduce the likelyhood of overinterrogation of the radar beacon which may be responding to a number of interrogators simultaneously. Beacons operating in the super-high-frequency X or K bands are limited to the use of relatively heavy transmitting equipment consisting of magnetrons and wave guides, while those operating in the lower frequency bands may utilize ordinary vacuum tubes and lumped constant circuits which in general are much lighter in weight. Both magnetrons and UHF triodes are used in the S-band.

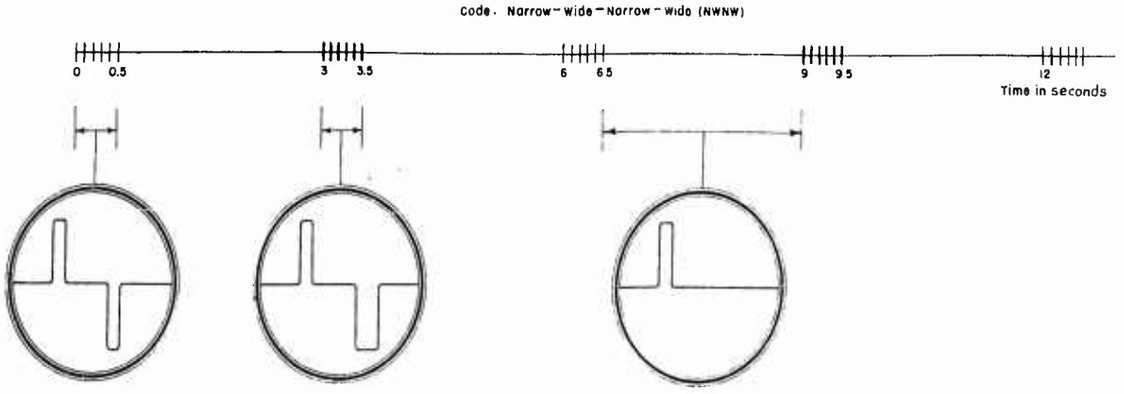
Uses

Radar beacons have a number of uses, the most important of which are: (a) fixed ground installations for general navigational use by aircraft. (b) portable and mobile beacons for temporary navigation (including homing). (c) airborne beacons for identification and control of aircraft both within and beyond normal radar range.

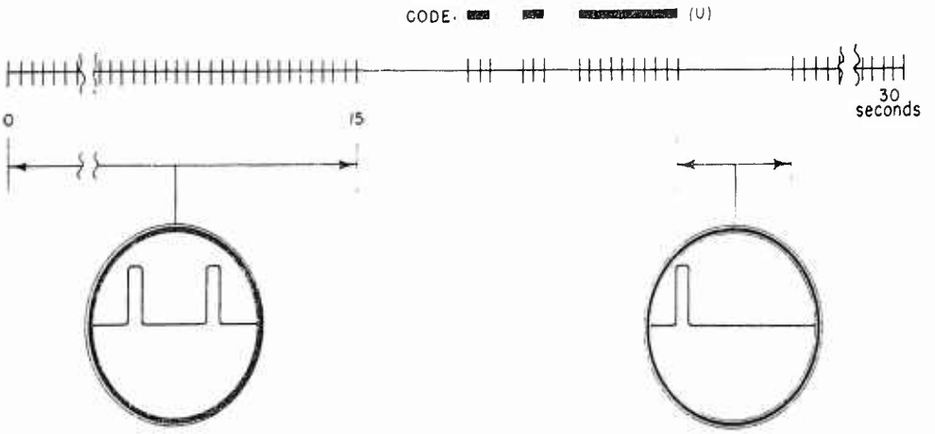
Triggering Requirements

The requirements of a beacon depend to a certain extent upon its particular use. With the exception of some IFF transponders, a beacon is designed so that it may be triggered or interrogated directly by pulses from radar sets operating anywhere within a particular frequency band such as the X-band or S-band. Most racons respond only to pulses having a time duration of between 2 and 4.5 microseconds, and are unaffected by normal radar search pulses most of which have a duration of one microsecond or less. Increased security may be obtained if necessary by the use of beacons requiring two interrogating pulses occurring simultaneously on different frequencies.

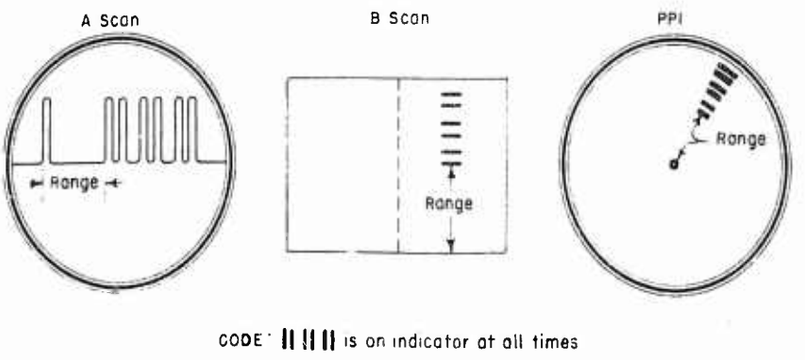
A radar responder beacon replies on a different frequency from that of the radar interrogation. In order to eliminate ground clutter and other radar echoes when observing beacon responses on a PPI, the receiver of the radar set is made sensitive to signals of the beacon response frequency and insensitive to the echo signals of the radar transmission frequency. For example, the standard X-band beacon response frequency is 9310 mcps which is just below the 9335 to 9415 mcps range of the standard aircraft X-band radar frequencies. A separate local oscillator is usually provided in the radar receiver for reception at the beacon response frequency. During reception at the beacon frequency, a loss which may amount to as much as 20 db occurs due to the presence of the TR switch which acts as a relatively high-Q band-pass filter tuned for best reception at the frequency of the radar transmitter rather than at the beacon response frequency. However in order



(a)



(b)



CODE · ▮▮▮▮ is on indicator at all times

(c)

Fig. 2-01 Types of beacon codes

to reduce the high TR loss, radars of recent design have incorporated a relay-operated device for automatic retuning of the TR box to the beacon frequency during beacon reception.

Coding

Beacon response signals may be coded for purposes of identification. Several types of coding are in use, the most common of which is known as range coding. Some IFF equipment however, makes use of either gap or sequence coding neither of which gives instantaneous identification as does range coding. The three types of coding are illustrated by the diagrams and cathode ray tube indications shown in Figure 2-01.

Sequence coding is illustrated in Figure 2-01(a). Several hundred consecutive responses appear as a single pip on the A scope lasting for about one half second, following which is a 2.5 second interval in which no signals are returned by the beacon and only the main bang is visible on the scope. Then the beacon responds again for one half second but this time returning wider pulses which show up as a wider response signal on the A scan. Groups of wide and narrow response pulses separated by longer no-response intervals follow one another in some definite sequence to form a code such as the narrow-wide-narrow-wide code illustrated in Figure 2-01(a).

Gap coding, illustrated in Figure 2-01(b) is similar to sequence coding in that considerable time is required in order to read the complete code from the oscilloscope. In gap coding the beacon response consists of a continuous series of identical pulses with occasional brief interruptions or gaps which are arranged to form a code such as the Morse letter U illustrated in Figure 2-01(b). A complete code re-occurs about every 30 seconds and consists of some combination of short and long reply periods separated by gaps which are short compared to those immediately preceding or following the code.

As illustrated in Figure 2-01(c) range coding gives immediate identification because the entire code appears at once on the screen of the oscilloscope. The beacon response to a single interrogating pulse consists of a series of from two to six appropriately spaced pulses. The spacing between any two pulses is usually either about 15 or 35 microseconds corresponding to range increments of about 1.2 or 2.9 nautical miles respectively. Both the number of pulses and the spacing between them may be varied to form different codes. On the screen of the oscilloscope the distance to the first beacon response signal is indicative of the range between the beacon and the interrogating radar.

Range coding can be read on intensity-modulated oscilloscopes (B or PPI scans) more easily than can either sequence or gap coding. Range codes are usually produced by an electronic coder, while sequence or gap codes are usually produced by mechanical coders.

Many interrogator-responser units of the type used primarily for homing operations make use of the L-scan type of presentation. The L-scan is sometimes referred to as a double A-scan. Ranges are indicated on the vertical scale and signal blips appear horizontally on either or both sides of a vertical center line as shown in Figure 2-02. Right and left steering directions for homing are usually indicated by inequality of amplitude of the signal blips appearing on the two sides of the scope presentation. This may be accomplished by simple lobe-switching technique aboard the navigating craft. Course or track indications may also

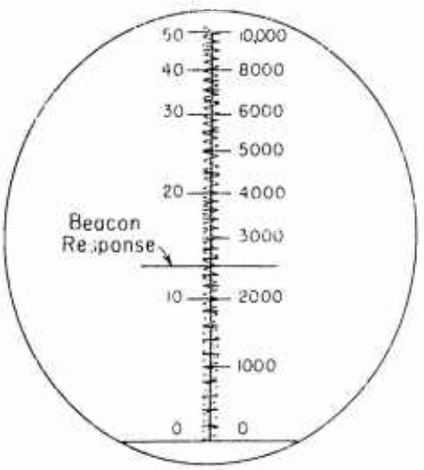


Fig. 2-C2 Example of L-scan presentation

be obtained if lobe-switching is also employed at the fixed ground beacon installation. (See Section 24).

Nature of Response Signals

As viewed on a PPI scan, a beacon response normally takes the form of a small arc similar to that produced by a radar echo signal from a large isolated object. However, there is considerable variation in the effective angular width of the radar beam for both interrogation and reception. As a radar beam sweeps over a beacon location, the time or angular spread within which the signal strength at the beacon site is sufficient to trigger the beacon depends upon the horizontal field pattern of the radar beam, and the maximum field strength at the beacon site, and also upon the sensitivity of the beacon receiver and the directivity characteristics of the beacon receiving antenna. The angular spread of the visual signal on the PPI tube depends upon all of the above and also upon the sensitivity and directivity characteristics of the radar receiving system. The angular spread for interrogation varies from 0° at maximum range to a full circle at close range. Between the maximum range and about 1/10 of maximum range, only the main lobe of the radar beam is sufficiently strong to interrogate the beacon. Below about 1/10 of the maximum range the side lobes may also interrogate the beacon, so that at close range the beacon response may appear as a full circle on a PPI scan, unless the directivity of the radar receiving antenna is sufficient to limit the angle through which the beacon response may be seen. It is thus quite apparent why beacon receivers should not be too sensitive. At close range the angle of interrogation may in some cases be reduced if an aircraft radar antenna is tilted upward to reduce the field strength at the ground beacon. The fact that most ground beacons have a rather sharp vertical directivity pattern beamed on the horizon helps somewhat in reducing the received signal strength at close range from aircraft at high altitudes. In fact the beacon response may even be lost entirely by an interrogating aircraft nearly over the beacon.

Radar beacon response pulses are usually of the order of 0.5 microsecond duration. Since 0.5 microsecond corresponds to the time required for an electromagnetic wave to travel about 1/10 mile, beacon response pulses of 0.5 microsecond duration often do not show up very clearly on a 100-mile sweep even though the video signal strength is adequate. The visibility of a beacon response on the PPI screen may be improved by "video stretching". The video stretching feature consists of lengthening the 0.5 microsecond video pulses to about 2.5 microseconds duration by means of an appropriate circuit.

Overinterrogation

The transmitter of a responder beacon has a limited traffic handling capacity. After an interrogating pulse has been accepted by the beacon discriminator circuit, the beacon receiver is made insensitive to further interrogation pulses for a period of about 200 microseconds. If a number of radars are working a responder beacon, a fraction of the interrogating signals sent out from each radar will go unanswered because they arrive at the beacon less than 200 microseconds after accepted sig-

nals from other radars. The code arcs on a PPI scan will then appear slightly broken up. If so many radars interrogate the beacon that its transmitter load reaches its safe upper limit, the period during which the beacon receiver is insensitive is automatically lengthened to a value sufficient to prevent further increase in the transmitter load. The beacon replies are shared statistically among the interrogating radars so that each radar will always receive some replies as long as its repetition rate is not synchronized with that of any other interrogating radar. Exact synchronization of repetition rates is a most unlikely occurrence. A microwave beacon such as AN/CPN-6 can serve as many as 50 to 100 aircraft. The number of aircraft which can simultaneously interrogate a beacon and receive intelligible responses signals depends upon the types of beacon and interrogating radars used.

Accuracy

The accuracy of measurement of the range or bearing of a beacon depends largely upon the interrogating radar equipment. Radars equipped with 10 to 15-mile sweeps with step range-delays can give the apparent slant range to within one-tenth mile or less. A correction of from 0.5 to 0.6 mile must be subtracted from the apparent slant range to compensate for delay in the beacon circuits. The measurement of azimuth or bearing of a ground beacon by an aircraft radar is limited to an accuracy of one or two degrees corresponding to an angular position error of 2 to 4 miles at a range of 100 miles. Since range can be measured with greater precision than azimuth, a more accurate navigational fix can in general be made by simultaneous measurement of the ranges to two beacons rather than by measurement of both range and azimuth of a single beacon.

Range and Siting of Microwave Beacons

Very-high-frequency radio waves travel in nearly straight lines, so that the maximum range at which a microwave beacon can be "seen", may be determined by simple geometry. For example, in Figure 2-03, the line BP tangent to the earth's surface illustrates the maximum possible range for the case of an aircraft at an altitude H_p interrogating a ground beacon the antenna of which is at a height H_b above the sea level surface of the earth. The maximum range between aircraft and beacon antenna is the sum of the respective "horizon ranges" R_b and R_p corresponding to the heights H_b and H_p. The average radar-horizon range, R, in nautical miles from any altitude, H, in feet is given by the formula $R = 1.22\sqrt{H}$. The above formula yields a value of R which is about 15 per cent larger than the geometrical horizon range illustrated in Figure 2-03, in order to allow for the average amount of bending (or refraction) of the tangent radio beam. To save numerical calculation, the chart of Figure 2-04 is provided for the determination of average radar-horizon ranges. The chart also contains in graphical form, information for the determination of the approximate total range between aircraft and ground beacon for the case in which an obstruction such as a building or hill causes the effective skyline to be at a small angle of elevation above the sea-level horizon. The number of angular degrees marking the dashed lines of Figure 2-04 correspond to the angle of elevation "A" above sea level as shown in Figure 2-05 or as shown with somewhat less distortion in Figure 2-06.

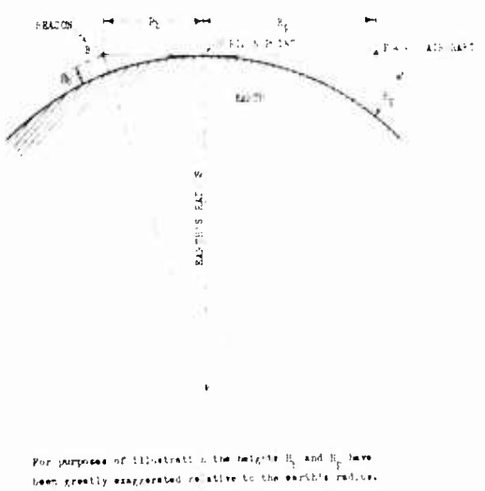


Fig. 2-03 Horizon-range diagram

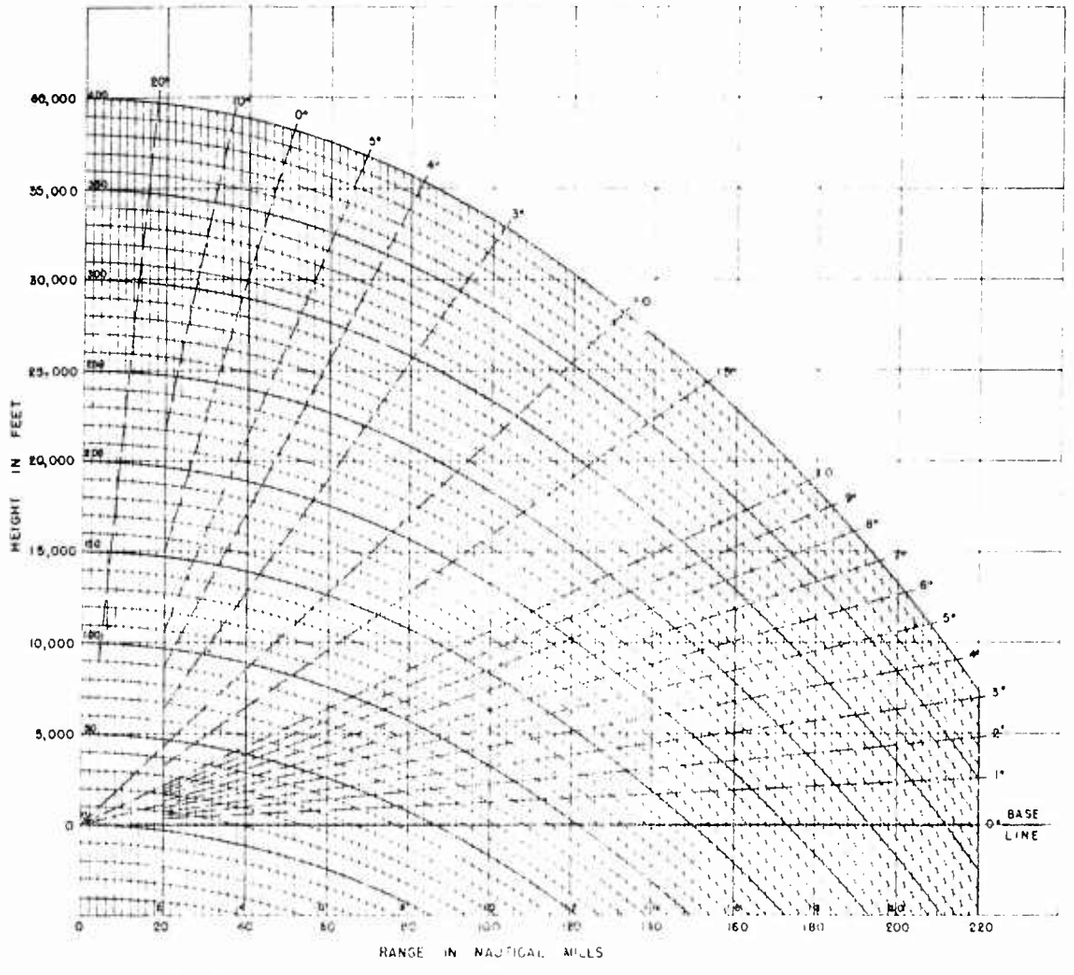


Fig. 2-04 Average radar-horizon range characteristics

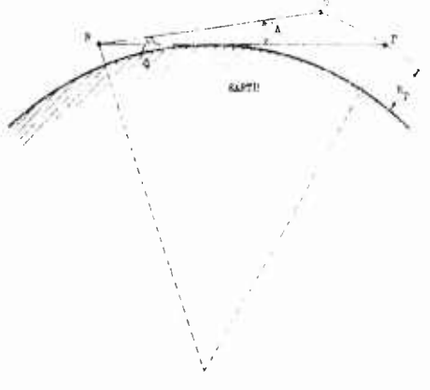


Fig. 2-05 Reduction of maximum range by skyline object "O"

The chart of Figure 2-04 is useful for the rapid determination of expected range vs. aircraft altitude charts for any beacon site. A skyline survey made with a good transit located at or very near to the beacon antenna yields the angle of elevation of important skyline features as a function of azimuth angle. The results of such a skyline survey might appear as shown in Figure 2-07 which is an imaginary set of data drawn to represent a typical seaside beacon having open sea from about 0^{o} to 180^{o} azimuth. Due to the elevation of the beacon antenna, the sea-level horizon-angle is in this case $-.18^{o}$. The angle A in Figure 2-06 is the angle of elevation measured above the sea-level horizon and would be .30+.18= .48 degrees for the highest point H to the northwest in Figure 2-07. At an inland beacon site the depression angle of the sea level horizon may be calculated from the formula: Depression angle $d = 0.018\sqrt{H_b}$ degrees with H_b in feet above sea level. The height of the beacon antenna used in the above numerical example was assumed to be 100 feet. With the aid of the chart of Figure 2-04, the data from the skyline survey may

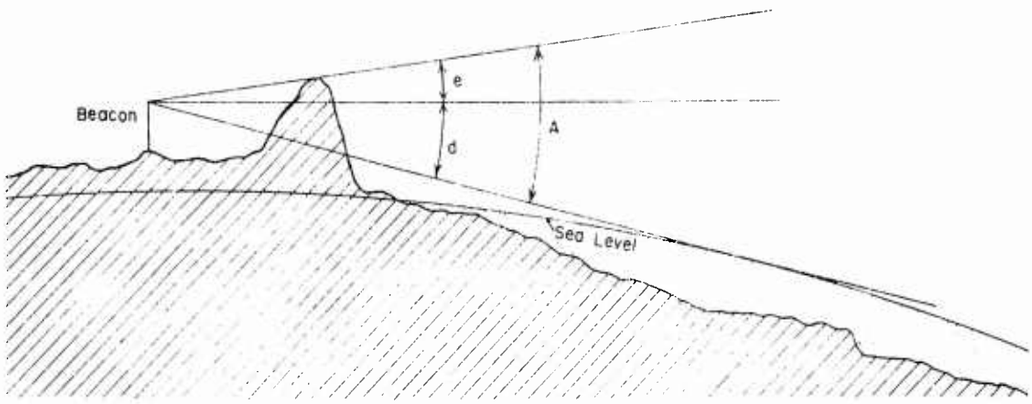


Fig. 2-06 Details of the angle of elevation A

be readily converted into a useful expected range vs. aircraft altitude chart such as that of Figure 2-08 for the given beacon. Maximum ranges for microwave beacons may be predicted by the above method more accurately than they can be checked without many hundreds of carefully controlled test flights for each beacon site.

As an aircraft approaches a beacon within the horizon range, interference effects may occur in the form of a slow recurrent fading of the beacon signals. The fading is due to partial cancellation between a direct signal and a signal reflected from the earth's surface. Over land, the fading due to interference effects is usually slight, but reflections from a water surface may cause the fading to amount to 20 db or more.

As long as an aircraft is above the radar horizon, the received signal power is given by the formula: $P_r = 1.85 \times 10^{-13} \frac{P_t G_p G_b \lambda^2}{R^2}$ watts where P_r is the power transmitted, G_p and G_b are the absolute gains of the aircraft and beacon antennas respectively, λ is the wavelength in centimeters, and R is the range in nautical miles. Either leg of the transmission - from aircraft to beacon or from beacon to aircraft - may be the limiting factor in determining the maximum usable range. An aircraft flying at an altitude of 30,000 feet should be able to obtain responses from beacons at ranges up to about 230 nautical miles (radar horizon). Beyond the radar

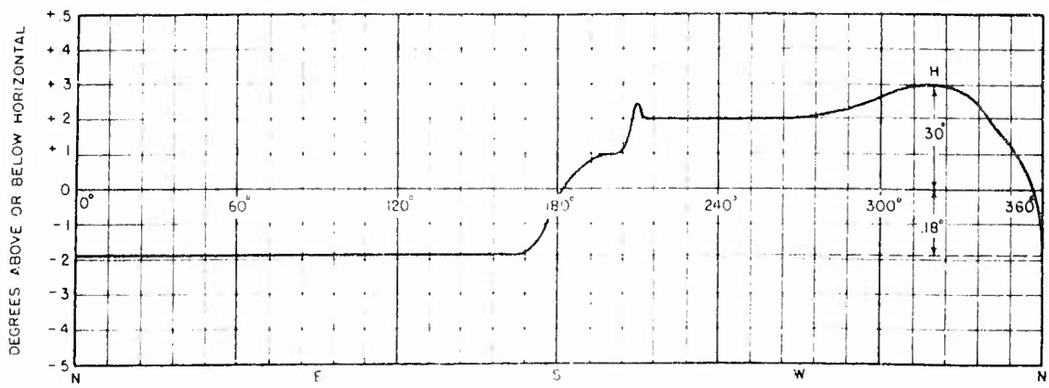


Fig. 2-07 Graph showing the elevation of the skyline from the beacon in the various directions of the compass. (Beacon height 100 feet)

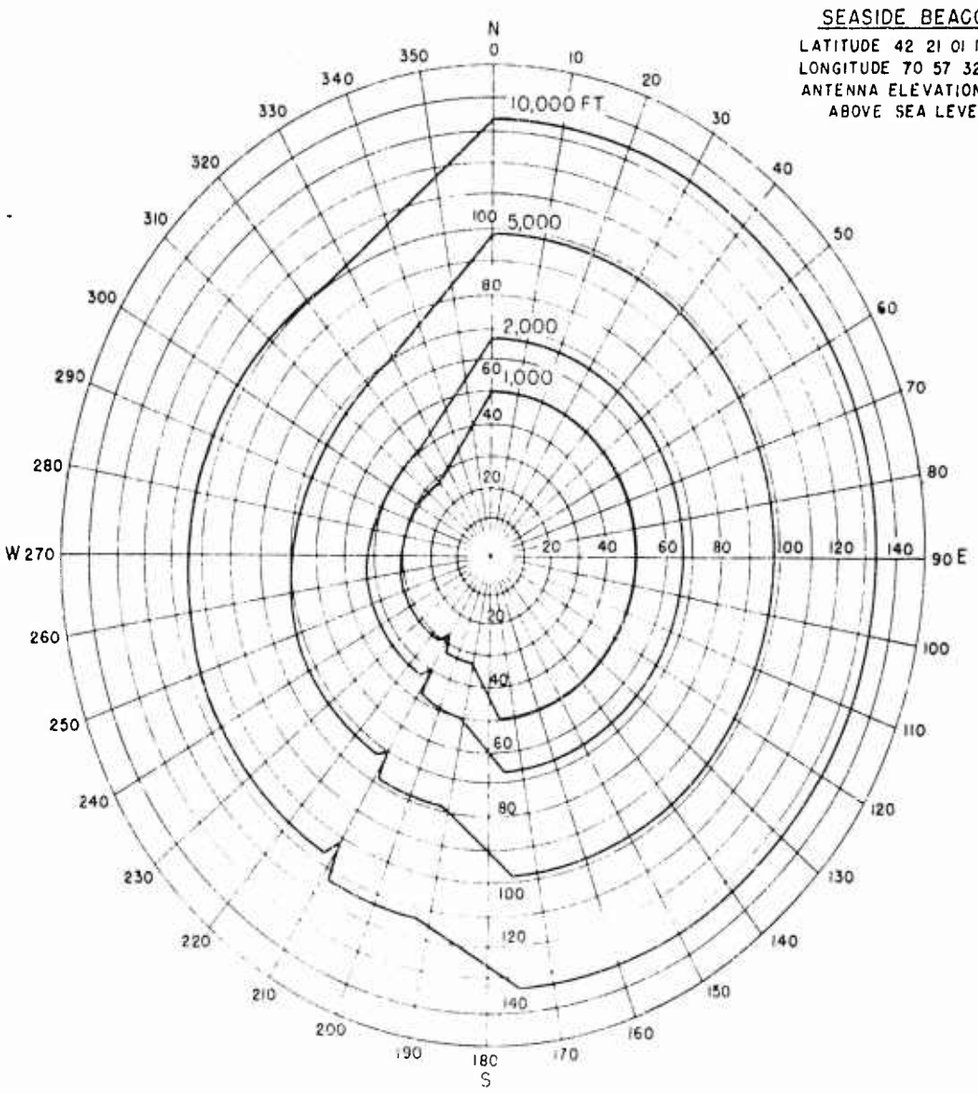


Fig. 2-08 Average beacon range in nautical miles for aircraft at elevation shown

horizon however, the signal strength drops off very rapidly and even a large increase of power would increase the attainable range by only a few miles.

Part II Description of a Typical Beacon (AN/CPN-6)

A description of a typical radar responder beacon follows: AN/CPN-6 is a heavy X-band radar responder beacon designed for ground, ship, or truck installation. An operational block diagram of this beacon is shown in Figure 2-09.

When a radar operator in an aircraft wishes to obtain a beacon signal, he turns a selector switch from SEARCH to BEACON. This changes his radar transmitter pulse width and receiver tuning so as to make possible interrogation and reception of the beacon.

The RF interrogating signal from the radar transmitter enters the omni-

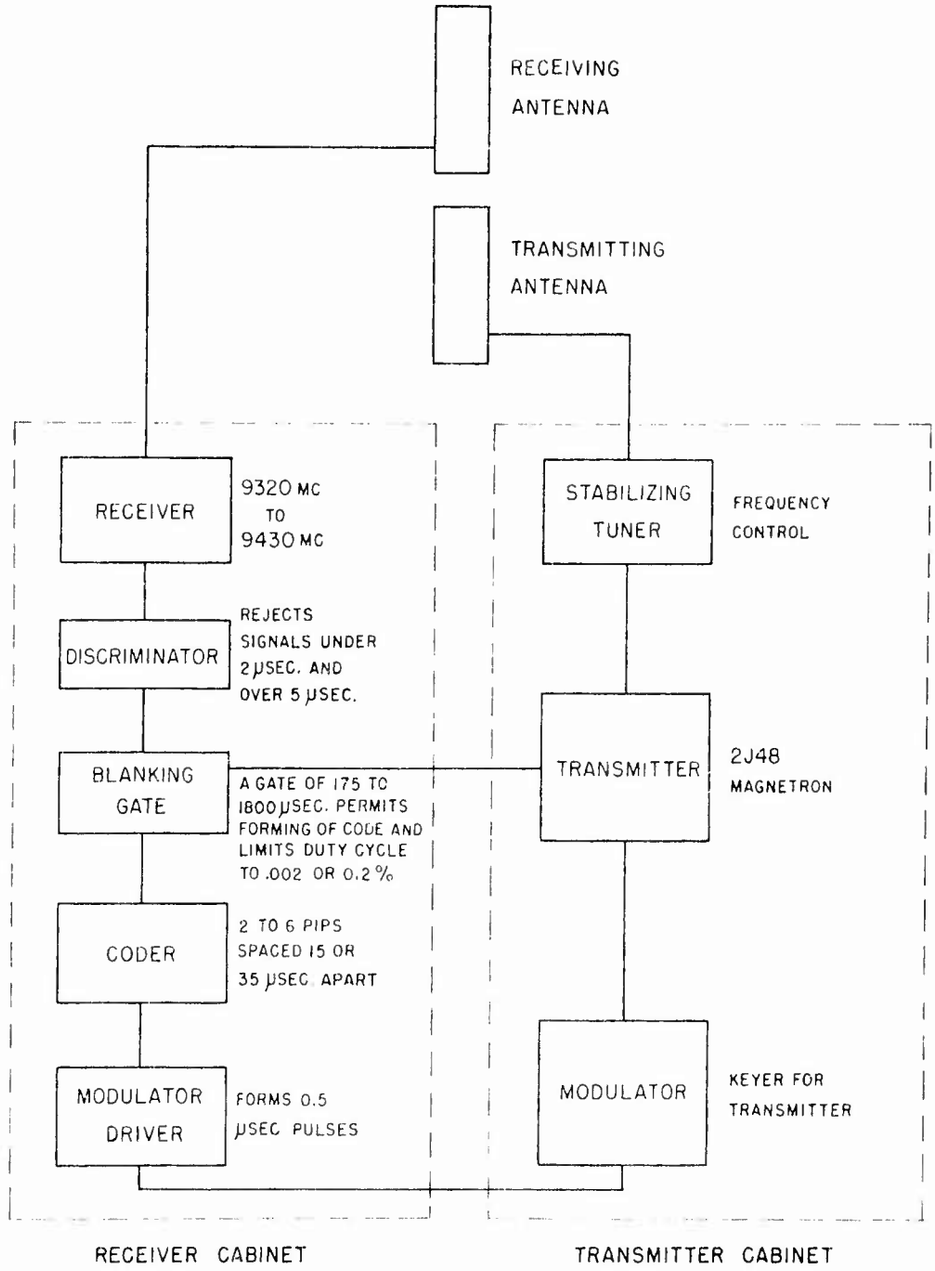


Fig. 2-09 Operational block diagram of X-band beacon AN/CPN-6

directional beacon receiving antenna and is led by wave-guide to the superheterodyne receiver. If the interrogating signal frequency lies within the receiver passband extending from 9320 mcps to 9430 mcps, it is converted to an intermediate frequency and amplified, converted to a "video" pulse envelope, amplified again and led to a pulse-width discriminator circuit. The discriminator circuit rejects ordinary search pulses shorter than two microseconds, or longer than five microseconds and passes beacon interrogation pulses of between two and five microseconds duration. A pulse which has passed through the discriminator circuit triggers a self-blanking multivibrator and also the first of a series of multivibrator circuits in the coder. The self-blanking multivibrator keeps the coder insensitive to incoming signals for a time somewhat longer than the duration of the code train. This limits

the maximum duty cycle and also prevents the beacon transmitter from triggering itself in a "ring around" fashion. The coder forms a series of from two to six trigger pulses with either short (1.5 microseconds) or long (3.5 microseconds) spaces between them, depending upon the setting of the code selector switches. The code trigger pulses are next sharpened, reduced in length to one-half microsecond, and amplified by the modulator driver. In the modulator the pulses are squared-up, further amplified to 11,000 volts peak, and applied to the magnetron transmitter operating at the X-band beacon frequency of 9310 mcps. A resonant cavity is used to tune the magnetron and stabilize its output frequency. The RF output of the magnetron is led by wave-guide to an omnidirectional transmitting antenna.

The beacon response signal is picked up by the radar set in the interrogating aircraft and displayed on the PPI screen as in Figure 2-01(c). The distance from the center of the PPI to the nearest small curved arc gives the slant range between beacon and aircraft (assuming an undelayed sweep). The series of arcs or dashes forms the code which identifies a particular beacon. The azimuth bearing of the beacon is read off the PPI in the same manner as for radar signals.

A brief description of some of the component parts of the racon system follows:

Antennas and RF Lines

A rectangular wave-guide 1 x 1/2 inch, is used for the transmission of RF energy because of its mechanical simplicity, low loss, and high power-handling capacity. Stub transformers are used at the base of each antenna unit to convert from the normal mode in the rectangular guide-feeder to the second mode (TM_{01}) in the cylindrical guide of the antenna or vice versa. Both transmitting and receiving antennas are of the slotted, cylindrical, wave-guide type giving horizontally polarized radiation with an omnidirectional pattern in the horizontal plane, and a half-power vertical beam width of five degrees centered on the horizon when the antenna axis is in a vertical position. The transmitting and receiving antennas are virtually identical, but the transmitting-antenna array is tuned for best operation at the beacon frequency of 9310 mcps while the receiving array is adjusted for best response at 9375 mcps, which is the center of the receiver pass band. For shipboard installations special antennas are provided which have a vertical beam width of 30 degrees at the half-power points, corresponding to a gain of only 3 compared to a gain of 20 for the 5 degree beam. This sacrifice of nearly 10 db in beacon performance is necessary in order to obtain such a broad beam that the beacon response will remain visible when the ship is rolling heavily.

The output frequency of the beacon transmitter is checked by a transmitter frequency monitor consisting of several components. A directional coupler extracts one part in 20,000 from the RF power output of the beacon transmitter. The directional coupler feeds a resonant cavity built of low temperature coefficient alloy, pretuned at the factory to the desired beacon frequency, and having a Q factor of about 10,000 so that its transmission is down fifty percent at plus or minus 0.5 mcps from the resonant frequency. The resonant cavity is followed by a crystal detector, amplifier, and indicating meter. The magnetron frequency puller (stabilizing tuner) is adjusted until the indicating meter of the frequency monitor reads a maximum. A similar receiver frequency-monitor is also provided for use in adjusting the local oscillator circuit.

Oscillator and IF Amplifier

A racon has the difficult job of responding to signals from radar sets whose transmitter frequencies lie scattered throughout a rather wide frequency band of approximately 150 mcps width. The actual bandwidth of the IF amplifier used in

this receiver is about 35 mcps extending from approximately 11 to 46 mcps. The required 110 mcps bandwidth is obtained by utilizing both sum and difference frequency components in the output from the converter, and by shifting the local oscillator frequency back and forth between two fixed values chosen such that the amplified radio-frequency bands are periodically shifted and overlap slightly to produce a wide effective RF pass band as illustrated in Figure 2-10. The switching of the local oscillator frequency takes place at a rate of between 150 and 200 times a second. An RF signal not lying in a region of overlap would of course be amplified only half of the time.

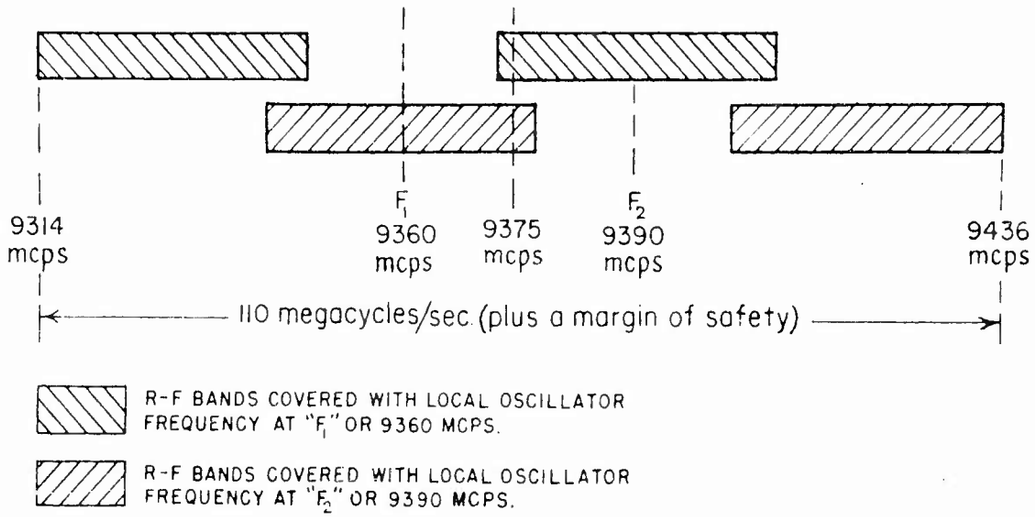


Fig. 2-10 Receiver band covered by switching frequency of local oscillator

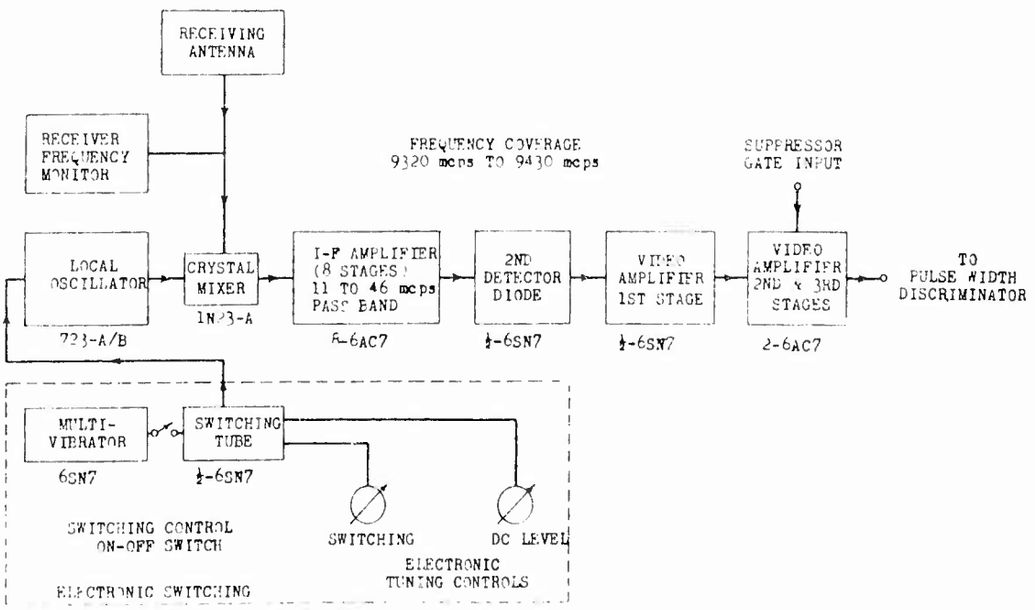


Fig. 2-11 Receiver block diagram (AN/CPN-6)

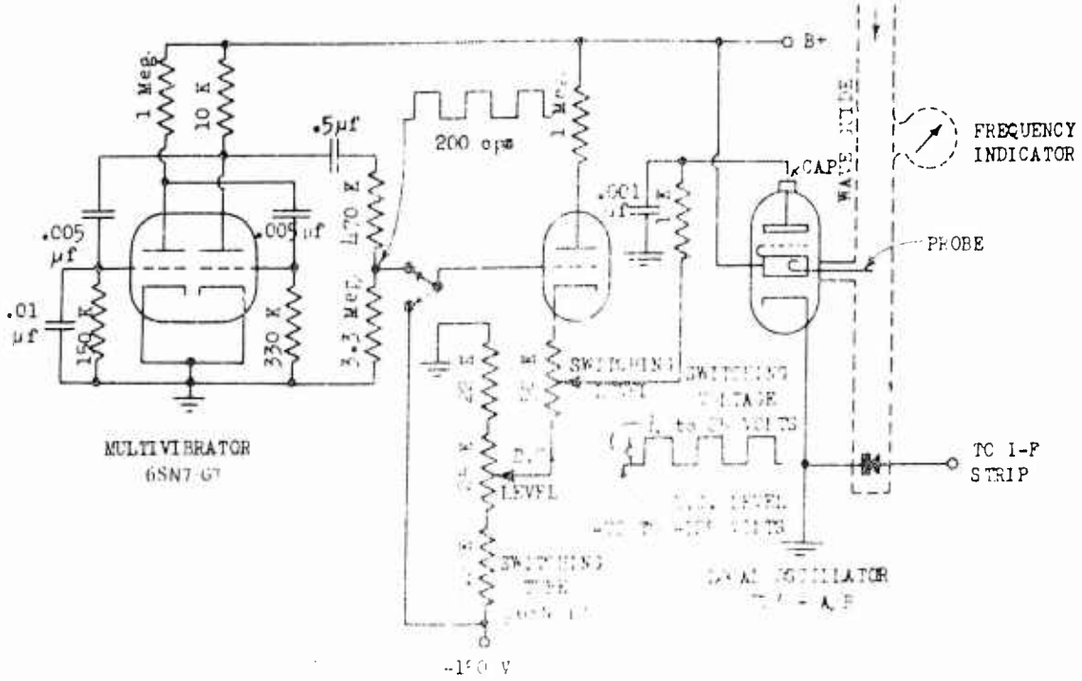


Fig. 2-12 Electronic switching circuit, local oscillator, and crystal mixer (AN/CPN-6)

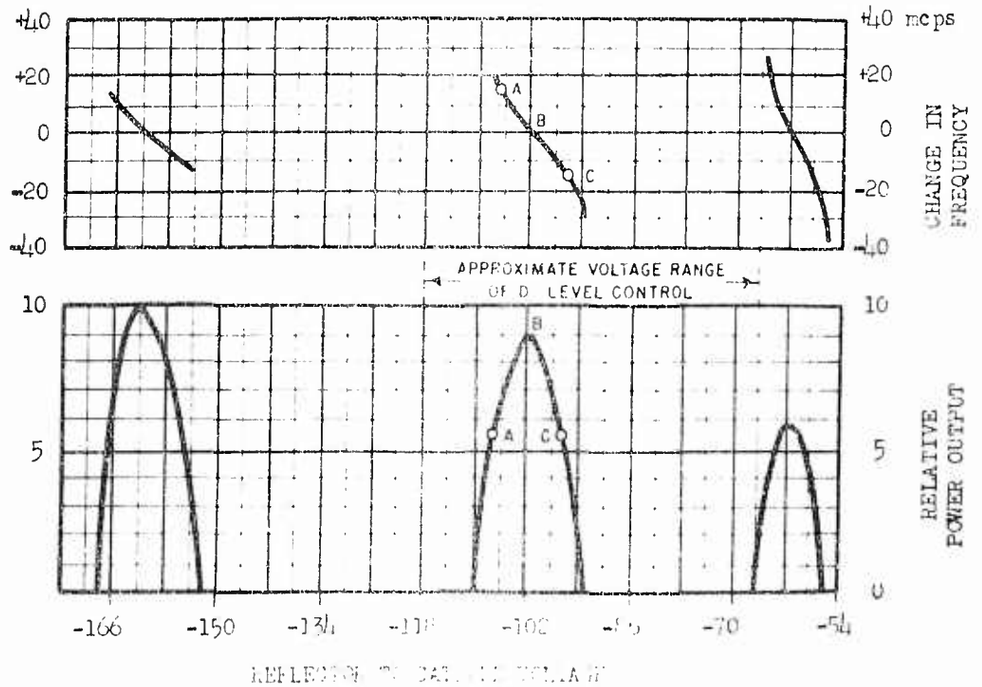


Fig. 2-13 Power output and frequency characteristics of a typical 725-A/B tube

A block diagram of the AN/CPN-6 receiver components is shown in Figure 2-11. The local oscillator-tube (type 723-A/B) is a velocity-modulated tube of the reflex type. Its frequency is caused to vary in jumps by application of a rectangular voltage to its reflector electrode, as indicated in Figure 2-12. The rectangular voltage waveform is generated by a multivibrator circuit and coupled to the local oscillator through a cathode-follower switching-tube which conducts for half the cycle. The voltage of the reflector electrode of the 723-A/B tube oscillates between two levels; a negative voltage set by the DC level control during the negative half of the multivibrator square-wave cycle, and a less-negative voltage determined by the setting of the switching-level control during the positive half of the multivibrator cycle. Frequency and power output characteristics of the local oscillator are shown in Figure 2-13 as a function of the reflector-to-cathode voltage. A mode such as the second from the left may be moved by mechanical tuning of the tube's resonant cavity until the center of the mode B is at about 9375 mcps which is the desired center-frequency of the receiver pass band. The switching of the local oscillator is adjusted by the DC level and switching controls so that half of the time the operating conditions correspond to point A (9390 mcps) and the other half of the time to point C (9360 mcps). A probe couples the cavity of the local oscillator tube to a section of wave guide containing the non-linear crystal mixing element, the output of which is led to the IF strip.

The IF amplifier-strip consists of eight identical stages the first of which and its input circuit from the crystal mixer are shown in Figure 2-14. Each IF stage is essentially a wide band video amplifier with series-shunt peaking compensation. The gain at frequencies below ten megacycles is greatly reduced by a

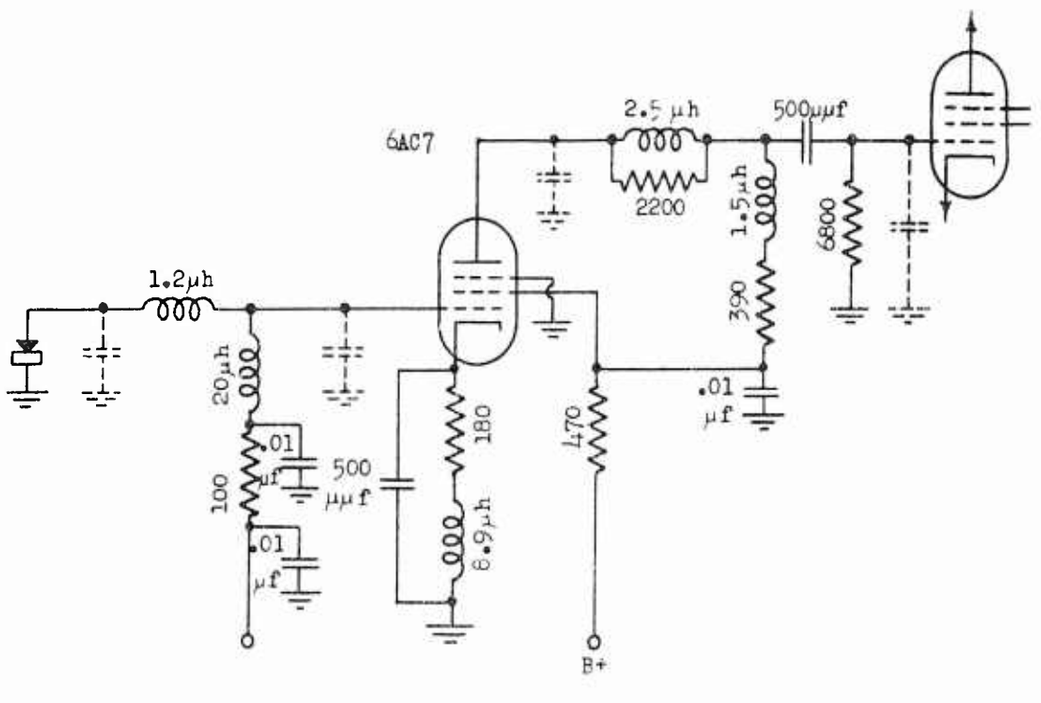


Fig. 2-14 IF input circuit and first IF amplifier stage

cathode degeneration circuit in order to obtain a band-pass characteristic extending from approximately 11 to 46 mcps. A typical overall response curve for the IF strip is shown in Figure 2-15.

The IF amplifier stages are followed by a diode detector which feeds the envelope pulse to three conventional video-amplifier stages the output of which goes to the pulse-width discriminator circuit.

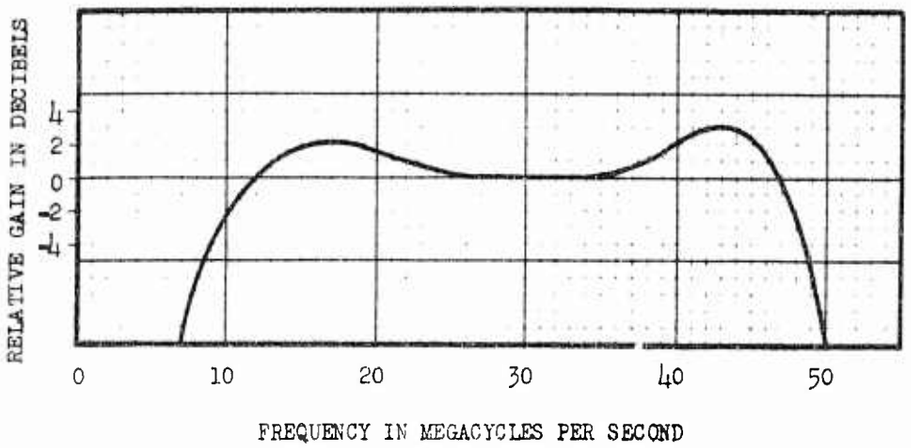


Fig. 2-15 Overall frequency response characteristic of the IF strip

Pulse-Width Discrimination

The pulse-width discriminator circuit is shown in Figure 2-16. The output of the final video-amplifier stage is applied to a diode clipper-circuit which passes the negative portion of a signal pulse to the grid of the unbiased "drooler" tube. This negative signal drives the drooler well beyond plate current cut-off and its plate potential then rises exponentially toward +250 volts as its plate-to-ground capacitance charges through the 270,000 ohm plate load resistor. The rise of plate potential, the first part of which is quite linear, is coupled to the grid of a cathode-follower which is normally biased beyond plate current cut-off. The plate circuit of this tube contains an inductive plate load which presents a significant impedance only to very rapid variations in plate current; but since this tube normally acts as a cathode-follower most of the time, it is referred to as such. The bias on the cathode-follower is adjusted (by the control labelled 2 MICROSECONDS in Figure 2-16) so that approximately 1.9 microseconds is required for the positive-going signal applied to the grid to raise its potential to the point at which plate current starts flowing. Then the plate potential of the cathode-follower drops to a lower value with the flow of plate current. If now the input pulse from the video stage should terminate at say 2.0 microseconds after its start, the drooler tube immediately becomes conducting and drives the cathode-follower beyond plate current cut-off. The sudden stopping of plate current in the inductive plate-circuit of the cathode-follower generates a positive pulse to trip the biased blocking-oscillator which in turn sends a negative triggering pulse to the coder. If however, a signal pulse from the video amplifier is shorter than about 1.9 microseconds, the cathode-follower never becomes conducting and no triggering pulse is sent to the coder. The circuit thus far described discriminates against pulses of shorter duration than about 1.9 microseconds (most radar search pulses are of the order of one microsecond or less) and allows pulses of about two microseconds or longer to trigger the coder.

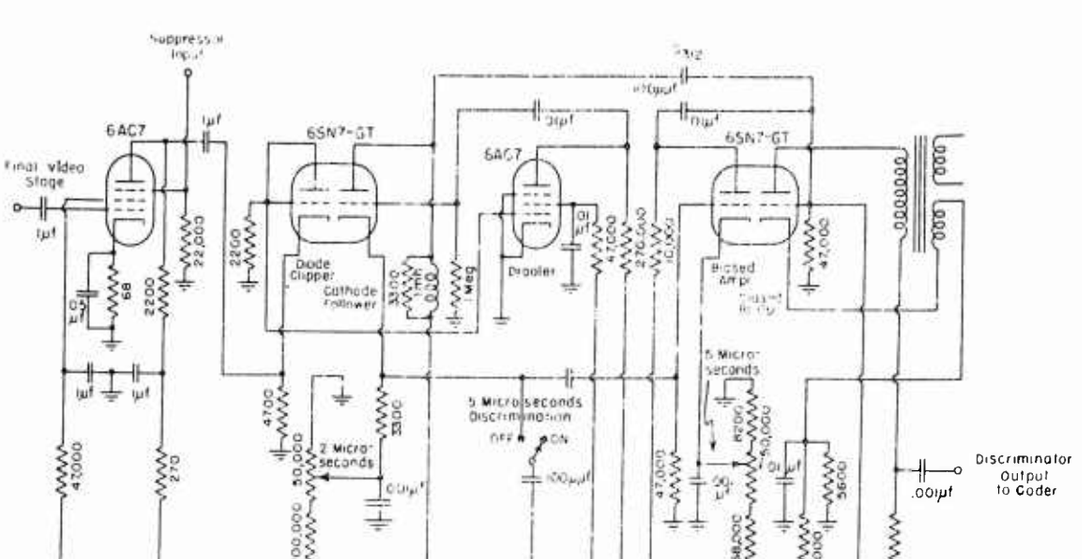


Fig. 2-16 Pulse width discriminator circuit

It is sometimes necessary to simultaneously discriminate against pulses longer than about five microseconds as well as shorter than two microseconds. This is accomplished in the circuit of Figure 2-16 by applying to the blocking oscillator grid a delayed negative signal of sufficient magnitude to completely overpower any positive pulse from the plate of the cathode-follower occurring upon the termination of a signal pulse longer than about five microseconds duration. During a long signal pulse the voltage at the cathode of the cathode-follower continues to rise. This voltage is coupled to the grid of an amplifier with sufficient negative bias to prevent the flow of plate current until five microseconds after the start of the positive-going signal from the cathode-follower. When plate current starts to flow in the biased amplifier, its plate potential drops and a negative gate-like signal is impressed on the grid of the blocking oscillator. Upon the termination of a long video-signal pulse, a positive trigger from the plate of the cathode-follower is applied to the grid of the blocking oscillator. The biased amplifier also suddenly stops conducting and its plate potential rises. However the plate-to-ground capacitance of the biased amplifier stage and also capacitor C-312 (see Figure 2-16) take sufficiently long to charge that there is still a negative signal at the grid of the blocking oscillator sufficient to prevent its triggering.

Formation of Code

Each output pulse from the discriminator triggers the coder, the function of which is to form a series of from 2 to 6 pips spaced 15 or 35 microseconds apart for use in controlling the range-coded beacon response. A schematic circuit diagram of the coder appears in Figure 2-17. It consists essentially of a chain of single-shot multivibrators, firing in sequence, the cycle of events for any one multivibrator being initiated at the close of the cycle for the previous stage. In each multivibrator a sudden drop of plate potential is differentiated to obtain sharp negative pips at the input to the collector-amplifier V-407. The grid resistor of the collector tube forms a differentiating circuit with the coupling capacitors from the output of each multivibrator. The response of the differentiator to the more slowly rising part of the plate voltage waveforms is negligibly small as shown by voltage waveform e_7 of Figure 2-18.

Briefly the operation of the coder is as follows: The negative trigger pulse from the discriminator circuit trips a "single shot" multivibrator circuit which generates a self-blanking gate that prevents further triggering of the coder for a period ranging from a normal length of about 175 microseconds to a maximum of about 1800 microseconds whenever too many aircraft are seeking replies from the beacon. Simultaneously with the triggering of the blanking gate, a negative pulse passes to the "collector" through capacitor C-407. At this instant the first pip-forming multivibrator is also triggered and either 15 or 35 microseconds later (depending upon the position of the first spacing control switch) this multivibrator delivers a second negative pulse to the collector through C-408. Each of the remaining pip-forming multivibrators then fire, one after another, to form the remainder of the code. The spacing between any two pips may be set to either 15 or 35 microseconds by changing the capacitive part of the time constant in the appropriate multivibrator. A selector switch is also available which grounds a grid of any of the last four multivibrators in order to provide for termination of the code at fewer than six pips. A few typical voltage waveforms are given in Figure 2-18.

The circuit used for protection against overinterrogation works in the following way: The first tube of the coder is a single-shot multivibrator which starts the operation of the coder when the grid of its normally conducting section V-401B is driven beyond cut-off by a negative pulse from the video amplifier. While the grid of V-401B is negative, the multivibrator is of course insensitive to further negative triggering pulses so that during its period of operation it generates its own blanking gate. A DC voltage from the transmitter circuit directly proportional to the magnetron current is fed to the grid of a biased DC amplifier tube (V-408 of Figure 2-17) which is non-conducting at low interrogation rates. When the average interrogation rate exceeds a certain level, V-408 conducts a current which passes through the bias and cathode-level control-circuits of the self-blanking multivibrator V-401, the effect of which is to increase the plate current drawn by the left hand or A section of V-401 during its conducting portion of the cycle. The accompanying increased drop of plate potential of V-401A drives the grid of V-401B further negative so that a longer time is required for its potential to drift back to cut-off. The greater DC voltage level of the cathodes also increases the length of the self-blanking gate by increasing the required voltage range through which the grid of V-401B must pass before getting back to cut-off potential after being driven negative. The gradual increase in the self-blanking gate from its normal 175 microseconds to a maximum

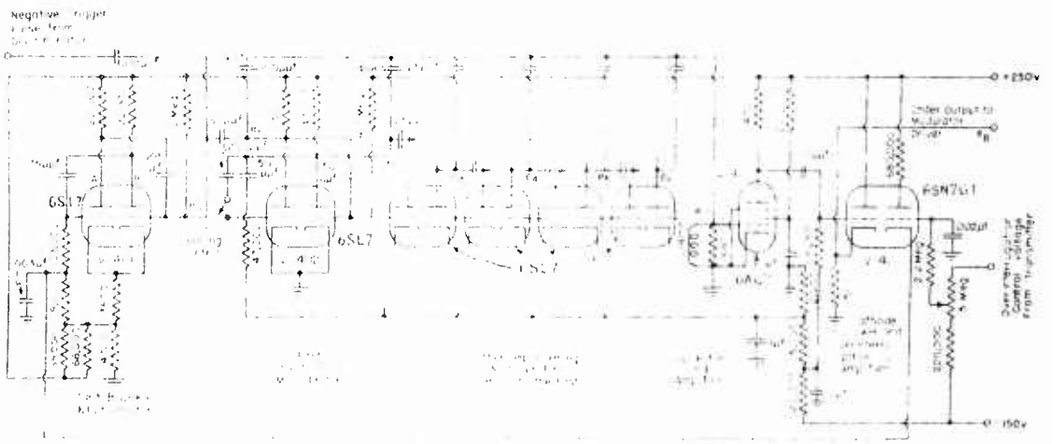


Fig. 2-17 Schematic diagram of coder

of about 1800 microseconds, lengthens the time that the coder is insensitive to further signals, thereby limiting the average rate of response to interrogations.

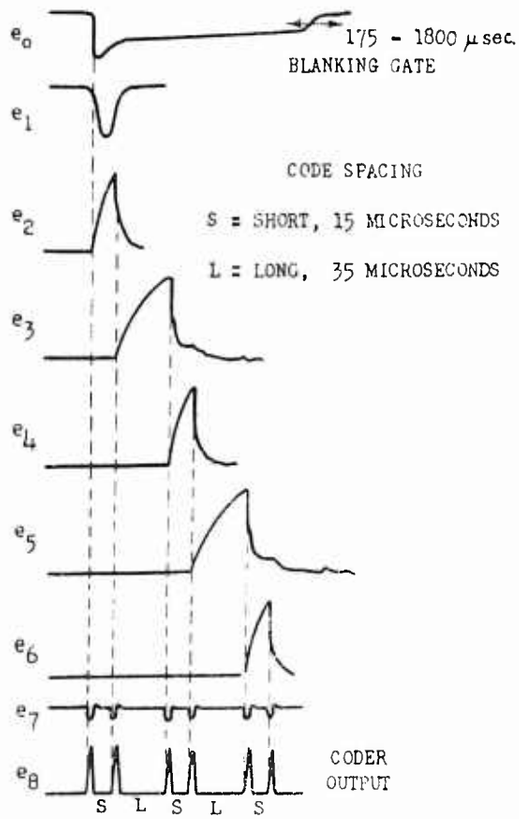


Fig. 2-18 Formation of a typical code

Transmitter Components

The output voltage pips from the coder must be suitably shaped and amplified for use in pulsing the magnetron. The circuits necessary to accomplish this are shown schematically in Figure 2-19. Each output voltage pip from the coder is amplified and sharpened in V-610 which triggers the blocking-oscillator V-611. A tuned circuit (L-601, C-608 and C-611) connected to the grid of the blocking-oscillator is used to control its period of oscillation. Regenerative action, followed a half-cycle later by degenerative action, takes place in the blocking-oscillator. The oscillatory circuit is tuned to about one mcps and makes one oscillation of large amplitude followed by a few highly damped oscillations. The output of the blocking-oscillator therefore consists of a positive pulse of one-half microsecond duration. This pulse is applied to the grids of the driver tube V-612 in which the pulse is still further amplified, and its top is flattened by limiting action in the grid circuit when grid current flows. The modulator tetrodes V-901 and V-902 are normally biased beyond cut-off. The pulse output from the driver stage causes the tetrodes to conduct for a period of one-half microsecond during which the plate potential of the modulators V-901 and V-902 is lowered from 15,000 to about 4000 volts. The high-voltage capacitor C-904 has previously been charged to a potential difference of 15,000 volts during the longer non-conducting period of the modulators. During the one half microsecond conducting period of the modulators, the lowering of the positive terminal of the high voltage capacitor from 15,000 to 4000 volts above ground results in the application of an 11,000 volt negative pulse to the cathode of

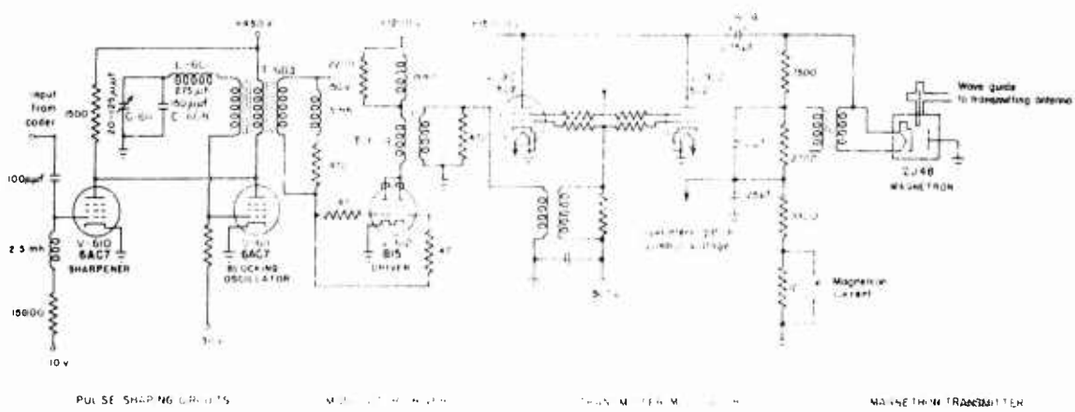


Fig. 2-19 Schematic circuit diagram of transmitter components

the magnetron the plate of which is at ground potential. During this time, the magnetron oscillates and radiates energy into the wave guide leading to the transmitting antenna.

Part III Brief Descriptions of Common Beacons and Interrogators

The remainder of this section contains very brief descriptions of some of the better known radar responder beacons and interrogator-responser units. The material has been taken mainly from section 4 of the U. S. Radar Survey.

A. Interrogator-Responsers

Lucero is a British airborne interrogator of high power, operating at frequencies between 171 and 238 mcps. It is used for the following purposes: (1) Homing onto long-range responder beacons; (2) Interrogation of IFF transponders on other aircraft; (3) Execution of rooster operations; (4) Beacon approach; (5) Homing at medium range to light transportable beacons; (6) Position-finding at medium ranges with Rebecca-H equipment.

Rooster operation consists of calling for support with a signal upon which other friendly aircraft can home. For example, a reconnaisance aircraft which may have located an enemy objective, hovers over the target with its rooster beacon turned on so that friendly bombers may reach the objective by homing on the beacon signal.

Rebecca is a low-power British airborne interrogator designed to operate with Eureka ground beacons at spot frequencies between 215 mcps and 235 mcps. It is used primarily for short-range homing operations. Range and homing indications are provided on an L-scan CRO.

AN/APN-2, 2A, 2Y is an airborne 135-cm. interrogator-responser. It provides range and relative bearing information for homing and navigational use. It is a modification of the SCR-729 to perform the function of the British Rebecca Mark II. Range measurements may be made to within 200 yards. The maximum usable range varies from 25 to 100 miles depending upon the type of responder beacon interrogated. The AN/APN-2A model may act either as an interrogator-responser or as a transponder.

B. Responders and Transponders

Eureka is a British low-power ultra-portable responder beacon operating at spot frequencies between 215 mcps and 235 mcps and designed for use with the British airborne interrogator Rebecca. It is used primarily for short-range homing operations and has a range of about 20-40 miles, depending upon the altitude of the interrogating aircraft.

BGX (AN/CPN-6) is a ground-based or shipborne X-band range-coded responder beacon. It supplies the interrogating aircraft with range, azimuth, and identification information for navigation and homing. Its useful range is line-of-sight.

BPS (AN/CPN-8) (an up-to-date version of BGS) is an air-transportable coded responder beacon which provides range, azimuth and identification for the guidance of aircraft equipped with S-band radar sets. Its maximum range is of the order of 100 miles.

Rosebud (AN/APN-19) is an S-band, range-coded beacon designed for use in aircraft. Installed in fighter aircraft, it enables GCI, SCI, MEW, or other radars to identify and vector such fighters at ranges greater than their detection ranges on enemy bombers. In fighters and bombers, Rosebud greatly increases the range and reliability of close-support bombing and photo-reconnaissance with SCR-584 radars equipped with plotting boards. The range is line-of-sight which corresponds to a maximum of about 250 miles at an altitude of 30,000 feet.

Aspen (AN/APA-9) is an airborne S-band beacon designed especially for the Oboe Mark II navigational system. The reliable range is to the horizon (approximately 250 miles from an altitude of 30,000 feet.)

BABS (AN/CPN-7) is a blind-approach beacon operating at a frequency of 173.5 mcps. The ground installation is designed for interrogation by aircraft equipped with either SCR-521 or SCR-729 to provide for instrument approach to a landing field. The airborne equipment provides range and homing information on an L-scan CRO. The aircraft is guided to within one mile of the runway at an altitude of 200 feet and the actual landing is accomplished visually.

Airborne Bups or Rosebups (AN/APN-29) is an S-band ultra-lightweight coded responder beacon designed for aircraft installation. Its range is line-of sight against a powerful radar.

BPP (AN/PPN-2) is a lightweight paratroop responder beacon for use with supply aircraft equipped with Rebecca (AN/APN-2) interrogators. The beacon operates in the 135-cm. wavelength region and has a range of at least 40 miles for aircraft at a height of 5000 feet.

AN/PPN-1 is a 135-cm. paratroop responder beacon for use with Rebecca interrogator-responser radars. It is designed especially for use with AN/APN-2, and is a close copy of the British Eureka Mark III. With AN/APN-2 at an altitude of 500 feet its range is about 18 miles with a 10 foot antenna height, and about 25 miles with a 50 foot antenna height.

YH or YH-1 is a 176 mcps land or shipborne beacon of use as a navigational aid. When interrogated by ASV, ASVC, ASE, AN/APX-2, and SCR-729 it responds with a coded reply on 177.5 mcps. It has a maximum range of the order of 100 miles.

YJ, YJ-1, YJ-2 are ground or ship-based responder beacons used as navigational aids to aircraft equipped with 176 mcps or 515 mcps search radar. The beacon replies with a gap-coded signal on either 177.5 mcps or 520 mcps depending upon the frequency of the interrogating pulse. The useful range extends to about 100 miles.

AN/CPN-3 is an S-band range-coded ground responder beacon designed to provide homing and navigational aid to aircraft equipped with SCR-517, -520, -717, -720, or AN/APS-2. The useful range is line-of-sight.

BLACK MARIA is special identification equipment designed for installation in aircraft. It is triggered only by the simultaneous reception of pulses in the S and G bands, and it responds in the G band.

BUPS (DC) (AN/UPN-1) is an S-band, battery-operated, self contained, ultra-portable, coded, responder beacon. Its reliable range is about 35 miles with SCR-717 or AN/APS-2 at 5000 feet.

BUPS (AC) (AN/UPN-2) is similar to AN/UPN-1 but is AC operated.

BUPX (AC) (AN/UPN-3) is an X-band, AC-operated ultraportable responder beacon. Its range is approximately 40 miles with AN/APS-3 or -4, and greater than 100 miles with AN/APS-10 or -30.

BUPX (DC) (AN/UPN-4) is similar to AN/UPN-3 except that it is battery operated.

AN/CPN-13, AN/CPN-15, and AN/PPN-8 are Mark V IFF transponder beacons.

Bibliography

Identification	Classification	Title	Issued by
Chapter XIII	Confidential	Principles of Radar (a book)	The Staff of the MIT Radar School
590	Confidential	Siting and Range of Microwave Beacons	MIT Rad. Lab.
	Secret	Airborne Beacons for Aiding Control of Aircraft by Ground Radar--First Preliminary Report of Special Committee on Beacons	General H.M.McClelland Communications Officer Army Air Forces
	Secret	Ground Beacons for Air-Ground Cooperation Second Preliminary Report of Special Committee on Beacons	General H.M.McClelland Communications Officer Army Air Forces
Ship 290	Confidential	Preliminary Instruction Book for Radar Equipment AN/CPN-6	U.S. Navy Dept. Bureau of Ships
602	Confidential	The Statistics of Beacon Interrogation	MIT Rad. Lab.
Section 4 Navigational Radar	Secret	U. S. Radar Survey	Div. 14 NDRC
Section 2 Airborne Radar	Secret	U. S. Radar Survey	Div. 14 NDRC
WA-3753-11	Confidential	LUCERO, T. R. 3566	Air Ministry
JEIA 3233	Secret	Rebecca and Eureka Equipment (Australian)	Council for Scientific and Industrial Research, Radio Physics Laboratory
91-3/31/44	Confidential	Video Stretching as a Method of Improving X-band Beacon Reception	MIT Rad. Lab.

Type of System
Range.

Useful Range
About 250 miles from 30,000 feet altitude.

Accuracy and Precision
The line of position of the aircraft is known to within about ± 25 yards.

Presentation of Data
Aural on the controlled aircraft.
Visual on PPI at the ground stations.

Operating Skills Required
Trained operators for aircraft.
Trained operators for ground stations.

Equipment Required
300 lbs. of airborne equipment (AN/APA-9).
Large heavy ground installations (modified SCR-584 or British Oboe Mark II).

RF Spectrum Allotments Required
Frequency 3150 to 3240 mcps.
Bandwidth = 8 mcps.

Present Status
Operational.

Oboe is an H or range type of system used primarily for precision blind bombing and photo reconaissance operations. The fundamental principles of operation may best be described with the aid of Figure 3-01. G_1 and G_2 are suitably positioned ground-stations each of which measures the range between it and the aircraft by pulse interrogation of a responder beacon in the aircraft. Station G_1 supplies the aircraft with sufficient information to enable the pilot to fly a circular course at constant radial distance from G_1. The radial range from G_1 is chosen so that the arc of flight passes through a preselected target. Station G_2 measures the ground speed of the bomber along the arc, and from this speed and a pre-knowledge of the aircraft altitude and type of bomb used, transmits a bomb release signal to the aircraft at the instant that it reaches the proper range.

The ground stations G_1 and G_2 are of the order of 100 miles apart, and control of the aircraft may take place at long ranges of 100 to 150 miles or more from the ground stations.

Various names are used to designate the stations G_1 and G_2 respectively such as: cat and mouse stations, tracking and release stations; or drift and rate stations.

Both cat and mouse stations transmit on the same radio frequency, but use different pulse repetition rates. The necessary signals to the pilot to keep the aircraft on course and to the bombardier to indicate the desired instant of bomb release are transmitted by means of either space or width modulation of the same pulses that are used for range measurement. The tracking signals from the cat station to the pilot of the aircraft consist of aural indications of the dot-dash type. A steady tone of moderate intensity is used for the "on course" indication. A series of dots or a series of dashes is heard if the bombing aircraft is off course to the right or to the left respectively. The intensity of both dots and dashes gradually increases

Type of System
Range.

Useful Range
About 250 miles from 30,000 feet altitude.

Accuracy and Precision
The line of position of the aircraft is known to within about ± 25 yards.

Presentation of Data
Aural on the controlled aircraft.
Visual on PPI at the ground stations.

Operating Skills Required
Trained operators for aircraft.
Trained operators for ground stations.

Equipment Required
300 lbs. of airborne equipment (AN/APA-9).
Large heavy ground installations (modified SCR-584 or British Oboe Mark II).

RF Spectrum Allotments Required
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Oboe is an H or range type of system used primarily for precision blind bombing and photo reconaissance operations. The fundamental principles of operation may best be described with the aid of Figure 3-01. G_1 and G_2 are suitably positioned ground-stations each of which measures the range between it and the aircraft by pulse interrogation of a responder beacon in the aircraft. Station G_1 supplies the aircraft with sufficient information to enable the pilot to fly a circular course at constant radial distance from G_1. The radial range from G_1 is chosen so that the arc of flight passes through a preselected target. Station G_2 measures the ground speed of the bomber along the arc, and from this speed and a pre-knowledge of the aircraft altitude and type of bomb used, transmits a bomb release signal to the aircraft at the instant that it reaches the proper range.

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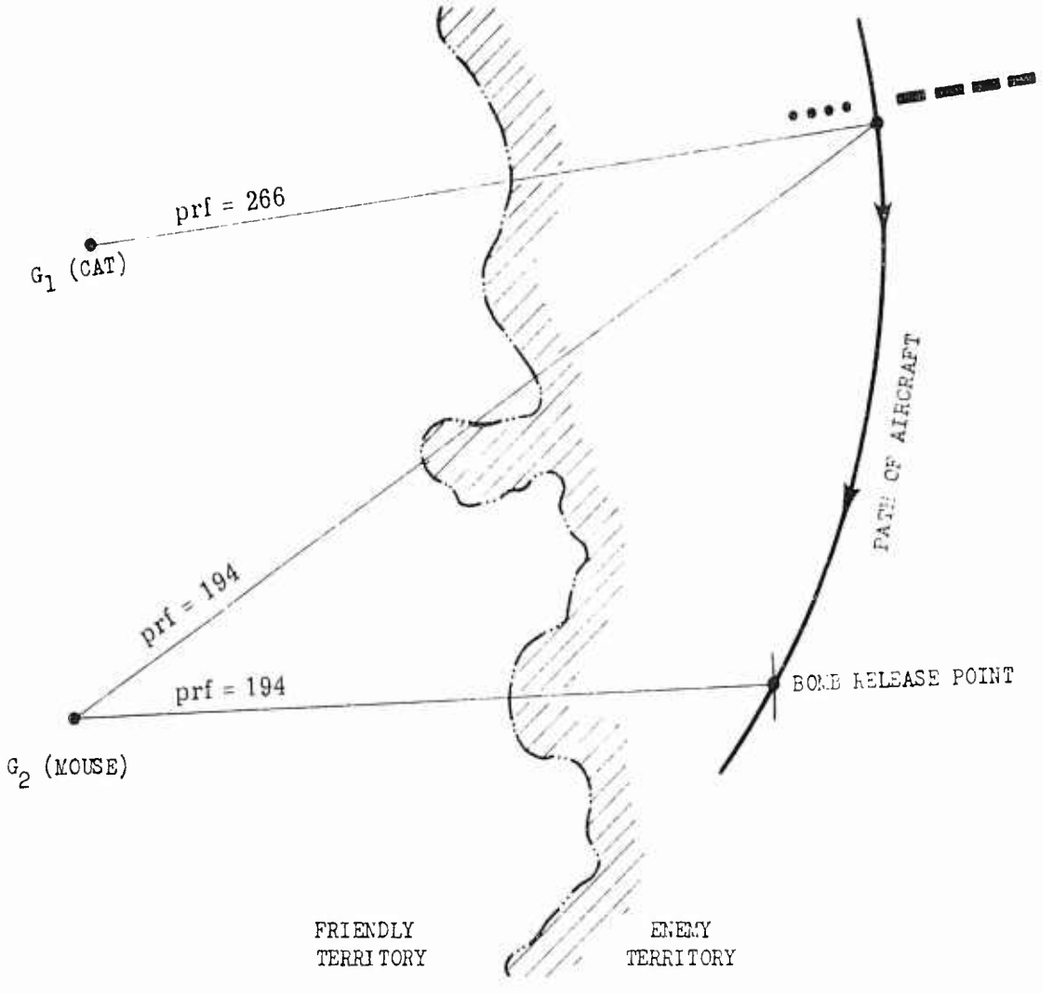


Fig. 3-01 Geometry of approach to the target in Oboe bombing system

The cat station G_1 transmits the tracking intelligence.
The mouse station G_2 transmits the bomb-release signal.

as the aircraft deviates further and further from its proper course until at a distance of about 200 yards off course a maximum tone is reached corresponding to 100% amplitude modulation; after which there is no further increase in the volume of dots or dashes with further deviation from the course.

The course information may be obtained by either space or width modulation of the pulses transmitted from the cat station. The space modulation scheme is illustrated by Figure 3-02. Every other transmitted pulse of the 266 or 194 pulses per second is fixed in time phase. The relative position of the intervening pulses can be varied so that they occur at any desired point between 1/2 and 3/4 of the time spacing between the fixed pulses. The normal "on course" position of the movable pulses is 5/8 of this distance. When in the 5/8 position, the energy in the movable pulses neither adds to nor subtracts from that contributed to the tuned filter by the fixed pulses. When the movable pulses are halfway between the fixed pulses, their energy adds to that of the fixed pulses and the response of the tuned filter in the receiver is a maximum; and when the movable pulses are located at three-quarters

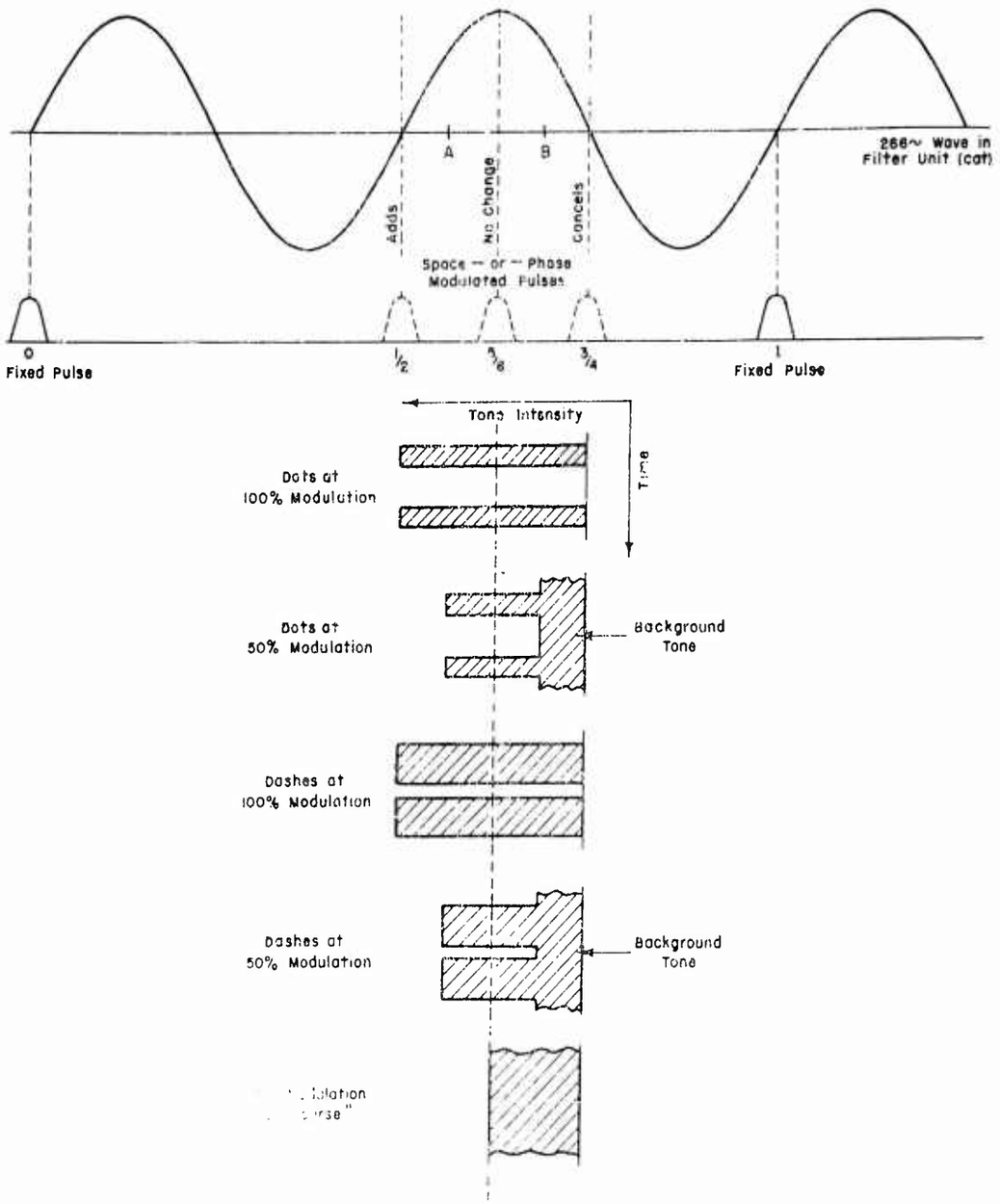


Fig. 3-02 Space or phase modulation of the ground-station signal pulses

of the way between the fixed pulses, the effects of the fixed and variable pulses cancel one another resulting in zero output signal from the tuned filter.

Whenever the aircraft is flying at the proper range from the cat station, the variable pulses are always in the 5/8 position resulting in a steady output tone of moderate intensity. If the aircraft deviates from the proper range, the phase of the variable pulses from the cat station is automatically keyed back and forth between certain limits (such as A and B in Figure 3-02) equidistant on either side of the 5/8 position. Within the 1/2 and 3/4 position limits, the amount of phase shift back and forth from the 5/8 position increases the further the aircraft is from its proper course, but the time spent in each position is not the same, and whichever time is the greater depends upon whether the range error is positive or negative.

For example, if the range of the aircraft from the cat station is slightly too small, the phase or position of the variable pulses might shift back and forth between the limits A and B of Figure 3-02, remaining in position A only long enough to allow for the transmission of a dot signal of increased intensity, and then shifting to position B for a somewhat longer period during which the tone intensity is reduced from that of the "on course" indication. If on the other hand, the range of the aircraft from the cat station is slightly too large, then the phase timing of the variable pulses transmitted from the cat station would be such that the phase corresponds to position A for a longer period than for position B so that the output signal from the tuned filter consists of dashes of increased intensity with shorter spaces of lesser intensity. Thus it is seen that either dots or dashes may be formed by shifting the movable pulses back and forth between limits corresponding to the depth of modulation, with the relative lengths of time during which the pulses remain in each position determining whether the output of the filter will consist of dots or dashes.

In the width-modulated system, all pulses transmitted from either the cat or mouse stations are fixed in their space or phase relationship, but vary in width in accordance with the modulation. Circuits in the aircraft receiver are so arranged that the intensity of the response of the tuned filter varies from zero to a maximum as the width of the received pulses varies from one to three microseconds duration. The "on course" signal is produced when all pulses have a width of two microseconds. Relative intensity modulation of the desired depth may be obtained by shifting the pulse width (within 1-3 microsecond range) back and forth between values equidistant above and below the "on course" value of two microseconds. By properly controlling the relative periods during which the pulse width is set at one or the other of the two limits, desired dot or dash signals may be produced in the same manner as in the space or phase modulation system previously described.

The airborne part of the Oboe equipment (Aspen) consists of the antenna system, including the RF plumbing and controls for directing the antennas towards the cat and mouse stations; a receiver; a repetition rate filter unit for obtaining audio signals for the pilot and bombadier; a modulator which includes the transmitting equipment and in which is also located the T-R box, the local oscillator and crystal mixer of the receiver, and a pre-amplifying unit which operates at the intermediate frequency of the receiver; a control-junction box which contains the controls for the system; and a power supply.

The operation of the Aspen unit of the Oboe system is illustrated by the block

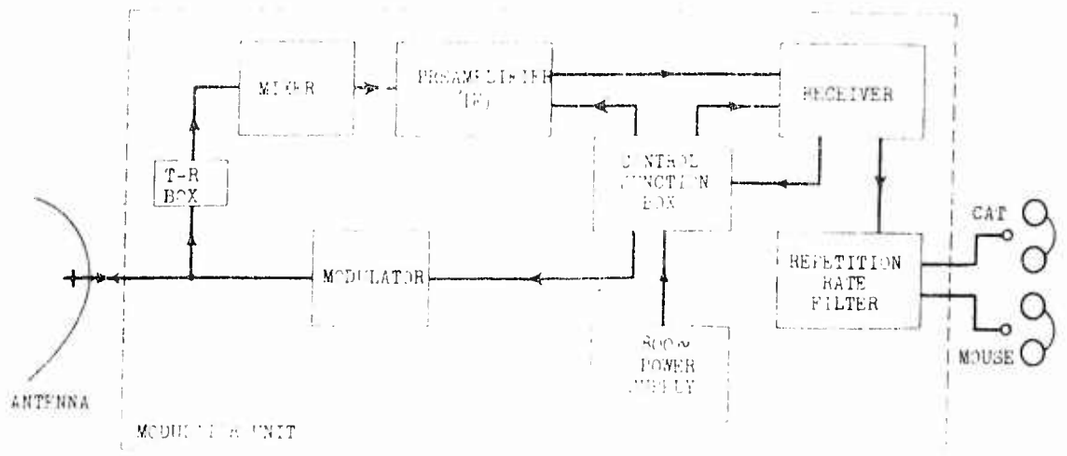


Fig. 3-03 Block diagram of the airborne Oboe equipment AN/APA-9 (Aspen)

diagram of Figure 3-03. An incoming RF signal pulse is received by the antenna and passes through a T-R box, into a crystal mixer. The resulting intermediate-frequency signal passes through a pre-amplifier and then to the receiver proper. The receiver is either a British "Penwiper" receiver or a British "Pepperbox" receiver. It has two outputs, one of which is a trigger which actuates the modulator and causes an RF beacon response pulse to be transmitted for each received signal pulse. The other output from the receiver is fed to a British filter box, which contains two peaked audio amplifiers one of which is resonant at the characteristic pulse repetition rate of the cat ground station, and the other of which is resonant at the repetition rate of the mouse ground station. The outputs of the filter unit are connected to the headphones of the pilot and bombadier so that the appropriate aural signals are conveyed to them for control of the aircraft course and to indicate the moment of bomb release. The amplifiers in the receiving system are made insensitive for a short interval during the transmission of the beacon response pulse. This gating function is indicated by lines from the control box in the block diagram of Figure 3-03.

The microwave (f = 3150 to 3240 mcps) Oboe ground stations used to track the aircraft are either Oboe Mark II, which is a modification of the original British Mark I system, or Oboe Mark II HSM which is a modified SCR-584. The British systems use the Mark I console, ASG modulator and RF head, and a modified antenna.

The basic geodetic data supplied to the ground stations for an Oboe operation consists of the ranges from the tracking and releasing stations to an aircraft at a pre-selected height directly above the target. A number of corrections must be applied in order to determine the correct range for bomb release. At long ranges where the curvature of the track is slight, very little error is introduced by using the measured average ground speed, but at short ranges where the angle of cut changes considerably, appreciable error may be introduced into the calculations due to the change in the angle between course and wind directions as the aircraft flies around the circular track. The ground speed would change even if the aircraft flew with constant "effort" but it flies with constant airspeed which further complicates the problem. The calculations necessary for the determination of the correct bomb-release range are discussed in AWAS note No. 16 entitled "Theory of the Average and Instantaneous Velocity Measuring Mouse".

Bibliography

Identification	Classification	Title	Issued by
M-148-c	Confidential	Handbook of Instructions for Radio Set AN/APA-9	MIT Rad. Lab.
Section 4 Navigational Radar	Secret	U. S. Radar Survey (pages 4-167 to 4-171)	Div. 14 NDRC
63-9/16/43	Confidential	Comparison of Vector and Dot-Dash Methods in the Oboe Steering Problem	MIT Rad. Lab.
Note No. 16 August 1943	Secret	Theory of the Average and Instantaneous Velocity Measuring Mouse	A.W.A.S.

Type of system

Range or distance (H system)

Frequency and Wavelength

210 - 320 mcps (1.43 - 0.94 meter). Bandwidth: 4 mcps.

Useful range

Line of sight, 180 miles at 12,000 feet. (depends on height of craft)

Accuracy

Estimated probable precision of fix (theoretical) ± 50 feet.

Equipment required

(a) Ground: Two beacon responders, transportable by truck. Directional antennas used, which may be mounted on 50 ft. masts. Careful location of beacons required to give estimated accuracy noted. (b) Craft: (AN/APN3) Interrogating transmitter, receiver and highly specialized timing and indicating circuits. Total weight: 232 lbs.

Operating Skill Required

(a) Ground beacons will run unattended but skilled crew is needed for triangulation of site and setting up of beacons. (b) Navigator with some special training required in craft.

Presentation

Pip matching on a 3-inch CRO. When this has been accomplished, Shoran distances from ground beacons are read directly on mileage dials.

Present status

Developed by RCA and extensively used in the latter part of 1944 and early part of 1945 in Europe as a precision bombing device. In this capacity, Shoran has given extremely accurate results.

General Features

The Shoran system was developed primarily as a precision blind bombing device, at relatively short ranges (100-200 miles). As with any device which can be used to navigate a craft to a specific point, Shoran can also be used as a precision navigational aid. However, it is not specifically adapted to flying a predetermined but arbitrarily selected course, and as a long-range navigational aid would be of no use in its present form. Accuracy was a first consideration in the development of the existing equipment, simplicity and man-power requirements being deliberately sacrificed. In use as a precision bombing device, a computer is added to the airborne equipment. Since this report is concerned with navigation, the action of the computer is not discussed.

Principles of the System

The two ground beacons are located in suitable positions (high ground). The accuracy of the system depends on the accuracy with which the beacon positions are known. The craft carries a transmitter (3 watts average power) which radiates pulses ($\frac{1}{2}$ microsecond duration) in alternate groups at two different frequencies. The beacon receivers are tuned to these two frequencies, so that both beacons are interrogated by the craft transmitter, but independently. The reception of a pulse from the craft by a beacon causes the beacon to re-radiate a pulse (on a different frequency) which travels back to the craft and is there received and displayed. Means are available in the craft for measuring accurately the time taken for the pulses to

travel from craft to beacon and back. The two time intervals so determined (one for each beacon) enable the craft to determine its distance from each of the two beacons. This yields a fix, as the point of intersection of the two circles whose centers are the two beacons and whose radii have been determined.

The two beacons are known as the "rate" and "drift" stations. To reach a predetermined point, whose Shoran distances from the rate and drift stations are known, the procedure is as follows. The craft will navigate (by Shoran or other means) until it is proceeding along an arc whose center is the drift station and whose radius is the required drift station distance from the destination. Proceeding along this arc, the distance from the rate station changes progressively. When this distance is equal to the required rate station distance from the destination (as observed by the navigator) the designated point has been reached.

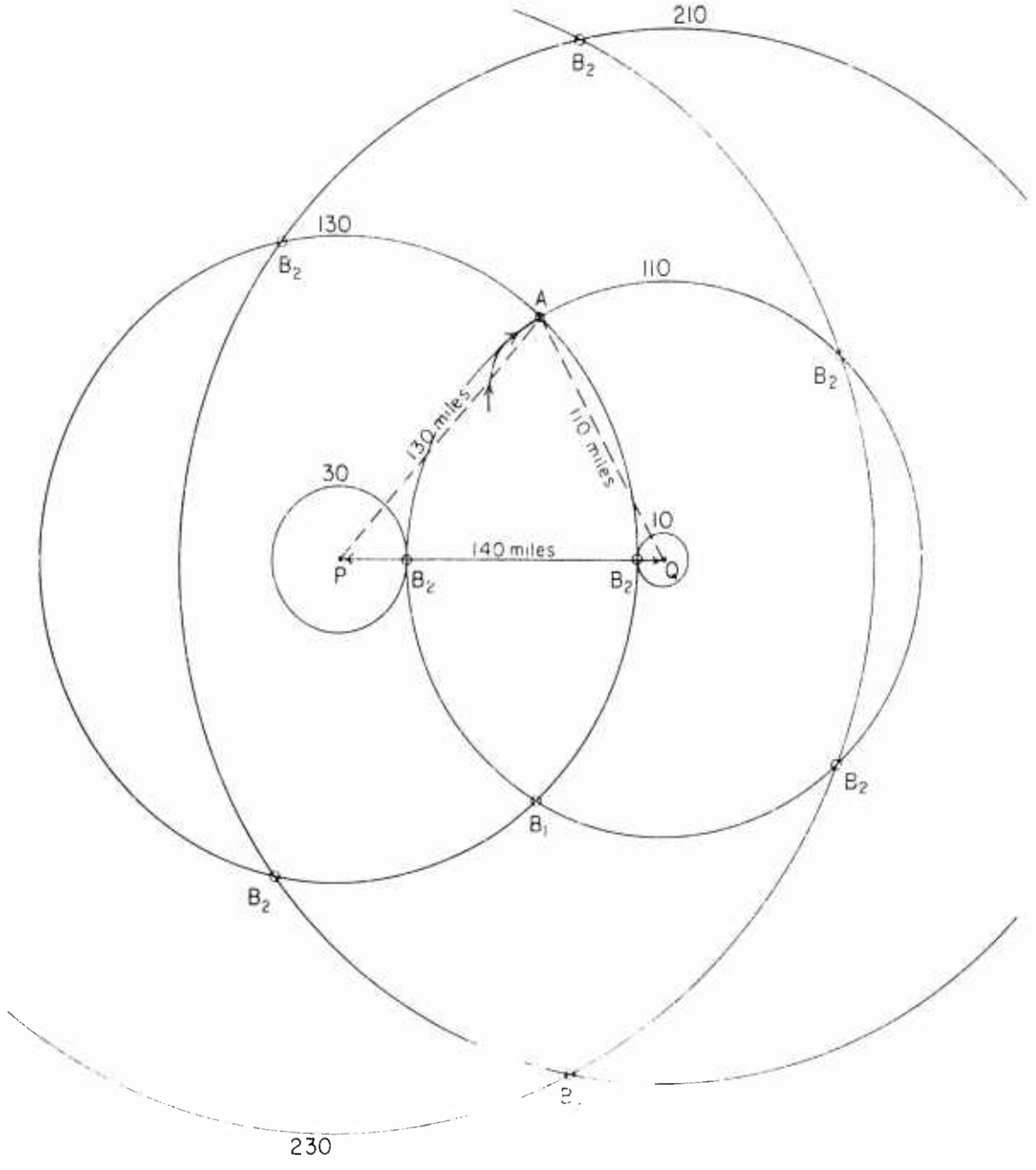


Fig. 4-01 Ambiguities

Referring to Figure 4-01, suppose that the destination point A is 130 miles from beacon P and 110 miles from beacon Q. If Q is to be the drift station, the approach may be as shown by arrows. Clearly the approach might have been from the opposite direction, and equally P might have been chosen as the drift station so that there are four possible lines of approach using the drift-and-rate procedure. The advantage of this procedure is that one of the distances being observed (the drift) remains constant during the final approach, leaving the navigator free to concentrate on the rate reading.

As in all systems of this type, there is ambiguity as between points A and B_1, both of which lie at the required distances from the beacons. It is assumed that the two sets of beacon pulses may be identified at the craft, so that the craft will not arrive at a point 130 miles from Q and 110 miles from P. Other ambiguities exist however, due to the fact that the Shoran indicator indicates tens and units of miles (as well as tenths and hundredths) but not hundreds of miles. Thus the Shoran indicator will also give the required indications at points B_2 (30,110; 130,10; 230,110; 230,210 etc.)

Shoran Distance

Distinction must be made between geographical (great circle) distances and Shoran distances.



Fig. 4-02 Shoran distance

Due to refraction, radio waves do not travel in straight lines. The assumption usually made is that above a certain height the actual path is an arc of about 15,000 miles radius. Furthermore the actual velocity of radio waves will not be constant along the Shoran path, neither will the heights of beacon and craft above sea level be the same in general. For these reasons, the Shoran distance (S, Figure 4-02) will be greater than the great-circle distance M by an amount A, so that $S = M + A$. The correction A is given to a close approximation by the formula

$$A = \frac{2{,}152}{10^8} M.(H + K) + \frac{1.794}{10^8} \frac{(H - K)^2}{M} - \frac{0{,}2477\ M^3}{10^8}$$

where the symbols have the meanings indicated in Figure 4-02 and H and K are measured in feet, A and M in miles (statute).

Regarding the theoretical precision of Shoran, RCA gives the following table of causes of error and their estimated contributions:

Source of Error	Maximum Estimated Error
(1) Residual approximation errors in the computed corrections	± 20 ft.
(2) Drift of craft timing frequency after checking with ground station	± 30 ft.
(3) Setting and reading mileage dials	± 10 ft.
(4) Scale non-linearity in craft timing phase-shift circuits	± 60 ft.
Maximum estimated possible error	± 120 ft.

Since it is unlikely that all four of the component errors will be simultaneously of the same sign, the estimated probable error is given as ± 50 ft. These errors refer to the Shoran distances of the craft from the beacons. Thus there will be an area of uncertainty determined by arcs of position representing the limits of rate and drift radii. This area of uncertainty will have a minimum value if the rate and drift circles intersect at right angles. (See Section 11).

Principles of Operation of the Equipment

Referring to the block diagram of the equipment carried in the craft (Figure 4-03), there is a commutator which is motor-driven from the main power source (d-c supply in the case of aircraft). This commutator performs a complete sequence of switching operations every 1/10 second. The craft transmitter (40) is pulsed by the timing gear at a pulse repetition rate of approximately 930 cps. Since the craft transmitter must interrogate two beacon transponders on different frequencies, and since the interrogating pulses for the rate beacon must be phased differently from those which are to interrogate the drift beacon, two pulse outputs are provided from the timing gear. These two pulse outputs are used alternately for periods of 1/40 second with idle periods of 1/40 second interspersed between them. This is one of the functions of the commutator. In synchronism with this operation, the radio frequency of the transmitter must be switched to coincide alternately with the frequencies assigned to the two beacon receivers. This is accomplished by having another section of the commutator operate a relay which short-circuits a portion of the transmission-line section which determines the transmitter oscillator frequency. This sequence of operations is represented in Figure 4-04. It will be seen that the plane transmitter frequency is shifted by an amount Δf during portions of the cycle. This amount is of the order of 15 - 30 mcps.

The frequency of the crystal oscillator is actually 93,109 cps. (93.109 kcps). In the block diagram and in the discussion which follows, this figure has been rounded off to 93 kcps for the sake of simplicity. The reasons for the selection of this basic frequency (identical in all Shoran timing circuits) is as follows:

(1) Consider a craft - beacon distance of 100 miles. The total distance to be covered by the pulse which interrogates the beacon and by the response transmitted back from beacon to craft will then be 200 miles and the time taken for its round trip is 1074 μsec. Since it is desirable to allow time for a response to be received due to each transmitted pulse before the emission of the next pulse, this means that the pulse repetition rate (prf) must not be greater than 931.09 pps (corresponding to a period of 1074 μsec.) if 100 miles is the maximum range to be indicated.

(2) Since the final indication is to be by means of pip alignment on a circular CRO

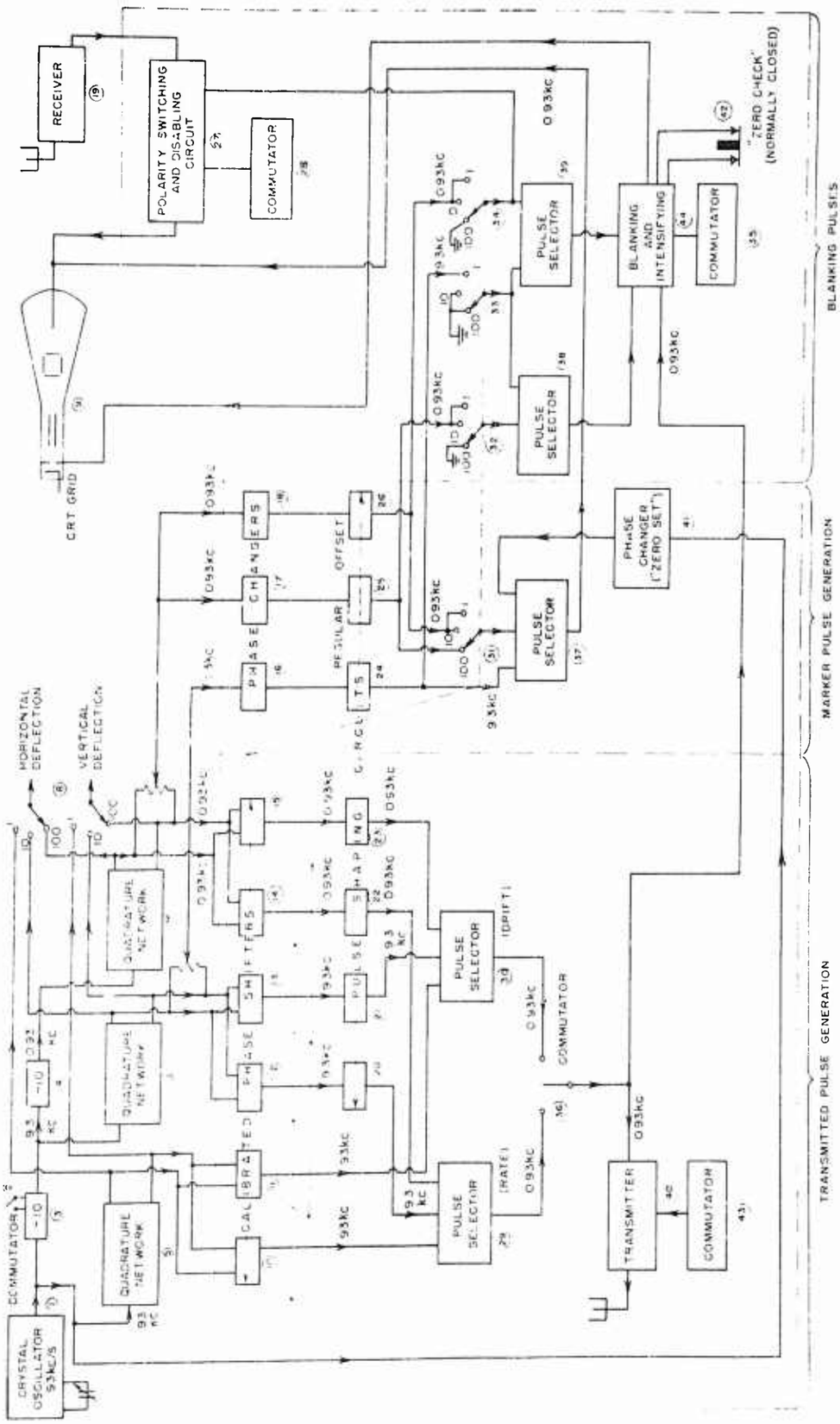


Fig. 4-03 Block diagram--timing and indicating circuits

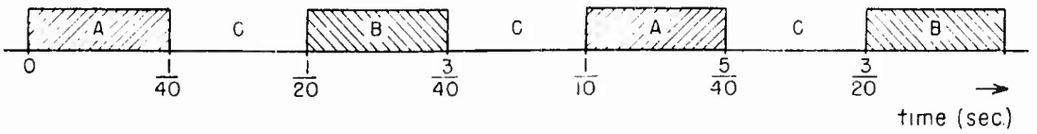


Fig. 4-04 Transmission sequence

A: plane transmitter interrogates beacon P on frequency f
B: plane transmitter interrogates beacon Q on frequency f + Δf
C: inactive periods

sweep, the frequency of the sweep should not be higher than 931.09 cps, in line with the above considerations.

(3) Accuracy demands that much higher sweep speeds should be available for determination of miles and fractions of miles. In the present case, sweep speeds of 9,310.9 cps (corresponding to a 10 mile range) and 93,109 cps (corresponding to a 1 mile range) are provided.

(4) A lower prf would allow ranges of over 100 miles to be indicated directly; but since the operational range of Shoran is limited by propagation considerations to something of the order of 200 - 250 miles, and since the operator is presumed to have other information which will enable him to supply the number of hundreds of miles, it is apparent that the extra complication introduced by a fourth sweep speed would not be justified.

(5) The prf should be as high as possible consistent with (1) above, in order to enable the maximum amount of intelligence to be transmitted in a given time. Furthermore, a prf of about 930 pps means that about 23 pulses will be transmitted in each 1/40 sec. period during which the transmitter is pulsed. It would not be desirable further to reduce this number.

In line with the above considerations, the crystal oscillator (1) is followed by two frequency dividers (3) and (4) each of which divides by 10. These are of the regenerative type, whose action may be explained by reference to Figure 4-05. The input signal, of frequency 93 kcps (f), is applied by way of T_1 to the control grid of the mixer tube V_2. The plate circuit of V_2 is tuned to 0.1 f (9.3 kcps). Assuming

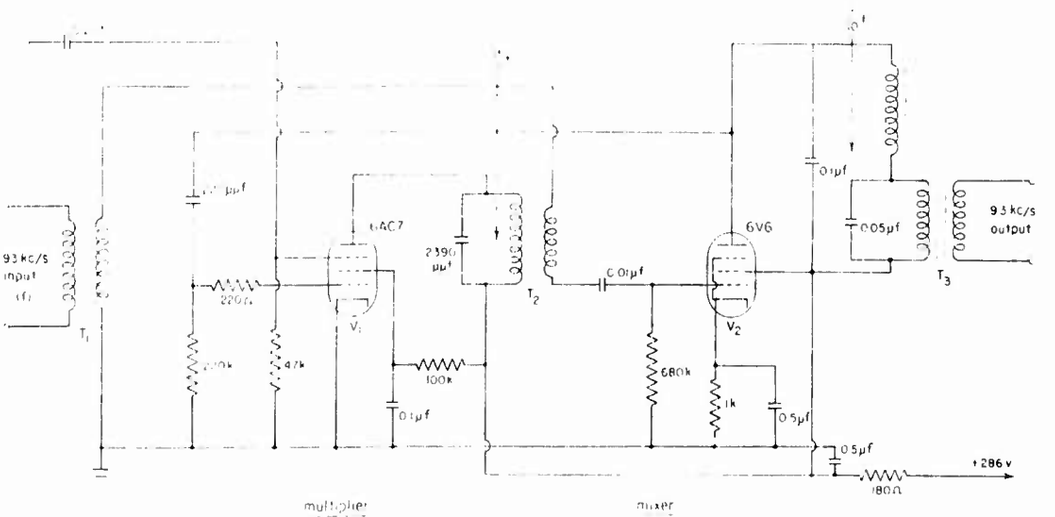


Fig. 4-05 Frequency divider

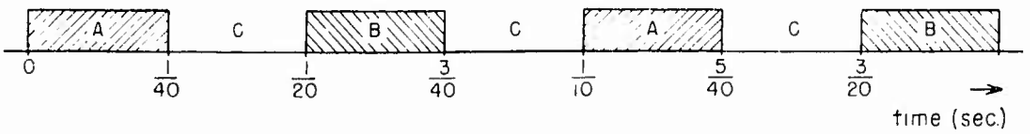


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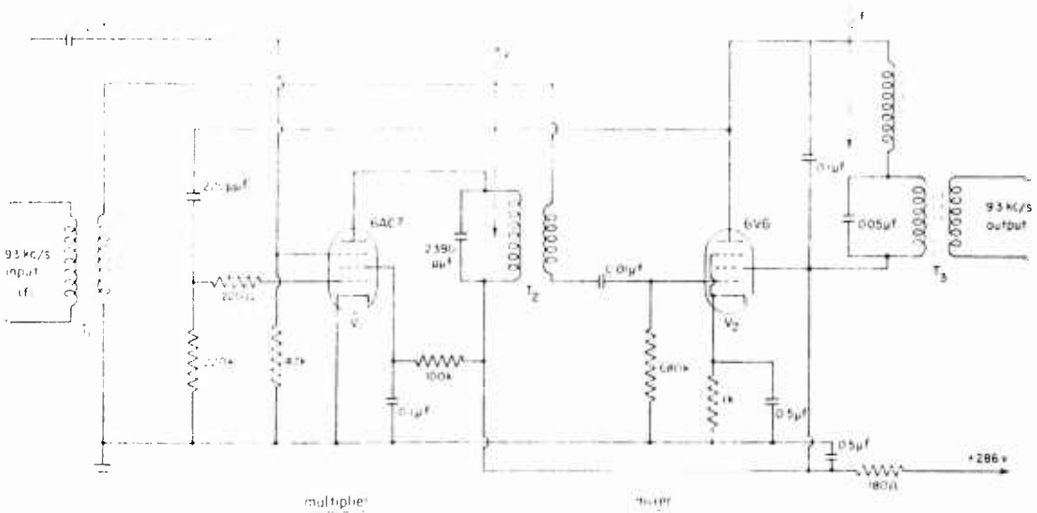


Fig. 4-05 Frequency divider

a signal to exist at this frequency, this signal is fed back to the control-grid of the multiplier tube V_1, which is driven sufficiently hard to operate in a non-linear manner. The plate circuit of V_1 is tuned to 0.9 f, and the resulting signal at this frequency is applied to the grid of V_2 together with the original input of frequency f. These two signals, beating in the non-linear mixer tube V_2, provide the necessary output at 1/10 f. This system may be thought of as a regenerative, non-linear amplifier with a tuned output, which is not self-sustaining. The phase of the output is stable and is correlated with that of the input.

Referring again to the block diagram (Figure 4-03) the oscillator (1) and frequency dividers (3) and (4) furnish signals of frequencies approximately 93 kcps, 9.3 kcps and 0.93 kcps. These three signals are applied to three suitably designed quadrature networks (5), (6), (7). Each quadrature network gives two outputs which are in quadrature (90^0 phase relationship) with respect to each other. These quadrature outputs are used for two general purposes: (a) generation of a circular sweep on the cathode-ray tube indicator, (b) generation of suitably phased marker pulses and transmitter pulses. The selector switch (8) (which is a part of the multi-gang range switch) places the selected pair of quadrature voltages on the horizontal and vertical deflection plates of the cathode-ray tube (9), thus yielding a circular sweep whose frequency is (approximately) 0.93-kcps on the 100 mile range, 9.3 kcps on the 10 mile range and 93-kcps on the 1 mile range.

There are three main functions performed by the remaining components of the timing circuits:

(a) Generation of pulses used to trigger the transmitter in the craft. As previously explained, the frequency of these pulses is 930 pps (on all ranges) and two sets of pulses are required to be available, with different phasing, one set used during periods A (Figure 4-04) when transmission is at the frequency to which the P beacon responds, and the other set used during periods B (Figure 4-04) when the frequency is changed to that to which the Q beacon responds.
(b) Generation of marker pulses. These serve as a fixed time reference: they appear as an outward deflection at the top of the circular sweep, and the received pulses from the beacon transponders are to be aligned with the marker pulses.
(c) Generation of suitable blanking and intensifying pulses.

If the marker pulses are to be fixed on the circular trace, and if the received pulses are to be aligned with them, it follows that the transmitted pulses must be advanced in phase with respect to the marker pulses by an amount whose corresponding time-advance is exactly equal to the time of transit of the interrogating and reply signals plus the delay time associated with the beacon. The latter time is standardized at 1.93μsec. corresponding to an extra distance of 0.18 mile for all Shoran beacons. This phase advance is performed by the calibrated variable phase shifters (10) through (15). These phase shifters are of the continuous type, in which the two quadrature inputs are applied to two stator coils oriented so that their planes intersect at an angle of 90^0, and the output is taken from a rotor coil, the angle of which (with respect to the stator coils) determines the relative phase of the output. Considerable care was taken in the design of these phase shifters to make them as nearly linear as possible, that is, the phase-shift obtained is very nearly proportional to the angle through which the rotor is turned. These components are among the most critical in the system: the indicating dials of the phase shifters are calibrated directly in miles, and the accuracy attainable depends on the precision with which the phase shifters can be constructed. The six phase shifters are ganged in two groups of three each: one set is concerned with the phasing of pulses for the rate station and the other for the drift station. Two "pulse selectors" (29) and (30) generate pulses for the craft transmitter. Each pulse selector receives three inputs: 93 kcps

sinusoidal, 9.3 kcps pulses (of width about 11 μ sec) and 0.93 kcps pulses (width about 110 μsec). These input pulses are produced by conventional clipping, differentiating and clipping circuits at (20) through (23). The action of the pulse selectors may be explained by reference to figures 4-06 and 4-07. The three inputs are applied to three grids of a multi-grid tube (Figure 4-06). Biasing potentials are so arranged that plate current will only flow if all three grids are simultaneously gated positively.

Considering now Figure 4-07, it is seen that only once in each period of 1074 μsec. (corresponding to a frequency of 0.93 kcps) will the required condition exist and plate current flow. The output at the plate of the tube will therefore consist of pulses at a repetition rate of 930 pps. The width of the pulses is about 2 μsec.

It will be observed that the exact position in time of these pulses depends on the phasing of the three inputs. One complete rotation of the 93-kcps phase shifter (360^{o} phase shift) will shift the pulses 10.74 μ sec. corresponding to a change in beacon-craft distance of 1 mile. Similarly one complete rotation of the 9.3-kcps phase shifter will produce a time-shift of 107.4 μ sec. (10 miles), and a complete revolution of the 0.93-kcps phase shifter will give a time-shift of 1074 μsec (100 miles). However, a given change in one phase shifter must be accompanied by a proportional change in each of the others, in order for the required time-coincidence between the waveforms of Figure 4-07 to be maintained. For this reason, the three phase shifters of each set are geared together. Twenty revolutions of the handwheel on the front panel produce one revolution of the 93-kcps phase shifter simultaneously with one-tenth of a revolution of the 9.3-kcps phase shifter and one one-hundredth of a revolution of the 0.93-kcps phase shifter. This process may be thought of as constituting a movement of the whole of Figure 4-07 to right (or

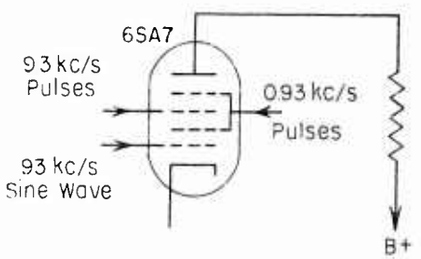


Fig. 4-06 Pulse selector

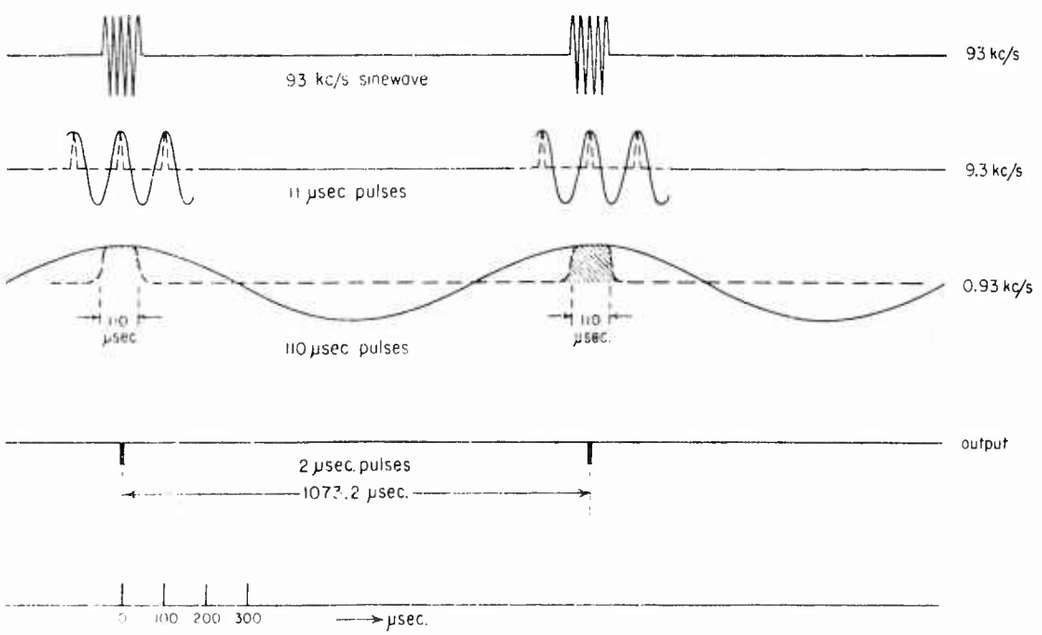


Fig. 4-07 Pulse selection

left) by 10.74 μ sec with respect to some arbitrary (but fixed) time scale. The number of rotations of the various phase shifters is recorded in units, tenths and hundredths of miles by suitably geared counters which therefore give direct range indications (one for the rate station and one for the drift station) on the front panel. Tens of miles are indicated on a dial mechanically connected to the 0.93-kcps phase shifter. As previously noted, the number of hundreds of miles must be known by other means. In order to avoid the very large amount of cranking that would be necessary for a shift of (say) 30 miles, provision is made for the 0.93-kcps phase shifter to be disconnected mechanically from the rest of the gear train and reset in any one of ten preset positions, any of which yields correct phasing and gives movements of multiples of 10 miles. Since the counters indicate nothing larger than ten miles, their indication is not upset by this operation.

(36) represents a part of the motor-driven commutator which performs the switching operations indicated in Figure 4-04, together with (43) which effects the change in the transmitter frequency. (42) is a push-button switch (normally closed) which normally allows the transmitter pulses to be used for blanking the CRO beam so that actual transmitted pulses (which may come through the receiver circuits even though receiver and transmitter are not tuned to the same frequency) will not be displayed on the CRO trace. To check the zero adjustment of the equipment, (42) is pressed. This allows the transmitter pulses to appear on the display. Since the 0.18 mile beacon delay must be allowed for, the marker and transmitter pulses should be aligned when the phase shifters are set for a corresponding delay. Since the phase shifters produce an advance (instead of a delay) in the transmitted pulse, they must be set at -0.18 mile, or in other words at 99.82 miles, when this adjustment is to be made. The marker pulses are then moved slightly by means of (41) until coincidence between them and the transmitted pulses is obtained.

Marker Pulse Generation and Blanking

The following problems arise in connection with the display of marker and received pulses:

(a) Marker pulses appear at a frequency of 0.93 kcps. On the 100-mile sweep, this results in one marker pulse per sweep, but on the 10-mile and 1-mile sweeps there will be one pulse every ten sweeps and one pulse every hundred sweeps respectively. The same considerations apply to the received pulses, which will have the same prf as the marker pulses. This would mean that the circular trace would be much brighter than the marker and received pulses when using the 10-mile and 1-mile sweeps. It is therefore desirable to blank out all sweeps except those during which the marker and received pulses occur and at the same time to intensify the desired sweeps. This function is known as "circle blanking" and is accomplished by pulse selectors (38) and (39).

(b) It is necessary to blank the CRO beam at the instants when the craft transmitter is pulsed. This is accomplished as already explained in connection with switch (42), which is in the cathode circuit of the blanking-pulse amplifier (44). The blanking pulses are mixed and applied to the grid of the cathode-ray tube.

(c) In order to distinguish between the received rate and drift pulses, the rate pulses are made to deflect the beam outward and the drift pulses inward. This is accomplished by (27) in conjunction with a section (28) of the commutator.

(d) If the output of the receiver (19) remained connected at all times to the central deflecting electrode of the CRO (9), noise voltages would be displayed as clutter on all parts of the sweep. For maximum operational range, the amount and intensity of the clutter should be as small as possible. For this reason, it is advantageous to disconnect the receiver output during the display of the marker pulses (see also (e) below). This is accomplished by suitable pulses taken from (34) and applied to (27) and is known as "receiver blanking".

(e) If the marker pulses occur on the same sweep as do the receiver pulses and if the pulses are being aligned, then when all three pulses are nearly in alignment it will be difficult to distinguish one pulse from another. This arises from the fact that as the pulses start to overlap, they will add instead of being superposed. Figure 4-08 illustrates this for idealised pulses.

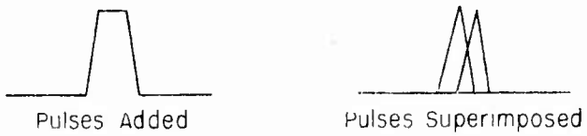


Fig. 4-08

This indicates that marker and received pulses should occur on different sweeps. Provided that the marker is accurately positioned on any sweep, it does not matter which sweep is used. On the 100-mile sweep, when a marker pulse occurs on every sweep, this "offsetting" of the marker pulse is not possible, but neither is it important, since the final pulse alignment will not be done on the 100-mile range. On the 10-mile and 1-mile sweeps, the marker pulse is offset by one and by ten sweeps respectively. This is accomplished by using a 0.93-kcps source which is phased differently from the regular 0.93-kcps source, for the generation of marker pulses in the 10-mile and 1-mile switch positions. This process is known as "marker offsetting".

Considering now the circuits by means of which the above five problems are solved, the pulse selector (37) operates in the same way as previously explained for (29) and (30), and its output consists of 2 μsec. pulses with a prf of 0.93 kcps which are to be used as markers. (41) allows for small changes in phase of the 93-kcps input for the purpose of zero setting as already explained. The 0.93-kcps input is taken either from the "regular" phase setting or from the "offset" phase setting, depending on the position of the range selector switch (31). The pulse selectors (38) and (39) have only two inputs (9.3 kcps and 0.93 kcps) and are only operative in certain switch positions. When operative, they function on the same principle as that described for the three-input pulse selectors, and deliver 110 μsec. pulses with a prf of 0.93 kcps, which are used to intensify the CRO beam (normally at threshold intensity) at appropriate periods as noted below. The phase changers (16) (17) (18) and the pulse-shaping circuits (24) (25) (26) have the same functions as described in connection with the generation of transmitter pulses.

Scrambling

Since a number of craft may be interrogating the beacons during any given period, there is a possibility that spurious pulses may appear on the display. That is, craft A may see the pulses resulting from beacon interrogation by craft B, as well as those produced by its own interrogation of the beacons. In order to minimize this effect, there is on the commutator a section (represented at (2)) which renders the first frequency divider inoperative (by gating its suppressor grid) for two periods of 1/40 sec. during each 1/10 sec. cycle of switching operations. This is represented at C in Figure 4-04. Now under the least favorable conditions, all the crystal oscillators in interrogating craft might have exactly the same frequency and all the spurious returns would therefore lock in stationary positions on all displays. But since the commutator is motor-driven from the craft's power source, and since the probability of 20 such motors running at precisely the same speed is extremely remote, the

sequence of dividing operations will not re-start in identical phase on all craft after each 1/40 sec. interruption. The spurious returns will therefore move at random all over the trace, and although contributing to clutter will not be confused with the craft's own return, which is locked in fixed position on the sweep. This function is known as "scrambling". A corresponding section of the commutator (35) ensures that the CRO beam is completely blanked while the scrambling switch is open, by cutting off the plate supply voltage to the blanking-pulse amplifier for appropriate intervals of time.

Consider now the situations existing on each of the three range-switch positions.

(a) 100-mile sweep: There are 930 rotations of the sweep per sec. Pulses are transmitted (and received) at a rate of 930 per sec. Every sweep is used and none are blanked, since the pulse selectors (38) and (39) receive no input signals. Marker pulses (regular) are generated by (37). The trace is blanked while the transmitter is operative. The brilliance of the display is controlled only by the intensity control on the CRO (not shown on the block diagram). 2000 rotations of the hand crank, causing 1 rotation of (14), 10 rotations of (12) and 100 rotations of (10), would cause the rate pulse to be shifted through one complete sweep (100 miles range change).

(b) 10-mile sweep: There are now 9,300 revolutions of the sweep per second and 930 marker pulses per second, also 930 beacon responses. The marker pulses are offset by a time corresponding to one sweep. Thus the beacon response, if visible at all, will occur on the sweep preceding that on which the marker pulse occurs. These two sweeps only are allowed to appear. The remaining 8 out of every 10 are blanked, since (38) and (39) now generate pulses which are used to intensify the beam during the two sweeps corresponding to marker and received pulses. The overall brilliance of the display is thus unchanged. The beam is also blanked while the transmitter is operative. A given rotation of the mileage dials will now produce ten times as much movement of the received pulses around the trace as it did in (a). Due to the position of switch (34) radial deflection due to receiver signals is now prevented during the sweeps on which the (offset) marker pulses occur.

It is to be noted that the received pulses will not appear on the display at all unless they were approximately aligned with the marker pulse on the 100-mile sweep.

The sequence of events now occurring is shown approximately to scale in Figure 4-09. In this diagram only one sequence of pulses is represented (rate or drift) and no attempt is made to show actual amplitudes or waveforms. Pulses which result in blanking or disabling are shown below the axis, and intensifying pulses above. It is assumed that the marker and received pulses have been correctly aligned, and that the approximate range shown on the dials is 30 miles.

(c) 1-mile sweep: There are now 93,000 sweep revolutions per second, and in each 100 of these there will occur one marker pulse and one received pulse. The marker pulses are offset by 10 miles = 10 sweeps. Supposing the marker and received pulses to be aligned, then if received pulses occur during the 1st, 101st, 201st.....sweeps of a particular sequence, marker pulses will occur during the 11th, 111th, 211th.....sweeps. The beam is blanked while the transmitter is operative. A given rotation of the mileage dials will now produce one hundred times the displacement of the received pulse compared with (a) above. (39) now generates intensifying pulses of 11 μsec. duration (= 1 sweep) and recurrence rate 930 pps., corresponding to the sweeps on which the (offset) marker pulses occur, and (38) performs the same function for the sweeps on which received pulses are liable to occur if the pulses have been previously aligned on the 100-mile and 10-mile range scales. Due to the position of (34), the receiver output

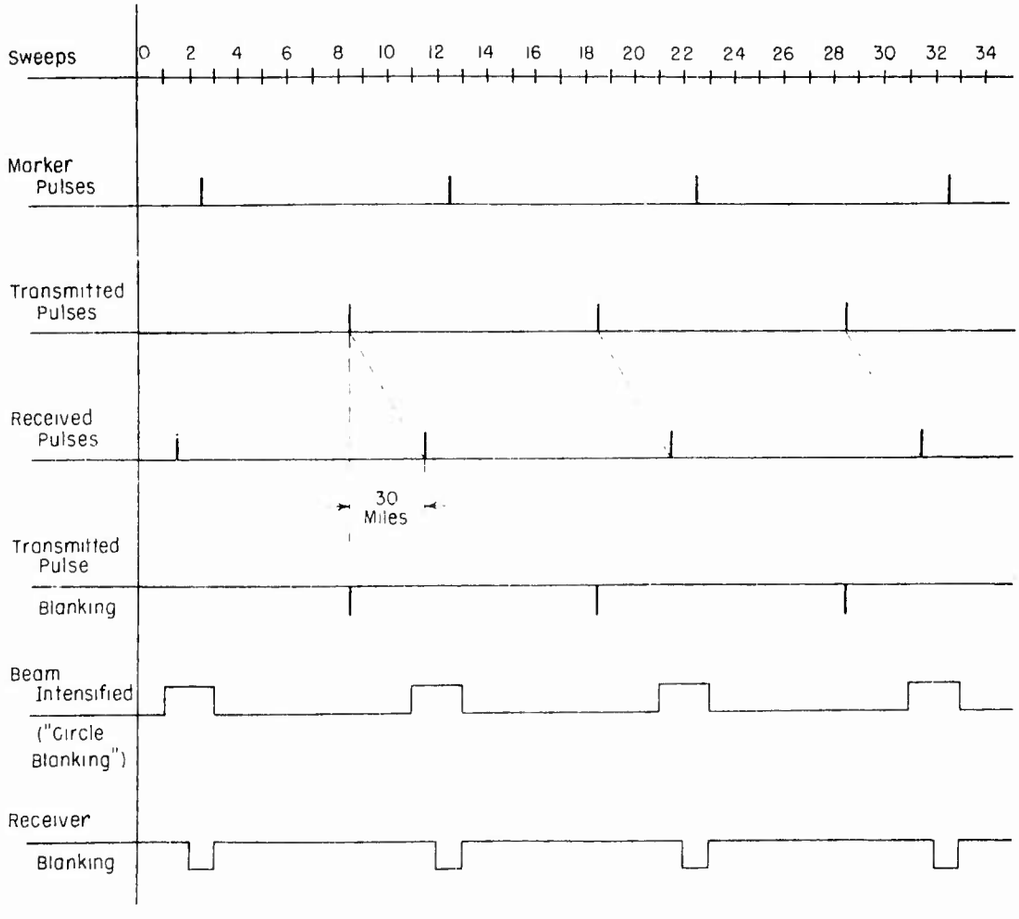


Fig. 4-09 Time relations

Note: each sweep represents 107.4 microseconds, or 10 miles range change.

is disconnected from the indicator for periods of 110 μsec. of which the 11 μ sec. sweep containing the marker pulse is the center portion. Operations controlled by the commutator (scrambling, 1/40 sec. CRO blanking, pulse polarity switching, transmitter frequency and pulse phase switching) proceed at all times, irrespective of the position of the range switch.

Polarity Switching and Disabling Circuit

The functioning of the block denoted as (27) is illustrated by the circuit of Figure 4-10. Receiver pulses are applied to the control grids of both T_1 and T_2 at A. The screen supplies of the two tubes are gated alternately by S which represents a section of the commutator ((28) in Figure 4-03). T_1 functions as a normal (inverting) amplifier and T_2 as a (non-inverting) cathode follower. The outputs of both tubes are placed in parallel by a 0.2 μf condenser, so that both tubes work into the same load. The amplitude of the output will be the same no matter which tube is on but will be inverted (with respect to the input) if T_1 is on, non-inverted if T_2 is on. The output is taken at B. Negative receiver-blanking pulses (from (34) in Figure 4-03) are applied at C, thereby gating the suppressor grid of T_1 or the screen grid of T_2 depending on which tube is on. This prevents any receiver signals from appearing at the output terminal B during the sweep on which the (offset) marker pulse occurs.

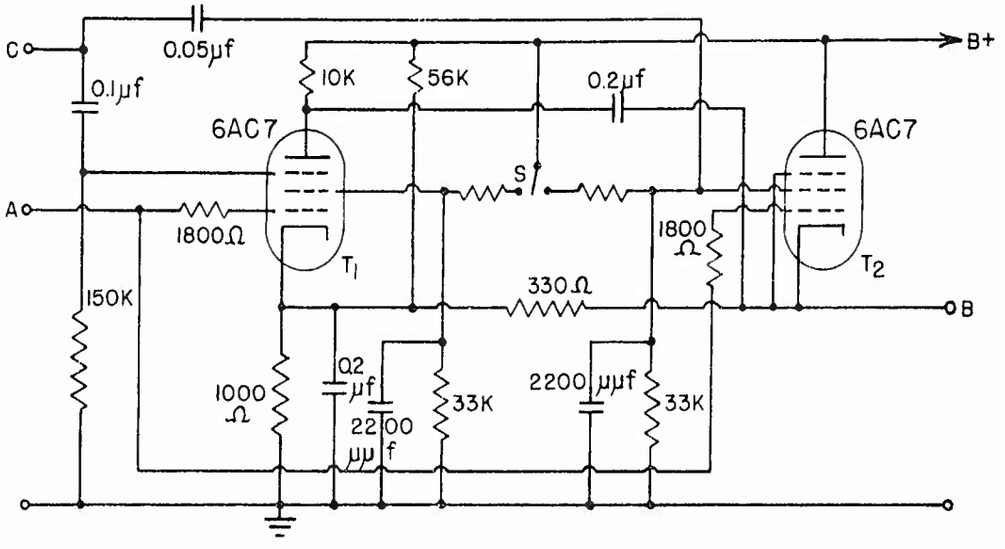


Fig. 4-10 Polarity switching circuit

Crystal Frequency Check

By means of a small variable shunting condenser, the frequency of the crystal oscillator (1) (Figure 4-03) may be adjusted to coincide with that of the crystal at one of the ground beacons, which is accurately stabilized. This operation is performed preferably immediately before a reading is taken. It will be realized that any departure of crystal frequency from its assigned value of 93.109 kcps represents a source of error in the system. When the frequency of the oscillator has been so adjusted, frequency-calibrating pulses transmitted from the ground stations and received at the craft will remain stationary on the display.

The information here presented was obtained from various copies of the periodical "Radar", and from the handbook of maintenance instructions for Radio Set AN/APN3 (CO-AN 08-30 APN3-2-M).

Type of System

Range.

Useful Range

Radar line-of-sight. For an aircraft altitude of 30,000 ft., the maximum range is about 230 nautical miles from the ground beacons.

Accuracy and Precision

The range of the aircraft from any beacon is accurate to about ± 50 yards.

Presentation of Data

Visual presentation on PPI.

Operating Skills Required

Trained radar operator in the aircraft. No operators required at ground beacon sites.

Equipment Required

The aircraft must carry a weight of about 370 lbs. of AN/APS-15 radar equipment in addition to the 15-lb. Micro-H attachment. Two AN/CPN-6 ground beacons are required.

RF Spectrum Allotments Required

X-band radar (9335-9415 mcps). Bandwidth about 2.5 mcps.

Present Status

Operational.

In the Micro-H system, a predetermined hyperbolic or circular course may be accurately maintained by an aircraft through the use of simultaneous range measurements to each of two ground responder-beacons. This method of triangulation from known beacon stations is capable of high precision since each beacon response is sharply defined in range, and no azimuth measurements are involved. Such a system, unlike Oboe, makes possible the use of beacon responses by many aircraft simultaneously; and in the case of Micro-H Mark II, these aircraft may fly on different courses. The system is used primarily for blind bombing.

Micro-H Mark I is a Micro-H system utilizing a time delay in the response of one of two ground beacons. Hyperbolic courses only may be flown in this system. No equipment other than AN/APS-15 (H2X) is required in the aircraft. The adjustable delay in one of the ground beacon responses may be set to any desired value corresponding to a given hyperbolic course. The controlled aircraft flies along the desired hyperbolic path by keeping the two beacon responses at the same apparent range on the PPI. This is easily done by following the beacon responses with the adjustable slant range marker. The bombs are released when the required range from the undelayed beacon is reached. With the Micro-H Mark I time delay equipment at one of the two ground beacon stations, all aircraft, using this pair of beacons for H-type navigation, are restricted to flying along a single hyperbola, the position of which is determined by the amount of time delay introduced at the ground beacon. The beacon containing the delayed response is useless for general navigation.

Micro-H Mark II (AN/APA-40) is an attachment for AN/APS-15 (H2X) equipment which provides for the introduction of appropriate time delays in beacon response circuits in the airborne equipment rather than at a ground beacon station. With this arrangement, an aircraft can fly either a hyperbolic or a cat-mouse course; and the choice of a particular hyperbola or a particular cat-mouse course is dependent only upon the settings of controls in the aircraft. The same ground beacons

may be used by aircraft flying on different missions.

For Micro-H Mark II, no additional time-delay circuits are required, other than the phantastrons already incorporated in the H2X equipment, but they need to be reshuffled somewhat for Micro-H operation. The AN/APS-15 (H2X) equipment is described in Section 22. The Micro-H Mark II attachment is essentially a switching device which provides for different sweep-delays and range-mark delays in each of two 180° azimuth sectors of the PPI scan. The switching device is synchronized with the rotation of the antenna spinner so that the range measuring circuits can be suitably adjusted for observation of beacon A during half a revolution and for beacon B during the other half revolution of the antenna. The mechanical motion of the antenna is transmitted by a synchro link to the Micro-H Mark II control unit where it runs a system of cams and microswitches which periodically change the sweep and range delays as the antenna turns through the two 180° azimuth sectors at some point within each of which the antenna looks towards one of the beacons. The switching action may be made to occur at any desired azimuth, such as midway between the two beacons. When flying a hyperbolic course, the beacon responses appear at the same apparent range as illustrated in Figure 5-01.

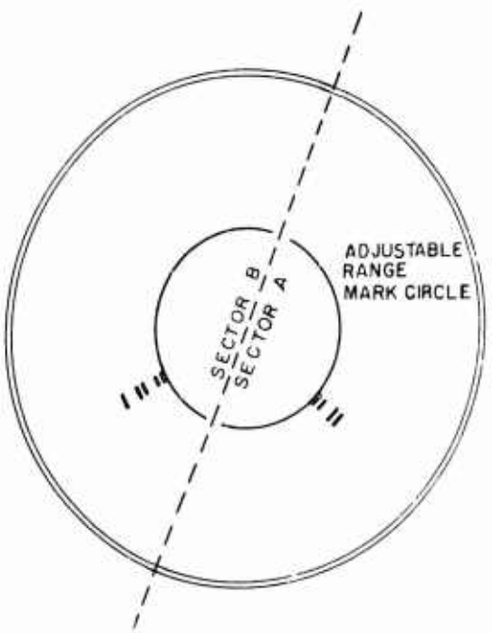


Fig. 5-01 Beacon responses for a hyperbolic course

The phantastron delay circuits are arranged as shown in the simplified block diagram of Figure 5-02. As in H2X, the step-delay phantastron can be made to open an eight-mile gate around any 10-mile crystal-controlled pip between 10 and 200 miles in order to obtain a trigger pulse delayed by an integral number of ten-mile steps. In Micro-H Mark II however, the control-voltage for this step-delay phantastron is alternately taken first from one and then from the other of two voltage-dividers which control the ten-mile-step sweep delays for the two sectors. The triggering of the PPI sweep is still further delayed by the altitude phantastron which introduces a continuously variable delay of any desired fraction of ten miles. The range mark may be delayed from the triggering of the PPI sweep by the range phantastron which introduces any desired delay between about 0.6 and 16 miles. The calibrated continuously-variable delays introduced by the altitude and range

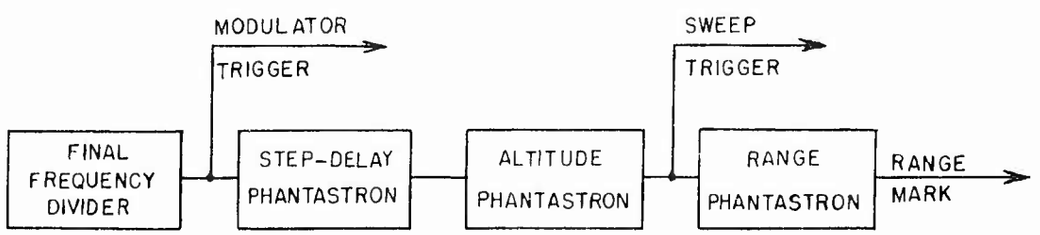
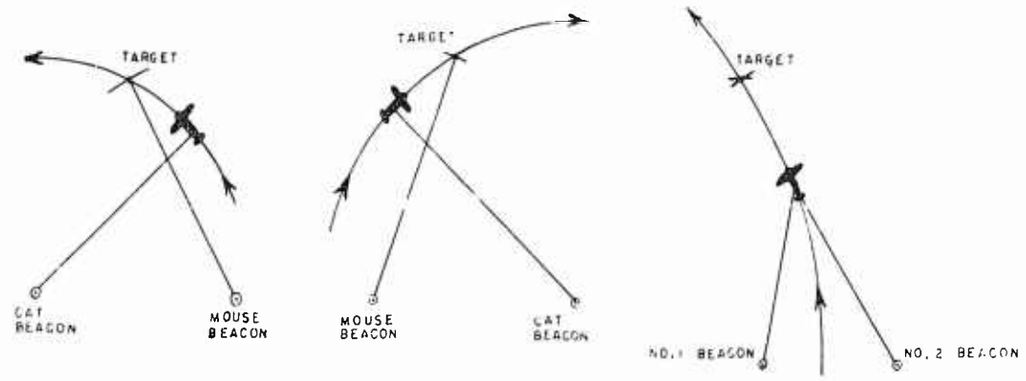


Fig. 5-02 Arrangement of delay circuits in Micro-H Mark II

phantastrons are adjusted by the controls on the drum computer and also by the settings of two additional control-voltage potentiometers (one for each phantastron) located in the Micro-H Mark II unit. The latter two controls may be set for a desired delay and locked in position. Thus provision is made so that any of the phantastrons may introduce a different delay in the different sectors of the PPI scan, although depending upon the type of course flown, it is desirable for one of the phantastrons to introduce the same delay for both sectors. The arrangement and switching of the delays depends upon the type of course to be flown.



Cat-mouse course (cat beacon in B-sector) | Cat-mouse course (cat beacon in A-sector) | Hyperbolic course

Fig. 5-03 Courses available with Micro-H Mark II

Three types of courses as illustrated in Figure 5-03 may be flown with the aid of a Micro-H Mark II attachment for H2X. For cat-mouse courses the aircraft flies along a circular arc at a constant range from one beacon (the cat beacon) and releases bombs when reaching the proper range from the other (the mouse) beacon. The cat-mouse roles of the beacons may be interchanged to provide an alternative direction of approach. For this type of course, the altitude phantastron introduces the same delay in both sectors. When flying a cat-mouse course, the start of the PPI sweep in the cat sector is delayed in time by an appropriate amount such that the first return from the cat beacon appears at a convenient place on the expanded sweep--say half way out. A fixed range mark is then set up so that it comes exactly at the desired cat range. In the mouse sector, the start of the PPI sweep is delayed so that all of the bombing run of perhaps 15 miles appears on the expanded sweep. The range mark is adjustable within this mouse sector by means of the drum computer, so that the operator can check his mouse range occasionally as he approaches the release-point range.

For a hyperbolic course, the delay introduced by the range phantastron is the same for both sectors, while the delays introduced by the other two phantastrons are different for each sector. In the case of a hyperbolic course, the start of the PPI sweep in the sector containing the nearer beacon is delayed so that all of the bombing run occurs within the range of the expanded sweep. The start of the PPI sweep in the sector containing the farther beacon is delayed by this same amount plus the required difference in the ranges to the two beacons corresponding to the particular hyperbolic course flown. The drum computer controls the position of the range mark in both sectors, and the two beacons will appear to be at the same range if the aircraft is on course.

With the Micro-H Mark II attachment for H2X, provision is also made for

the use of sector scan in normal beacon navigation. When used in this way for beacon navigation, the PPI sweep is delayed in each sector only in steps of ten miles to which must be added the appropriate range mark delay in order to obtain the range of a beacon in that sector.

Bibliography

Identification	Classification	Title	Issued by
M-197	Confidential	Handbook of Maintenance Instructions for AN/APA-40 (Micro-H Mark II)	MIT Rad. Lab.
Section 4 Navigational Radar	Secret	U. S. Radar Survey (pages 4-163 to 4-166)	Div. 14 NDRC

Type of system

Pure range or "H" system.

Useful range

36 miles for experimental model.

Accuracy and precision

Not known; probably better than ± 1/2 mile.

Presentation

Dial indicates range (distance).

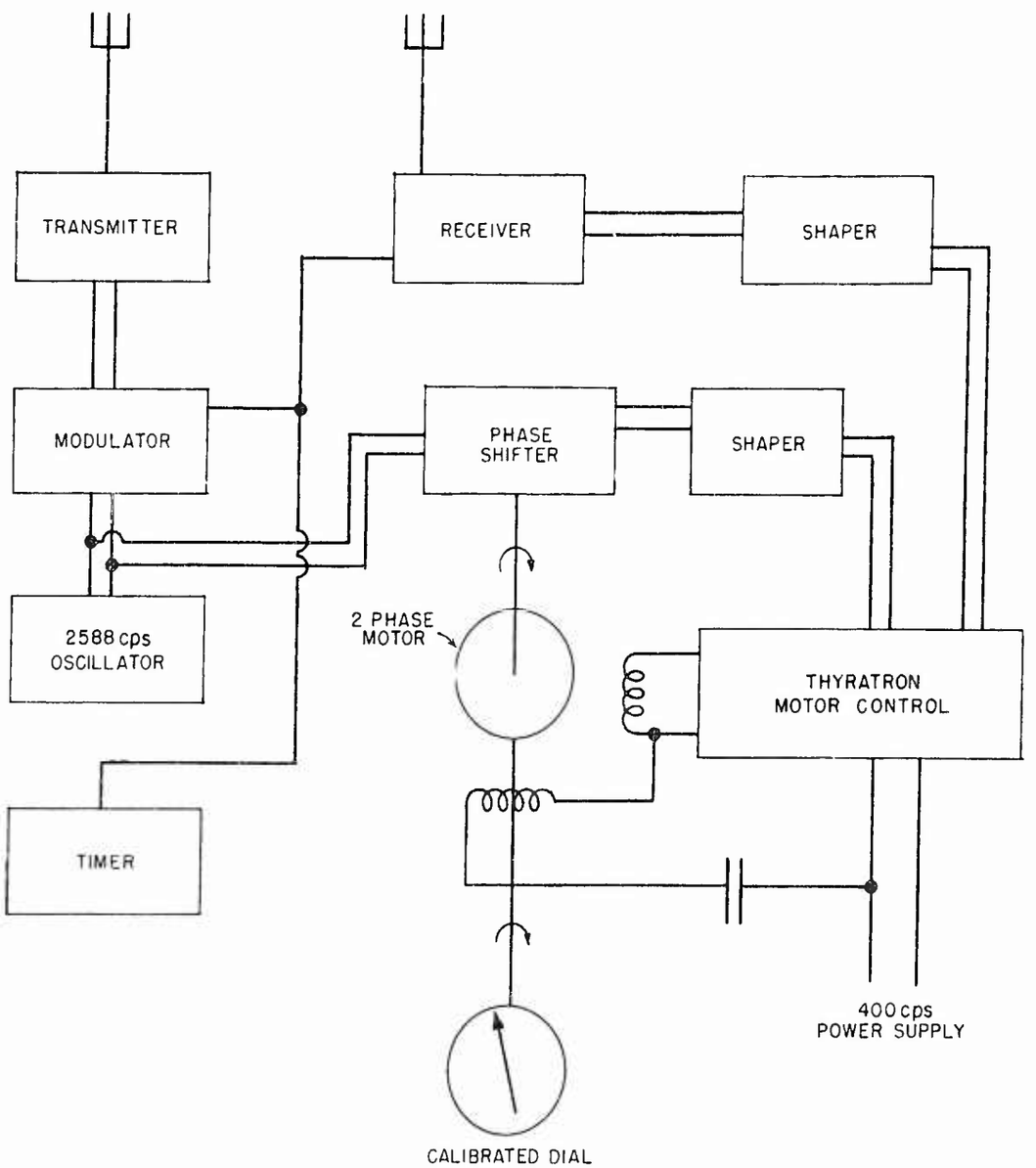


Fig. 6-01 Block diagram of system

Operating skill required

(a) At ground beacon: can operate unattended.
(b) In aircraft: none - read dial.
(c) Time required to get reading: instantaneous - reading is correct every two seconds.

Equipment required

(a) At ground beacon: transmitter and receiver at frequency different by about 10 kcps. The transmitter may be a localizer transmitter adapted to simultaneously re-transmit the aircraft interrogation modulation-frequency of 2588 cps. Fairly simple to service.

Radio-frequency spectrum allotments required

Response - 110 mcps - 6 kcps bandwidth. Interrogation - 100 or 120 mcps - 6 kcps bandwidth.

Present status

Developmental.

This distance meter is of the intermittent phase-comparison type. The phase-comparison method of distance-measurement was used by the Germans in their Benito system which is described in section 30. Figure 6-01 is a block diagram of the airborne equipment. An oscillator operating at 2588 cps supplies the voltage used for phase comparison. A timing circuit permits the transmitter to transmit for one twenty-fifth second every two seconds. This transmission is modulated by the 2588-cps audio frequency. The receiver is gated on during the time that the transmitter is transmitting.

At the ground the interrogating signal is received and the recovered modulation frequency of 2588 cps is used to modulate a transmitter on a different frequency. The ground equipment is designed so that the phase shift is very small and constant.

The Bell Telephone Laboratories published an unfavorable report on the use of the phase-comparison principle using existing communication equipment in ground vehicles. They stated that the condition of small and constant phase shift could not be satisfactorily met. It should be borne in mind that this should not condemn the system as such, since the communication equipment tested worked at frequencies of only a few megacycles and had quite a narrow bandwidth. The resultant steep phase vs. frequency characteristic made this particular application of the principle impractical.

The retransmitted signal from the ground is received at the aircraft and the phase of the recovered 2588-cps frequency is compared with the phase of the 2588-cps voltage used to modulate the interrogating transmitter. The 2588 cps was chosen since 36 miles distance (total path-length 72 miles) will give a phase lag of 360°.

The phase comparison is accomplished by an automatic phase follow-up system. This system drives a calibrated continuous phase shifter in such a way that the output of the phase shifter will be kept in phase with the returning signal.

Figure 6-02 is a diagram of the phase-sensitive thyratron motor-control

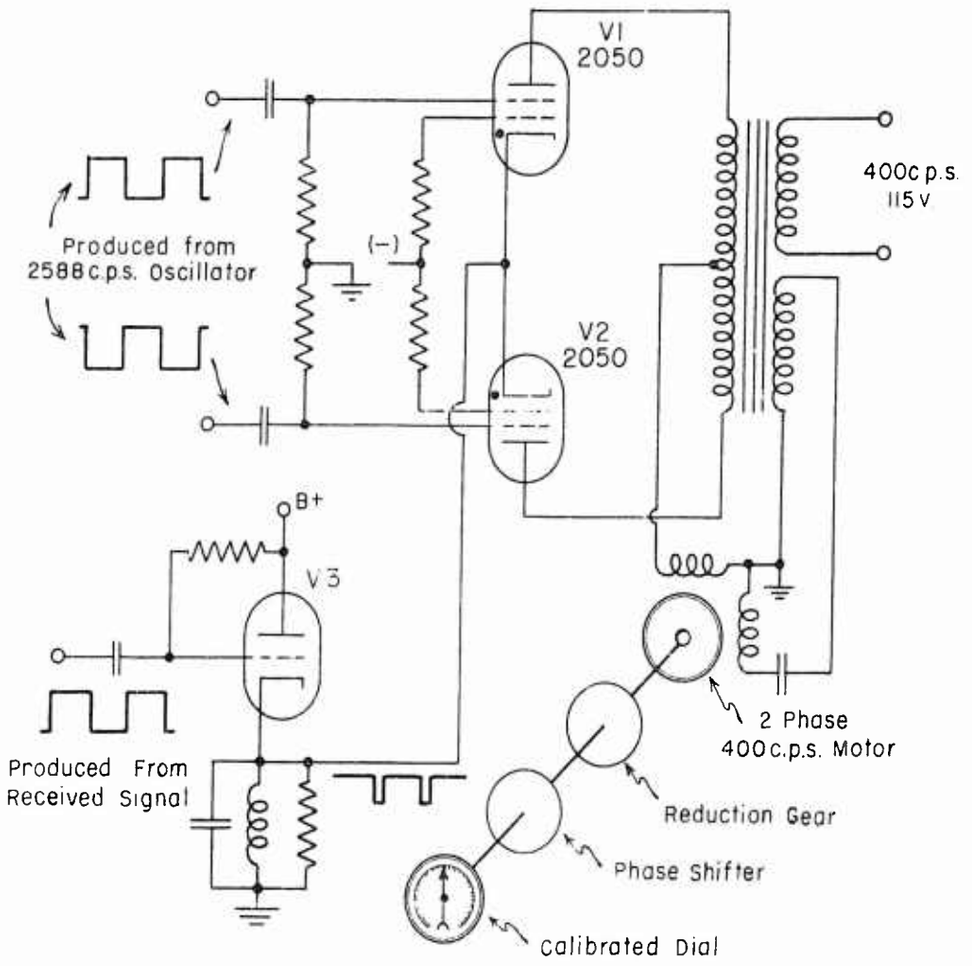


Fig. 6-02 Phase-sensitive motor-control circuit

circuit. The output of the phase shifter is shaped into a square wave and applied to the shield grids of the two thyratrons in opposite phase. The signal received from the ground transmitter is shaped into a square wave and applied to the grid of V_3. On the negative swings of this voltage V_3 is cut off and the damped parallel circuit in the cathode starts a highly damped train of oscillations. The first swing will be negative. The cathodes of the two thyratrons are directly connected to the cathode of V_3 so that the negative pulse is applied to these two cathodes. The plates of the two thyratrons are connected to opposite ends of the secondary of the 400-cps power transformer. The center tap supplies one winding of the two-phase motor. The current in the other winding of this motor is shifted 90° by the use of a series capacitor. The phase of the current through the controlled winding of the motor and hence the direction of rotation of the motor depends upon which thyratron is firing. Figure 6-03 illustrates the voltages applied to the shield grids and cathodes of the thyratrons. Either thyratron can only be fired by the negative cathode pulse if the positive half of the square wave is present on the shield grid. The square waves applied to the shield grids are not of sufficient amplitude to cut off the thyratrons once they have been fired. They are only extinguished when the 400 cps plate supply voltage goes negative. As drawn in Figure 6-03 both thyratrons would fire and

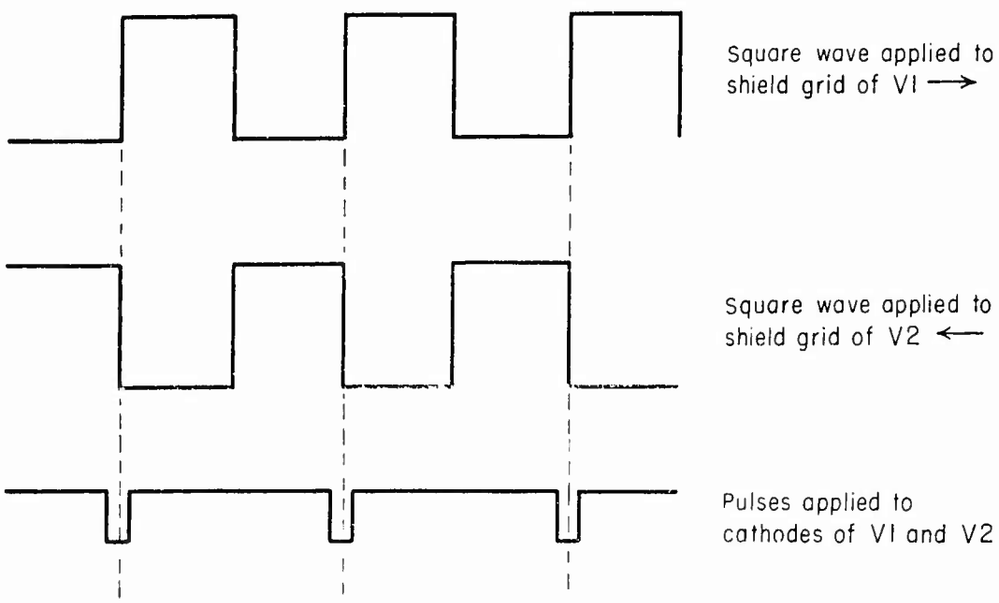


Fig. 6-03 Waveforms of phase-sensitive motor-control

therefore there would be no resultant motor torque. If the pulses shift slightly to the right in phase V_1 only will be fired. The motor rotation produced will drive the phase shifter in such a direction that the two square waves are shifted to the right in phase and the balanced condition of Figure 6-03 is re-established. The calibrated dial indicates the phase shift required to bring about this balanced condition.

The chief reason for developing such a phase-comparison distance-meter is the fact that it could tie in very well with an existing blind approach system. The localizer of this system radiates two lobes modulated by 90 cps and 150 cps respectively. It is thought that this transmitter and antenna system could be used as the ground responding transmitter in this system. The 2588-cps modulation could be radiated by both antennas. The localizer receiver in the aircraft could be used and the 2588 cps separated from the 90 cps and 150 cps by filtering.

Type of system

Pure range or "H" system.

Useful range

50 to 100 miles.

Accuracy and precision

No values available.

Presentation

Veeder counter.

Operating skill required

(a) At the ground beacon: can operate unattended.
(b) In the navigated craft: direct-reading Veeder counter.
(c) Time to obtain a reading: instantaneous.

Equipment required

(a) At the ground beacon: Responder beacon - skill to service fairly complicated equipment.
(b) In the navigated craft: Interrogator-responser and fairly complicated indicating system.

Radio-frequency spectrum allotments required

Not known.

Present status

Developmental.

Description of system

This system is of the type that transmits an interrogating pulse to a ground beacon. The beacon receives this interrogating pulse and transmits a response pulse presumably on a different frequency. The equipment in the aircraft measures the time delay between the interrogating pulse and the response pulse. The system to be described is unusual in that it uses the very low recurrence rate of 1 pulse per second. The circuit is designed so that it can measure distance using a single pulse; thus it can be called a one-shot system. The fundamental time-measuring circuit is a gated charging circuit for a capacitor as shown in Figure 7-01. Tube V_2 is fired by the transmitted pulse and C_1 begins to charge. The received pulse fires V_1. This drops the plate voltage of V_2 to about -15 volts. Since C_1 has acquired some charge the cathode of V_2 will be positive and V_2 will be cut off. The charge on C_1 therefore depends upon the time between transmitted pulse and received pulse. The switch S_2 is opened to cut off V_1 and make the circuit ready for another cycle. The switch S_1 is also closed to the bottom side to short C_1 once each cycle. The voltage at point X indicates the distance. An electronic follow-up drives a calibrated voltage divider so that its voltage equals the voltage at point X. Figure 7-02 is a block diagram of the follow-up circuit. The voltage from point X and the voltage from the voltage divider are applied to a balanced vacuum-tube voltmeter circuit (similar to the voltohmist circuit). The output of the voltmeter circuit controls a ring modulator circuit. A 400-cps voltage is supplied to the ring modulator circuit. The 400-cps output will be of 0° phase if the voltage of X is greater than that from the voltage divider. If the voltage of X is less than that from the voltage divider the output phase will be 180°. The amplified output of this ring modulator controls a

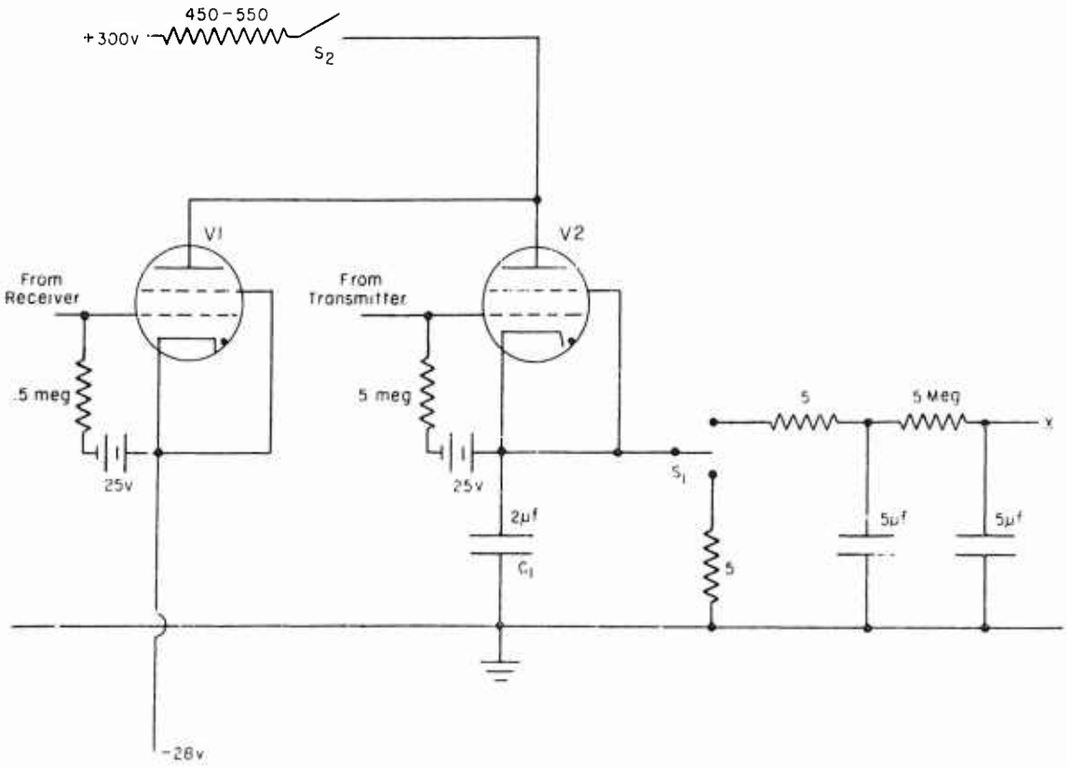


Fig. 7-01 Gated charging circuit

thyratron phase-sensitive motor-control circuit. This phase-sensitive motor-control supplies one stator winding of a two-phase motor. The other stator winding is supplied through a 90^{0} phase shifter from the 400 cps supply.

Figure 7-03 is a complete circuit diagram of time-measuring circuit and follow-up system.

Figure 7-04 is a diagram of the phase relations present in the motor-control circuit. Figure 7-04 (a) represents the phase relations present when the control voltage is zero (zero error-voltage). The plates of V_7 and V_8 are supplied with 400-cps voltages 180^{0} out of phase. The cathodes are also supplied with 400-cps bias voltage 180^{0} out of phase. The bias voltage of each tube is made to lag the plate voltage by approximately 135^{0}. The control voltage is applied to the two grids in phase. When no control voltage is present both tubes will conduct for a short period each cycle. Since the two tubes will supply equal currents through the stator winding no torque will be produced. When a control signal is present as shown in Figure 7-04 (b) one tube will conduct for a longer period than the other due to the fact that one grid signal is shifted so that it lags the plate voltage by a lesser amount and the grid signal of the other tube is shifted so that it is more nearly 180^{0} out of phase with its plate voltage. This will unbalance the current supplied the stator winding and a torque in one direction will be produced. When the phase of the control signal is reversed as shown in Figure 7-04 (c) the unbalance of conducting times is reversed and a torque in the opposite direction will be produced. The two-phase motor will be driven in such a direction as to make the error voltage applied to the voltmeter circuit zero. This motor also drives a P.M. field

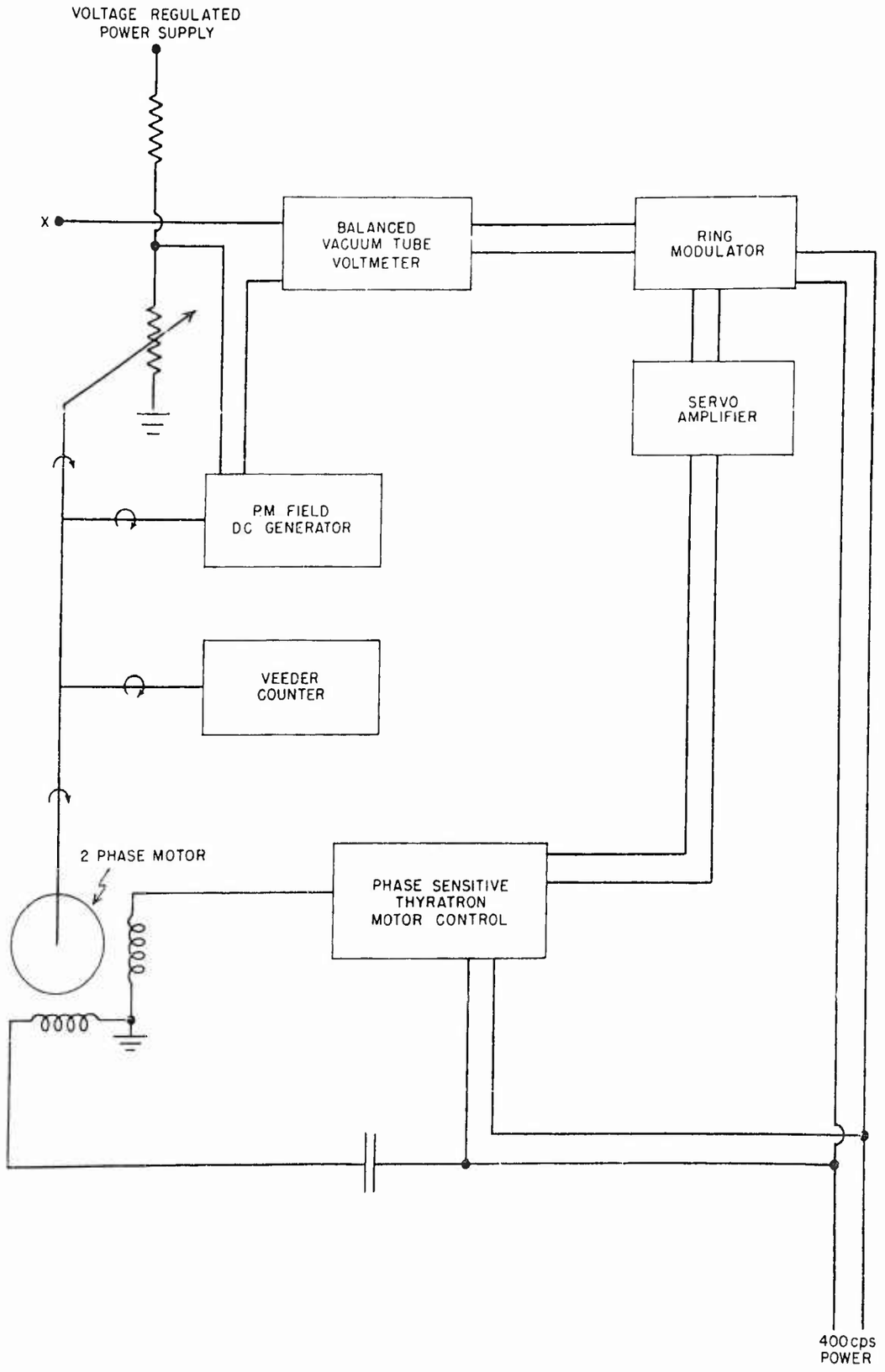


Fig. 7-02 D. C. follow up

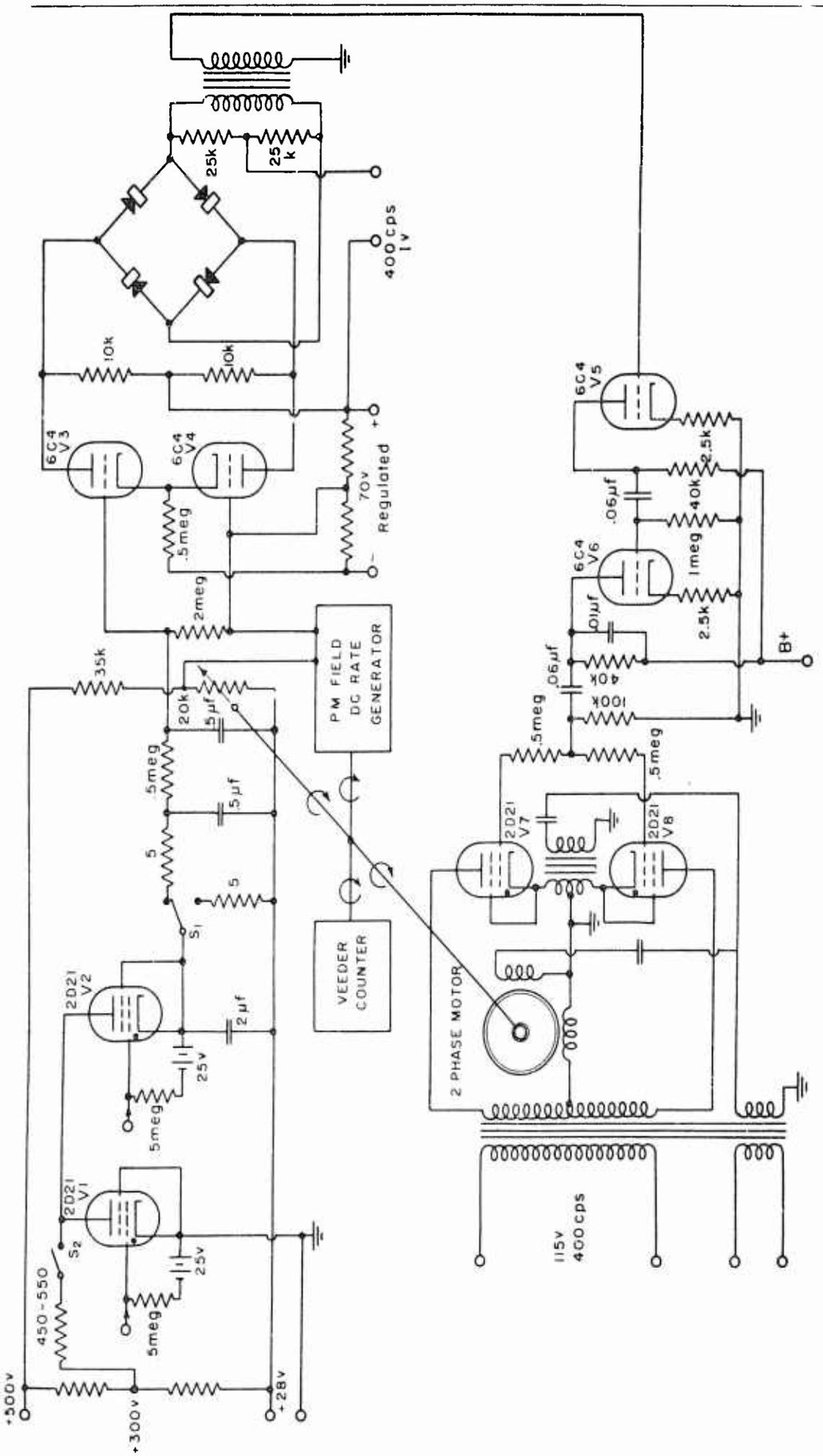


Fig. 7-03 Circuit diagram of one-shot distance meter

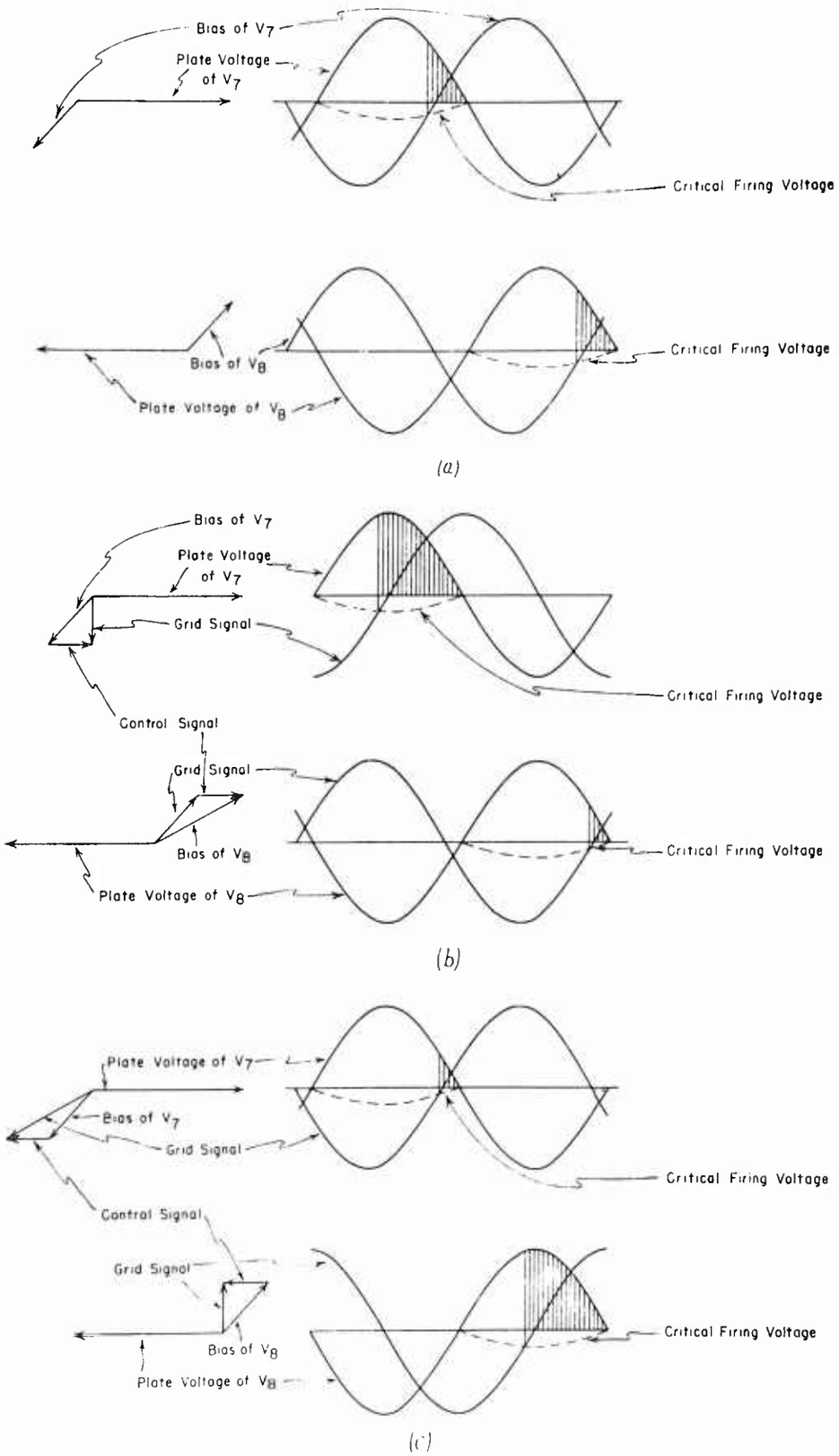


Fig 7-04 Phase relations in motor-control circuit

DC generator. The output of this generator is applied in series with the voltage from the voltage divider which is applied to the voltmeter circuit. Since the polarity of this voltage is opposite to the error voltage and proportional to the speed of the motor it serves as an anti-hunt element. This is a typical "error plus first derivative" servo-system which is widely used in a variety of forms. The motor drives a Veeder counter which indicates the distance.

Since quite short pulses may be used and because of the very low repetition rate, high peak powers can be used. It also means that a large number of aircraft can interrogate one beacon.

Type of system

Pure range or "H" system.

Useful range

50 miles at 1000 feet; 100 miles maximum range.

Accuracy and precision

(a) Calculated and estimated errors ± 1 mile.
(b) Errors revealed by operational use ± 1 mile.

Presentation

Visual presentation on meter.

Operating skill required

(a) At ground beacon - may operate unattended. Skill to service responder beacon required. (b) In the navigated craft - Little skill required. Manual range search must be turned until lock-on light lights and then switch is thrown to automatic follow-up. (c) Time required to obtain a distance measurement - Time to read meter if follow-up is tracking; time to search and lock on: 30 seconds to 1 minute (limit is beacon coding time).

Equipment required

(a) At ground beacon: Fairly complex responder beacon. Weight 1000 to 2000 lbs. (b) In navigated craft: Fairly complex interrogator-responser and automatic range follow-up. Weight 22 lbs. installed.

Radio-frequency spectrum allotments required

Frequency -
Interrogation - 202 mcps airways
222 mcps approach — subject to change
Response - 212 mcps
Bandwidth - 3 to 4 mcps

Present status

Experimental.

Description of system

This system uses an interrogator-responser on the craft and a responder beacon on the ground. The pulse repetition frequency of the interrogator is approximately 200 pps. The interrogating pulses are 2 microseconds long and the interrogation frequency is 202 mcps for airways beacons and 222 mcps for runway approach beacons. The beacons respond with a 5-microsecond pulse on 212 mcps. An automatic range-tracking circuit tracks the beacon in range and gives a meter indication. A manual range search must be used originally to select the desired beacon. A rate-of-approach meter has also been developed and flight tested.

Figure 8-01 is a block diagram of the interrogator-responsor. The pulse repetition frequency is determined by a free-running multivibrator. The output of this multivibrator is applied to a special sawtooth generator. The slope and linearity of the sawtooth are very constant. The slope of this sawtooth is negative. This sawtooth is applied to two circuits called "snaps". These snaps have the property of generating a pulse at the instant the sawtooth voltage equals an exter-

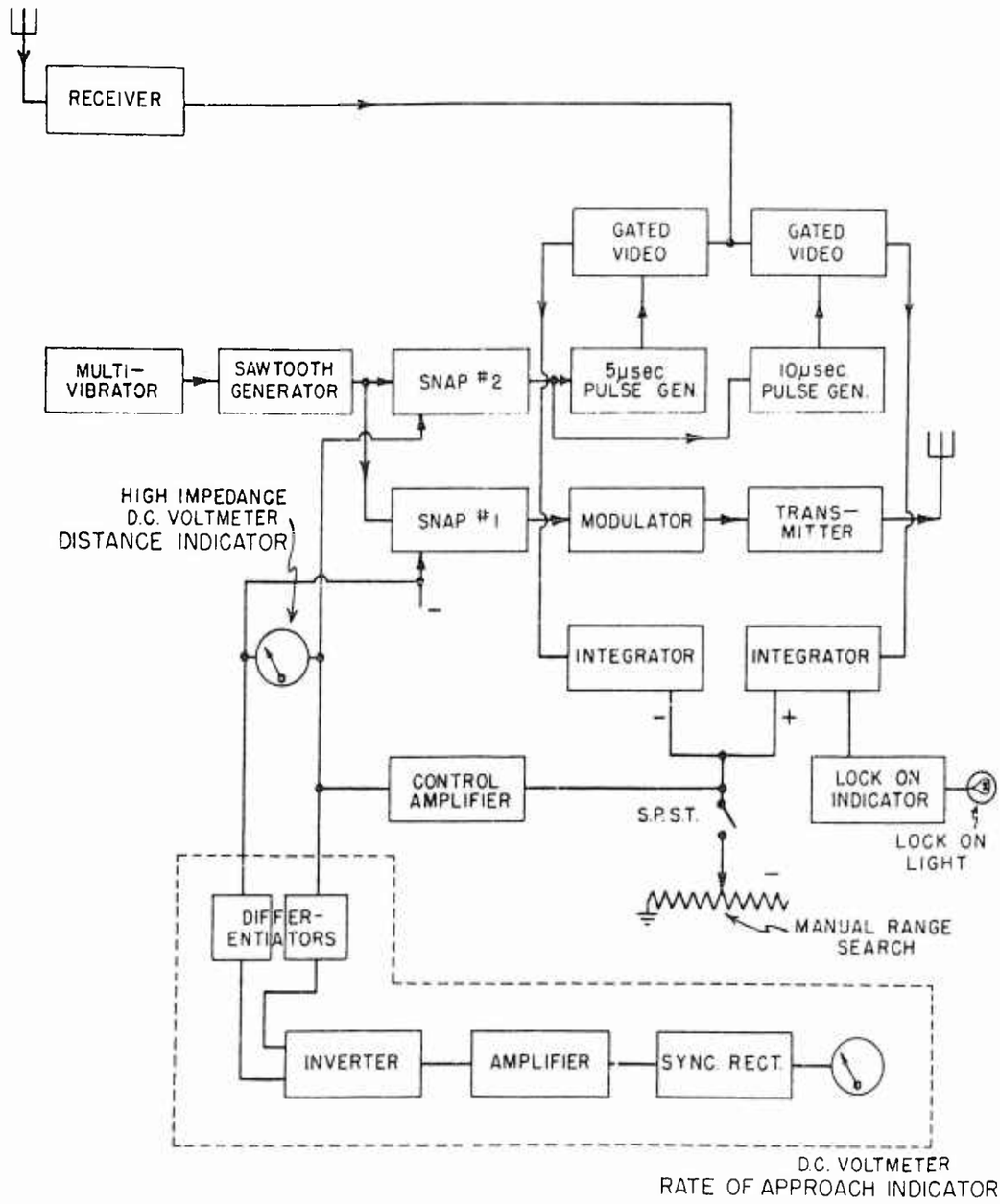


Fig. 8-01 Block diagram of system

nally applied DC control voltage. A fixed bias is applied to snap 1 sufficient to make it fire on the linear part of the sawtooth. This output pulse drives the modulator which in turn drives the transmitter. The output of snap 2 drives two pulse-generators. The pulses produced by these two pulse-generators gate two video amplifiers connected to the receiver output. The two gates and received pulse are shown in Figure 8-02. The output of these two gated video amplifiers is integrated and mixed. The 10-microsecond gate gives a positive output voltage. The 5-microsecond

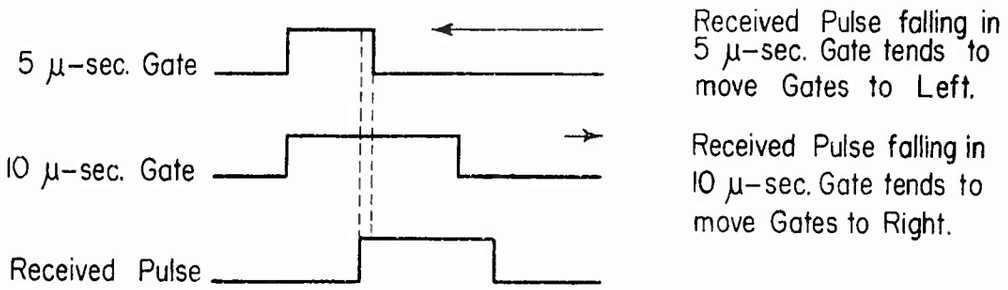


Fig. 8-02 Video gates and received pulse

gate gives a negative output voltage and has 20 to 30 times the effect of the 10-microsecond gate. The mixed output of these two gated channels is applied to a control amplifier. This control amplifier employs an electronically-amplified time-constant and will hang on for several minutes if the control voltage disappears. The output of this control amplifier controls snap 2. A positive voltage applied to the control amplifier results in an increase in the spacing of the pulses produced by the two snaps. The output of the 10-microsecond gated channel therefore tends to move the pulse of snap 2 farther from that of snap 1. The output of the 5-microsecond gated channel (with about 20 to 30 times the effect of the other) tends to move the gates closer to the pulse of snap 1. This results in an automatic follow up which will track the received pulse in range. Since the 5-microsecond gated channel has the greater gain the follow-up will lock on to the leading edge of the received pulse.

When it is desired that the system track a particular response the SPST switch must be thrown to manual track and the manual range-search potentiometer varied until the beacon response falls into the 10 microsecond gate. The lock-on-light will light when this condition is reached. The beacon code may be read from the lock-on light. The switch may then be thrown to automatic track.

Since the spacing of the gates from the pulse of snap 1 depends upon the difference in two DC voltages a voltmeter can be connected between these two points and used to measure the distance.

The circuit of the linear sawtooth generator used to trigger the two snaps is given in Figure 8-03. This circuit, sometimes called a Miller Rundown, makes use of negative feedback to obtain a very linear sawtooth. A positive rectangular pulse is applied to the screen grid of V3 from the cathode follower which is driven by the timing multivibrator. This positive pulse on the screen grid increases the plate current and the plate voltage of V3 begins to decrease. This decrease is applied to the grid by the coupling capacitor connected from plate to grid. Thus the grid voltage is lowered and the plate current is prevented from rising to as high a value as it would in the absence of the coupling capacitor. Thus the plate voltage decreases slowly and very linearly. The output is taken directly from the plate of V3.

The circuit given in Figure 8-04 is that called the "snap". The sawtooth waveform from the Miller Rundown is applied through a decoupling filter and the

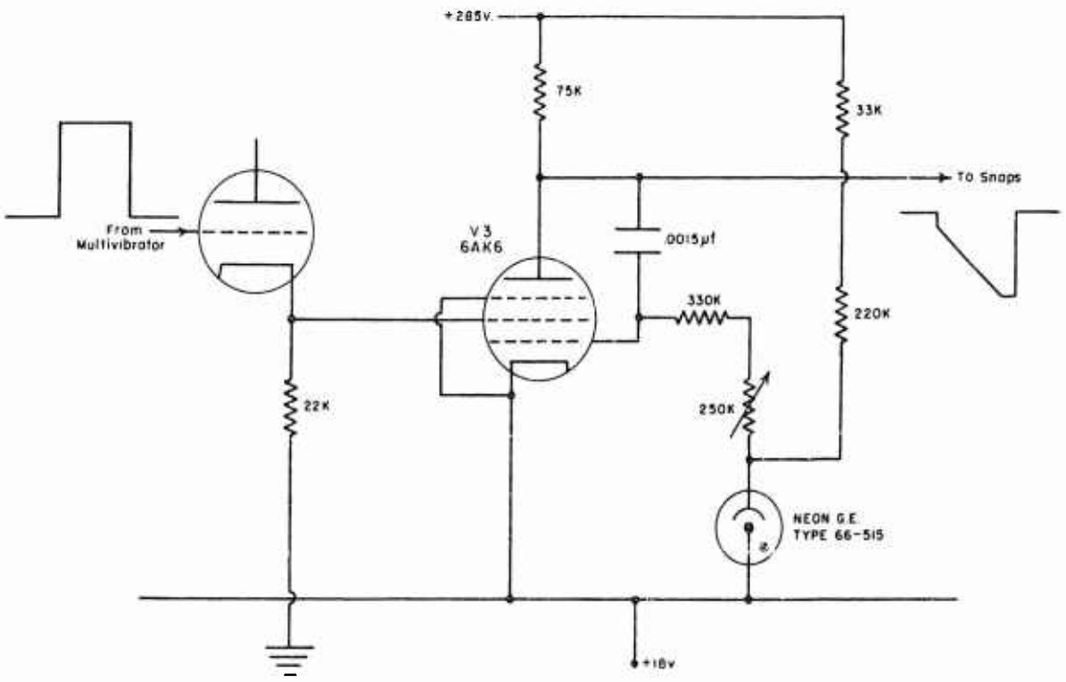


Fig. 8-03 Sawtooth generator

secondary of the transformer to the cathode of V4. The plate of V4 is connected to +200 volts through a large resistor. This plate is also coupled to the grid of V5. As long as the sawtooth voltage is greater than 200 volts V4 cannot conduct. The plate current of V5 will be high since the only bias will be the contact potential bias developed across the 2.2 megohm grid resistor. When the sawtooth voltage reaches 200 volts the diode V4 will begin to conduct and the grid voltage of V5 will start dropping. The plate current of V5 will start to decrease. The transformer B.O.-1 is phased in such a way that the decreasing cathode current induces a voltage in the secondary of the polarity given on the diagram. This lowers the grid voltage still farther. This is a regenerative action resulting in a sudden plate-current cutoff. The plate-current of the tube is then held at zero since the sawtooth is differentiated by the grid coupling circuit and holds the grid below cutoff. The positive pulse output is taken from the plate of V5. Two of these snap circuits are used. The one shown is the one that times the transmitted pulse. The other one controls the timing of the tracking gates. This second snap is the same as the one shown in Figure 8-04 with the exception that a variable control voltage is applied instead of the fixed 200-volt control voltage.

Figure 8-05 is a diagram of the diode control-voltage comparator. The output of each gate is a negative pulse if the response pulse falls in the gate. The negative pulse from the 5-microsecond gate is applied to the cathode of V16b through the .006-μf coupling capacitor. The negative pulse from the 10-microsecond gate is applied to the cathode of V16a through the .0005-μf capacitor. When the output of the 10-microsecond gate swings negative V16a conducts and the .0005-μf capacitor is charged with the polarity shown. When the negative pulse is over the cathode of V16a swings positive due to the charge on the .0005-μf capacitor. This positive voltage is connected to the output through the 4.7-megohm resistor. When response pulses fall in the 5-microsecond gate V16b will conduct for each negative pulse and supply a negative control-voltage through the 470-thousand-ohm resistor.

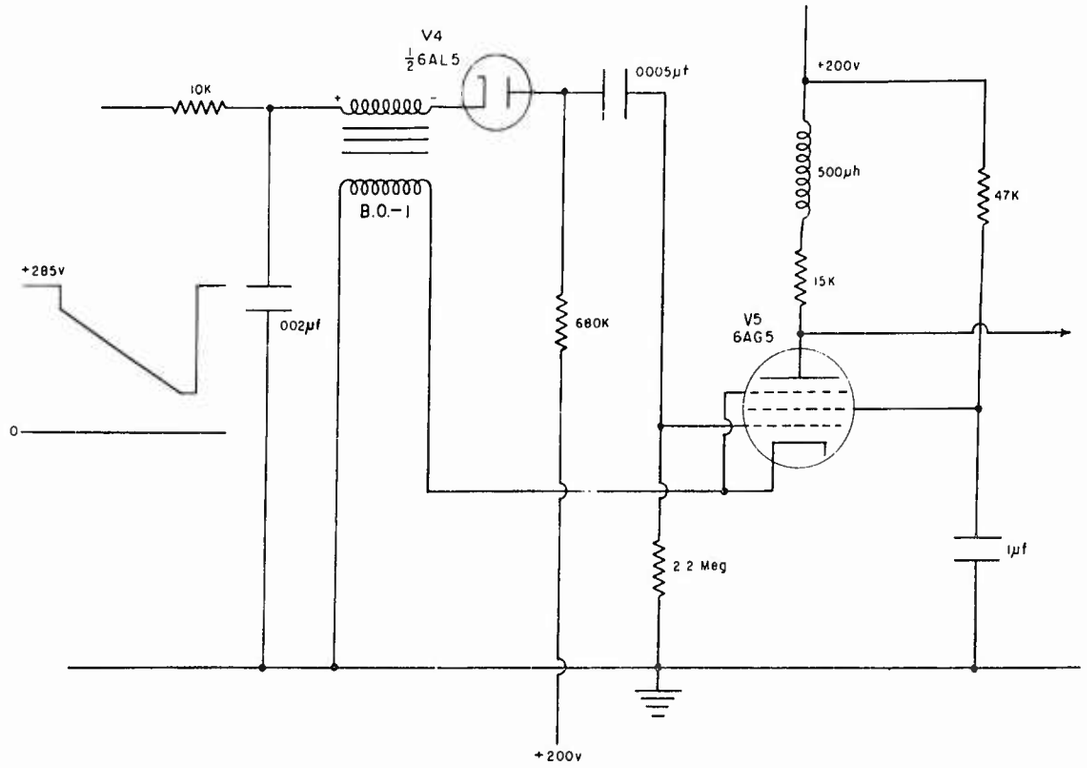


Fig. 8-04 Snap circuit

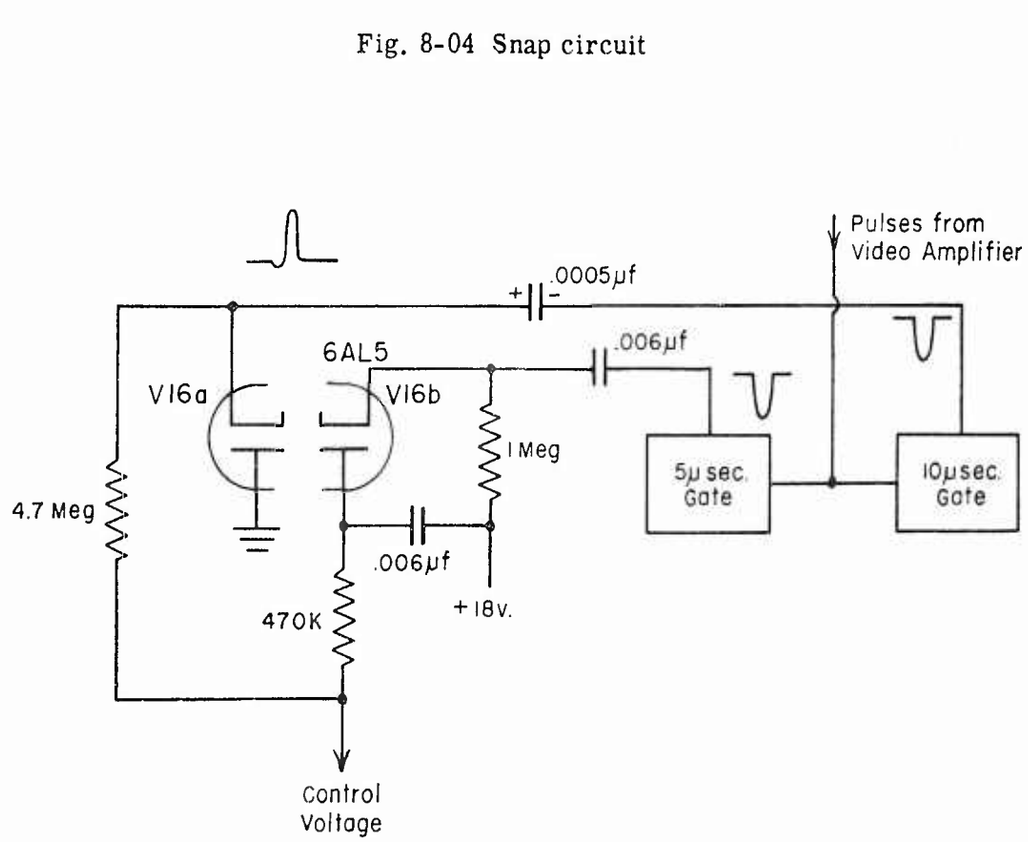


Fig. 8-05 Diode Comparator

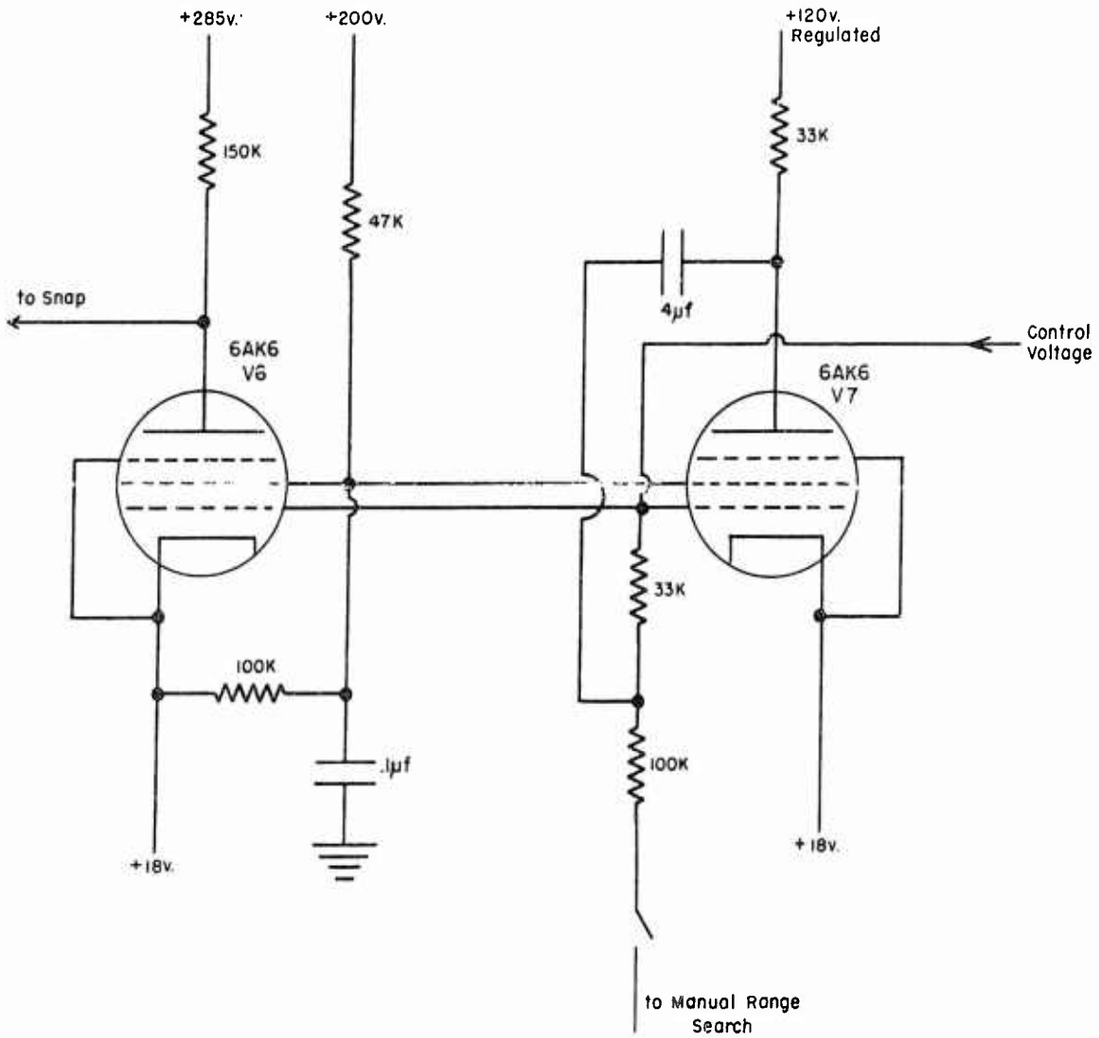


Fig. 8-06 DC control amplifier

The pulse from the 5-microsecond gate is therefore more effective in making the control voltage negative than the pulse from the 10-microsecond gate is in making the control voltage positive. In order to attain a stable intermediate control voltage the output pulse from the 5-microsecond gate must be very short.

Figure 8-06 is a diagram of the control amplifier that controls the variable snap. The 4μf-coupling capacitor between plate and grid of V7 gives this tube an amplified time-constant effect. The functions of this control amplifier are to retain temporarily the condition established by the most recent control pulses, to smooth out pulsations from the control voltage and to bridge gaps due to short-period interruptions. The control voltage is applied to the grid. If this control voltage is removed the grid voltage will change very slowly since the only DC return of this grid circuit is the leakage resistance. If for instance the grid voltage tended to increase the plate voltage would decrease and this decrease could be coupled back to the grid through the 4 μf. coupling capacitor. This grid is tied directly

to the grid of V6 which acts as a DC amplifier to control the triggering voltage on the variable snap. The plate voltage of V6 is the bias voltage of the variable snap. The time delay between the triggering of the fixed snap and the variable snap is a function of this bias voltage. As this bias becomes less positive the time delay increases. If the response pulse falls only in the 10-microsecond gate the control voltage developed is positive. The bias applied to the variable snap is therefore made less positive and the time delay between the transmitted pulse and the tracking gates increases. This delay will increase until the leading edge of the response pulse enters the trailing edge of the 5-microsecond gate enough to being about a balanced condition.

The complete circuit diagram is given in Figure 8-07.

The part of Figure 8-01 enclosed in the dotted line is the circuit for producing the rate-of-approach indication. The DC bias voltage and the slowly-changing bias voltage applied to the distance meter are applied to two differentiators having a time constant of 1 second. A differentiator is used on the DC bias voltage to eliminate errors due to voltage fluctuations. The outputs of these two differentiators are applied to a vibrating-reed inverter and converted to AC. This AC is amplified in a stable amplifier. The output of this amplifier is rectified by a vibrating-reed synchronous rectifier and applied to a DC meter which indicates rate-of-approach. The heading for zero rate-of-approach can be determined to $\pm 1^{0}$ or better. The heading for maximizing the rate-of-approach can be determined to $\pm 6^{0}$ or better.

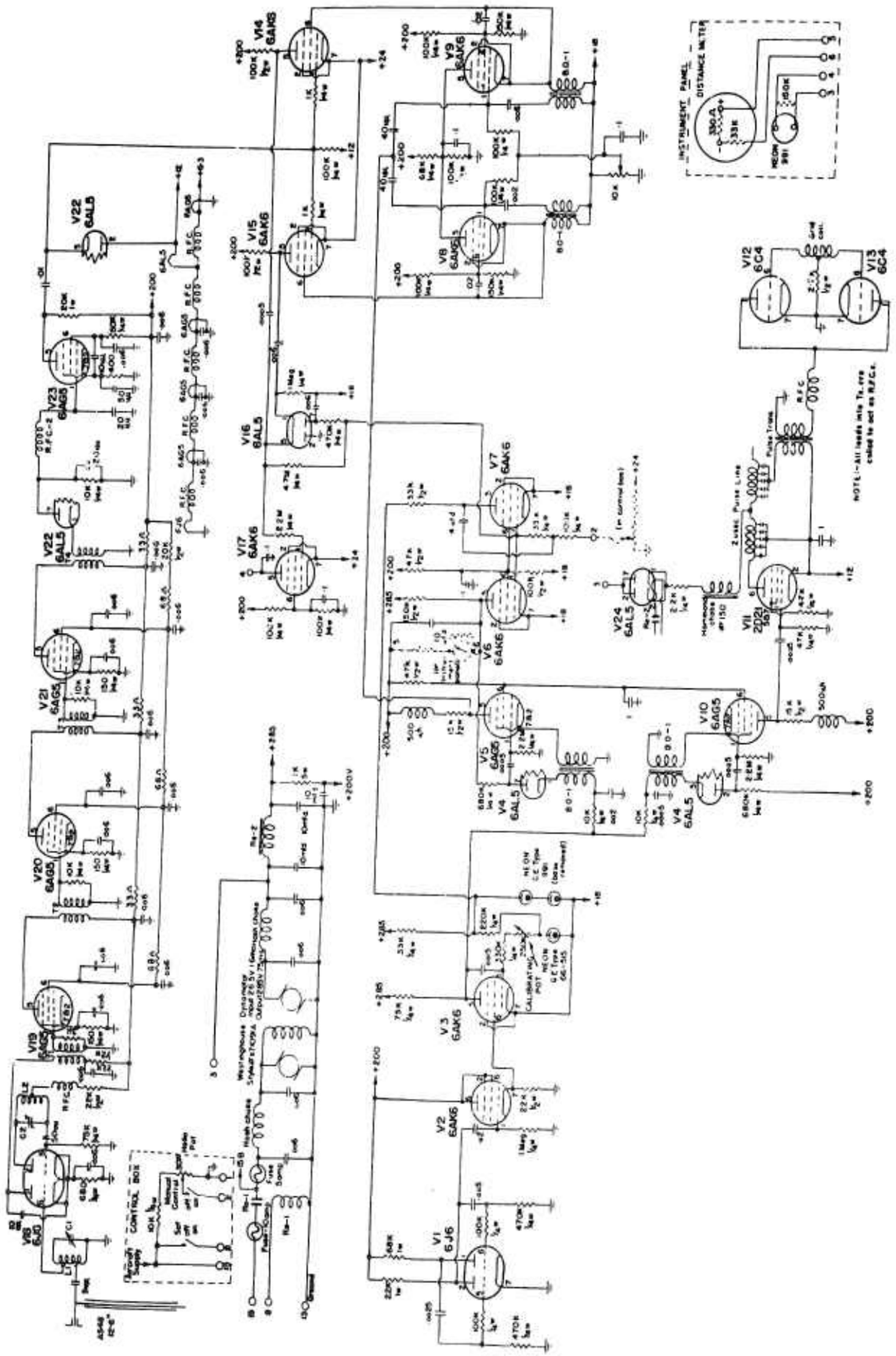


Fig. 8-07 Circuit diagram

Identification	Classification	Title	Issued by
	Confidential	Airborne Distance Indicator	National Research Council of Canada Radio Branch 15 July 1945

Type of system

Pure range or "H" system.

Useful range

Not known - probably 100 miles.

Accuracy and precision

Not known.

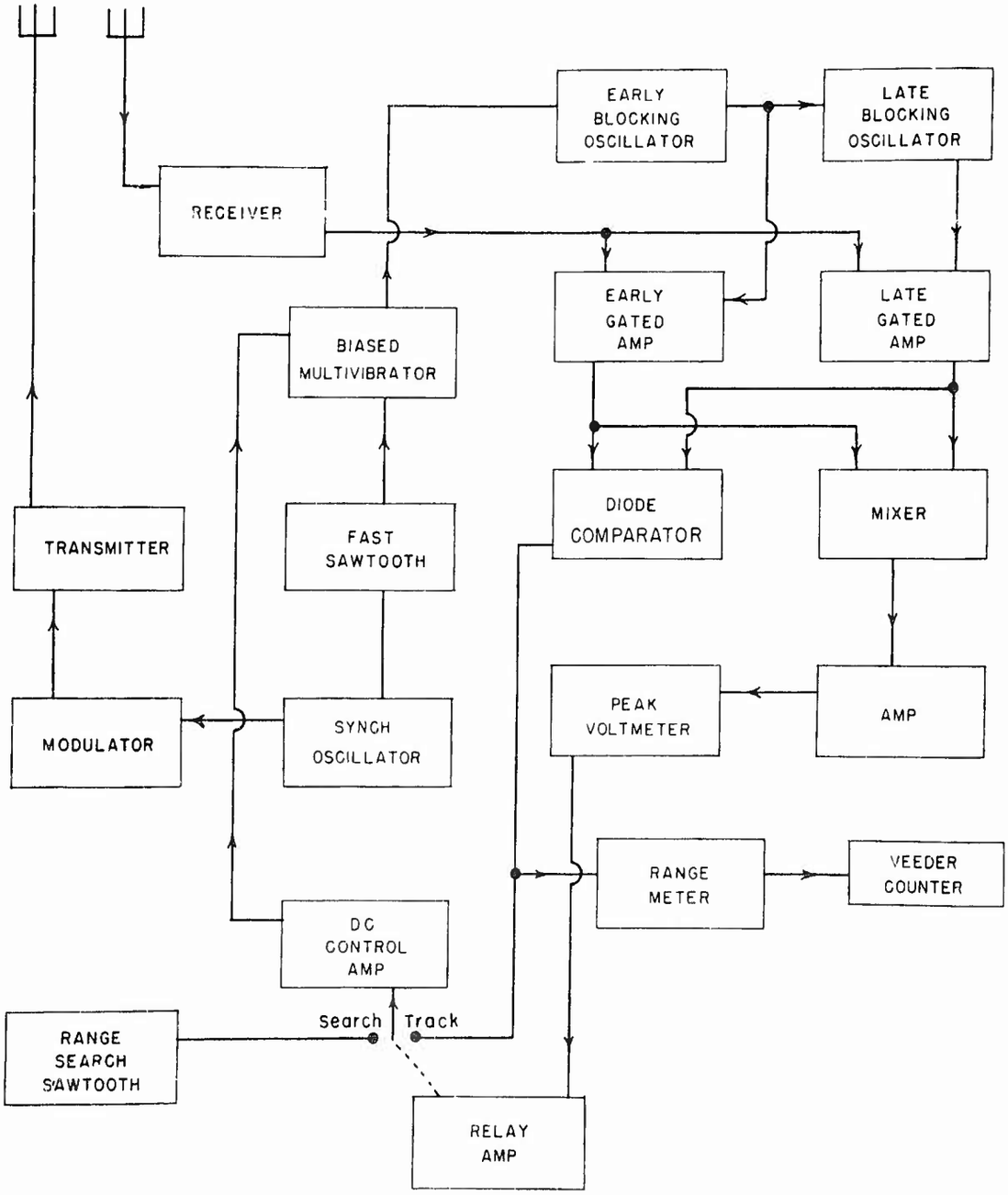


Fig. 9-01 Block diagram

Presentation

Veeder counter.

Operating skill required

(a) At ground beacon: can operate unattended.
(b) In the navigated craft: no special skill required--automatic presentation.
(c) Time required to obtain a reading: instantaneous.

Equipment required

(a) At ground beacon: responder beacon - requires highly trained personnel to service.
(b) In the navigated craft: interrogator, receiver and automatic follow-up. Fairly complicated and requires highly trained personnel to service.

Radio frequency spectrum allotments required

Not known.

Present status of development

Proposed.

Description of system

In this system the equipment on the navigated craft interrogates a ground responder beacon and measures distance by measuring the delay between the transmitted pulse and the beacon response. An unstable oscillator supplies the synchronization for the system. It triggers the modulator which contains a pulse shaping circuit. The modulator in turn pulses the transmitter. An automatic range follow-up system is used. The output of the receiver is applied to an early gated amplifier and to a late gated amplifier. The outputs of these gated amplifiers which are of opposite polarity are compared in the diode comparator and the difference used to control a biased multivibrator delay circuit through a DC control amplifier. The fast sawtooth is triggered by the synchronizing oscillator and is applied to the biased delay multivibrator. The delay produced is directly proportional to the bias voltage from the DC control amplifier. When the tracking gates are locked on the response pulse the DC bias applied to the delay multivibrator produces a time delay equal to the delay between transmitted pulse and response pulse. When the delay between the transmitted pulse and the response pulse changes, the bias on the delay multivibrator changes and the delay produced by the delay multivibrator changes so as to make the tracking gates follow the response pulse. An automatic range search is obtained by switching the DC control amplifier to a slow-range search sawtooth. When the gates are moved to a delay such as to accept response pulses the relay amplifier is energized and switches the DC control amplifier over to the automatic follow-up gates. Presumably a DC follow-up is used to drive the Veeder counter distance-indicator.

Type of system

Pure range or "H" system.

Useful range

100 miles maximum.

Accuracy and precision

Not known.

Presentation

Meter.

Operating skill required

(a) At ground beacon: Operates unattended. (b) In the aircraft: No special skill required. (c) Time to obtain a fix: Instantaneous.

Equipment required

(a) At ground beacon: Responder beacon and 800-cps timer. (b) In the aircraft: Interrogator-responser and fairly complicated control circuit.

Radio-frequency spectrum allotments required

Not known.

Present status

Proposed.

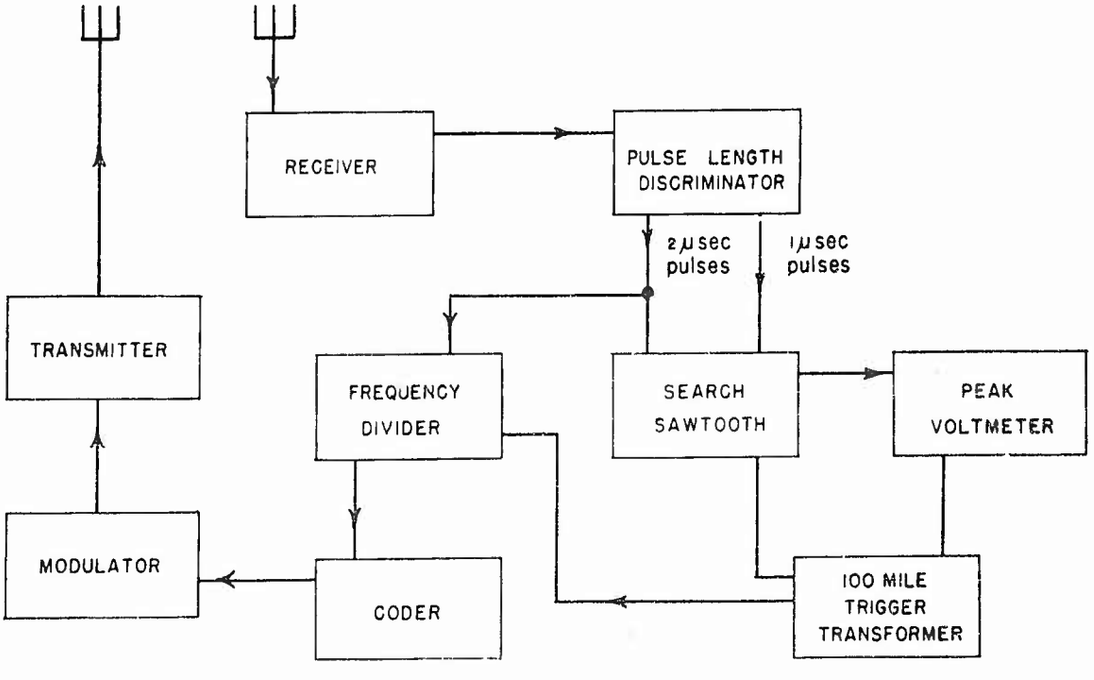


Fig. 10-01 Block diagram

Description of system

This system uses an interrogator-responser on the aircraft and a responder on the ground. This system is unusual in the fact that the interrogations are invited by the ground beacon. The ground beacon transmits 2-microsecond invitation pulses at a rate of 800 pps. In the aircraft equipment the 2-microsecond pulses are selected by a pulse-length discriminator. These pulses are applied to a frequency divider which steps the frequency down to 16 cps. The aircraft interrogates at a 16-pps rate. There are therefore 50 time-channels available for 50 interrogating aircraft. In the aircraft equipment there is an automatic search circuit which finds an empty time channel and transmits its interrogating pulses in that channel. The beacon responds to an interrogation with a 1-microsecond pulse. These 1-microsecond pulses occurring at a 16-pps rate are separated from the 2-microsecond invitation pulses by a pulse-length discriminator. Since the distance corresponding to the period of an 800-cps frequency is 116 miles the maximum distance is limited to 100 miles.

A block diagram of the craft equipment is shown in Figure 10-01.

GEE (OR G) SYSTEM OF NAVIGATION

Type of system: Differential range (hyperbolic)

Useful range and coverage area

Since the frequencies used with Gee are of the order of 20-85 mcps., reception is essentially limited to line-of-sight range, although refraction and ducting extend this somewhat. Gee fixes have been obtained by sky-wave, but this is not to be relied upon. The range practically attainable therefore depends mainly upon the height of the craft and the siting of the transmitter. This statement assumes that adequate power is radiated for good signal-to-noise ratio at ranges corresponding to the maximum operational craft heights encountered. Another way of stating this is to remark that if a given average radiated power provides satisfactory reception at a line-of-sight range corresponding to a craft height of (say) 20,000 feet, then the range at this and lower altitudes will not be materially increased by increasing the transmitted power.

Formulae are available for computing ranges at various heights (see section 2 of this document).

Line-of-sight ranges for various craft altitudes, assuming favorable transmitter locations (on the forward side of a high hill) but making no allowance for ducting and refraction effects, are as follows:

Height of craft (feet)	Range (statute miles)
5000	126
10000	161
20000	212
30000	250
40000	283

As previously mentioned, the effect of refraction and ducting will be to increase these figures, so that at 10,000 feet (for example) the range might be extended from 161 miles to 250 or 300 miles. As a result of this, the maximum operational range of Gee at heights of 30,000 feet and over has been considered as about 400 miles.

Accuracy and Precision

It is shown later in this discussion that time measurements with the Gee indicator can be made to within 2/3 microsecond under good conditions. Position-line precision is greatest along the base-line (see Fig. 11-02). In this location, an error of 2/3 microsecond in time measurement produces an error of 0.062 mile = 327 feet in line of position. As with all hyperbolic systems, the error in line of position resulting from a given error in time measurement varies according to the craft's position on the family of hyperbolic position-lines. This subject is discussed elsewhere (see page 12.10). Error in a fix is discussed in section 1. These errors are theoretical. Operational data indicate an average accuracy of 2 to 3 miles in position-line determination (average of many results under varying conditions).

Type of presentation

Visual. Pulse alignment and time-marker counting on a cathode-ray tube.

Operating skill required

(a) Ground installations: A full-time trained monitor operator is required for each Gee station. (b) Craft: The operator must have instruction in the use of the specialized equipment. The actual operations follow a routine and are in them-

selves simple. (c) Time to obtain a fix: Approximately 1 minute. Running fix technique is not required.

Equipment required

(a) Ground installations: Each station consists of a pulse transmitter, with appropriate timing circuits and test gear. One chain of four fixed stations gives a fix over its coverage area. The fourth transmitter makes accuracy possible in areas where the accuracy of fix obtained from the other three would be poor. Craft: A specialized Gee receiver and indicator are required, together with Gee charts.

Frequency and wavelength

The system has been used on frequencies within the 20-85 mcps band (15-3.5 meters). The bandwidth of the receiver is about 1 mcps.

Present Status

Gee has been the standard British aircraft electronic navigational aid used during the war. It was the principal navigational aid used during the initial landings in France on D-Day, 1945. German use of Gee transmissions is known as Hyperbol.

Principle of operation

The four ground stations comprising a chain transmit on the same frequency. The four stations are here designated A, B, C and D. A is the "master" station and the others are "slaves". The A station transmits pulses of 2 - 10 microseconds width with a pulse repetition frequency of 500 pps. Stations B and C transmit pulses with a repetition frequency of 250 pps, the two stations being synchronized to alternate pulses from the A station. The exact synchronization of the slave stations to the transmission from the master station is essential to the accuracy of the system and represents the manual control mentioned above. The D station transmits double pulses, and has a repetition frequency of 500/3 pps.

The transmissions from the slave stations are triggered by the master station. That is, pulses radiated from the master station (where the prf is accurately controlled by a carefully stabilized crystal oscillator) arrive at a slave station, are received and cause the slave station to emit pulses of its own. The exact timing of the pulses will therefore depend on the distances between the master and each of the slave stations. This distance is of the order of 70 - 80 miles, representing a time of transmission of about 400 microseconds. To this there is added at the slave station a delay-time which is a constant and which represents a controlling factor in the location of the position lines obtained.

Assuming (for purposes of illustration) that a time interval of 500 microseconds elapses between the emission of a pulse from the master station and emission of the triggered pulses from any of the three slave stations, the sequence of events would be as shown in Figure 11-01. (Note that 500 microseconds = 0.5 milliseconds). Certain of the A pulses are double: this point is referred to later.

A Gee receiver at some definite location will receive signals from all four transmitters, but the time relations existing among the received pulses at the location of the craft will not be the same as in the diagram of Figure 11-01 on account of the different distances between the four transmitters and the receiver. It is by measurement of the time delays between the A, B, C and D pulses that a fix is obtained. To amplify this statement, consider the hypothetical location of the four transmitting stations represented in Figure 11-02.

A craft located anywhere on the line a_0b_0 (the perpendicular bisector of the line AB joining the A and B transmitters) will receive the A and B pulses in the

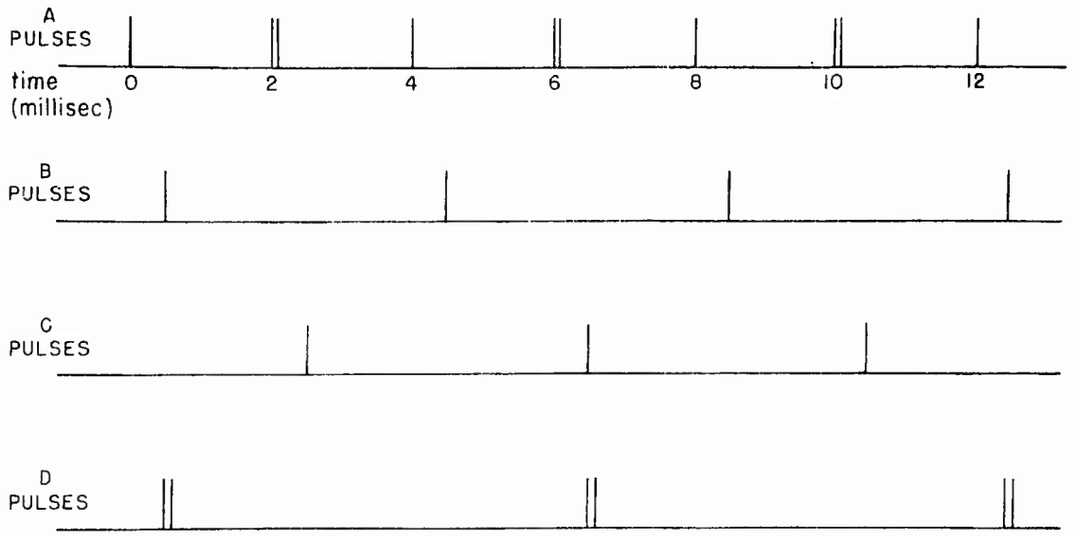


Fig. 11-01

same time relationship as that obtaining between the original transmissions, since both signals will have experienced the same time delay in reaching the craft. This line is therefore the locus of all points for which the relative time delay between the received A and B pulses is constant and equal to that between the transmitted pulses.

Another line $a_1 b_1$ may be drawn such that for any point on it the relative time delay between the received A and B pulses is some other fixed amount. This line is a portion of a hyperbola, of which A and B are the foci. There is an infinite family of such hyperbolae, each one characterized by a definite fixed time delay. Thus if the operator on the craft can determine the relative time delay between the received A and B signals, and also which signal came first, he may locate himself as being on one of the hyperbolic position lines. This function is performed by means of the Gee receiver and indicator, which displays the received pulses on a suitable time-base which can also be furnished with time-marker pips. The problem of determining which signal arrived first is avoided due to the fact that slave pulses are triggered by the arrival of master pulses. There is thus no point at which the slave pulse can arrive first.

Observations on pulses from stations A and C will likewise give a set of hyperbolic position lines (dotted lines in Figure 11-02). The intersections of these two families of hyperbolae yield a set of fixes. Gee charts are provided on which these hyperbolae are overprinted, different colors being used for different pairs of stations.

There are certain intersections in this lattice of intersecting hyperbolae at which the angle of intersection is so acute as to lead to considerable possible error in the fix obtained. In these positions, observations from stations A and D are used in place of either the A-B or the A-C set of pulses. Station D is so positioned as to give the necessary coverage in these areas. Constructions for areas of coverage, variations in precision in different regions on a family of hyperbolae, and sources of error will be discussed in connection with the Loran system. Gee and Loran are both

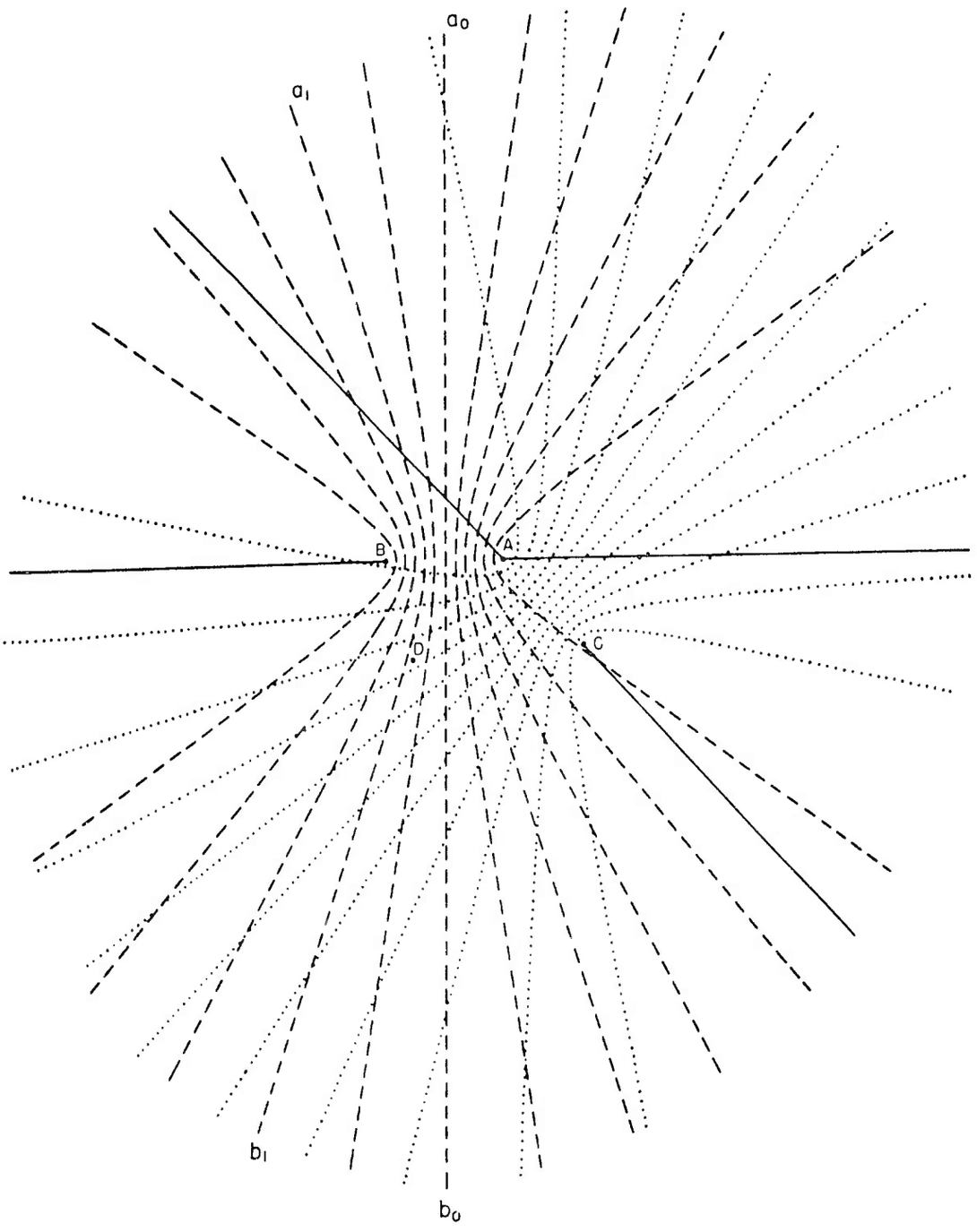


Fig. 11-02 Intersecting Gee lattices

hyperbolic navigation systems and depend on the same principles, differing mainly in the frequency used and coverage area attained, and in certain details of the indicator circuits. The general considerations relating to hyperbolic systems are discussed more fully in the Loran section of this report, for the reason that this material is more easily available in various Loran publications.

Gee System Transmitter

The transmitter must be capable of putting out short pulses of RF energy and must be very accurately synchronized. At master stations, the transmitter is synchronized to pulses obtained from a crystal-controlled frequency-divider rack. At slave stations, synchronization is from the output of a receiver which picks up the pulses from the master station. A suitable fixed time delay is introduced between the output of the receiver and the pulsing circuits.

The signal received by the receiver at slave stations will be weak, and it is essential that the performance of the receiver shall not be affected by spurious signals from the slave transmitter itself. This transmitter must therefore be of the type in which the main oscillator is pulsed, so that this oscillator will not be radiating at the time of arrival of the next synchronizing pulse from the master station.

Furthermore, the synchronization of the transmitted pulses must not be subject to random variations due to changes in the small but finite time required for an oscillator to build up from zero when pulsed. For this reason, a priming oscillator is used, very lightly coupled to the main oscillator. This priming oscillator is itself pulsed slightly in advance of the pulse which permits the main oscillator to oscillate.

Monitoring is provided by a fixed cathode ray oscillograph whose sweep is initiated by the priming pulse. The vertical deflection plates of this oscillograph may be connected to various test points throughout the transmitter. Provision is also made for triggering the sweep of an external cathode ray oscillograph.

Figure 11-03 shows a block diagram of the transmitter and associated timing circuits (omitting power supplies and control equipment).

The pulse-shaping tube V_1 is a pentode amplifier which is normally cut off. The positive pulses applied to its grid are large enough to draw grid current. The output from the plate is therefore a large, square negative pulse. A part of this output is applied to V_7, whence it is used to trip the priming oscillator, the sweep of the monitor CRO and also an external monitor sweep if desired. V_2 is normally conducting and has its grid leak returned to the B+ line. It is a pentode, and the screen and plate resistors are of large value so that the screen and plate potentials are normally of the order of 10 - 15 volts above ground. The plate and screen are direct-coupled to the control grids of V_3 and V_4 respectively, and in both plate and screen circuits there are shunt RC combinations of variable time-constant. When therefore the grid of V_2 is cut off by the arrival of the negative pulse from V_1, its plate voltage rises exponentially with a time constant which is adjustable (preset "delay" control). Since the cathode of V_3 is held constant at approximately +50v, a certain time elapses before V_3 starts to conduct. This delay (adjustable) is of the order of 3-8 microseconds and represents the delay between the pulsing of the priming oscillator and that of the main oscillator. This and other waveforms are shown in Figure 11-04. When V_3 conducts its plate voltage drops sharply. This provides a timing edge to which the pulsing of the main oscillator is synchronized. The magnitude of the change in plate voltage of V_3 is controlled by having its plate supply voltage variable. This provides a control over the width of the pulse actually used to trip the main oscillator ("width trim 1"). V_4 is a similar stage to V_3, but fed from the screen of V_2 instead of from

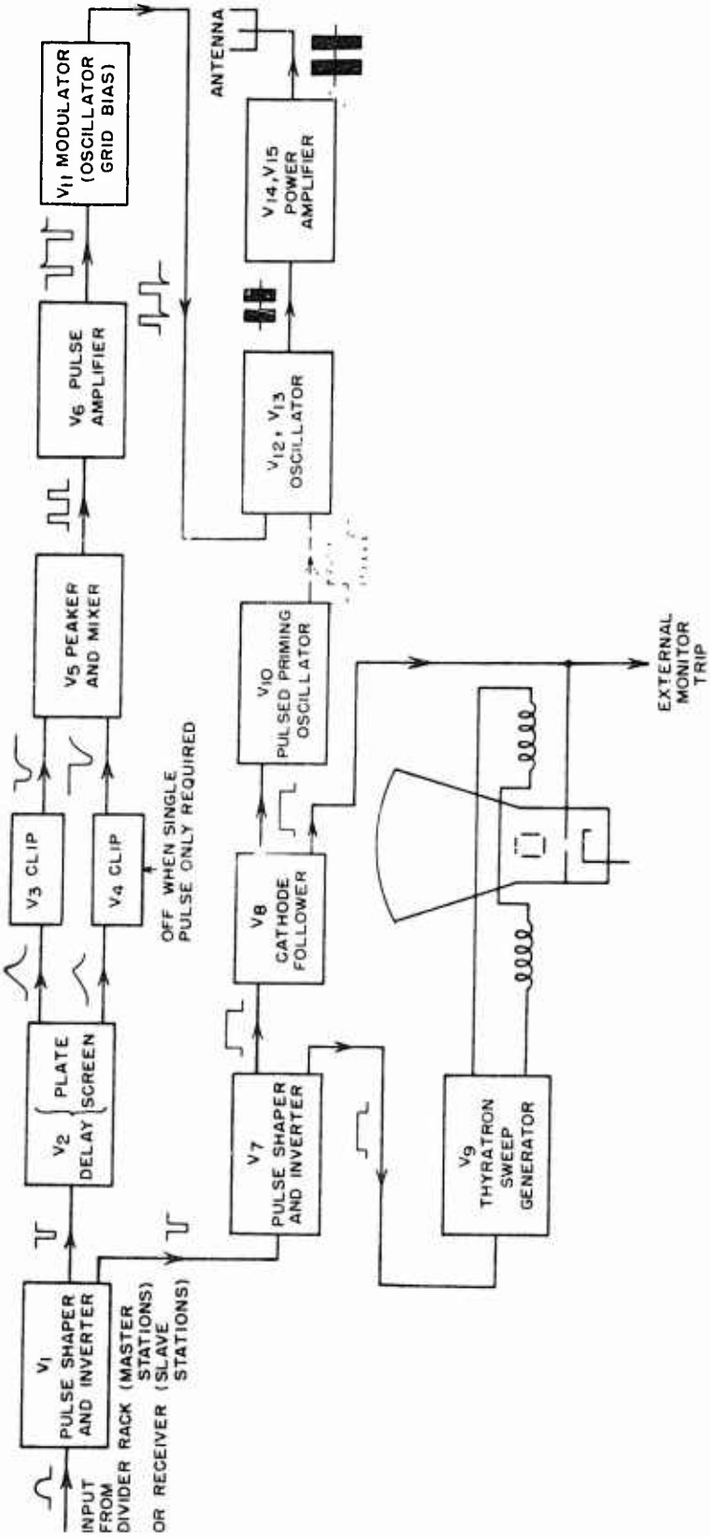


Fig. 11-03 Block diagram--transmitter

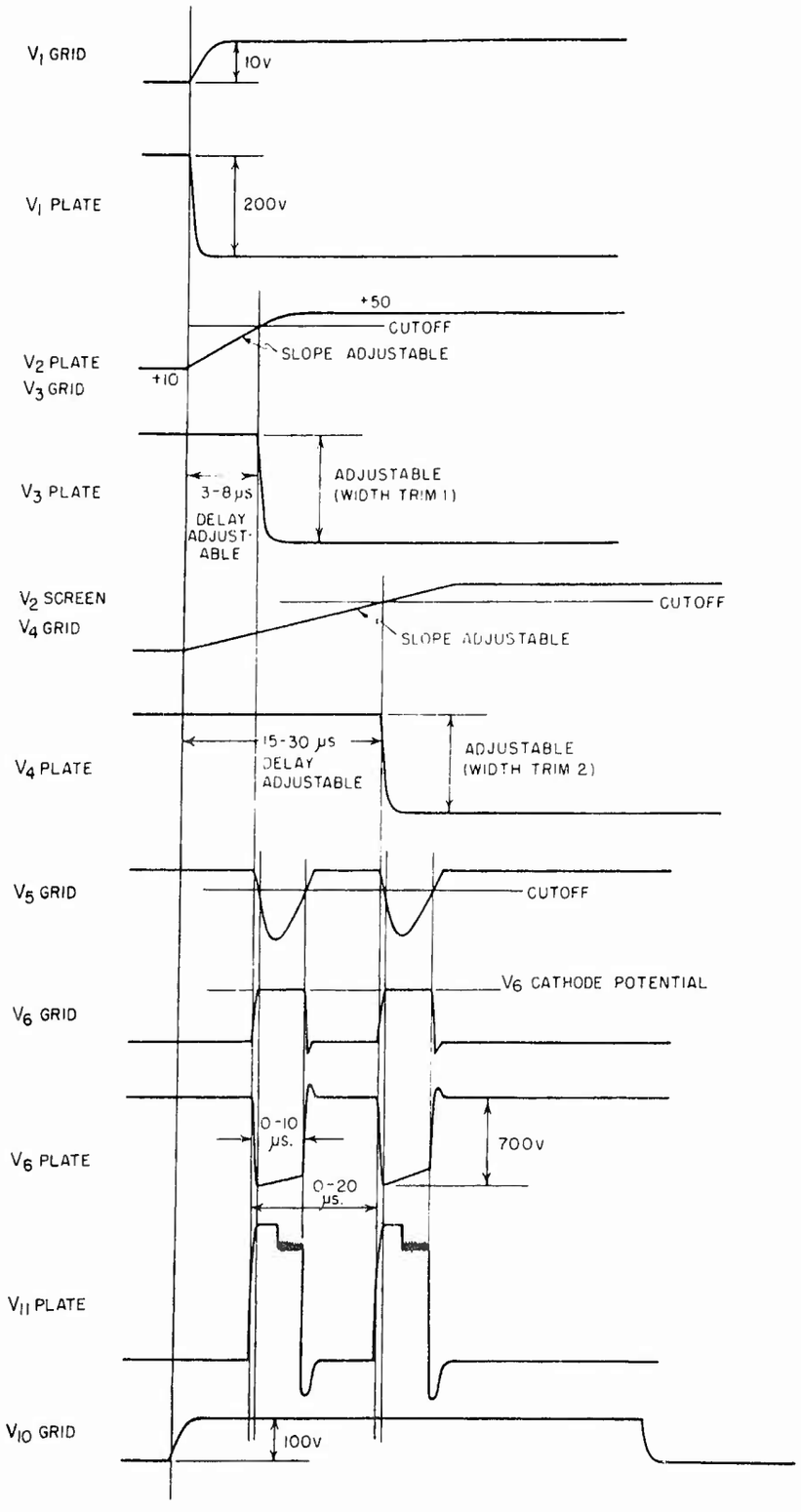


Fig. 11-04 Transmitter waveforms

the plate, and having a longer time constant in its grid circuit than is the case with V_3. The negative timing edge produced at the plate of V_4 will therefore be delayed with respect to the timing edge produced by V_3. This delay is of the order of 10-20 microseconds and is adjustable by changing the screen resistor of V_2 ("spacing" control). The reason for this second timing edge is to enable the transmitter to radiate double pulses if used at a "D" slave station. V_4 may be disabled (by removing its screen voltage) if double pulses are not required. The depth of the timing edge produced is likewise adjustable by varying the plate supply voltage to V_4 ("width trim 2").

The outputs of V_3 and V_4 are differentiated and combined at the grid of V_5. The grid resistor of V_5 is returned to the B+ line so that the tube is normally conducting. Positive pulses therefore occur at the plate of V_5, synchronized to the timing edges produced by V_3 and V_4. Further provision for varying the width of these pulses is made by changing the time constant of the grid circuit of V_5. The output from V_5 is applied to V_6 and the tops of the pulses are squared by grid-circuit clipping. The plate circuit of V_6 contains an inductance and is fed from a supply at about 750v. Its output therefore consists of negative pulses of about 700v, with an overshoot (due to the inductance) on the trailing edge. Its output is applied to the modulator tube V_{11} and the overshoot results in a sharp cutting-off of the RF pulses emitted by the transmitter. The modulator V_{11} has its cathode held at -2000v, and its plate resistor returned to ground. This plate resistor is of 3000 ohms, and serves also as the grid leak of the oscillator stage. V_{11} runs at zero bias and therefore draws a large current (over 0.5 amp). Its plate voltage with respect to ground is normally -1600, which is sufficient to cut the oscillator off. When the 700v. negative pulses are applied to its grid, corresponding positive pulses appear at the plate and in this way the oscillator is pulsed.

The oscillator (V_{12}, V_{13}) is of the push-pull TGTP type. When it is pulsed, there is sufficient coupling with the priming oscillator (which is already oscillating) so that the build-up time is short and of constant duration. The power amplifier stage (V_{14}, V_{15}) is also push-pull and is fed by a tuned section of transmission line from the oscillator plates. The antenna is coupled to the power amplifier either by a tapped coil or by a tapped length of short-circuited transmission line.

The priming oscillator (V_{10}) is a Hartley circuit, pulsed by the output from V_1 taken through a suitable inverter and cathode follower (V_7, V_8). The grid circuit of V_7 is arranged to have a time constant such that the tube is cut off for about 50 microseconds by the negative pulses from V_1. This is the duration of the pulses applied to the priming oscillator, which will therefore continue to oscillate after the main oscillator has stopped. But when a double pulse is required, the priming oscillator will still be functioning for the second pulse. Since the pulse repetition period is 4000 microseconds (at slave stations) the priming oscillator will be cut off long before the receiver is sensitized for the reception of the next transmitted pulse from the A station, and no difficulty will be experienced with feedback.

The plate supply to the final power amplifier stage is variable from 2000v to to 28,000v and the maximum peak power output is about 300 kw.

The Gee Receiver and Indicator, Principles of Operation

(1) Basic Timing Device:

The craft equipment comprises a superheterodyne receiver incorporating certain anti-jamming features, together with timing circuits and a cathode-ray tube indicator.

The equipment measures accurately the time interval between the arrival of an A (master) pulse and that of a B (slave) pulse, and simultaneously the time

interval between A and C pulses. Since both these measurements are made after the same set of adjustments, and at the same time, ideal conditions exist for obtaining a fix at a definite instant in time.

The basic timing device at the craft is a 75-kcps crystal oscillator whose frequency is adjustable within a narrow range. This oscillator has its output circuit tuned to 150 kcps. and performs two main functions:

(a) It provides two sets of timing markers on the display, at 150 kcps and 15 kcps frequency respectively (6.67 and 66.7 microsecond intervals between markers). Furthermore, when using either set of markers, every fifth marker is raised to facilitate counting.
(b) It is used to synchronize the sweep frequency to 500 cps.

Since the prf of the master station is 500 pps. and that of the slave stations 250 pps (A and B) or 500/3 pps (D), it follows that the received pulses will remain locked in stationary positions on the display if, and only if, the frequency of the crystal in the craft is adjusted (by means of the fine frequency control) to agree exactly with that of the crystal at the master station, where the prf is accurately controlled. It follows therefore that the accuracy of the timing markers is automatically that of the timing gear at the master station. The latter is of course very carefully controlled

(2) Display:
The display in the Gee indicator consists of a linear sweep on which the pulses and time markers are displayed. In order to lengthen the sweep and so permit more accurate time measurement, the sweep is divided into two parts, which appear as two horizontal lines, one vertically under the other. The frequency of the entire display is therefore 250 cps. Referring to Figure 11-05, the actual motion of the CRT beam is as follows:
P to Q: beam on, first half of sweep, one A and one B pulse displayed.*
Q to R: return trace, beam blanked.
R to S: beam on, second half of sweep, one A and one C pulse displayed.
S to P: return trace, beam blanked.

(3) Clearing Switch:
By means of a two-position selector known as the clearing switch, either time-marker pips or received pulses are displayed on the sweep, but not both.

(4) Sweep Speeds:
Three sweep speeds are provided. These are:
(a) Main sweep, 250 cps, in two horizontal sections. This is used for approximate pulse alignment, and for counting the whole number of 15-kcps time markers between A and B or A and C pulses.
(b) Strobe sweep. This is much faster, and is divided into four parts, one for each of the four pulses visible on the display. It is used for accurate pulse alignment, and for counting the number of 150-kcps time markers (or tenths of 15-kcps intervals) in the time intervals to be measured. The position of the time intervals corresponding to the strobe sweeps is indicated relative to the main sweep by a small depressed section of the main sweep when this is in use. By means of fine and coarse controls, these time intervals corresponding to the B and C strobe sweeps can be shifted relative to the main sweep.

* D pulses also appear during alternate sweeps on each trace, since the prf of the D station is 500/3 pps. For purposes of explanation only the B and C pulses are presently considered.

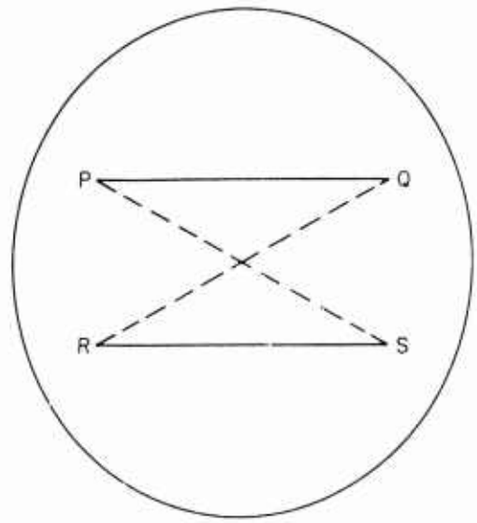


Fig. 11-05 Sweep sequence

Since time markers still appear on the strobes, the fine and coarse controls need not be linear in themselves, but need only be stable over a period of time.

(c) Expanded strobe sweep. Faster than the strobe sweep, likewise divided into four parts, used for final pulse alignment and for estimation of tenths of the spacings between 150-kcps markers (or hundredths of 15-kcps intervals).

The appearance of the indicator under various conditions, illustrating the details of the three sweeps available, is shown in Figure 11-06. The ghost pulse beside the A pulse on the lower trace is used to identify the two parts of the display, so that the operator may know which of the slave pulses should be positioned on the lower trace.

Accuracy of Time Measurement

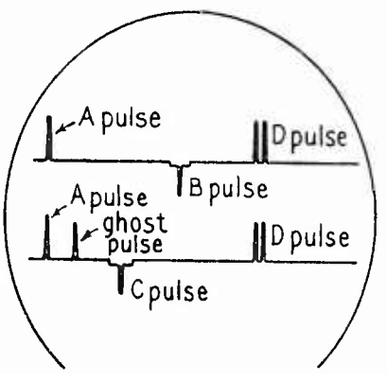
It will be seen that by the above means, time intervals may be estimated to about one-tenth of a 150-kcps time-marker interval, or to 2/3 microsecond, if the pulse alignment and estimation are done with care. The sharpness of the pulses to be aligned (and therefore the accuracy with which they may be so aligned) depends on the band width of the receiver and also on the transmitter characteristics. With present equipment, it seems probable that the errors introduced due to unsatisfactory pulse-shape will be smaller than the residual error in estimation of time intervals, having regard to the radio-frequency used.

Error in the master oscillator used for timing the pulses transmitted from a master station should be extremely small if the crystal temperature is closely controlled, so that this source of error is negligible compared to the others mentioned.

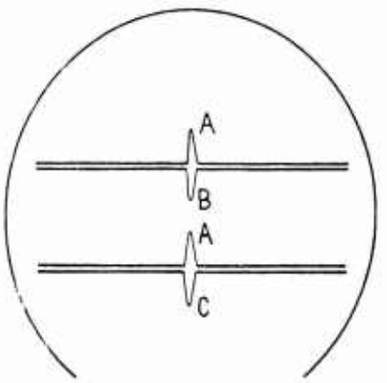
There remain errors due to propagation conditions. These may be serious under certain conditions. They are of the same nature as those encountered in other hyperbolic systems such as Loran, and are discussed in more detail in section 1.

Procedure used in obtaining a fix

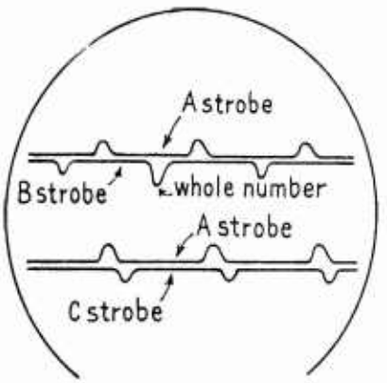
Starting with the main sweep and with received pulses displayed, the fine fre-



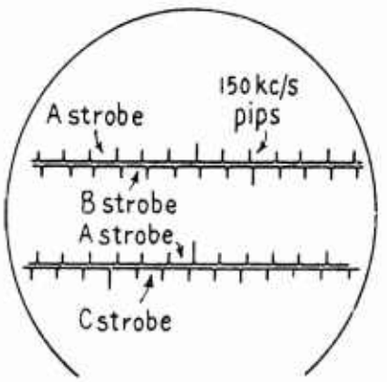
(a) Main time-base, clearing switch up, signals on strobes



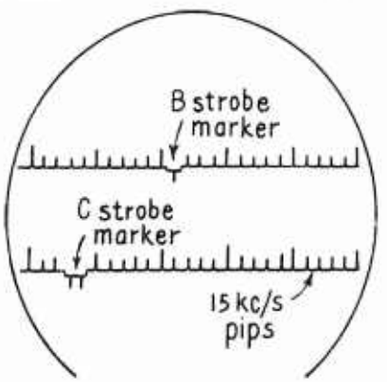
(b) Strobe time-base, pulses correctly aligned



(c) Expanded strobe time-base, clearing switch down



(d) Strobe time-base, clearing switch down



(e) Main time-base, clearing switch down

Fig. 11-06 Indicator displays

quency control of the crystal oscillator is first adjusted so that pulses remain stationary, with the A pulses at the left end of the traces. The coarse B and C strobe controls are now adjusted until the strobe markers on the main sweep are so positioned that the B and C pulses stand on them. Switching to strobe time base, so that those intervals which were formerly strobe markers on the main sweep now are themselves expanded into full sweeps, the fine B and C strobe controls are now adjusted so that the B and C pulses are aligned with the two A pulses, all four pulses lying vertically one under the other. This process is completed using the expanded strobe sweep.

The clearing switch is now moved so that time markers are displayed instead of received pulses. 150-kcps markers are used first, the tenths and whole numbers of markers being counted with the expanded strobe and strobe sweeps respectively. The time of the fix is noted at the instant when the tenths are read. Finally, returning to the main sweep the number of whole 15-kcps time markers is counted. The final count therefore gives the time intervals between the A and B pulse positions, and between alternate A and C pulse positions, to 1/100 of a 15-kcps time-marker interval.

It will be seen that with this system, the time interval read is not directly that between pulses, but rather that between strobes which have been positioned so that the pulses lie in corresponding positions on them. The two operations requiring care (matching of pulses, counting of time intervals) have therefore been separated so that the full concentration of the operator may be exerted on each. It will be noted that the receiver gain used is the same for all received pulses. This means that for certain positions of the craft, in which the craft-station distances (and therefore the amplitudes of the corresponding received pulses) are of considerably different value, the heights of the displayed pulses will not be the same. Since leading edges of pulses are to be matched, and since the slope of a leading edge is influenced by the peak height of the pulse, this feature imposes a certain limitation on the accuracy attainable.

On the other hand, both sets of pulses are displayed simultaneously, so that a fix is obtained at a definite instant, and the time required to make the adjustments for a fix is less than in the case of systems where the two position-lines necessary for a fix are separately obtained.

Indicator Circuits

Figure 11-07 shows a block diagram of the timing and indicating circuits.

The master oscillator (V_{12}) is crystal controlled with a 75 kcps crystal in the grid circuit. A 50 $\mu\mu$f. variable condenser in parallel with the crystal gives fine control of frequency. The plate circuit is tuned to 150 kcps. V_{13} is a blocking oscillator (squegger) whose output is a series of sharp pulses at 150 kcps. V_{14} is a second blocking oscillator arranged to give a frequency division of 5. V_{15} is a similar stage dividing by 2. V_{16} likewise divides by 5. The 3 kcps output from V_{16} drives a multivibrator (V_{17} V_{18}) which may be switched to divide by 5, 6, or 7. Division by 6 is the normal arrangement, yielding a 500-cps pulse output. V_8 and V_9 form a square-wave generator, giving a 250-cps square-wave output. V_7 and V_{10} are identical stages. The output of each is a rectangular (positive) pulse whose leading edge is locked to the trailing edge of a half-cycle of the 250-cps. square-wave input. V_7 and V_{10} are driven by opposite phases of the square-wave. The duration of the output pulses is accurately controllable, coarse and fine adjustment being provided on the control panel in each case.

These pulses (known as strobe timing pulses) together with the output of the 500 cps multivibrator V_{17} V_{18} may be used to initiate the cathode-ray sweep. V_{11}

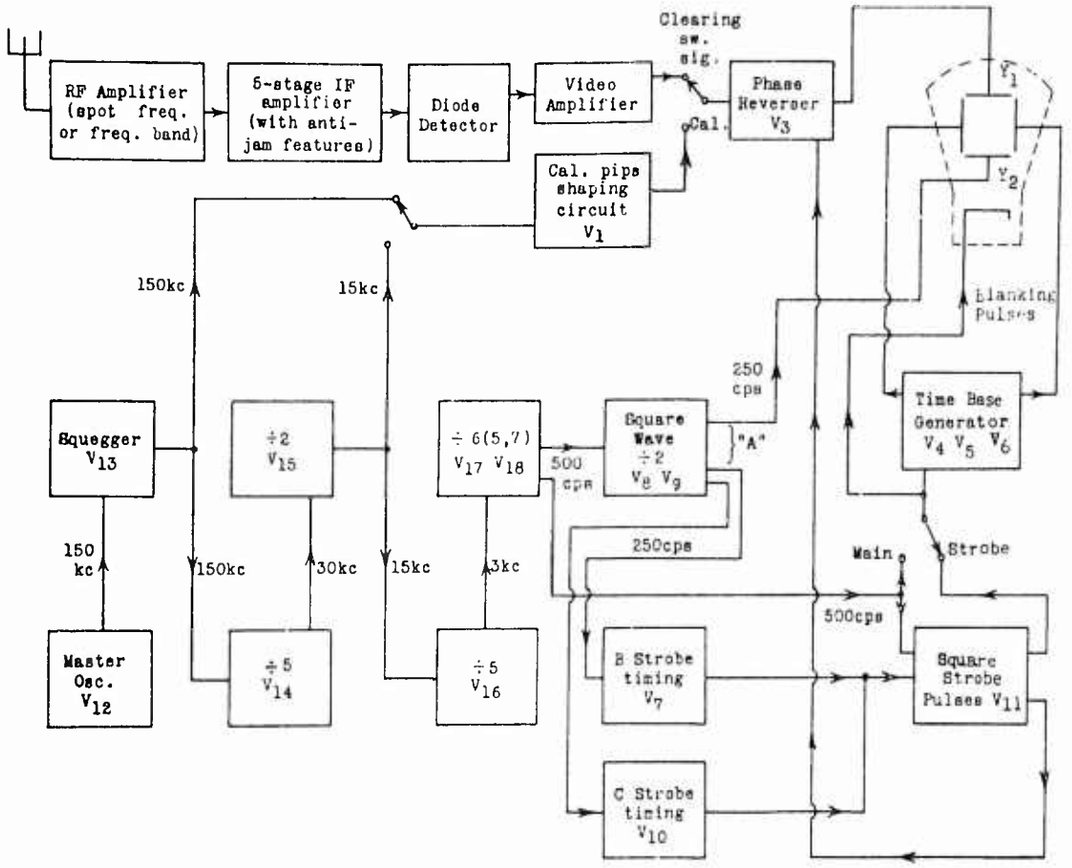


Fig. 11-07 Block diagram--indicating and timing circuits

is a stage in which all the pulses to be used for initiating the sweep are combined together. The 500-cps multivibrator pulses are applied through a clamping circuit to the suppressor grid of a pentode, while the control grid receives both the B and C strobe timing pulses. As a result the output at the plate of V_{11} is a combination of three sets of positive pulses: (1) the A strobe pulses, 500 cps, leading edge locked to the trailing edge of the 500-cps multivibrator output, (2) the B strobe pulses, 250 cps, leading edge delayed (as explained in connection with V_7 and V_{10}) behind the trailing edge of the 500-cps multivibrator output, (3) the C strobe pulses, 250 cps, similarly delayed but by a different interval and following alternate 500-cps multivibrator pulses. This output is sketched in Figure 11-08.

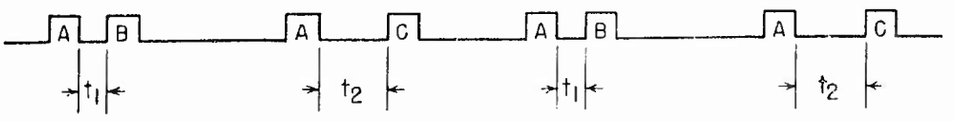


Fig. 11-08 Sweep initiating pulses

t_1 controlled by B strobe timing controls (coarse and fine)
t_2 controlled by C strobe timing controls (coarse and fine)

The waveform at the screen of V_{11} will be similar but without the A pulses, since changes of suppressor grid voltage do not materially affect conditions in the screen circuit.

The time-base generator may be triggered either by the pulse output just described (strobe position) or directly by the 500-cps multivibrator pulses (main position). This generator (V_4 V_5 V_6) is of the type which produces a sawtooth sweep correspond-

ing to each pulse supplied to it. The initiating pulses (or gating pulses) are applied to the suppressor grid of a pentode having a condenser connected between plate and grid. The grid-leak is returned to a point at some positive potential. When the suppressor grid is gated by a negative pulse, the condenser charges up. When the suppressor is returned to zero potential, the condenser discharges at a rate determined by the positive potential of the point to which the grid leak is returned. A sawtooth sweep is therefore produced for each pulse applied, the start of the sawtooth coinciding with the trailing edge of the initiating pulse. The output is push-pull so that both sets of horizontal deflecting plates are driven. The following sweeps are available:

(1) Sweep selector in "main" position, grid leak returned to a point of low positive potential, 500 sweeps per second. Each sweep is of about 2000 μsec. duration.
(2) Sweep selector in "strobe" position, grid leak returned to a point of high positive potential, 1000 sweeps per second of which 500 will be A strobe, 250 B strobe and 250 C strobe. Each sweep is of about 80 μsec. duration.
(3) As in (2) but the size of the condenser is reduced, giving an "expanded strobe" sweep. Each sweep is of about 20 μsec. duration.

These displays may be identified in Figure 11-06.

The 250-cps square wave from V_8 V_9 is applied to one of the vertical deflection plates. The main presentation therefore shows two horizontal time bases, one above the other. In addition, those sections of the main time base corresponding (in time) to the B and C strobe sweeps are slightly displaced downward. This is accomplished by V_3, whose action includes several functions now to be described.

Two types of deflecting voltage can be applied to the upper vertical deflection plate:

(1) The output of the receiver (positive pulses) containing received pulses from the A station (500 per second) from the B and C stations (250 per second) and from the D station (double pulses, 500/3 per second).
(2) Calibration pips, of either 15-kcps or 150-kcps frequency. The calibration pips (positive) are passed through a shaping circuit consisting of a cathode-follower clipper (V_1). Either of these sets of signals (selected by the "clearing switch") is applied to the control grid of V_3. The screen of V_3 is fed in the usual way by a dropping resistor and bypass condenser. The suppressor grid of V_3 is normally at -80v (thereby cutting the tube off) but is gated to 0v by positive pulses corresponding to the B and C strobe initiating pulses (these are obtained from the screen circuit of V_{11}.) A large amount of negative feedback is used (resistance-capacitance coupling from plate to grid). As a result of this, three significant effects are produced:
    (a) At times other than those occupied by the B and C strobes, V_3 is cut off and positive pulses (either received pulses or calibration pips) appear at the plate via the feedback network.
    (b) During the time occupied by the B and C strobes, V_3 conducts, and the signals appear inverted at the plate. The amount of feedback is pre-adjusted so that the amplitude of the output is the same as before.
    (c) During the B and C strobes, the voltage level at the plate of V_3 is lowered due to the fact that the tube is now conducting, and this portion of the sweep will therefore be lower than the main part.

Figure 11-06 (page 11.11) shows the appearance of the display under various conditions.

The D pulses appear on both traces of the main time-base because their spacing is 6 milliseconds whereas the time of one trace (plus return) is 2 milliseconds. The

period of the whole display is 4 milliseconds.

When signals are received, the repetition rate at the transmitter (500 cps) may not agree exactly with that at the receiver, causing the received pulses to drift sideways. This is corrected by a vernier adjustment to the crystal frequency. When the pattern is thus locked, the operator proceeds with pulse alignment and time-marker counting as already described. By means of special Gee charts, on which the hyperbolic lines of position for varying numbers of 15-kcps time-interval markers are overprinted in color, a fix may be plotted.

In areas where the A - B and A - C lattices intersect at too acute an angle for good accuracy, the D pulses may be used instead of either the B or the C pulses. Since the D pulses occur on both traces, the appropriate strobe marker can be used as desired.

The usual arrangements are made to blank out the cathode-ray beam during flyback, and also to intensify the beam during the B and C strobe time-base traces.

Bibliography

Identification	Classification	Title	Issued by
CD 0808 D	Confidential	Gee - R ARI 5342	WDGS
CD 0895 D	Confidential	Type 7000 Station T1365	WDGS
JEIA 1342	Secret	Evaluation of S.W. Gee chain	CCDU, RAF
CD 0895 F	Confidential	Type 7000 Station Ground Equipment	Air Ministry
CD 0208A (2)	Confidential	G-H Airborne equipment MkI ARI5525	Air Ministry
JEIA 7031	Secret	Accuracy of Gee	Coastal Command
SD 0208(2)	Secret	Gee MkII Equipment ARI 5083	Air Ministry
WA 116 36	Confidential	How Gee works	Air Ministry
JEIA 8883	Secret	Trials of G-H MkII	Intelligence Division, U.S.N.
Report 625	Secret	The Future of Hyperbolic Navigation	MIT

Type of System

Differential range, yielding hyperbolic lines of position.

Useful Range

Approximate practical maximum ranges over sea are given in Table 12-01. It should be noted that areas adjacent to transmitting stations are areas of low precision and in some cases are not usable; also that a craft must be within the service area of each of two Loran pairs in order to obtain a fix. Figures given are for the 70-100 kw. transmitters in present use.

Table 12-01 Maximum range (statute miles) over sea.

	Day		Night	
	Ground Wave	Sky Wave	Ground Wave	Sky Wave
Standard Loran	850	-	600	1600
SS Loran	-	-		1600
LF Loran	1500-2000			

All figures in the above table are based on tests made in temperate latitudes. Received noise level is greater in tropical latitudes and less in polar regions, modifying the figures accordingly. Regular Loran readings have been made (by skywave) at distances of over 2000 miles, but such distances cannot be relied upon. Higher noise level during night hours accounts for the reduced night-time ground-wave ranges.

Accuracy and Precision

See discussion on pages 12.09-12.12.

Presentation or use of Data

The presentation is visual (pulse matching and time-marker counting on the screen of a cathode-ray tube). Proposals have been made for an automatic plotting board which would obviate time-marker counting and interpolation of a line of position on the Loran chart. A recent modification presents time-differences on a mechanical counter, obviating actual counting of time-markers.

Operating Skill Required

(a) Ground Stations: The maintenance of synchronization between "master" and "slave" stations (see below) calls for skilled monitoring. The operator should know all that the craft navigator knows, and more besides. The crew required at a standard Loran station with its own power supply is from 20 to 30 men.

(b) Craft: The Loran operator must be trained in the use of the specialized receiver and indicator, and also in the interpretation of the received pulses displayed. 40 or more hours of instruction are given to operators having a previous knowledge of general navigation.

(c) With ground-wave signals, a line of position is obtainable in approximately one minute, a fix in from two to five minutes. With sky-wave signals, the operator maintains a continuous watch and obtains lines of position when conditions are favorable.

Equipment Required

(a) Ground: A chain of Loran stations, providing the two sets of hyperbolic position lines necessary for a fix, may consist of four stations, of which two are masters and two slaves. In the case of standard Loran, one master may control two slaves, or one slave may be pulsed by two masters, making a total of three transmitters, each of which will be of 70-100 kw. peak power. Mast or inverted-L anten-

nas are used. Receivers and monitoring equipment are also required, and (in the case of slave stations) synchronizing equipment.

(b) Craft: A specialized Loran receiver and indicator are used, weighing about 70 lbs. (Airborne equipment).

Radio Frequency Spectrum Allotments Required

Standard and SS Loran (see page 12.08) use frequencies in the range 1700-2000 kcps (wavelength 176-150 meters). For LF Loran, a frequency of 180 kcps is proposed (1667 meters). Since the transmission consists of pulses, the bandwidth required may be given a nominal value of 50 to 70 kcps for Standard and SS Loran, 10 kcps for LF Loran. Channel space is however economized by having several pairs of stations transmit on the same frequency, using different pulse repetition rates. The optimum bandwidth for the receiver is stated to be about 50 kcps (at 6 db. down).

Present Status of Development

Standard Loran is a well-established long-distance navigational aid. It is the only long-distance radio navigational aid available at the present time over large areas of the Atlantic and Pacific.

SS Loran, originally proposed as a night-bombing aid over Germany, is well established but not so widely used as Standard Loran.

L.F. Loran is expected to be in operation in the Pacific in the fall or winter of 1945.

General Principles of Operation

The "master" station of a Loran pair transmits pulses (of about 40 microseconds duration for Standard Loran, or 300 microseconds for LF Loran) at a repetition rate which is characteristic of the particular pair. For most Standard Loran stations this is near 25 pps, for SS Loran near 33 1/3 pps. Pulses from the master station are received at the craft after an interval representing the time taken for the transmission to travel the distance from master station to craft. Pulses from the master station are also received at the "slave" station after some other interval which is characteristic of a given pair of stations and is proportional to the baseline used (distance from master to slave). These received pulses cause the slave station to transmit pulses of its own at the same repetition rate. A fixed delay time is introduced at the slave station between received and transmitted pulses, for reasons which will be explained below. The slave transmission is thus synchronized with, or locked to, the master transmission. This is the significance of the terms "master" and "slave". Pulses from the slave station arrive at the craft after a time interval representing the distance from slave to craft. The craft therefore receives two series of pulses, one from master and one from slave. The time interval between the arrival of master and slave pulses is measured at the craft by means of the indicator on which the received pulses, and also suitable time-marker pips, are displayed. From the discussion of hyperbolic systems given in section 1, it will be seen that the time delay between received master and slave pulses is characteristic of a hyperbolic line of position, and that two intersecting lines (obtained from different Loran pairs) yield a fix.

The Loran indicator makes use of a cathode-ray tube, on which appear two linear time-base sweeps, swept in succession and displayed one under the other. If the prf is 25 per second, then one master pulse and one slave pulse will be displayed every 40,000 microseconds. Now the measurement process requires that of these two pulses, one appear on the upper part of the sweep and the other on the lower part. Therefore, the slave pulse should be delayed by at least one-half of the

repetition period, or 20,000 microseconds, to ensure this result. Furthermore, in order to accomodate the time differences to be encountered at extreme parts of the desired coverage area, an additional "coding" delay is introduced at the slave station. These delays in the emission of the slave pulses constitute the fixed time delays mentioned above.

These and other time intervals are represented in a system of symbols which has become standard terminology in Loran. They are as follows:

c = velocity of radio propagation (= 186,200 statute miles per second, or 0.1862 miles per microsecond)
T = indicated time difference
T' = true time difference
L = recurrence interval
D = absolute delay
δ = coding delay
β = time taken for pulse to travel from master to slave

All times are measured in microseconds.

Consider the distance-time relations for the locations of master, slave and craft shown in Figure 12-01. Since the velocity of propagation of radio waves may be taken as constant (186,200 miles per sec.), it is convenient to measure any distance in terms of the time (in microseconds) required for transmission over that distance. Thus the base-line AB is β microseconds long, where $\beta = AB/c$. Assume now that a pulse is radiated from the master station A at some arbitrary time t = o. This pulse will arrive at slave B at a later time $t = \beta$, and the slave pulse will be radiated from B at a still later time $t = \beta + L/2 + \delta$. The absolute delay D between the emission of master and slave pulses is therefore $D = \beta + L/2 + \delta$

If the craft were situated at P, the distances AP and BP being equal, the true time difference between received pulses will also be $\beta + L/2 + \delta$. This will be the case at any point on the line PP' which is the perpendicular bisector of AB. However, due to the fact that a time difference of L/2 is automatically taken care of by the presentation of the two pulses on the upper and lower parts of the linear time base, the lower trace of which starts exactly L/2 microseconds after the start of the upper trace, the indicated time difference as read by the navigator anywhere on PP' will be $\beta + \delta$

Suppose that RR' is a hyperbola such that the difference between the slave and master distances to any point on it (BR - AR) is constant and equal to x. Then the true and indicated time differences for this line will be $T' = \beta + L/2 + \delta + x/c$, and $T = \beta + \delta + x/c$. Likewise for the hyperbola QQ', on which x' = (BQ - AQ), the time differences are $T' = \beta + L/2 + \delta + x'/c$ and $T = \beta + \delta + x'/c$. Here x' will be numerically a negative quantity. The extensions of the baseline, which are the limiting hyperbolae, correspond to indicated time differences of δ and $2\beta + \delta$ as shown on Figure 12-01. It follows that a set of hyperbolae can be drawn on a chart, and can be marked with the indicated time differences (allowing for slave station coding delay) they represent. Thus the navigator measures his indicated time difference and obtains a line of position, by interpolation between the printed hyperbolae if necessary.

Disposition of Stations, Coverage Areas

(a) Standard Loran: In Standard Loran, the maximum practical base-line length is about 600 miles. This is so because reliable ground-wave reception, with adequate signal-to-noise ratio for synchronization of slave to master, is not obtainable over much larger distances than this. A 300-mile base line is conventional and gives β = 1611 microseconds. δ is customarily fixed at 1000 microseconds. This

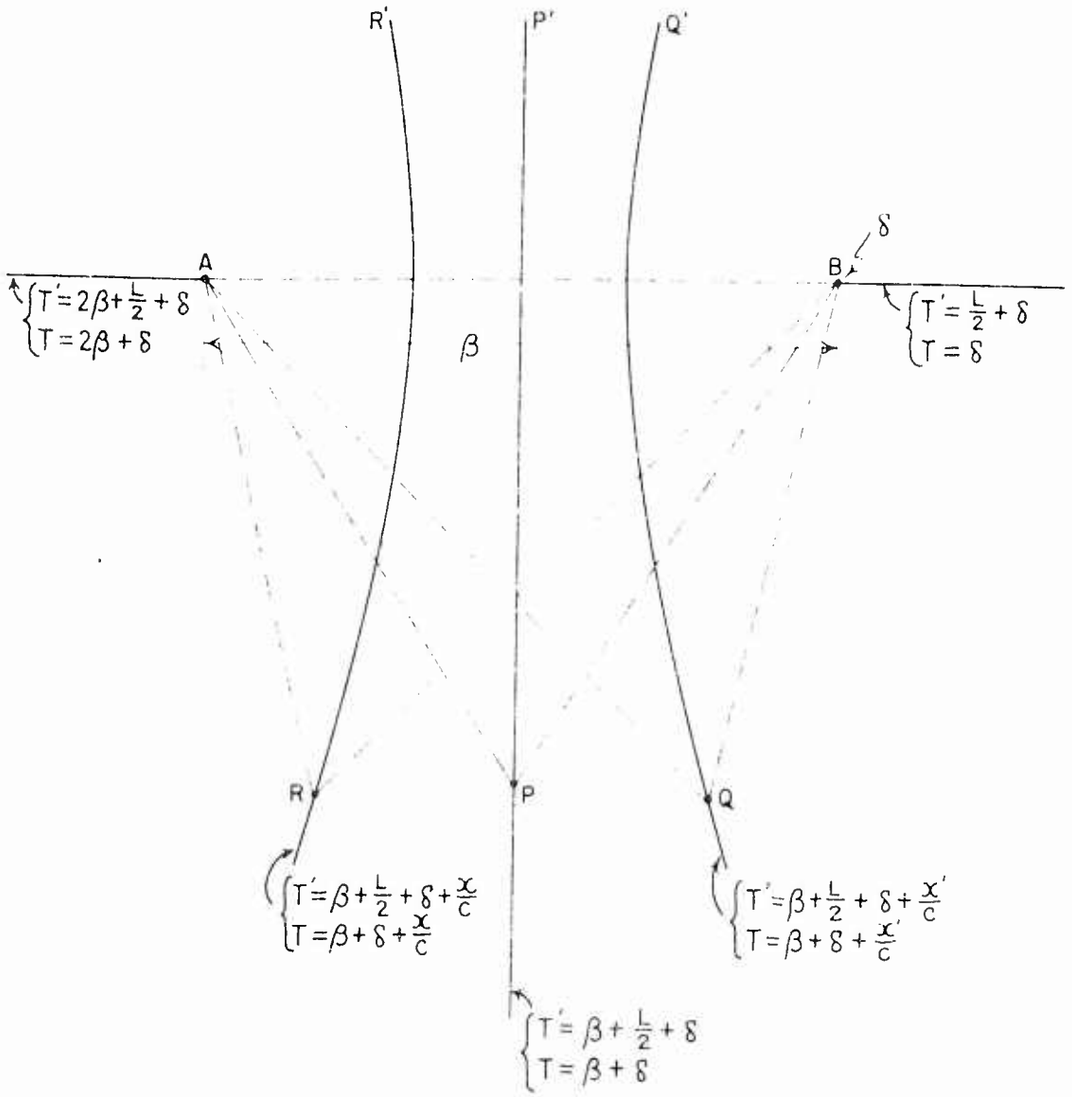


Fig. 12-01 Loran: distance-time relations

gives maximum and minimum indicated time differences of 1000 microseconds and 4222 microseconds. Charts are prepared with hyperbolae marked every 100 microseconds. A set of hyperbolic position lines is shown in Figure 12-02, and two sets, using a master station and two slaves with base-lines intersecting at 135°, in Figure 12-03. With the latter arrangement, or with a straight-line chain, the coverage area for a fix will be determined by the limit at which ground-wave or sky-wave reception from all three stations is obtainable. Sky-wave reception at these frequencies can be relied upon only at night, and then should not be used at distances less than 300 miles. The outer limit for sky-wave reception is (as already stated) about 1600 miles. Figure 12-04 (a) shows the ground-wave service area of a 3-station chain. The full lines indicate the area within which a line of position may be obtained from master A and slave B. A fix may then be obtained within the shaded area. A base-line of 300 miles is assumed (600 miles from B to C). Figure 12-04 (b) is drawn to one-half of the scale of (a), and shows the sky-wave coverage (shaded area). The dotted lines in both figures show the boundaries of areas adjacent to the base-line within

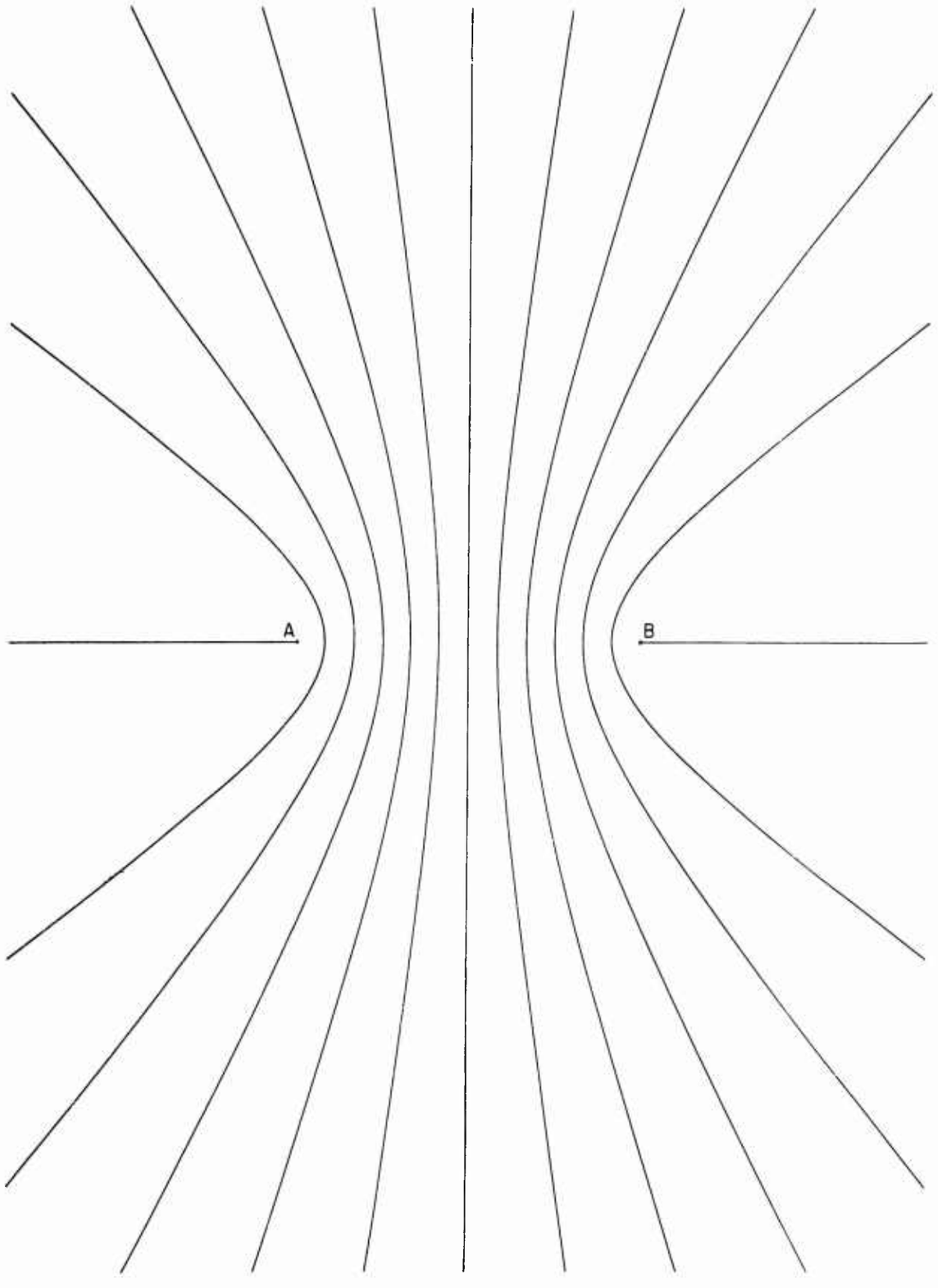


Fig. 12-02 Loran pair

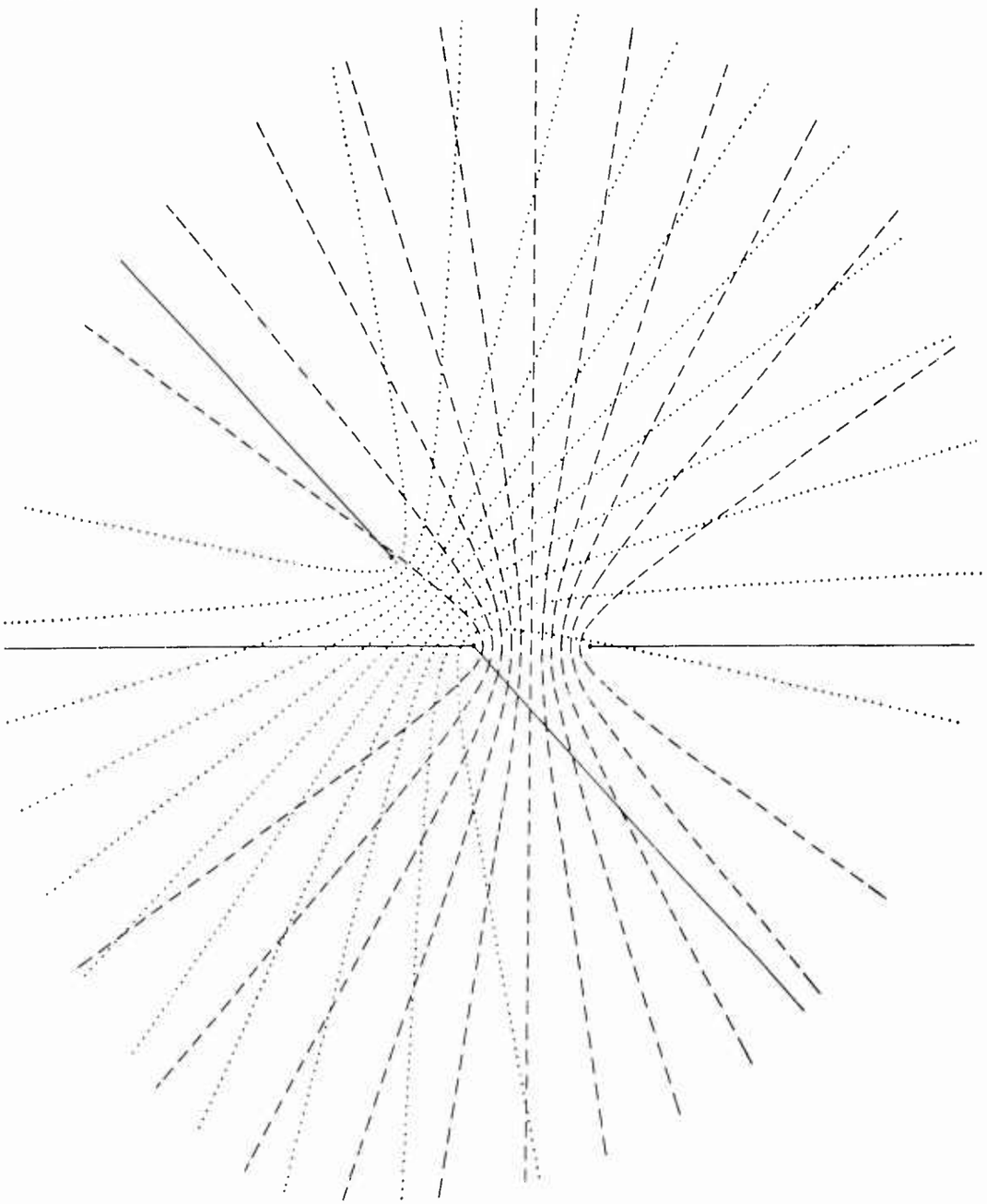
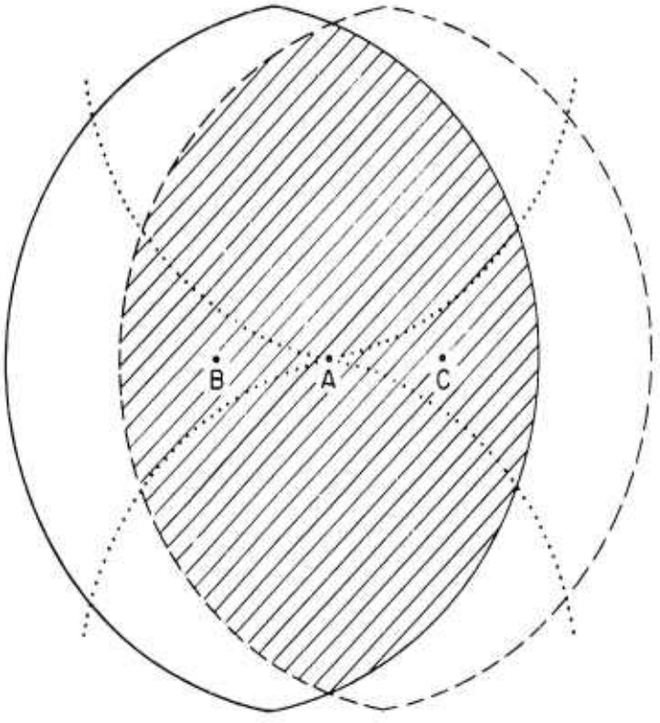


Fig. 12-03 Loran triplet

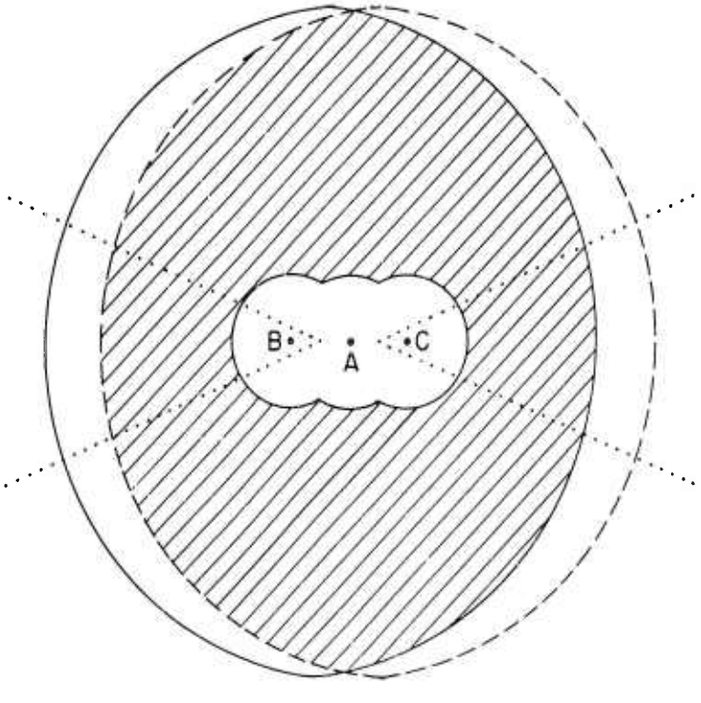
which the "geometrical precision" is poor (lower than 1 mile/microsecond for ground-wave) for one or other of the pairs. Geometrical precision is further discussed on page 12.10.

It will be seen that a chain of Loran stations will have a useful sea coverage area which is roughly in the form of a strip extending parallel to the coast line on which the stations are located.

(b) SS Loran: Other factors being constant, the greatest precision of fix will be obtained in areas where Loran hyperbolae intersect at right angles. With Standard Loran, such areas are localized and are small in extent. The longer the base-lines used, the more extensive will these areas of high precision be. This leads to the use of sky-wave transmission for slave synchronization, the base-line between master



(a) Ground wave



(b) Sky wave

Fig. 12-04 Standard Loran coverage areas

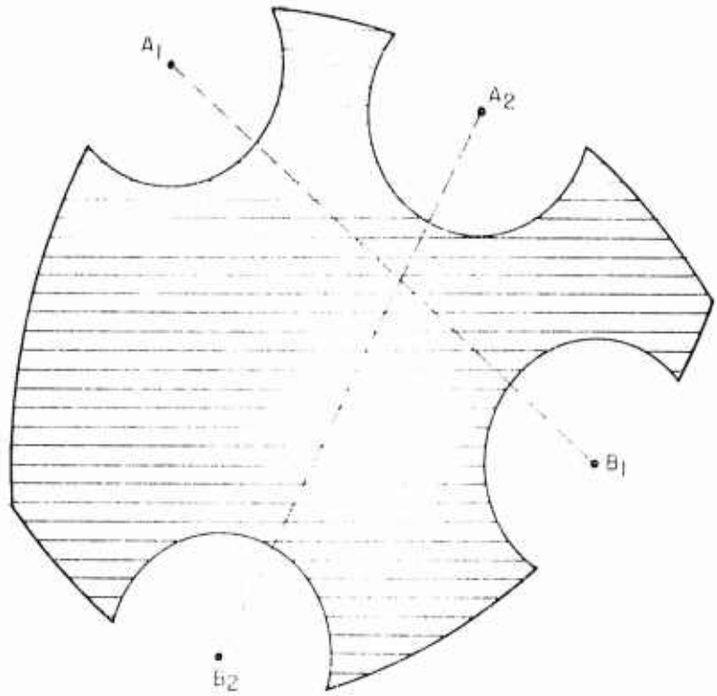


Fig. 12-05 SS Loran coverage area

and slave being extended to 1300 miles or more. With SS (Sky-wave synchronized) Loran, the two pairs are located so as to straddle the required coverage area, their base lines being approximately at right angles. This gives a large area in which the Loran hyperbolae are approximately straight and parallel lines, the two sets intersecting nearly at right-angles.

Figure 12-05 shows the coverage area for 1500-mile base-lines and station locations as shown. Ground waves are not normally used with SS Loran, since this would usually involve cross-matching (one ground wave and one sky wave). Areas within 300 miles of any of the stations are therefore not represented as covered.

(c) LF Loran. Using frequencies of the order of 180 kcps, ground-wave propagation may be relied upon to distances of about 1500 to 2000 miles with the transmitter power contemplated. This means that longer base-lines may be used, with ground-wave service areas and precision comparable to those given by SS Loran, but without the disadvantages attendant on the use of sky waves. Longer pulses (300 microseconds) and very large antennas (625 feet, umbrella loaded) are proposed. Since transmission at these frequencies must of necessity involve the use of bandwidths narrower than 50 kcps, the rise time of the pulses will be longer than is the case with standard Loran practice. This means that the pulse-matching technique used must take rather carefully into account the details of pulse form, since it is not usually possible to match amplitudes in order that similar portions of the leading edges of pulses will have the same slope. The reason for this is that since long pulses are used, there is the danger that sky-wave returns, mixing in variable phase and amplitude with ground-wave returns, will distort all but the initial portion of the rising pulse-front. Since this initial portion is of rather gradual slope, a limitation is thus imposed on the precision of match attainable.

A technique of "Cycle matching" has therefore been proposed for possible use in slave-station synchronization, and perhaps ultimately for use in the craft. Individual RF cycles at corresponding positions in the two pulse envelopes would be selected and used for comparison. This refinement is still in the experimental stage. A further discussion of the effect of tuned circuits on pulse rise times is given in section 1.

Pulse Rates

Since the received pulses are displayed on a time-base on a CRO screen, the recurrence rate of the time-base must be synchronized to that of the pulses if a stationary display is to be obtained. Since it must be made possible to receive several pairs of stations to give fix coverage over different areas, two possible methods of accomodating these various channels exist.

(a) Different radio frequency for each pair, same prf for all stations.

(b) Same radio frequency for all stations, different prf for each pair.

With pulse transmissions at this frequency, the spectrum allotments required would be prohibitive if scheme (a) were used. Loran therefore uses scheme (b) allowing several pairs of stations to be "stacked" at the same frequency.

Provided that the pulses to be observed stand still, the operator will not be unduly distracted if the rate of drift of other pulses (to whose prf he is not synchronized) across the CRO screen is quite slow. The prf's ("rates") used need not therefore differ by large amounts. Adjacent pulse repetition periods differ by 100 microseconds. Corresponding prf's, periods and "rates" are as follows:

prf (per second) (approximate)	25	$25\frac{1}{16}$	$25\frac{1}{8}$	$25\frac{3}{16}$	etc. up to	$25\frac{7}{16}$
period (microseconds)	40,000	39,900	39,800	39,700	etc. up to	39,300
"rate" (station pair)	0	1	2	3	etc. up to	7

A similar group of pulse repetition frequencies based on $33\frac{1}{3}$ pps is also used. The navigator has on the indicator panel a multi-position switch, which selects the rate desired; that is, causes the received pulses from the two stations corresponding to this rate to remain stationary on the screen, while any pulses which may be received on other rates drift by.

Uncertainties in Loran Line of Position

Various factors combine to produce uncertainties in a line of position, expressed as the probable error of a numerical indicated time difference. These factors may be classed in two groups:

(a) Systematic. This includes all effects traceable to the layout of the system itself.

(b) Operational. This includes human factors, both at the craft and in slave-station synchronization, and effects which cannot be predicted, such as variations in noise level and in ionospheric conditions. Some notes on various factors follow:

1. Errors in measurement of time intervals with the Loran indicator.

It has been estimated, on the basis of large numbers of observations made under average conditions, that the probable error of a Standard Loran time measurement is about 1 microsecond. This means that out of a large number of measurements, 50 per cent will depart from the true value by less than 1 microsecond and 50 per cent by more than 1 microsecond. Assuming a standard error curve distri-

bution, another way of stating this result is to say that 90 per cent of the measurements will be in error by less than 2.44 microseconds and 10 per cent by more than this amount. These figures are obtained from many measurements. Under good conditions and with a skilled observer, readings in error by only 0.5 microsecond have been consistently obtained. It is clear that no one figure for this error will be acceptable to all interested persons.

2. Errors in synchronization.

The slave station operator has essentially the same problem as the craft navigator. Master and slave pulses are displayed on his monitoring oscilloscope, and he must maintain the correct time delay between them. With SS Loran, there will be periods when reliable observations are impossible owing to varying ionospheric conditions. Accordingly, the timing oscillator at slave stations must be so carefully stabilized as to be capable of running free during these periods with negligible drift. However, errors in synchronization have been known to occur.

3. Resultant error in a line of position.

The effects of the two errors just mentioned are to broaden Loran hyperbolae into bands, and to change the location of the hyperbolae slightly. The resultant error in line of position varies with the location of the craft, since the hyperbolae spread further apart as the distance from the stations increases. The error in line of position is therefore the product of two quantities:

(a) The net timing error in microseconds.

(b) The change in position per unit change in time difference, measured in miles per microsecond, at the point in question.

The first of these quantities is statistical and has already been discussed; the second is purely geometrical. For example, two hyperbolae, corresponding to time differences which are 1 microsecond apart, cut the base line at points which are separated by 0.093 mile, or 492 feet. Thus, on the base line a timing uncertainty of 2.44 microseconds corresponds to a positional uncertainty of 2.44 x 492 or 1200 feet (0.23 miles). This is the minimum positional uncertainty for a timing uncertainty of 2.44 microseconds. At points far distant from the base line, the positional uncertainty may be several miles.

Regarding the second, or geometrical, quantity, it may be shown that the number of miles error per microsecond error is constant for all points on an arc of a circle which passes through the locations of master and slave stations. A family of such circles (of which the base line and the extensions of the base line are the limiting cases) is shown in Figure 12-06. Portions of the 1 mile microsecond arc were drawn in Figure 12-02 (a), and these define the wedge-shaped areas adjacent to the base line extensions in which poor precision is obtained. It should be pointed out that the error in position per microsecond error for the circles in Figure 12-06 is measured normal to the hyperbolic position lines and not along the circles themselves. It will be realized from Figure 12-06 that the longer the base line is, the larger will be the area over which a given precision is attainable. SS Loran makes use of this fact.

4. Error in a fix.

Since a fix is determined by the intersection of two hyperbolae, and since uncertainty exists as to the location of each hyperbola, the actual position of the craft is somewhere within an area whose boundaries are the limits of uncertainty of the two hyperbolae. The shape, area and dimensions of this figure of uncertainty depend on the angle of cut between the hyperbolae, and this makes quotation of numerical values for error in a fix impossible. The subject is discussed further in section 1.

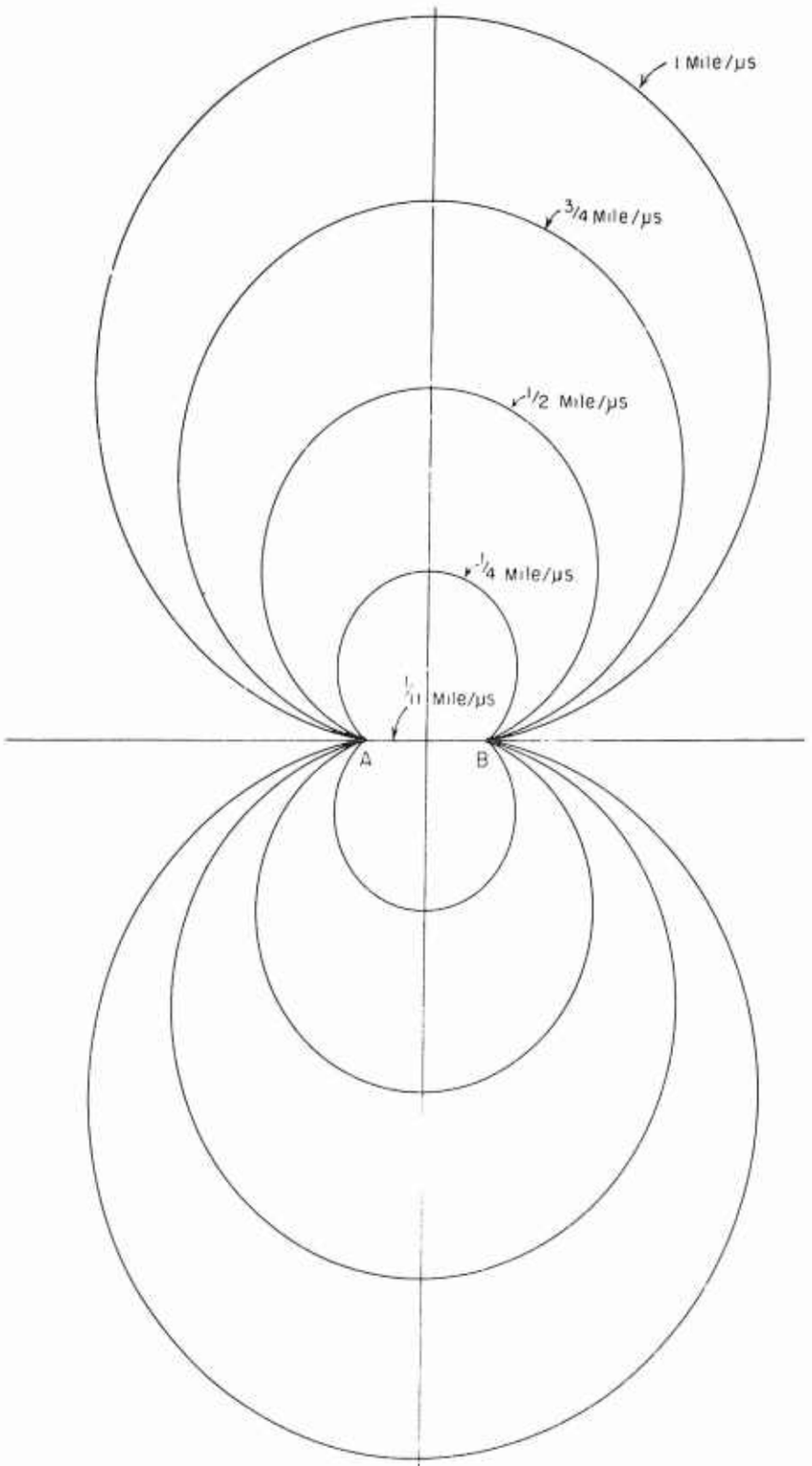


Fig. 12-06 Circles of constant miles per microsecond error

5. Errors in assumed values of base-line length and velocity of propagation.

These factors amount to a change in the orientation and location of the Loran hyperbolae. Their effect is further discussed in section 1.

6. Skywave errors.

If skywave measurements are made with Standard Loran, a skywave correction must be applied, due to the fact that the difference between the skywave propagation paths to the craft is not the same as that between ground wave paths unless the craft happens to be on the perpendicular bisector of the base line. This correction is printed on the appropriate parts of Loran charts. It varies with position, being large at points which are close to one transmitter of a pair but far from the other. Since the skywave delay curve flattens out to a constant value for large distances (see Section 1), the skywave correction (which is equal to the difference between the two skywave delay values) tends toward zero as the distances of the craft from the two transmitters increase. Since the height of the E-layer of the ionosphere is not constant, the skywave delays for the two transmission paths involved, and therefore the skywave correction, are subject to changes. These changes introduce random errors, so that the probable error of a skywave reading is several times that of a ground-wave reading.

With SS Loran, where skywaves are used both for position determination and also for slave station synchronization, such errors partially cancel. A more extended discussion of skywave propagation and resultant errors is given in section 1. One of the merits of SS Loran, however, is that random errors due to changes in propagation conditions are somewhat offset by the excellent angle of cut obtainable over most of the service area, and by the greater area over which a given geometrical precision is attained, due to the long base-lines.

7. Errors due to incorrect interpretation of received pulses.

When skywaves are used, the received signal is not a single pulse, but consists of a train of pulses reflected from various layers of the ionosphere. For Loran purposes, the pulse received by single-hop transmission from the E-layer of the ionosphere, known as the E_1 pulse, is chosen. If a ground-wave pulse is visible, the E_1 pulse will be the first one following it. Since the intensity of reflection and the degree and nature of the polarization of the various components of the signal are non-related functions of time, the observer sees a constantly changing picture. A reliable fix using skywaves thus demands an experienced operator who can recognize "normal" conditions and take a measurement when he sees that these conditions exist. If a ground wave pulse is used by mistake for an E_1 pulse, large errors are introduced and these are usually detectable by their inconsistency with other data at hand.

The Loran Receiver and Indicator

Several different models of Loran craft equipment are in use. The differences between them are in general differences in detail only. In one model (the DBE, in production) the time-difference is shown on a direct-reading mechanical counter driven by the knobs used for pulse alignment, and time-markers on the CRO pattern are therefore not provided. In another model (AN/APN 9), the fast sweep is logarithmic and a three-inch cathode-ray tube is used. The descriptions which follow are concerned with the AN/APN 4 equipment.

Receiver (R - 9/APN 4)

Figure 12-07 shows a block diagram of the receiver. The R.F. amplifier is tunable to four frequencies, selected by a four-position switch. These are 1750, 1850, 1900 and 1950 kcps in model R-9B/APN4; and 1850, 1900, 1950 kcps and 9600 kcps (no longer used) in model R-9A/APN4. Three wave-traps are provided, tuned to the intermediate frequency which is 1050 kcps. The bandwidth of the IF amplifier

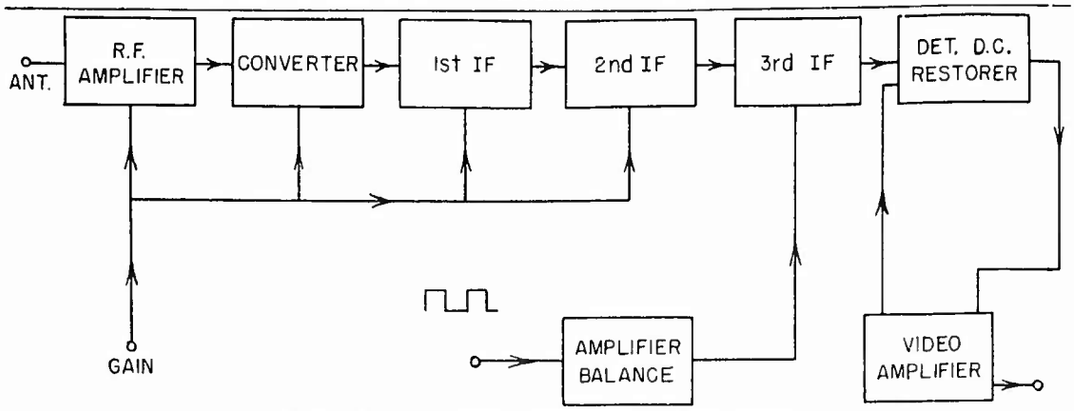


Fig. 12-07 Block diagram -- Receiver

is 45-60 kcps. The gain control is variable cathode-biasing applied to the RF amplifier, converter and first two IF stages. The gain of the 3rd IF stage is gated in synchronism with the two parts of the indicator display, so that different degrees of gain may be used for master and slave pulses in order that pulse amplitudes may be matched on the display. The detector stage is a conventional diode with resistance-capacitance load except that the input is to the diode cathode rather than to its plate. A high-pass filter, which may be switched out, is provided between detector and video amplifier. This is useful for the suppression of low-frequency components of noise. The video amplifier consists of one (triode) stage of amplification, which gives limiting action and feeds a cathode follower. A clamping diode is used at the grid of the cathode follower. The DC power-supply for both receiver and indicator is at 260v, voltage-regulated.

Indicator ID-6B/APN4

General Principles

Figure 12-08 shows a block diagram of the indicator circuits. Power supplies are not shown. A linear sawtooth time-base voltage is applied to the horizontal deflection plates of the C.R. tube. The sweep-generator is of the triggered type, so that different sweep speeds may be used. Video signals from the receiver, or alternatively time markers, are applied to one of the vertical deflection plates, and a square-wave trace-separation voltage to the other. Since the repetition rate of the entire display is 25 cps (on station-rate 0), the square wave must have this basic frequency. Video pulses from the receiver, pedestal voltages and 10-microsecond markers deflect the cathode-ray beam upwards; 50-microsecond and 500-microsecond markers produce downward deflections, and 2500-microsecond markers deflect the beam both above and below the time base.

All timing operations are controlled by a 100-kcps crystal oscillator. This is of the tuned-plate tuned-grid type, and its frequency is variable by $\pm$ 35 cps by means of two small trimming condensers. One of these constitutes the framing control: if this condenser is adjusted so that the received pulses are stationary on the display, the oscillator must then be in exact synchronism with the accurately controlled crystal at the transmitter, and the various time markers will be accurately positioned. The other trimming condenser allows the pulses to be shifted to right or left on the display (see Left-Right circuits, page 12.20).

Six counters follow for frequency division. The sixth counter is arranged to divide by either 3 or 4 (High or Low prf) to accomodate the two basic groups of repetition rates used, based on 25 and 33 cps frequency. The frequencies and repetition periods of the pulses at various points in this divider chain are as shown in Figure 12-08. Signals from the crystal and from the outputs of the first and third counters are used to form the 10-microsecond, 50-microsecond and 500-microsecond time markers by way of suitable pulse-shaping circuits. 2500-microsecond time markers are obtained from the output of the fourth counter.

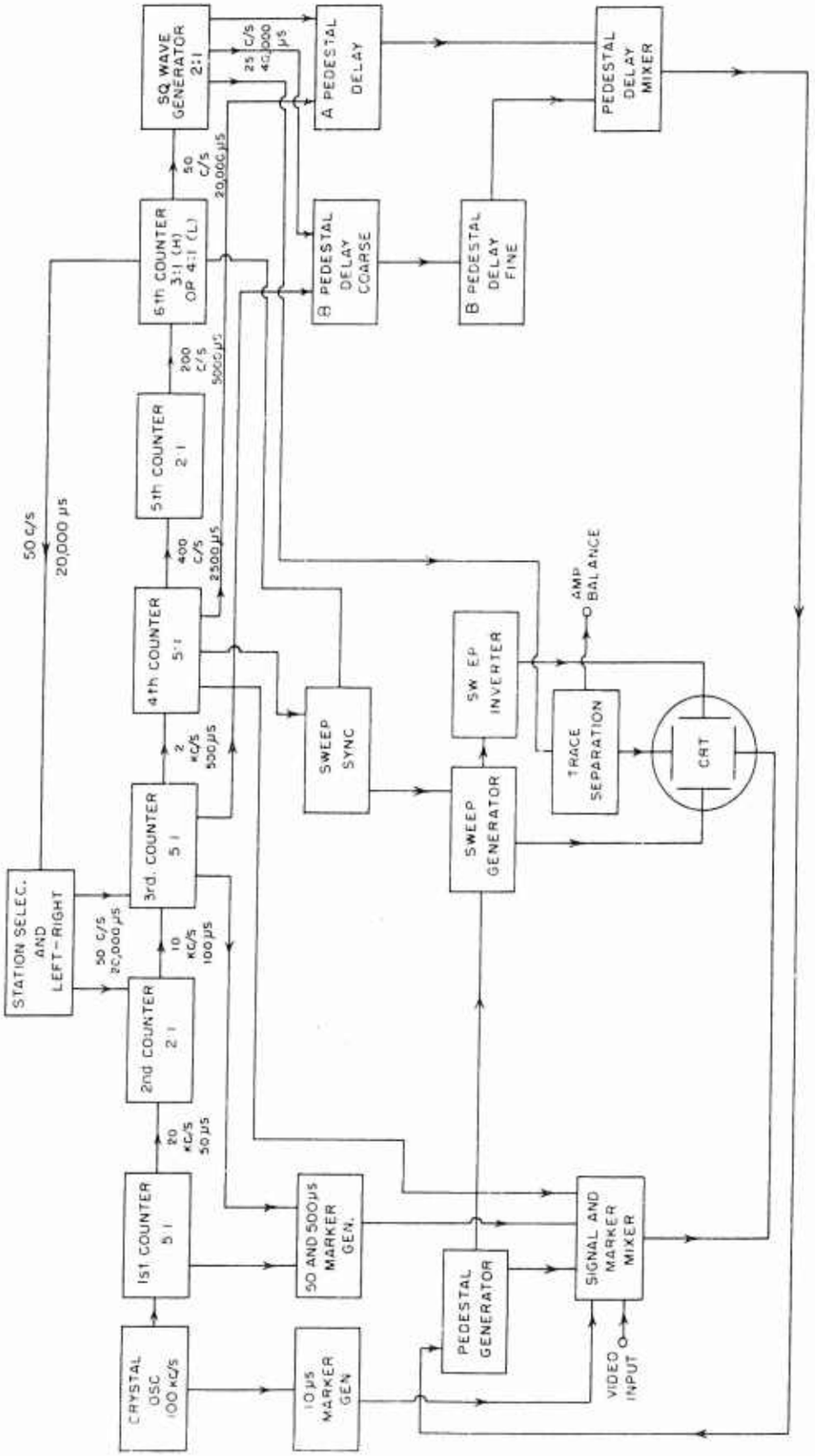


Fig. 12-08 Block diagram, Indicator and timing circuits

Time-difference measurement is accomplished by bringing the pulses on the upper (A) and lower (B) traces into alignment, and then counting time markers to obtain the time interval through which the lower pulse (B) was shifted to attain this result. For this purpose two pedestals are used. These are raised sections of the main sweep traces and are obtained by applying rectangular pulses to the lower CRO deflection plate. The A pedestal is delayed after the beginning of the main A sweep by a fixed amount (2500 microseconds). The corresponding video pulse is made to occupy a position on the A pedestal by momentarily changing the frequency of the sweep, thus causing the pulse to drift across the display: at the same time the B video pulse will of course move in the same direction on the lower trace of the display and by the same amount. This is accomplished by means of the Left-Right switch, whose action will be described later. The B pedestal is delayed after the start of the B sweep by an amount which is variable by coarse and fine controls: thus, by the use of these controls, the B pedestal may be brought under the B video pulse.

Switching to a faster sweep speed, the two sweeps are of shorter duration and are now initiated and terminated by the leading and trailing edges of the rectangular pulses which previously formed the pedestals. This amounts to spreading out the time scale until the pedestals themselves are the sweeps. The A and B pulses are now accurately aligned by further use of the B pedestal fine delay control. The exact sequence of operations, including counting, is given later.

As noted above, the A pedestal delay is fixed at 2500 microseconds. The B pedestal delay is variable from 1700 to 13,200 microseconds, the coarse control giving delays of 1500 to 12,500 microseconds in steps of 500 microseconds, and the fine control being continuously variable from 200 to 700 microseconds. The duration of the pedestals is 250 or 750 microseconds, controlled by the setting of the sweep-speed switch.

The six counters are of the step-counter blocking-oscillator type with grid bias applied to the counter tube. A condenser in the grid-circuit is charged in steps by pulses fed in from the preceding counter. The counter tube fires when its grid condenser has acquired a definite number of these "step" charges, the number depending on the bias and circuit constants used. Thus the first counter fires every five cycles of the 100 kcps pulses, the second counter fires every other time the first counter fires, and so forth. To secure the correct prf for the received pulses to be used, feedback is taken from the output of the sixth counter to either the second or third counter grid condensers, or to both. Likewise in order to move the video pulses to right or left on the display, the feedback arrangements may be temporarily altered. These processes and the circuits connected with them will now be explained. No two counters have identical circuits, but all counters operate on the same principle. The first and second counter circuits are shown here.

Figure 12-09 shows the circuit of the first counter. The 100 kcps crystal oscillator is followed by a limiter stage (not shown), in which a triode tube is driven from cut-off to saturation. The resulting voltage waveform as shown is applied at A to a cathode-follower buffer stage T_1, which drives the blocking-oscillator counter tube T_2. The positive bias and the time constant in the grid circuit are so arranged that T_2 fires on every fifth pulse from T_1. The output at the plate consists of sharp negative and positive pulses as shown at B.

The circuit of the second counter is shown in Figure 12-10. The diode T_1 clips the negative pulses, and T_2 transmits the positive pulses. The 330 $\mu\mu$f. condenser is charged by steps, and the bias on T_3 is so adjusted that this tube fires on

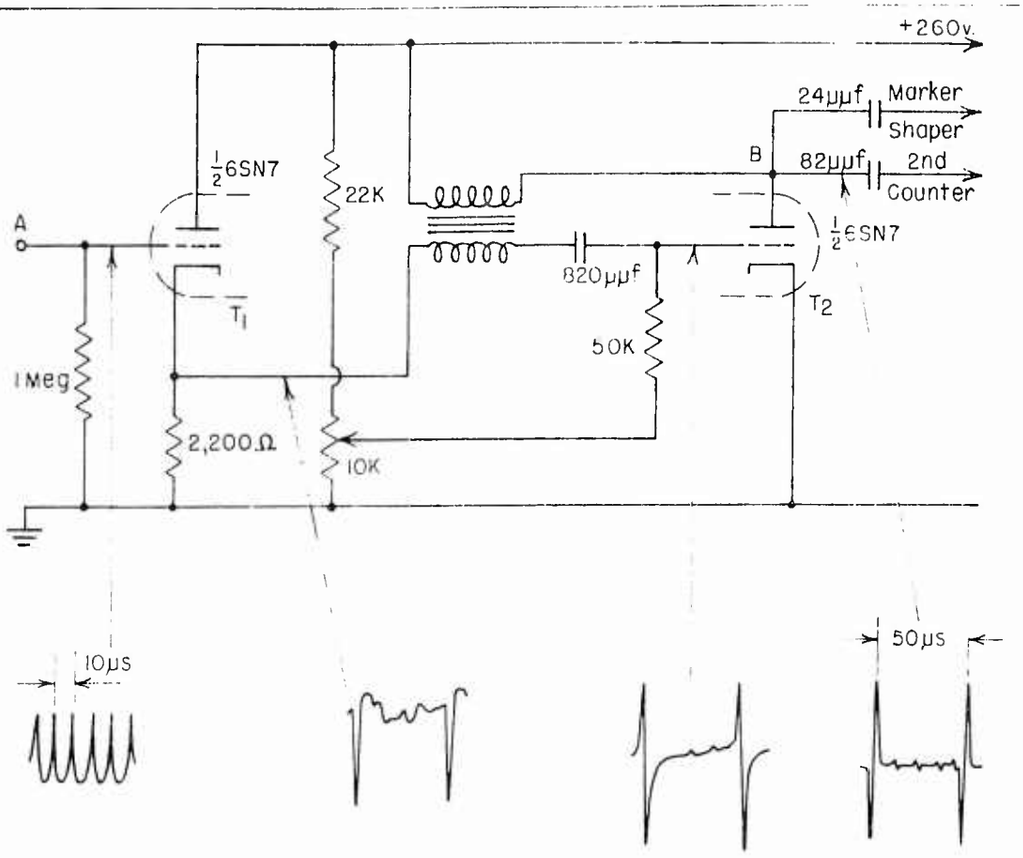


Fig. 12-09 First counter circuit

the second step. When the tube fires, the 330 $\mu\mu$f condenser is discharged via the grid circuit and the cycle repeats. The output to the third counter therefore consists of sharp negative and positive pulses as shown.

It will be observed that the 330 $\mu\mu$f condenser may also be charged (or discharged) by feedback from the sixth counter. If an auxiliary charge of one step is applied in this fashion, the result will be to eliminate one 50-microsecond interval from the cycle of operations every time the sixth counter fires. This process is further discussed under the heading of station selection.

The remaining counters differ mainly in the sizes of the components used, and in the exact method of obtaining bias for the counter tube. The fifth and sixth counters are coupled by a tuned circuit which "rings" when pulsed, and the sixth counter is actually triggered by the first positive peak of the damped oscillation thus produced. This introduces a constant delay of about 25 microseconds in the firing of the sixth counter tube. The reason for this is to ensure that the auxiliary step charges, placed on the second and third counter condensers when feedback is used, shall not coincide with normal step charges from the preceding counter stages. The sixth counter also has two possible values of grid bias, to allow division by 3 (output, pulses of 15,000-microsecond repetition period) or by 4 (output, pulses of 20,000-microsecond repetition period) for the 33 1/3 cps or 25 cps repetition rates.

Figure 12-11 shows the station selector and left-right circuits. It will be

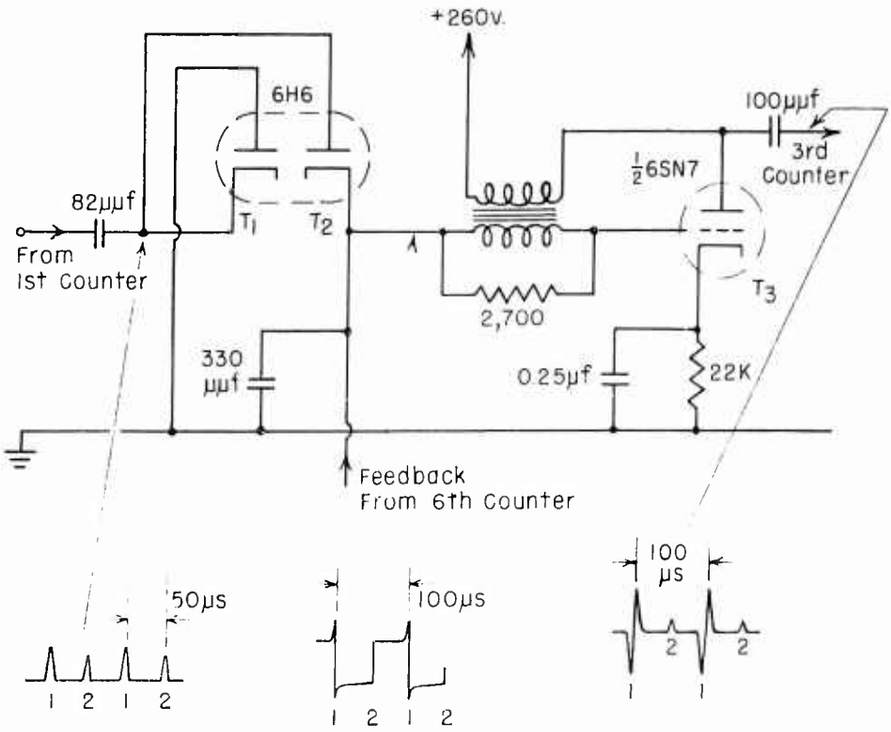


Fig. 12-10 Second counter circuit

recalled that Loran pairs operate on the same radio frequency but with different pulse repetition rates which are as follows:

Rate (station)	p.r.f.	Rate (station)	p.r.f.
0	25 cps	4	$25\frac{1}{4}$ cps
1	$25\frac{1}{16}$ cps	5	$25\frac{5}{16}$ cps
2	$25\frac{1}{8}$ cps	6	$25\frac{3}{8}$ cps
3	$25\frac{3}{16}$ cps	7	$25\frac{7}{16}$ cps

A similar group of prf's, based on $33\frac{1}{3}$ cps, may be used by allowing the sixth counter to divide by 3 instead of by 4 (prf switch). In the explanation that follows, only the 25 cps group is considered, for the sake of simplicity.

Station (Rate) Selection

Consider the change of frequency required in switching from rate 0 to rate 1. If this were done by changing the crystal oscillator frequency, the necessary change would be 250 cps. This would introduce an error in the spacing of all the time markers, and in addition, would seriously reduce the amplitude of the crystal output. The change must therefore be made in the counter operations rather than in the crystal frequency.

Referring to Figure 12-11, pulses from the 6th counter may be fed back to either the second or third counters or to both. On rate 0 there is no feedback and the prf is 25 cps. On rate 1, feedback is to the second counter only by way of

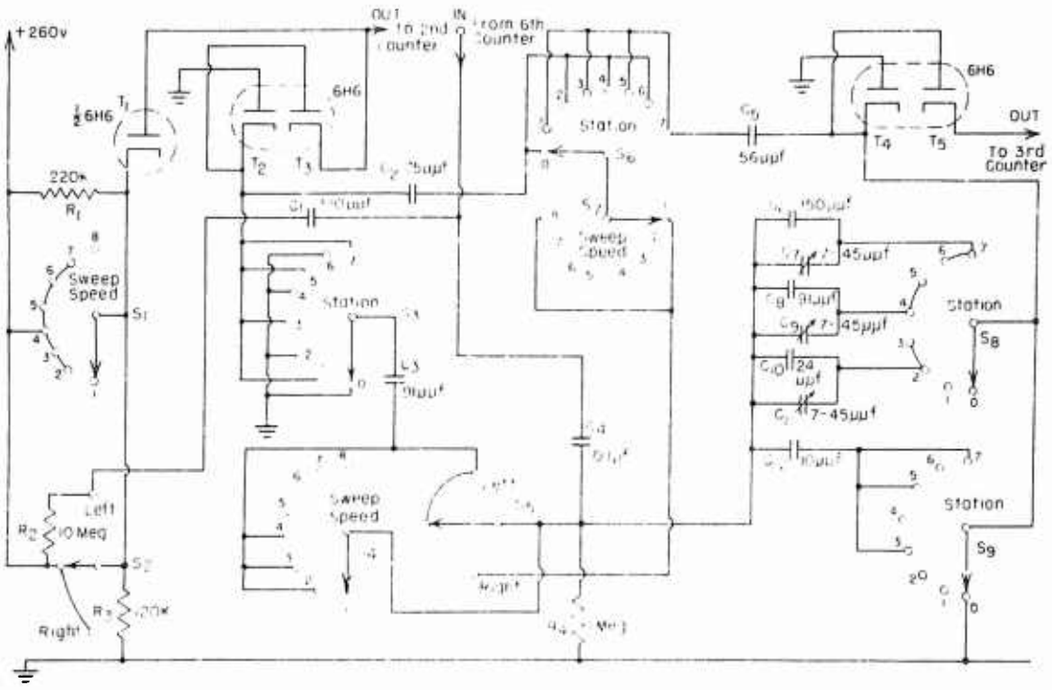


Fig. 12-11 Station and Left-Right circuits

Ganged switches: sweep speed: S_1, S_4, S_7
station: S_3, S_6, S_8, S_9
Left-Right: S_2, S_5

C_4, S_5, C_3, S_3, and the diodes T_2 and T_3. Negative pulses are clipped by T_2 and positive pulses transmitted by T_3. The magnitude of the feedback pulse is controlled by C_3, and is such that the firing of the second counter is advanced one step. On rate 2, there is no feedback to the second counter (S_3 being then grounded) but feedback is applied to the third counter via C_4, C_{10} and C_{11} in parallel, S_8 and the diodes T_4 and T_5. T_4 clips negative pulses and T_5 transmits positive pulses. The magnitude of the feedback is such as to charge the third counter condenser by one step, being controlled by the adjustment of C_{11} which is critical.

On rate 3, one-step feedback is applied to the second counter by way of C_3 and S_3, and at the same time one-step feedback is still applied to the third counter since positions 2 and 3 on S_8 are connected. The feedback to the third counter is slightly augmented by C_{12} (which is in parallel with C_{10} and C_{11} for position 3 of S_8 and S_9) to allow for the extra loading on the feedback source imposed by the second and third counter circuits simultaneously absorbing pulse energy.

On rate 4, no feedback is applied to the second counter, but two-step feedback is applied to the third counter via C_4, C_8 and C_9 in parallel, S_8, T_4 and T_5. The necessary two-step magnitude is adjusted by C_9, the combined capacitance of C_8 and C_9 being greater than that of C_{10} and C_{11}. Proceeding in this fashion, the application of feedback to the second and third counters for the eight "station" switch positions is as follows:

Station switch position	Feedback to Second Counter	Feedback to Third Counter
0	none	none
1	one step	none
2	none	one step
3	one step	one step
4	none	two steps
5	one step	two steps
6	none	three steps
7	one step	three steps

Considering now the effects produced, it will be seen that feedback is applied once during each sixth-counter cycle. One-step feedback to the second counter causes this and all succeeding counters to fire 50 microseconds earlier than would otherwise have been the case, and therefore shortens the sixth counter period by this amount. Since the square-wave generator which determines the frequency of the display is in effect a 2:1 frequency divider, the change in the display period (prf) will be 100 microseconds (twice that of the sixth counter period).

One-step feedback to the third counter changes the sixth counter period by 100 microseconds, and the prf by 200 microseconds. The overall effect of the feedback in various switch positions is therefore as follows:

Station switch position	Change in Sixth Counter Period	Sixth Counter Period	Display Repetition Period
0	0	20,000 Microseconds	40,000 Microseconds
1	50 Microseconds	19,950 "	39,900 "
2	100 "	19,900 "	39,800 "
3	150 "	19,850 "	39,700 "
4	200 "	19,800 "	39,600 "
5	250 "	19,750 "	39,500 "
6	300 "	19,700 "	39,400 "
7	350 "	19,650 "	39,300 "

Operation of the Left-Right Switch

Assuming that the crystal fine frequency control has been adjusted to give a stationary pulse display, it is still necessary to be able to move the pulses on to their respective pedestals. This is done by momentarily changing the prf of the display, causing the pulses to drift across it. Now if this were to be done by changing the crystal frequency, the change required with slow sweep speeds would be inconveniently large for a reasonably rapid rate of drift of the pulses on the display. It is therefore done both by a slight change in crystal frequency (effective at fast sweepspeeds) and by applying either positive or negative feedback (in addition to any feedback used for station selection) from the sixth counter to the second and third counters, effective at slow sweep speeds only.

Referring to Figure 12-11, the cathode of T_1 is normally at +92 volts (due to R_1 and R_3) which is sufficient to maintain the tube in a non-conducting condition. If S_2 is moved to the "left" position, pulses from the sixth counter are applied to the cathode of T_1 via C_1, and the tube therefore conducts during negative pulses. Each time T_1 conducts, the second counter condenser is discharged through it, so that an extra 50 microsecond interval is added to the sixth counter period. This will cause the frequency of the sweep to be lower, and the pulses will drift to the left on the display. R_2 serves to prevent the accumulation of d-c charge on C_1, also being so large that negligible pulse voltage appears across R_3 when S_2 is at normal or in the "right" position. S_1 places the cathode of T_1 at +260v in sweep-speed positions 2 through 7 so that the only adjustment of the pulse position possible on these speeds is by slight changes in crystal oscillator frequency as noted above.

In order to move the pulses to the right on the display, the prf must be temporarily raised. This is accomplished by feeding pulses from the sixth counter through S_5 ("right" position), S_7 (positions 1 or 8), and S_6 to either the second or third counters, depending on the position of S_6. It should be noted that S_6 and S_7 are not ganged together. Thus in station positions 0, 2, 4, 6, the second counter (which is not used for normal "station" feedback in these positions) is accelerated, whereas in positions 1, 3, 5 and 7 the third counter (already in use for "station" feedback in positions 3, 5, 7) is accelerated by an extra step, any feedback applied to the second counter for "station" purposes being thereby transferred to the third counter. This is possible in the case of the third counter because it is a five-step counter, whereas the second counter uses only two steps. S_7 disables the feedback right-shifting function for all sweep-speeds except 1 and 8. On the fast sweep-speeds (2, 3, 4, 5, and 6) left-right motion is performed only by changes in crystal oscillator frequency as already noted. Thus the function of the left-right switch comprises two operations: (1) Changes in crystal frequency (operative on all sweep-speeds, but effective on speeds 2 through 7 only). (2) Changes in feedback arrangements (operative on speeds 1 and 8 only). The descriptions which follow assume that the L-R switch is in the neutral position, and the station selector switch in position 0 (prf 25 cps).

Square-wave Generator

The square-wave generator is an Eccles-Jordan trigger circuit, triggered in the cathode circuit by the output from the sixth counter, the positive pulses of which have been clipped off.

Pedestal Delay Multivibrators

The A-pedestal delay is a multivibrator, shown in Figure 12-12. The output of the fourth counter is applied to T_1, which with its associated elements clips the positive pulses and passes the negative pulses to the grid of T_2, where they are mixed with the differentiated output of the square-wave generator.

T_2 and T_3 form a one-shot multivibrator. T_3 is normally conducting, and

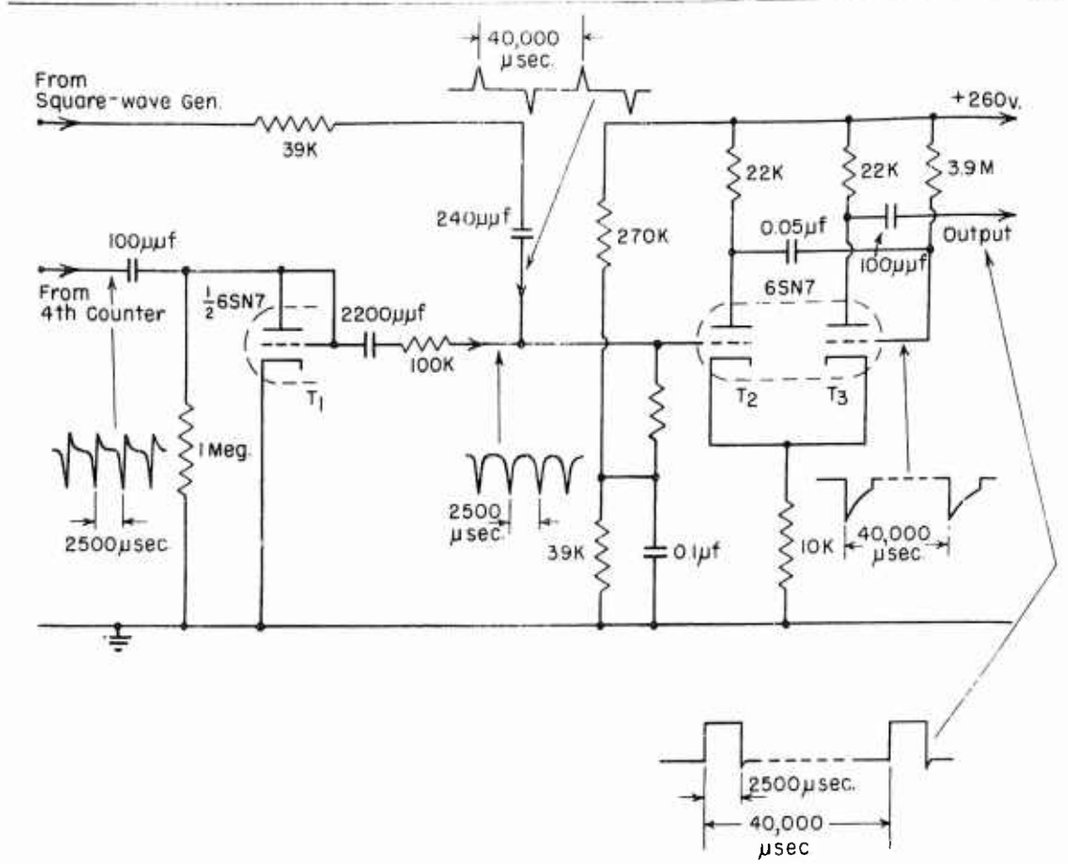


Fig. 12-12 A-pedestal delay multivibrator

T_2 cut off, due to the fact that the grid of T_3 is returned to +260v and that of T_2 to only +35v, together with the fact that both tubes share a common cathode resistor. Positive pulses from the square-wave generator trigger the circuit, causing T_2 to conduct and T_3 to be cut off. The next negative fourth-counter pulse triggers the circuit in the reverse direction, the grid-circuit time-constant of T_3 being so chosen that T_3 is nearly conducting of its own accord at this time. Further negative pulses have no effect since T_2 is now again cut off, and the circuit is ready for the next positive square-wave generator pulse. The output at the plate of T_3 therefore consists of rectangular positive pulses, of width 2500 microseconds. The width of the pulses is accurately controlled by the period of the fourth counter, and their recurrence rate by that of the square-wave generator. The B-pedestal coarse delay is a one-shot multivibrator similar to that just described, except that the inputs are from the opposite phase of the square-wave generator and the third counter respectively, and that the grid return of the first triode section is to a point of variable positive potential. As this potential is varied, the trailing edge of the multivibrator pulse coincides in turn with any one of a sequence of third counter pulses. The width of the output pulse is therefore variable in steps of 500 microseconds (on rate 0).

The B-pedestal fine delay is likewise a one-shot multivibrator, but in this case there is only one input (the inverted and differentiated output of the B-pedestal coarse delay multivibrator) and the fine delay is therefore continuously variable since the termination of the output pulse depends only on the time-constant and grid-bias voltage used. Note that the leading edge of the fine delay output pulse is locked to the trailing edge of the coarse delay pulse. The total delay is therefore the sum of the fine and coarse delays.

Pedestal Generator

This is a one-shot multivibrator similar to the preceding three. The outputs

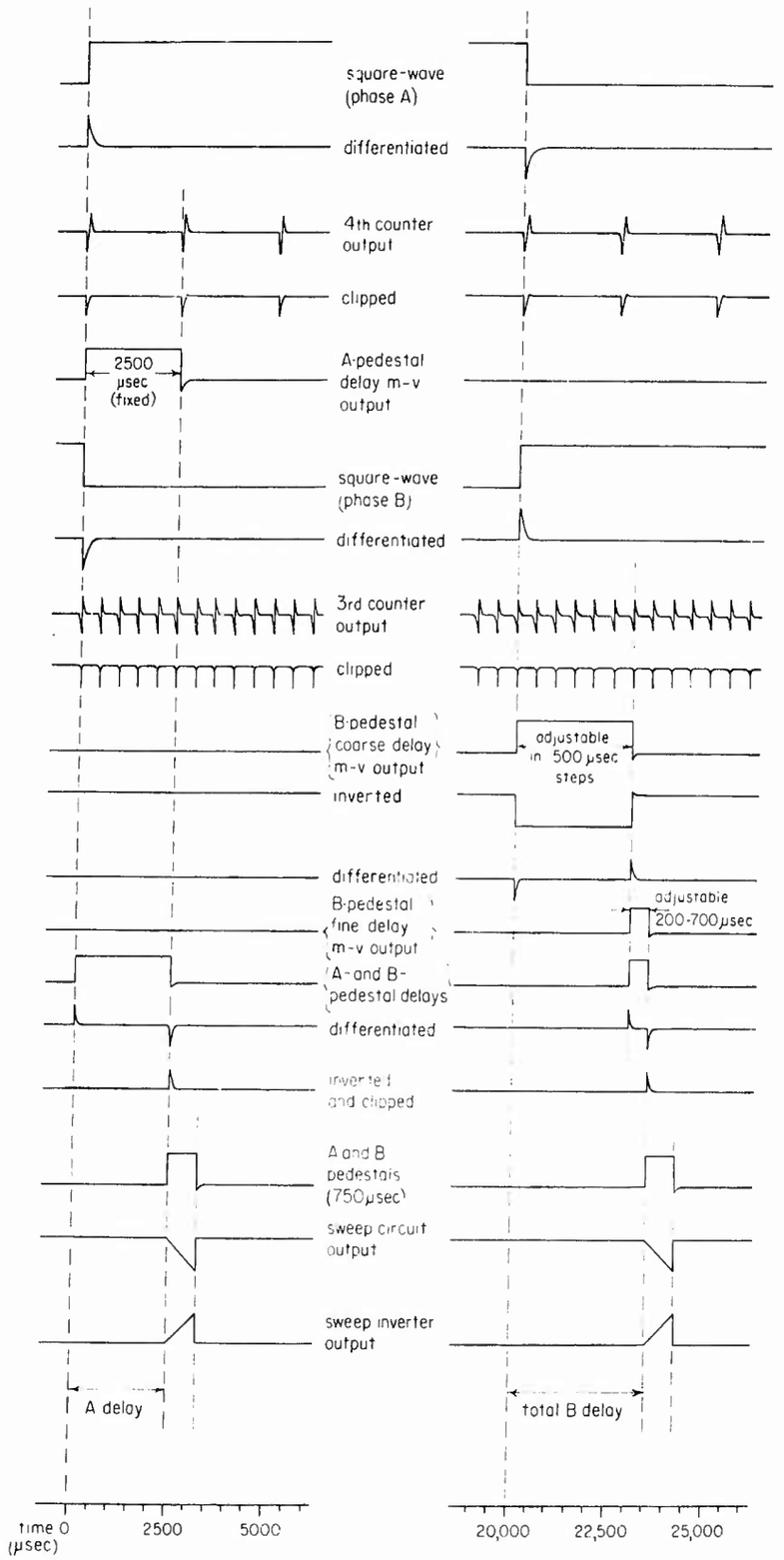


Fig. 12-13 Indicator waveforms

from the A-pedestal delay and B-pedestal fine delay circuits are differentiated and then inverted by an amplifier stage in which the tube runs at zero bias so that the original positive pulses are clipped. The output of this inverter (positive pulses corresponding to the negative pulses from the A- and B-fine delay circuits) is the input to the pedestal generator multivibrator. The output (pedestals) are therefore positive rectangular pulses whose leading edges are delayed alternately 2500 microseconds after the beginning of the A sweep, and by a variable amount (coarse and fine controls) after the beginning of the B sweep. The duration of the pedestals may be either 750 microseconds (sweep-speeds 1, 2, 6, and 7) or 250 microseconds (sweep-speeds 3, 4, and 5), controlled by the setting of a switch which changes the grid bias applied to the second triode section of the multivibrator. The time relationships between these different pulses are shown in Figure 12-13, in which some of the time intervals are not drawn to scale for obvious reasons.

Sweep Voltage Generator

This circuit is shown in Figure 12-14. It is of the triggered type, and triggering pulses are applied from either the sixth counter, the fourth counter, or the pedestal generator according to the position of the sweep-speed selector switch.

Referring to Figure 12-14, tubes T_1 and T_2 and switch sections S_1, S_2 and S_3 are concerned with the selection and shaping of the sweep triggering pulses. In positions 1, 7, and 8 of S_1, the outputs of the fourth or sixth counters are clipped by T_1 so that only negative pulses are transmitted to S_2. S_2 selects either these pulses (positions 1, 7, and 8) or the output of the pedestal generator. The output from S_2 is clamped by T_2 so that the negative voltage excursions at the plate of this tube take place from ground potential downwards. These triggering pulses are applied to the suppressor grid of T_3. S_3 passes negative blanking pulses to the CRT grid by way of C_2 for all switch positions except 8, and also connects C_1 (220 $\mu\mu$f) in parallel with the pulse input, broadening the narrow sweep trigger pulses sufficiently to ensure stable action. Some delay is thereby introduced in the initiation of the sweep voltage, but since this is constant it is not objectionable.

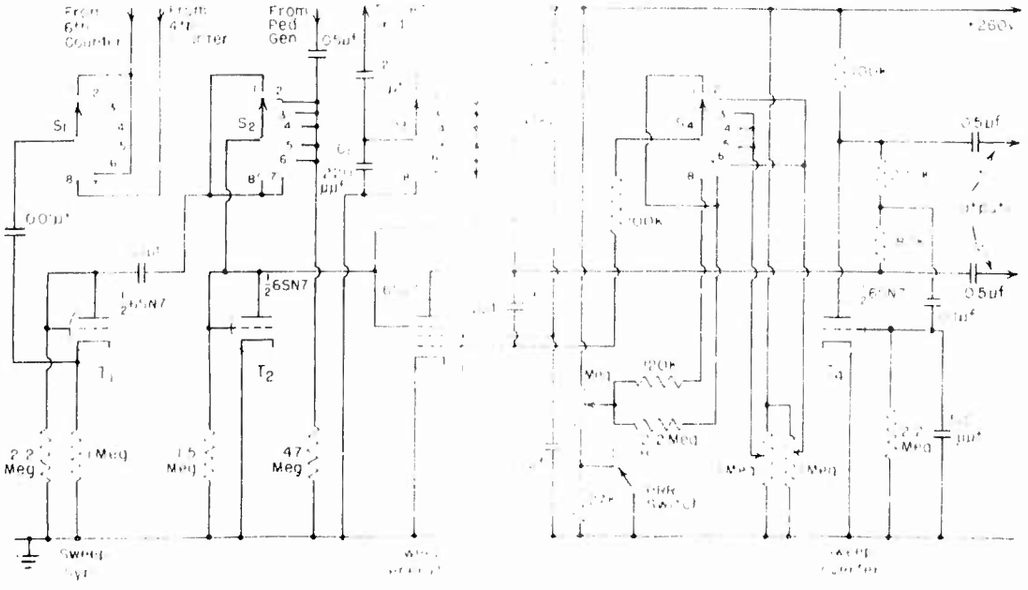
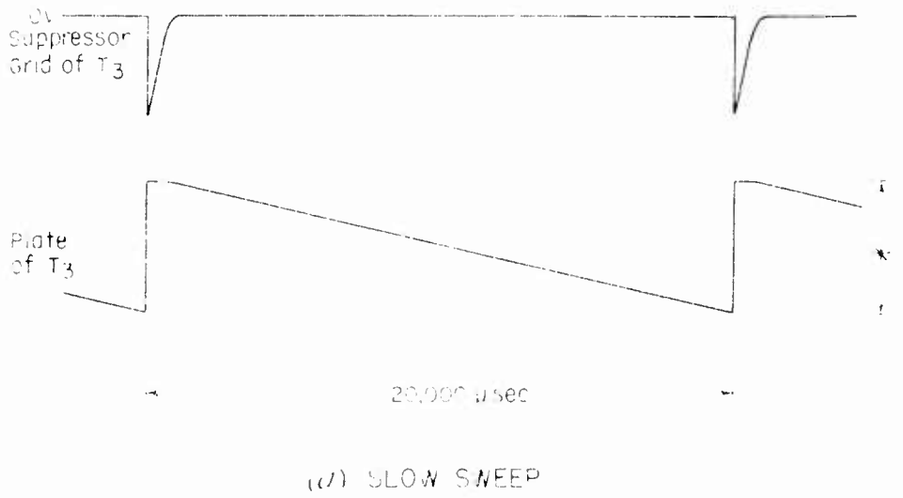
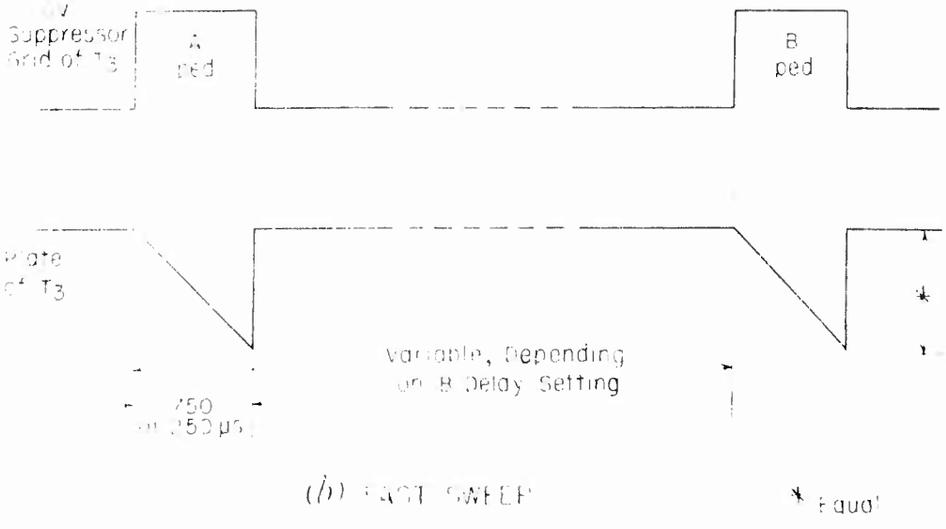


Fig. 12-14 Sweep circuit

Supposing that the suppressor grid of T_3 is at ground potential, T_3 is conducting and its plate potential is low. The control grid of T_3 is slightly above ground potential and grid current is flowing, due to the fact that the grid is returned through a 100,000 ohm resistor to a point at some positive potential provided by the resistor network controlled by S_4. When a triggering pulse arrives, the suppressor grid is suddenly driven negative and the tube cut off. The plate voltage rises sharply, the control grid remaining substantially constant in potential in spite of C_3, due to the fact that grid current is flowing. This condition will persist as long as T_3 is cut off. When the suppressor grid is returned to ground potential, the tube again conducts and the potential at the plate tends to fall. Due to the coupling action of C_3 from plate to grid, and to the large amplification of the tube, this fall is relatively slow and extremely linear over most of its range, the control grid now being negative.



(a) SLOW SWEEP



(b) FAST SWEEP

Fig. 12-15 Triggering and sweep voltages

If this condition were allowed to persist, the fall of plate potential would eventually flatten out. The rate of fall is controlled by the positive potential to which the grid is returned (S_4 and associated voltage-divider networks). The values selected for the various positions of S_4 are such that for all sweep speeds the amplitude of potential change at the plate of T_3 is the same, and is not sufficient to extend into the non-linear portion of the operating range.

Referring to Figure 12-15, which shows the triggering and output voltages for either type of sweep, it is seen that the slow-speed sweeps are initiated by negative pulses from the fourth or sixth counters, and that the fast sweeps correspond exactly in time with the tops of the pedestals used to produce them (250 or 750 microseconds). Provision for changing the positive grid return potential of T_3 must be made for each different sweep duration, and a section of the pulse repetition rate switch accomodates the 25 cps and 33 1/3 cps basic repetition rates.

T_4 is a sweep inverter tube. By means of a suitable voltage divider and negative feedback network, the output from its plate is arranged to be of the same amplitude as that from the plate of T_3, but inverted.

The two push-pull voltages so obtained are applied to the horizontal deflection plates of the cathode-ray tube through suitable clamping circuits which ensure stability in the horizontal position of the display. Clamping is also applied to the CRT control grid, so that the maximum intensity of any part of the display is the same for all sweep speeds. The focus and intensity controls of the CRT, and the accelerating voltage circuits, are conventional in design.

Signal-marker Mixer

Time markers are clipped and shaped, and are mixed with pedestal voltages and video signals, in a network which is essentially a four-input vacuum-tube mixing circuit, in which the four mixing tubes have a common plate resistor. Suitable switching arrangements enable video signals to be eliminated on sweep speeds 5, 6, 7 and 8, and markers on speeds 1, 2, 3 and 4.

Trace Separation and Amplitude Balance

For these purposes, outputs from both sides of the square-wave generator are applied to a twin cathode-follower. A potentiometer connected between the two cathodes of the tube enables a square-wave voltage of adjustable amplitude and either sense to be applied to the cathode of the third I.F. amplifier tube for amplitude balance as between the A and B pulses. Trace separation voltages, different in amplitude for different sweep speeds, are taken from potentiometers connected across one side of the push-pull square-wave output.

Feedback Alignment

In position 8 of the sweep-speed switch, the sweep generator is triggered by the output from the fourth counter and the recurrence rate is therefore 400 sweeps per second. The vertical deflection plates are connected to the grid of the third counter, whose step-voltage pattern (2000 sequences per second) is therefore seen on the display. The feedback trimmers, some of which are critical and may require readjustment at varying operating temperatures, are conveniently adjusted with this display.

The timing circuits used with the Loran indicator are complex but ingenious, and may be said to represent a high degree of attainment in the art.

Summary of Displays and Sweep Speeds

Sweep Speed Switch position	Duration of each sweep* (microseconds)	Nature of Display
1	20,000	two traces, A and B pedestals, A and B received pulses.
2	750	Two traces (tops of pedestals). A and B pulses
3	250	two traces. A and B pulses.
4	250	traces superimposed. Adjust pulses to coincide.
5	250	two traces, video pulses replaced by 10-microsecond and 50-microsecond markers.
6	750	two traces, 10, 50 and 500-microsecond markers.
7	20,000	two traces, pedestals, 50 microsecond, 500 microsecond, and 2500 microsecond markers.
8	2,500	Third counter step waveform

* includes fly-back time.

Bibliography

Identification	Classification	Title	Issued by
JEIA 7292	Secret	Report of Loran Tests on 8th Air Force Heavy Weather Reconnaissance Missions	BBRL
ASE no. 223	Secret	Trials of Loran Interference with Port Wave W/T and R/T Communication	ASE
IRPL-R7	Confidential	Second Report on Experimental studies of Ionospheric Propagation as applied to the Loran System	IRPL
JEIA 6914-6915	Secret	Effect of Loran Interference on range of radio signals	British Post Office
Loran Memo 116	Secret	Flight tests over Bermuda	MIT
Loran Memo 122	Secret	Report on three-line fixes	MIT
Loran Memo 28	Confidential	Service areas of Loran pairs and chains	MIT
Loran Memo 134	Confidential	Notes on 2 mc Loran Propagation	MIT
Loran Memo 137	Confidential	Optimum bandwidth for Loran receivers	MIT
Loran Memo 26	Confidential	Determination of errors in the Loran System	MIT
Loran Memo 138	Confidential	Index of Loran Reports and Instruction Manuals	MIT
AWAS no. 17	Secret	Notes on the Loran Skywave delay	AWAS
Dwg. no. A-2693	Secret	Block diagram, Indicator Timer and Receiver LRN no. 1	MIT
Loran Report no. 499	Confidential	Elements of Loran	MIT
JEIA 8417	Secret	Aids to Navigation Memorandum no. 7	Coastal Command

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Identification	Classification	Title	Issued by
WA 993 2a(4)	Secret	Ionospheric notes on SS Loran proposals	Air Ministry
NAR: X5016	Secret	Considerations of the application of the SS Loran scheme in ETO by RAF	NAR
BDU/S. 566/R	Secret	Trials of SS Loran Chain	BDU, RAF
Loran Report SS 1	Secret	Proposal for a Loran System using sky-wave synchronization	MIT
11-6/22/43	Secret	Notes on the SS Loran System	MIT
11-8/2/43	Secret	Flight of the Texan, July 20-26, 1943	MIT
JEIA 8816	Secret	European and Eastern Atlantic SS Loran Chain	NAA London
Loga Q-392	Secret	Proposed Antenna Design for LF Loran	Chief Signal Officer
WA-4052 5	Secret	Proposals for European and Eastern Atlantic SS Loran systems	BBRL
JEIA 10,001	Confidential	Suggested Improvements for Loran system	NRL
JEIA 10,036	Secret	Loran trials in Mosquito VI and Oxford aircraft	Naval Intelligence
NAVAER 00-80V-48	Restricted	Pocket handbook of airborne Loran	CNO, U.S. Navy
JEIA 9435		Report of Loran operational tests aboard USS Plunkett	BUSHIPS
AN 16-30 APN4-3	Restricted	Handbook of Maintenance Instructions for Radio set AN/APN 4	U.S. War Dept.
AN 08-30 APN 4-2	Restricted	Handbook of Operating Instructions for Radio set AN/APN 4	U.S. War Dept.
HO Misc 11,701	Confidential	Report of Atlantic Loran Research Flight	H.O.

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Identification	Classification	Title	Issued by
S 67-5 Serial 001695/P20	Secret	Comparison of various navigational systems	(Letter: J.A.Pierce to L.A.Dubridge)
Report 625	Secret	The Future of Hyperbolic Navigation	MIT

Bibliography (cont.)

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Report 625	Secret	The Future of Hyperbolic Navigation	MIT

Type of system

Differential distance or hyperbolic system.

Useful range

Day - 1500 miles (estimated)
Night - 1500 miles (estimated).

Accuracy

Theoretical accuracy:
Lateral error at 400 miles ± .027 miles
at 1000 miles ± .068 miles
Practical accuracy:
Lateral error at 400 miles ± .05 miles
at 1000 miles - no data available

Ambiguities: Complete ambiguity between closely spaced lines. Must have good DF fix or know point of departure. If meters are set at known point of departure and continue to operate there is no ambiguity. A system of sector identification has been worked out. No details of this system are available.

Frequency

20 kcps to 200 kcps.

Wavelength

1500 meters to 15,000 meters.

Bandwidth

Ground station: Single frequency.
Receiver: Single frequency. Three frequencies, two of them related to the third by simple fractions such as 3/2 and 1/3 are required.

Presentation

Line of position (from one pair of stations, master station and one slave) indicated on dial-type phase meter (similar to a watthour or gas meter). Second line of position (from master and second slave station) indicated on second phase meter. Meters give continuous indication and no adjustments are necessary to obtain readings. Both lines of position are available simultaneously.

Skill

Ground: Well-trained operators to maintain phase lock at slave stations.
Craft: Little skill required. Intelligent use must be made of indications so ambiguities can be resolved and blind faith in indications will not obtain.

Equipment required

Ground: 2 C.W. transmitters for a line of position and 3 C.W. transmitters for a fix. Master station relatively simple. Slave stations are rather complicated and specialized. Low frequencies used require large and expensive antenna system.
Craft: Very specialized equipment including two radio-frequency amplifiers for line of position or three radio-frequency amplifiers for fix. Two or four frequency multipliers and one or two integrating phase meters.
Weight: 85 pounds - portable model is being produced to weigh 25 pounds.

Present status

Experimental.

Description of system

Differential distance may be measured by measuring the difference in the

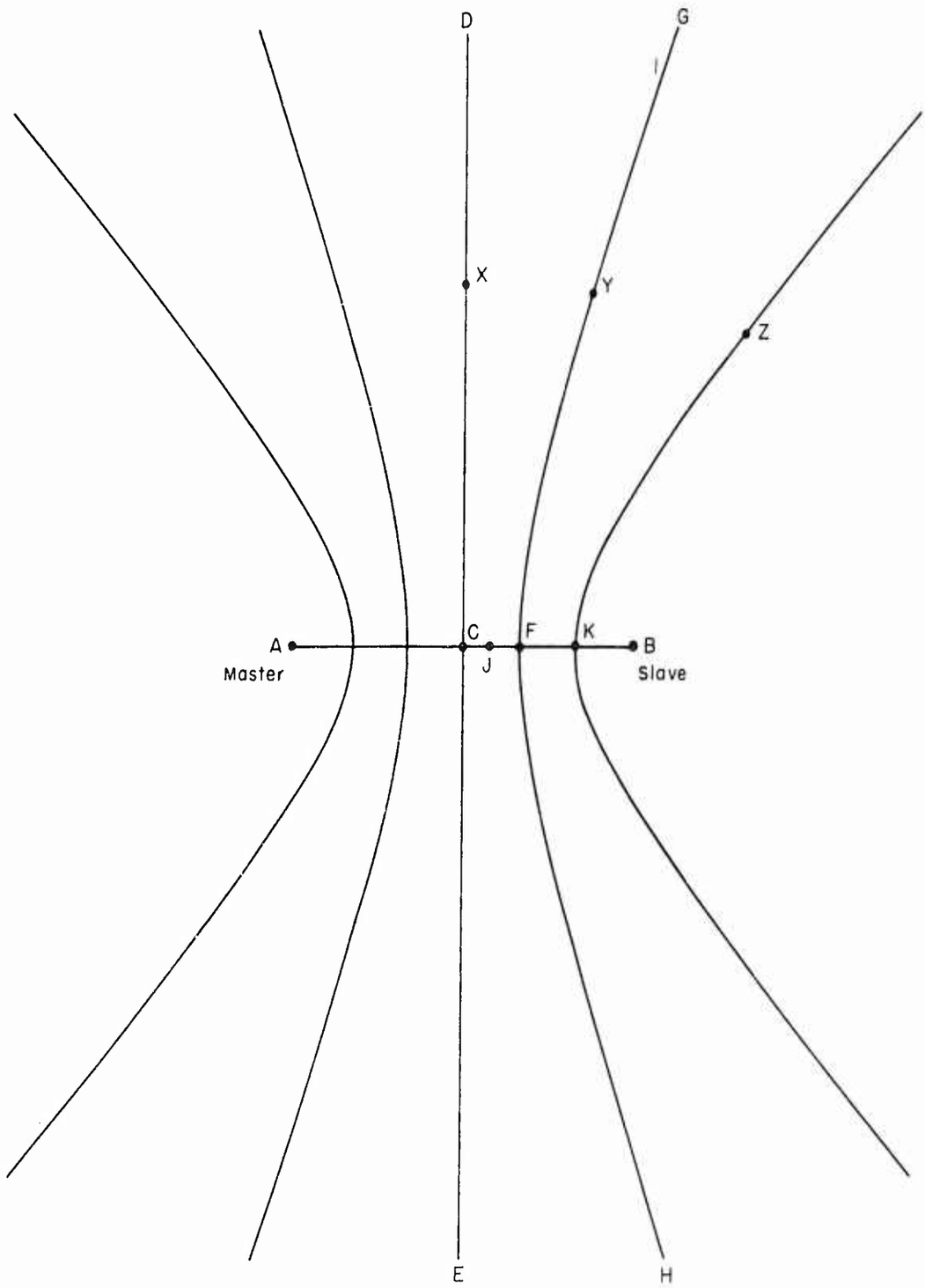


Fig. 13-01 Fundamentals of system

time of arrival of pulses from a master and a slave station. It may also be measured by comparing the phase of radio-frequency signals from a master and a slave station. This latter phase comparison method is used in the Decca system.

A simple explanation based on Figure 13-01 may be used even though in practice some complications must be introduced to make the system workable.

A is the master station and B is the slave station. For a simple explanation we can assume that they both radiate a signal of 340 kcps (wavelength of 882.3 meters) and that these two radiations are exactly in phase. At the point C, bisecting the line between the stations A and B, the signals from the two stations travel an equal distance and are therefore in phase when they arrive. This same condition applies to any point on the line DCE. Let us now consider the point F. If this is assumed to be 441.15 meters (one half wavelength) to the right of point C, the distance AF will be one wavelength greater than the distance BF. The signals from A and B are therefore in phase at F. The curve GFH is such that any point Y on it will be one wavelength closer to B than to A. The areas between lines of zero relative phase angle are called "lanes". If one moved from C to F along the line AB the relative phase angle would go from 0° to 360° going through 180° at the point J. In moving from X to Y the relative phase angle also goes from 0° to 360°. In this system an integrating phase meter is used. If it were set to zero at X and then moved to Z along any path it would read 720° phase shift. This integrating phase meter has no spring return to zero and will therefore maintain its reading if the signal is interrupted for any reason. This makes it possible for this system to function on very poor signals. The signals may disappear completely for short periods but when they reappear they turn the phase meter to the correct reading. If the phase meter has been reading zero on the signals at point C and these signals are absent as the craft moves from C to a point slightly to the right of J the phase meter will indicate 0° instead of 360° when the point F is reached. In general if the signals are absent during the time that the craft moves slightly more than one half a "lane" the indication will be in error by one "lane".

Since it is impractical, and in fact almost impossible, to receive simultaneously, but separately, two signals of the same frequency from two stations, the method used in the above simplified explanation cannot be used. Instead two different frequencies that are simply related to the 340 kcps may be transmitted from two stations and received separately and simultaneously. The two frequencies used could be 340/4 kcps = 85 kcps and 340/3 kcps = 113 1/3 kcps. (See Fig. 13-02). At the craft the 85-kcps signal frequency may be multiplied by 4 to yield 340 kcps and the 113 1/3 kcps yields 340 kcps when multiplied by 3. This method is exactly equivalent in phase measurements to the simplified explanation above.

In order to obtain a fix two sets of lines of position are necessary so that another phase comparison system is necessary. The frequency at which this comparison is made may be 255 kcps. Since this is 3 x 85 kcps the master signal frequency of 85 kcps can be used to provide one of the 255-kcps voltages. The other can be provided from a third station transmitting a 127.5-kcps signal. This can be multiplied by 2 to yield a 255-kcps voltage.

Three fixed transmitters and their associated control circuits are required on the ground. The equipment on the craft comprises three phase-stable amplifiers, four frequency-multipliers and two integrating phase-meters.

The fixed ground equipment consists of a master transmitter and two slave transmitters. The master transmitter A is crystal-controlled and special provision

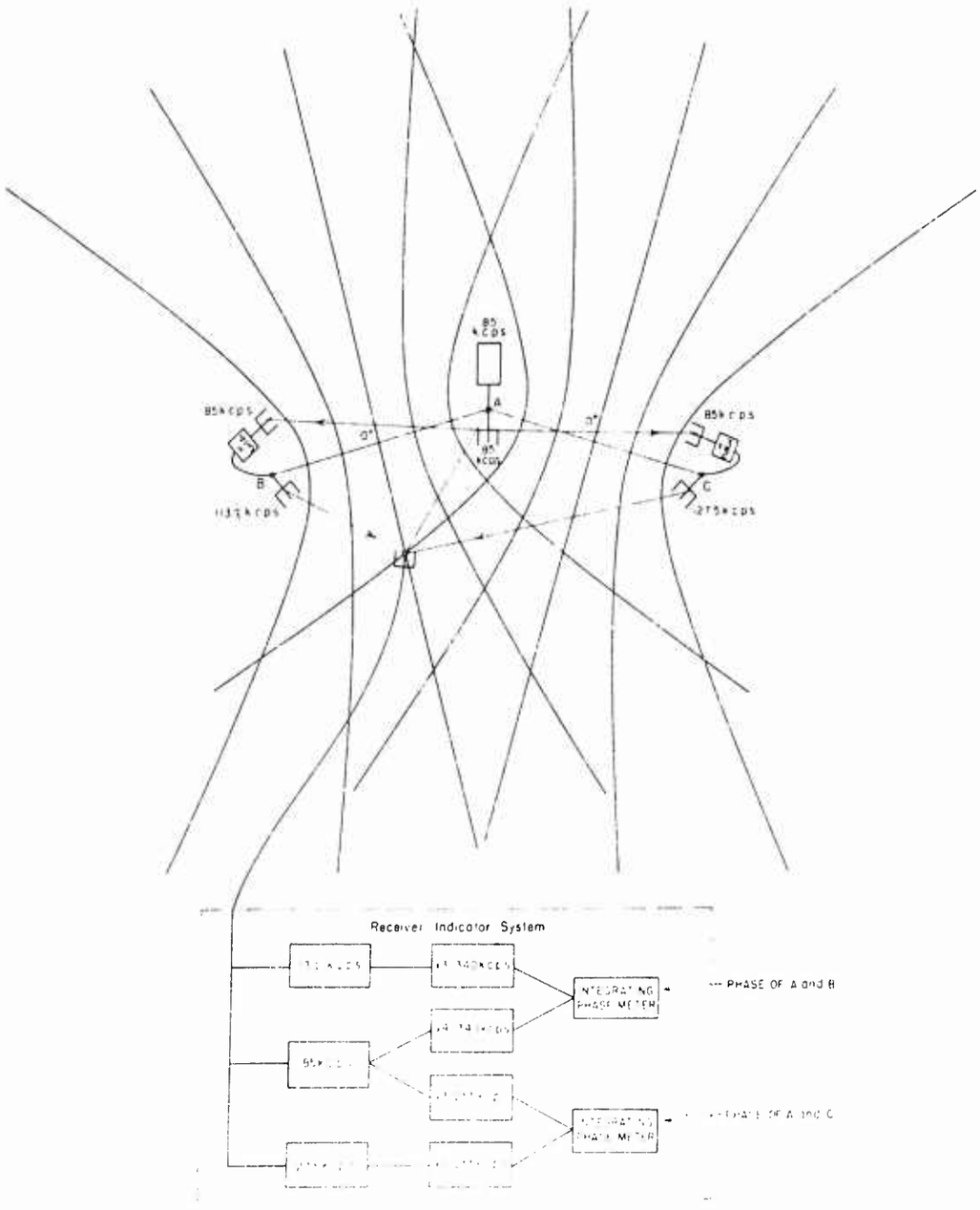


Fig. 13-02 Diagram of triplet

is made for keeping the phase of the radiated signal constant with respect to the crystal. The frequency of this master station A is 85 kcps. At slave station B this 85-kcps signal from the master station is received and amplified and its frequency is multiplied by 4/3 and the resulting frequency of 113 1/3 kcps is used to drive the transmitter. A phase-locking system is used to compensate for random phase variations in the transmitter and antenna.

At slave station C the 85-kcps signal is received and multiplied by 3/2 and the resulting frequency of 127.5 kcps is transmitted. A similar phase-lock system is used here.

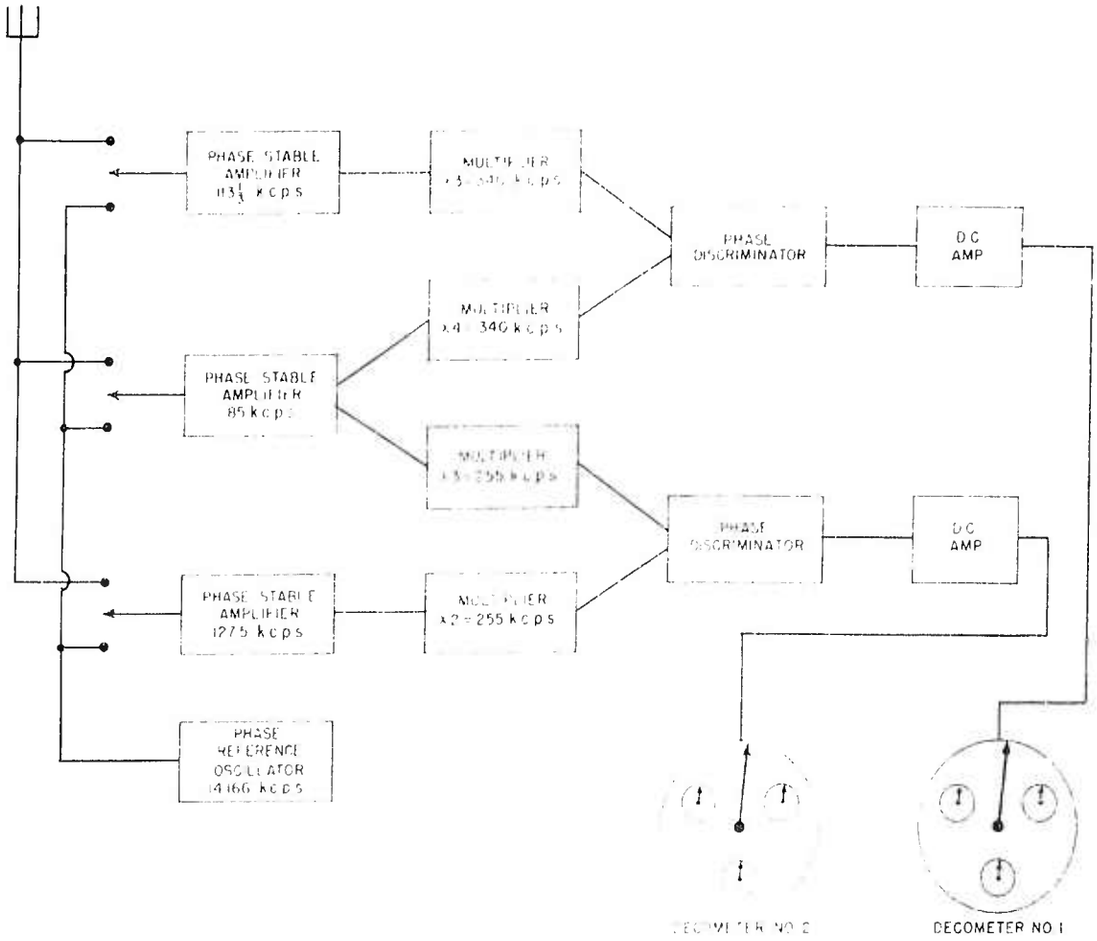


Fig. 13-03 Block diagram of receiver-indicator

Figure 13-03 is a block diagram of the receiver indicator. The accuracy of measurement depends upon the amount and constancy of the phase shift in the various elements of the system. In order to provide a means for checking and adjusting the phase shift of the three channels a phase-reference oscillator is provided. In the example given the frequency of this oscillator is 14.166 kcps. The 6th harmonic is 85 kcps, the 8th harmonic is 113 1/3 kcps, and the 9th harmonic is 127.5 kcps. Since the 14.166-kcps output consists of very sharp pulses, all these harmonics are inherently in phase when multiplied to a common comparison frequency so that the two decometers should indicate zero phase shift. A switch is provided to enable this check to be made whenever desired. The exact circuit of the phase discriminator and decometers is not available but a possible circuit is that of Figure 13-04. Two phase-discriminating rectifier circuits are used. The output of each phase-discriminating rectifier controls two DC amplifier tubes. The plate currents of these two tubes flow through two differentially-wound coils in such a way that the field is zero if the plate currents are equal. If the phase-discriminating rectifier supplies control voltages to the DC amplifier tubes the plate current becomes unbalanced and a net field is established in the coils. The magnitude and sense of this field depends upon the relative phase of the two applied signals and is in fact proportional to the sine of the phase difference. The second phase-discriminating rectifier and DC amplifiers control the field of a second set

of coils located at right angles to the first set of coils. The magnitude and sense of the field in this second set of coils depend upon the relative phase of the signals applied to it. The 340 kcps from the A station is applied to both phase-discriminators in phase. The 340 kcps from the B station is applied to the two phase-discriminators 90^{0} out of phase thus producing a flux component proportional to the cosine of the phase difference. These two crossed sets of coils set up a field whose direction indicates the phase angle between the signals from the A and B channels. A small permanent magnet is pivoted in this field and is geared to indicating pointers. This magnet indicates the direction of the field and therefore the relative phase of the A and B signals. The geared indicators integrate the phase shift.

Figure 13-05 is the block diagram of a typical slave station giving details of the phase-lock system. An antenna or loop (a) picks up the 85-kcps transmission from the master station. This is so placed and orientated that it has a maximum response to the master station's signal and a minimum to its own transmitting antenna. This signal is amplified by a phase-stable amplifier and is then multiplied by 4/3 to yield the 113 1/3-kcps signal used to drive the transmitter. This can be accomplished by dividing the 85-kcps frequency by 3 and then multiplying this resultant 28 1/3 kcps by 4. This 113 1/3-kcps signal is then fed through an electronic

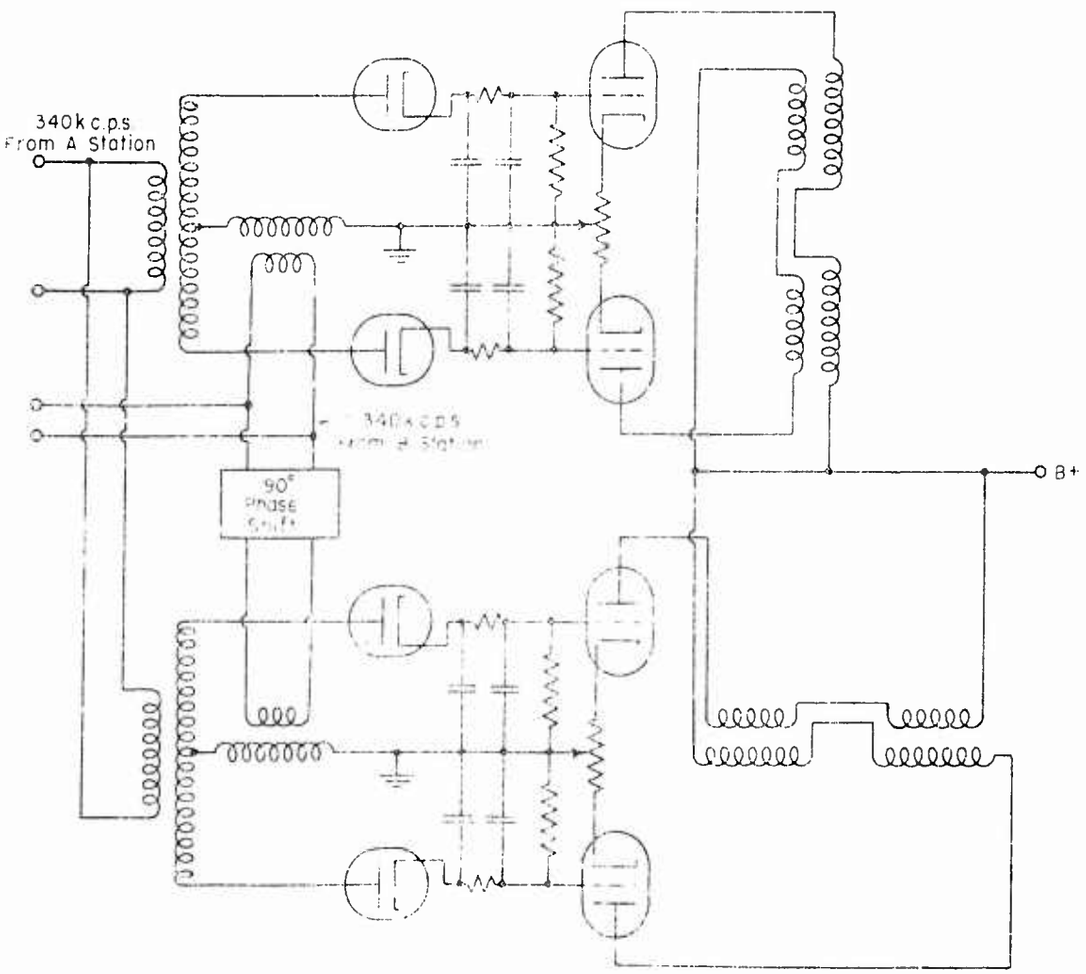


Fig. 13-04 Suggested phase meter circuit

phase-shifter and then to the transmitter. In order to maintain the correct phase of transmission an automatic phase-locking monitor is used. Two phase-stable amplifiers are used. One amplifies the 85-kcps signal from the receiving antenna A. The other amplifies the 113 1/3-kcps signal from a loop near the transmitting antenna. The 85-kcps frequency is then multiplied by 4 and the 113 1/3-kcps frequency is multiplied by 3 so that two 340-kcps frequencies are produced for phase comparison. These two voltages are applied to a phase-discriminator similar to that used in the receiver-indicator. A DC control voltage obtained from the phase discriminator is used to control an electronic phase-shifter in the transmitter channel. A decometer is also connected to this phase discriminator. The electronic phase shift works in such a way that it tends to keep the decometer reading zero. The phase of the 340 kcps derived from the 113 1/3-kcps voltage relative to the 340 kcps derived from the 85-kcps voltage therefore depends upon the relative phase shifts in the two channels of the phase-locking monitor. Since zero relative phase between the 340 kcps derived from the 85 kcps and the 340 kcps derived from the 113 1/3-kcps transmission may not be that desired, it is possible to establish whatever phase is desired by a manual phase control in the 113 1/3-kcps channel. This can be set and checked by switching the inputs of the two channels to the phase-reference oscillator and adjusting the manual phase control for the proper decometer reading. The electronic phase shifter is disconnected while this check is made so that the transmitter phase will not be greatly disturbed. A manual phase correction control is provided in the transmitter channel to correct long term phase shifts. Thus the electronic phase control only has to correct the phase shift due to antenna sway, voltage variations, and so forth.

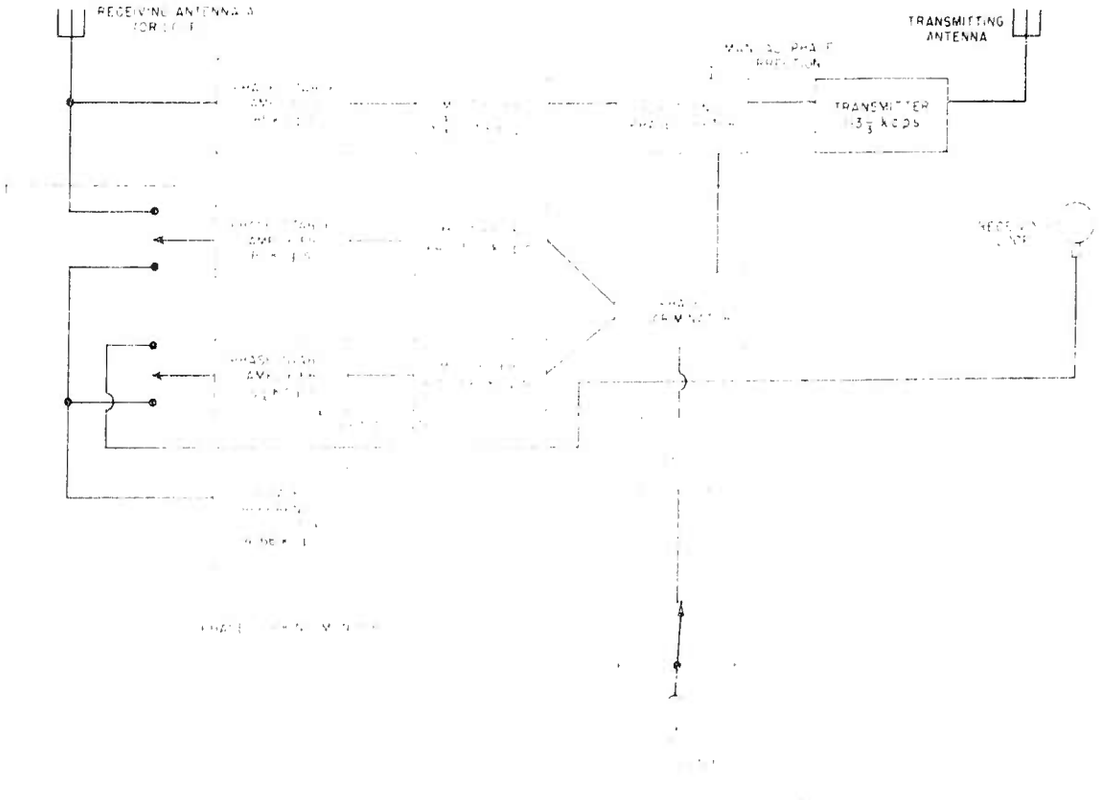


Fig. 13-05 Block diagram of slave station

Identification	Classification	Title	Issued by
JEIA 7080	Secret	Investigation of Sonne and Decca	Intelligence Division C.N.O.
JEIA 7081	Secret	Further Notes on Decca Navigational System	Intelligence Division C.N.O.

POPI (Post-Office Position Indicator)

Type of system

Differential Phase (hyperbolic position lines).

Useful Range

Depends on siting and power of transmitter and on height of receiver. A range of 1500 miles over sea by day and by night is considered easily attainable.

Accuracy and Precision

The theoretical precision attainable depends on the antenna spacing used and on the distance of the craft from the transmitter. See Table 14-01, page 14.07. The accuracy attainable in practice under full-scale operating conditions is not predictable, due to the tentative nature of present development.

Presentation

Several types of presentation have been proposed. One uses an adjustable phase-shifter and a meter. The operator adjusts the phase-shifter for a null on the meter, and the line of position is then read from graduations on the scale of the phase-shifter. Another uses two pointer-and-scale meters, which together give indication of a line of position.

Operating Skills Required

(a) If the direct-reading meter type of presentation is used, the only operations required at the craft are the tuning of a radio receiver to the frequencies of the beacon transmitters used. (b) For ground-stations, monitoring is required.

Equipment Required

(a) Ground: Each beacon consists of four antennas driven by two transmitters, spaced as discussed below. The transmitting equipment could be transportable. Two beacons are required for a fix. (b) Craft: A normal communications receiver is required. Automatic volume control and an IF crystal filter are desirable but not essential. In addition, a special POPI indicator is required. This can be of the direct-reading type (pointer and scale) and in its simplest form does not require any additional tubes apart from those in the communications receiver. The indicator is suitable for use by the pilot of an aircraft and is easily adaptable for homing and for blind landing. (c) Monitoring: Each beacon requires a monitor station, located near the beacon. Control of the beacon transmission from the monitoring point could be made fully automatic but this has not so far been attempted due to the limited scale of the trials made.

Radio-Frequency Spectrum Allotments Required

This system has been tested on a small scale at a frequency of about 750 kcps (400 meters). The frequency used is not critical as far as the system is concerned, and the choice would presumably be governed by the coverage required. Since the transmissions are CW, with slow keying, the bandwidth required is of the order of 1 kcps.

Present Status

This system has been tried out experimentally, on a small scale, the receiving equipment being in a road vehicle. So far as we are aware, no full scale tests have been carried out, nor has the equipment been air- or water-borne.

Principle of Operation

The four antennas of a beacon are arranged at the corners and center of an equilateral triangle (see Figure 14-01). Antennas A, B and C are fed from a central

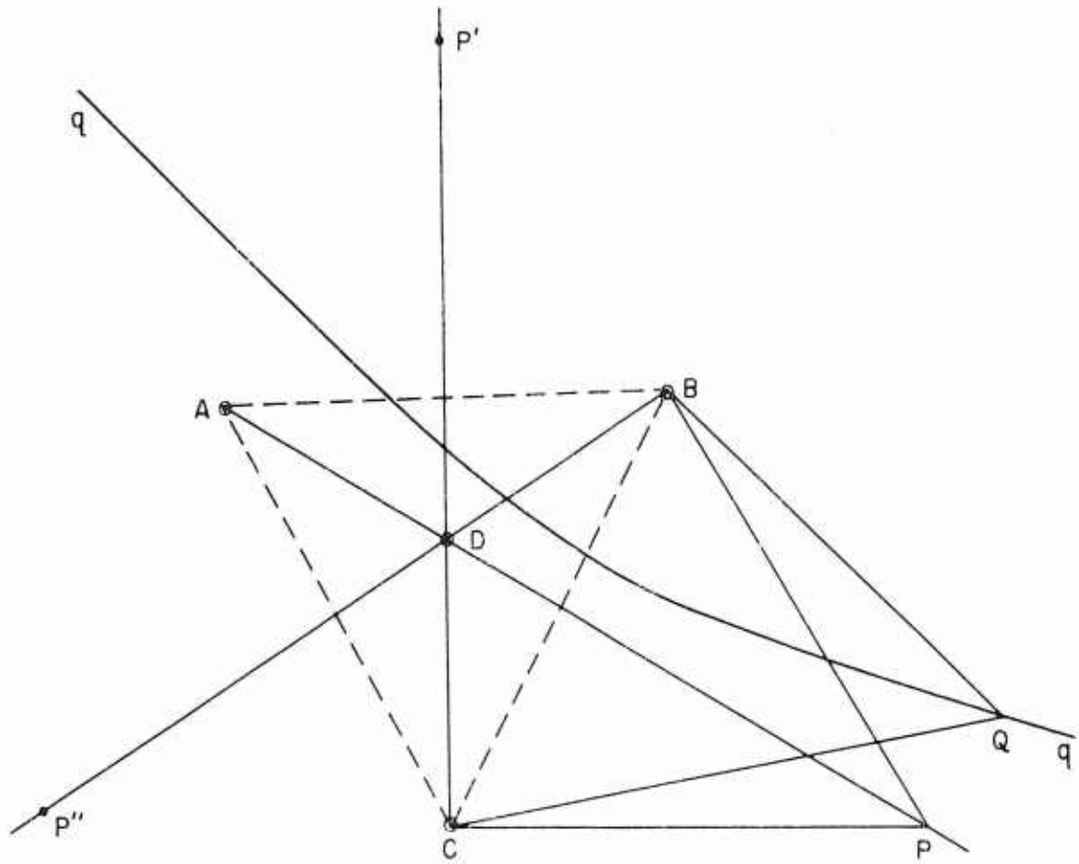


Fig. 14-01 POPI beacon

transmitter through suitable keying, phase-shifting and power-amplifying stages. Figure 14-02 shows a block diagram of a suitable arrangement.

Referring to Figures 14-01 and 14-02, the A, B and C antennas radiate an unmodulated signal at the frequency f_1. These three transmissions are keyed at a slow rate so that the sequence is as follows: transmission from A, transmission from B, transmission from C, space. See Figure 14-03.

The rate of keying used is such that five complete cycles of the sequence occur per second. Each individual transmission, and the space where no signal is transmitted, would then be of 1/20 second duration. The keying is accomplished electronically, using a second oscillator (of low audio-frequency f_2) followed by a frequency divider (dividing by n) and pulse generator. The output of this same audio-frequency oscillator is mixed with the output of the RF oscillator and selectively amplified. The resulting signal, which is unmodulated but of frequency $f_1 + f_2$ is radiated continuously by the fourth antenna D.

The phases of the signals transmitted by antennas A, B, and C may have any desired relationship, but it is assumed for purposes of explanation that the phases are identical. Referring to Figure 14-01, a receiver situated at P, on the perpendi-

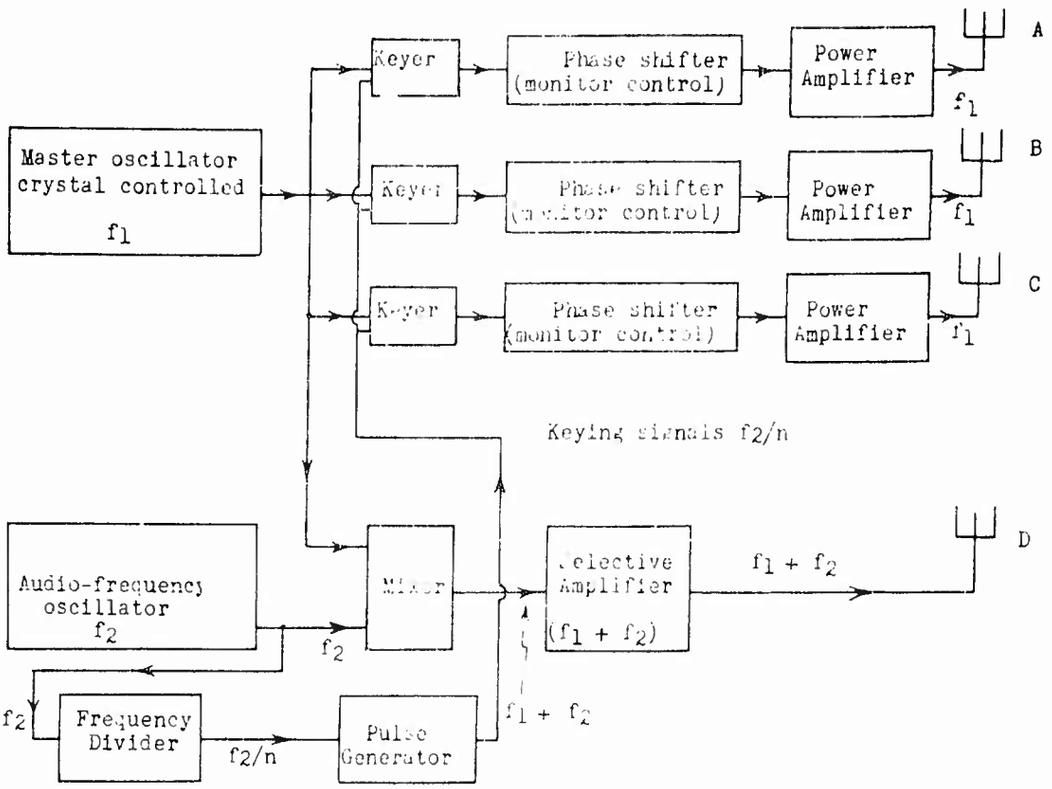


Fig. 14-02 Block diagram--POPI beacon

cular bisector of the line joining B and C, will receive the B and C signal in phase since the distances BP and CP are equal. The same will be true of points P' and P'' if the transmissions from A and B and from A and C respectively are considered. At Q there will be a phase difference between the received B and C signals. The locus of all points for which this received phase difference is constant is the hyperbola qq. There is therefore a family of hyperbolae of constant phase difference for the B and C signals. This follows from exactly the same fundamental reasoning as that which applies to the Loran, Gee and other "hyperbolic" systems, since time difference in a pulse system and phase difference in a C W system are fundamentally the same. Thus a craft equipped with a receiver and POPI indicator giving the relative phase of the B and C signals can locate itself on one of these hyperbolic position lines. Similar families of hyperbolae exist for the A and B transmissions and for the A and C transmissions - three families of hyperbolae in all. Sector ambiguity with regard to the B and C transmissions is solved by a reading taken on either the A and B or the A and C positions. A unique position line with respect to the site of the beacon is thus obtained.

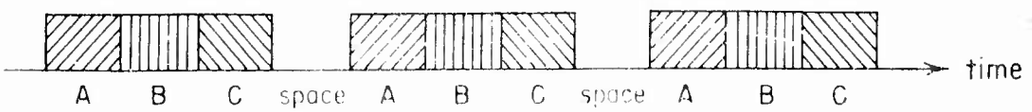


Fig. 14-03 Transmission sequence

With the antenna spacing proposed, the three families of hyperbolae associated with a particular beacon degenerate into radial straight lines (with negligible error) at distances which are small compared with the maximum working range proposed. For this reason, the loci of constant phase difference shown in Figures 14-04 and 14-05 are drawn as radial straight lines. It should be realized that these are actually hyperbolic, and due attention should be paid to this fact in the layout of charts to be used with this system in areas close to the transmitters.

If readings on a second similar beacon are taken, the intersection of the two position lines gives a fix.

The problem at the receiver is therefore to compare the phase of two transmissions occurring on the same radio frequency but consecutively in time. The radiation from the fourth antenna (D) is a continuous unmodulated carrier wave of a slightly higher frequency. The audio output of the receiver will therefore be the difference frequency, or f_2 the original audio frequency. The phase of the carrier of frequency f_1 will be preserved in the phase of the audio output f_2. The problem at the receiver therefore resolves itself into phase comparison of two audio-frequency signals representing the beat signals from B and D and from C and D respectively.

The fact that differences in RF phase are preserved as differences in audio (beat note) phase may be proved as follows:

Let the received signals be given by:

$E_1 \sin \omega_1 t$	from B
$E_2 \sin (\omega_1 t + \phi)$	from C
$E_3 \sin [(\omega_1 + \omega_2)t + \theta]$	from D

Assume also square-law detection. Then during the B transmission the output from the detector will contain the signal

$$\{E_1 \sin \omega_1 t + E_3 \sin [(\omega_1 + \omega_2)t + \theta]\}^2$$

The audio-frequency term of this expression is given by

$$E_1 E_3 \cos (\omega_2 t + \theta) \qquad (1)$$

During the C transmission the output from the detector will contain the signal

$$\{E_2 \sin (\omega_1 t + \phi) + E_3 \sin [(\omega_1 + \omega_2)t + \theta]\}^2$$

And the audio-frequency term is given by

$$E_2 E_3 \cos (\omega_2 t + \theta - \phi) \qquad (2)$$

It will be seen that the phase difference between (1) and (2) is ϕ, and this is the same phase difference as that between the original B and C transmissions.

Spacing of position-lines obtained

The configuration of the hyperbolic position lines (degenerating into radial lines at a distance) depends on the antenna spacing. Four points are of interest in this connection:

(1) If the spacing between antennas is greater than one-half wavelength, there is a sector ambiguity. Consider for example the case where the spacing is two wavelengths. The loci of constant phase difference are as shown in Figure 14-04, where

PQ represents the line joining one pair of antennas and the radial lines are loci of constant phase difference. The choice of + or - sign at any particular point depends on whether the phase of B is measured relative to that of C or vice versa. There is ambiguity between the right-hand and left-hand halves of the diagram, but this is present in all hyperbolic systems and it is assumed that a navigator will know whether he is east or west of the beacon location. However, in addition to this the following ambiguities exist in Figure 14-04:

(a) It will be seen that any particular reading occurs twice in the right-hand half of the diagram. For example, -240^{0} occurs in both the sectors PR and RS. (It is assumed that the indicator used will be able to distinguish between $+240^{0}$ and -240^{0}, i.e. whether B is leading C or C leading B. This is taken care of in the indicator to be described in connection with POPI).

(b) There is also ambiguity as between -240^{0} and $+120^{0}$ since the navigator knows only the existing phase relationship and not the process by which it got that way. Thus there is a four-fold ambiguity in Figure 14-04.

If the spacing is between one wavelength and one half of a wavelength, there is still a two-fold ambiguity. If the spacing is reduced to one half of a wavelength or

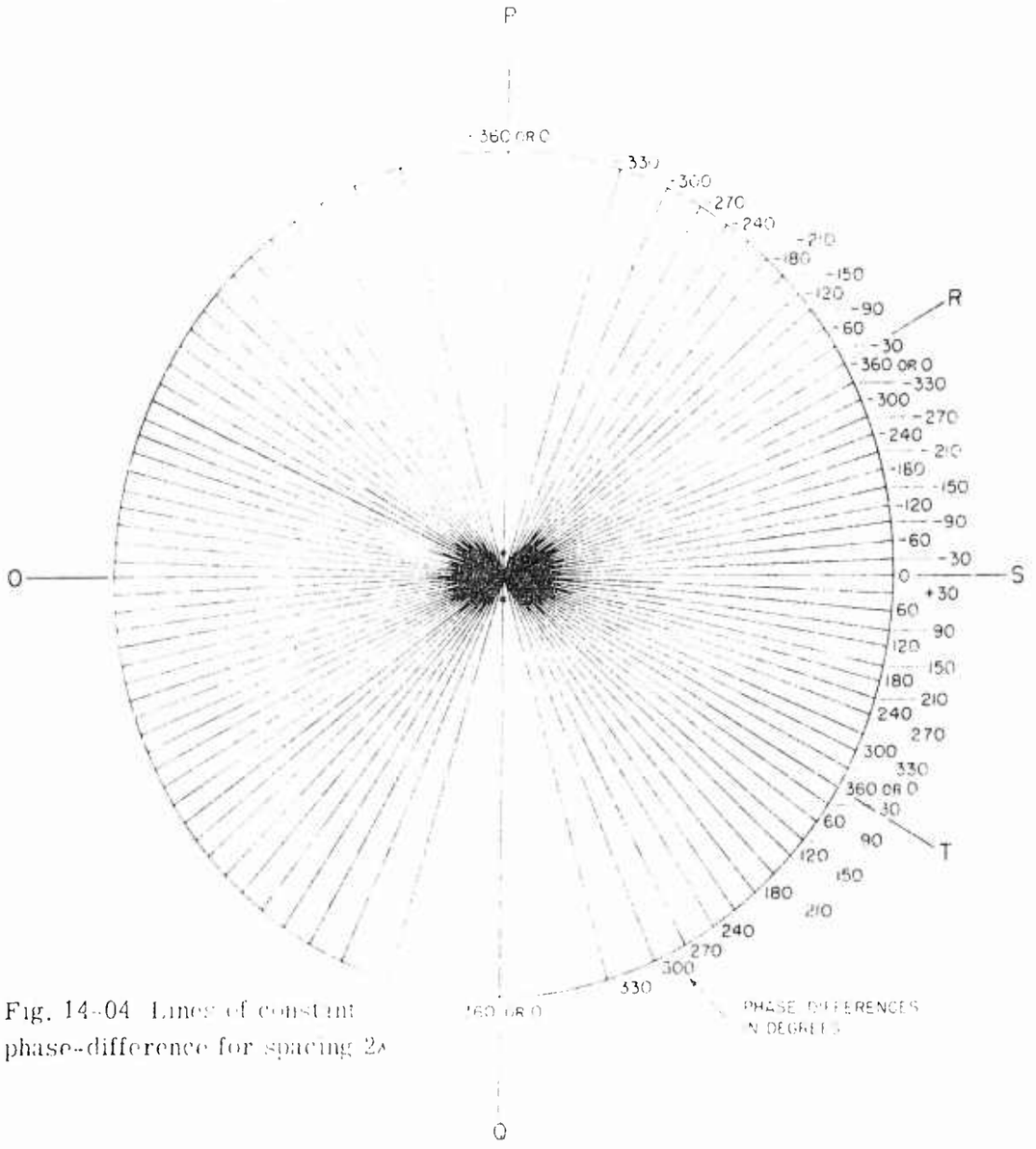


Fig. 14-04 Lines of constant phase-difference for spacing 2λ

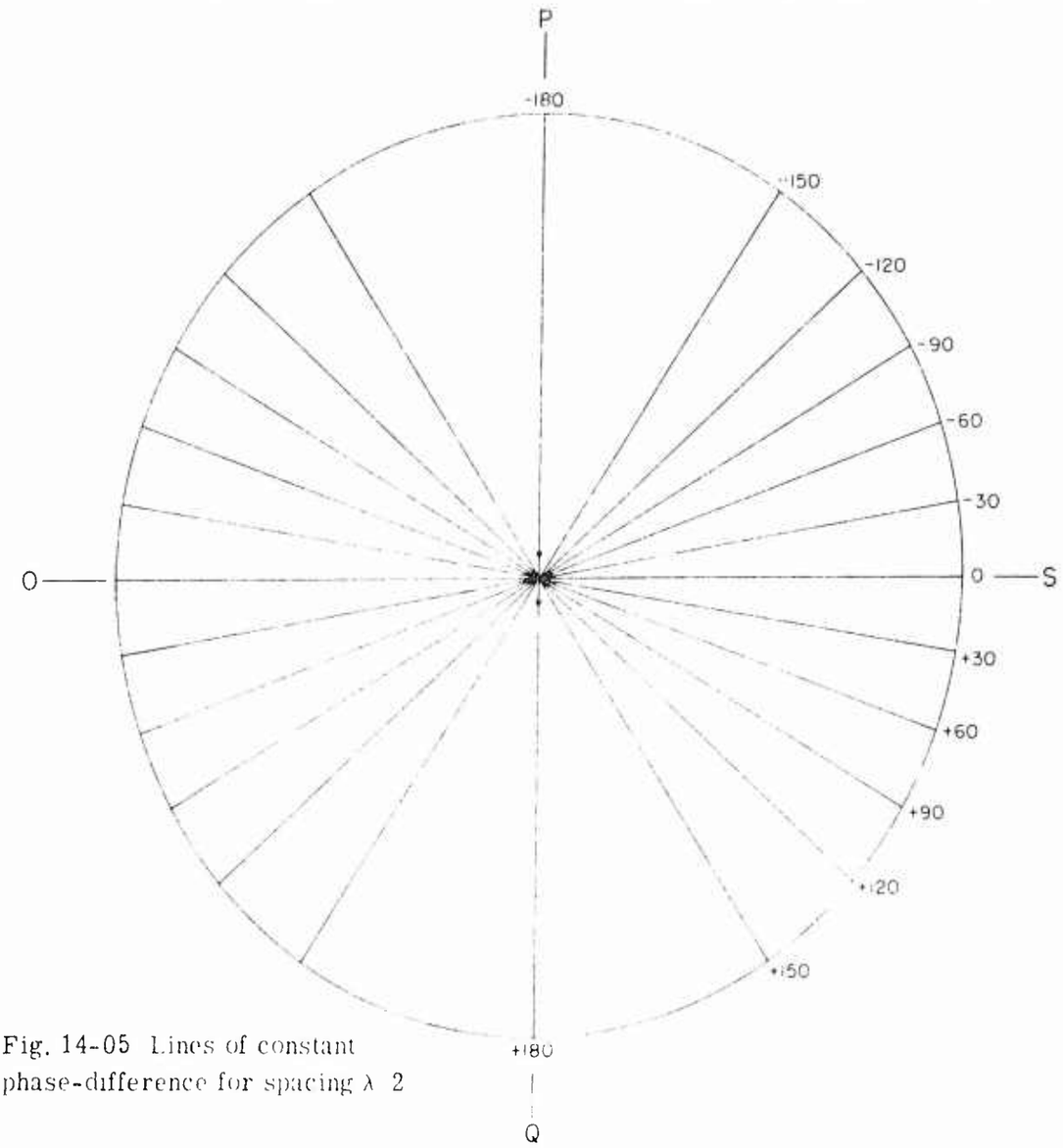


Fig. 14-05 Lines of constant phase-difference for spacing λ 2

less, there is no ambiguity. Figure 14-05 shows the phase loci for a half-wavelength spacing.

(2) The accuracy of position discrimination for a given minimum phase discrimination is not uniform. It is greatest along the line OS which is the perpendicular bisector of the line joining the transmitting antennas, and least (zero) along the line PQ joining the antennas. This is true for all antenna spacings. However, within an arc 60^{O} on either side of OS the attainable precision does not depart too far from the maximum value (one half). Exact figures on theoretical precision are given in Table 14-01.

(3) The maximum accuracy attainable (along the line OS) is greater with wide antenna spacing than with narrow spacing. Table 14-01 gives calculated results for various spacings, both in the direction of maximum accuracy (OS) and also in a direction 60^{O} from this. It should be emphasized that these figures represent theoretical accuracy only. In the interests of removing ambiguity, the system to be described further assumes an antenna spacing of 0.5 wavelengths (line 1 in Table 14-01).

(4) At distances greater than about five times the antenna spacing, the hyperbolic position lines are so nearly straight that negligible error is introduced by making

Antenna Spacing (Wavelengths)	Max. discrimination (on normal) for 2° phase discrimination		Discrimination (60° off normal) for 2° phase discrimination	
	degrees azimuth	Miles at 1000 miles	degrees azimuth	Miles at 1000 miles
0.5	0.636	11.2	1.272	22.4
1.0	0.318	5.6	0.636	11.2
2.0	0.159	2.8	0.318	5.6
4.0	0.079	1.4	0.159	2.8
10.0	0.032	0.56	0.064	1.12

Table 14-01

this assumption. Figure 14-04 was drawn under this assumption, and also Figure 14-05, which shows lines of equal phase difference for a spacing of 0.5 wavelength between antennas. The absence of ambiguity and the reduction in maximum accuracy of discrimination will be noted.

Craft Equipment: The receiver is tuned to the frequency of the carrier. Since the frequency difference between the D transmission and that from A, B, or C is small, and the keying rate slow, the bandwidth required is small and a crystal filter might be used if the signal-to-noise ratio is poor. In the following discussion, the audio frequency is assumed to be 80 cps and the switching rate 5 sequences per second.

After detection, the audio signal will consist of three consecutive dashes of 80 cps tone followed by a blank space. The relative phase of the three carriers received will be preserved in the relative phases of the 80 cps dashes, as previously proved. The problem is now to compare the phase of one 80 cps dash with that of another 80 cps dash which occurs at a different time. To do this accurately does not appear to be easy and in our opinion this stage in the operation of the system presents the greatest difficulty in regard to reliability, accuracy and simplicity. An outline of the proposed scheme follows.

Referring to Figure 14-06, the audio output from the receiver is applied to a rotating switch with four contact sectors. The rotating arm is driven (through reduction gearing) from a synchronous motor which is in turn driven by an 80-cps oscillator. This oscillator is synchronized through a phase-shifting circuit from one of the 80-cps outputs from the rotating switch. The desired condition is that the four contacts in the switch shall receive respectively the A, B and C signals and the no-signal space; i.e. the periods of time during which the four sectors are successively in contact with the rotating arm shall be synchronized with the four periods in each received cycle of events. This condition is indicated by zero deflection of the meter M which is a direct-current meter fed with the smoothed, full-wave rectified output from the fourth sector. This indication is obtained by changing the adjustment of the phase shifter and therefore the phase of the synchronous motor. The separated A, B and C outputs are filtered and may then be amplified as indicated.

However, the authors of the original scheme were anxious to preserve maximum simplicity in the additional indicating equipment required. For this reason

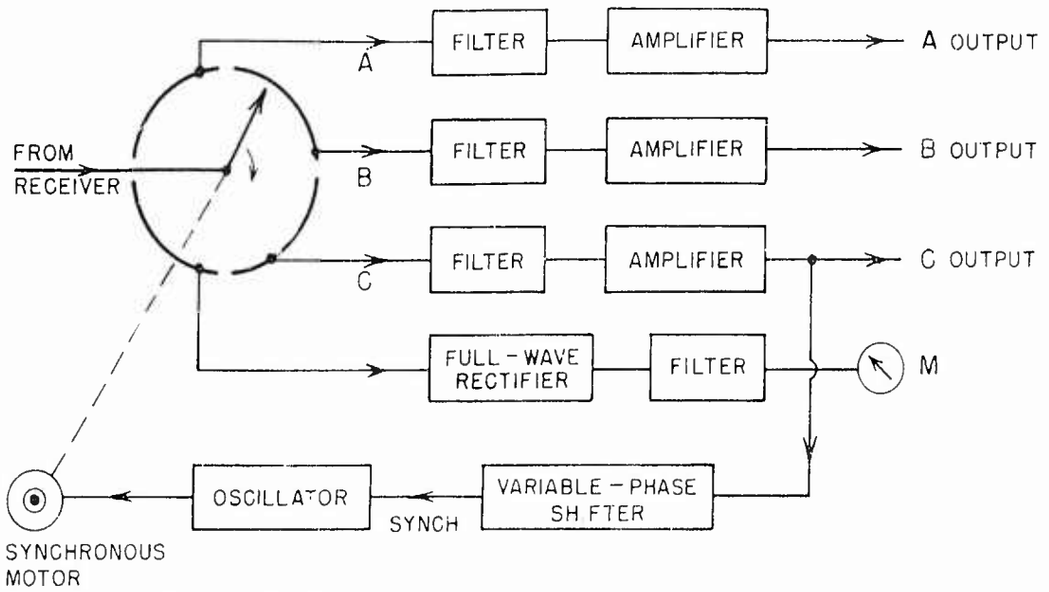


Fig 14-06 Block diagram--received signal separation

they designed and used a type of phase-comparison indicator which requires no extra tubes and no additional power supplies. Using this instrument the additional amplifiers shown in Figure 14-06 would not be used. This type of indicator is illustrated in Figure 14-07, and operated as follows:

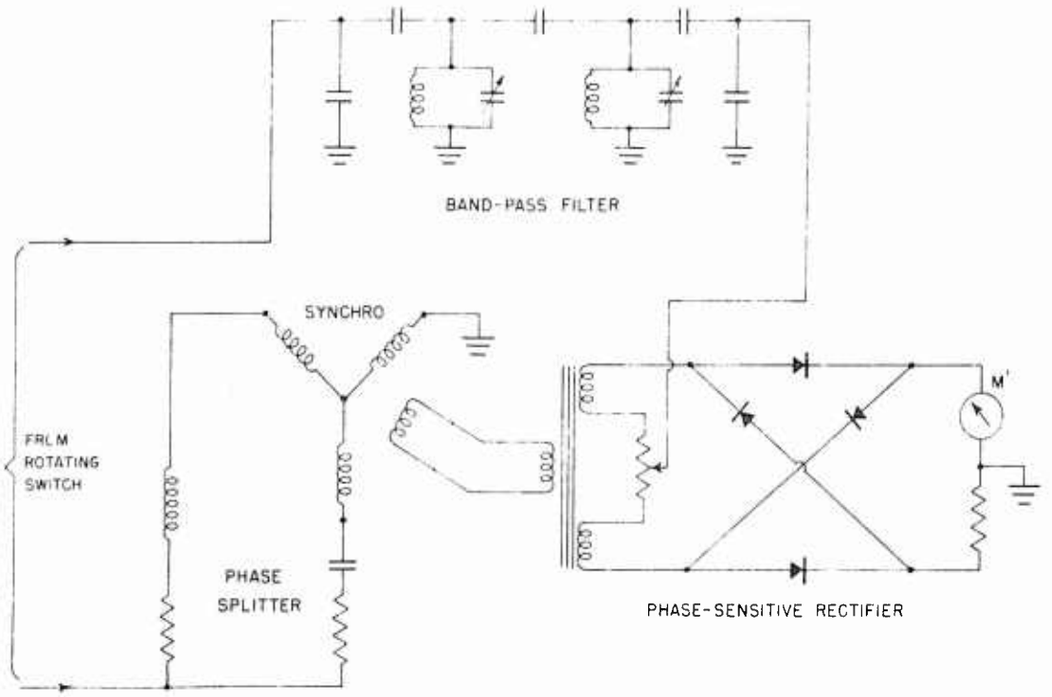


Fig. 14-07

For phase comparison, one of the three outputs is selected and passed to a band-pass filter tuned to 80 cps and having a bandwidth of 2 cps. This in effect constitutes a ringing circuit and it is desired that the 80-cps output from the circuit shall continue during the absence of an input signal. The phase of this output is dictated by the samples of 80-cps signal periodically fed to the input. Another of the switch outputs is applied to a calibrated phase-shifter (not to be confused with the phase-shifter of Figure 14-06). The output from the phase-shifter and that from the ringing circuit are then compared by a phasemeter and the phase-shifter adjusted for zero phase difference. The difference in phase between the two channels selected is then read from the calibrated phase-shifter and a line of position thus selected, using charts on which the lines of POPI equal phase-difference have been overprinted.

Referring to Figure 14-07, the calibrated phase shifter consists of a synchro unit, whose three fixed windings are suitably fed, and from the rotor of which a variable-phase signal is taken. This signal and the output from the band pass filter (or ringing circuit) are supplied to the phase-sensitive rectifier shown. The meter M' will read zero if the two inputs are 90^{0} or 270^{0} out of phase. These circuits are

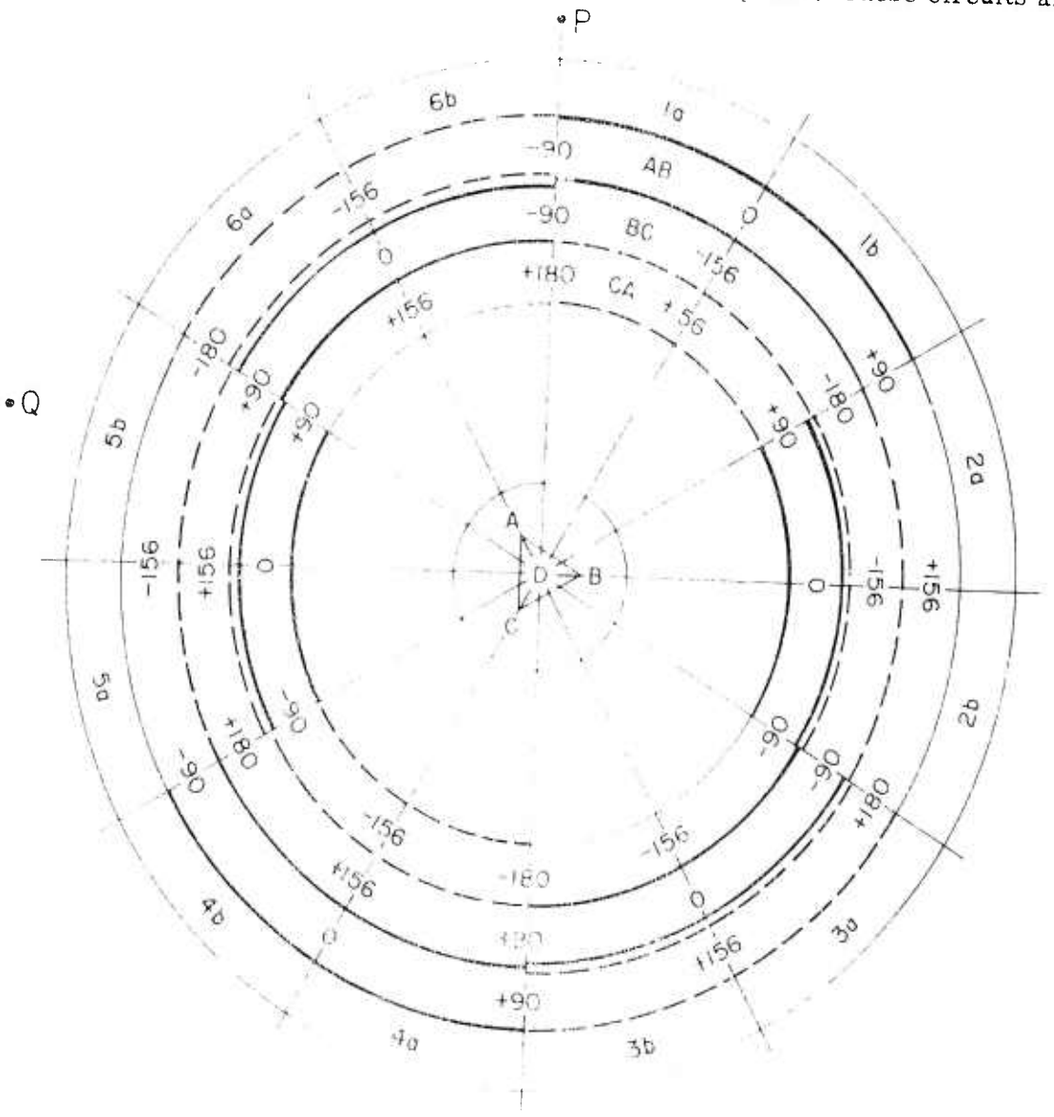


Fig. 14-08 Phase differences at receiver

taken from the proposals in the original paper in which the principal advantage claimed was the absence of tubes and power supplies other than those in the receiver itself. The circuits do not necessarily represent the most efficient and accurate way of accomplishing the phase comparison; and it is our opinion that, should this system be developed further, other phasemeters could be tried with advantage, for example that described in the report on the Decca system. It is also desirable to use a direct-reading phasemeter which does not involve matching for a null reading on a meter.

Sector Identification

Assume now that this difficulty has been overcome and that a suitable direct-reading phasemeter is available. The following discussion summarizes the original proposals. Referring to Figures 14-06 and 14-07, it will be seen that there are three outputs from the rotating switch and two inputs to the phase-comparing circuits. The layout of the beacon antennas is such that there are three sets of hyperbolic position lines (which degenerate into great-circle position lines at some distance out from the beacon), one set for each pair of antennas. There is thus an opportunity to make use of only the sector of maximum discrimination in each case.

Figure 14-08 illustrates the phase differences between pairs of received signals at 30° (azimuthal) intervals. The antenna spacing for each pair is assumed to be $\lambda/2$. The numbers in the outer ring are arbitrarily numbered sectors. The next ring (AB) gives the phase of B relative to A, the next ring (BC) the phase of C relative to B and the inmost ring (CA) the phase of A relative to C. The phase of A relative to B will of course be the reverse of AB and will be denoted by BA, the first letter in each case giving the phase reference. An observer in sectors 1 should use the A and B signals for maximum precision. Likewise an observer in sectors 2 should use the A and C signals, and so forth, as indicated by the thick lines enclosing the sectors. In either case the observed phase angle for the chosen pair lies between -90° and $+90^{\circ}$, i.e. in the first or fourth quadrants of a direct-reading phasemeter with 360° scale.

Table 14-02 lists the quadrants in which the phase angles observed will lie for any pair of signals.

Sectors	AB	BA	BC	CB	CA	AC
1	4 or 1	1 or 4	3	2	2	3
2	2	3	3	2	1 or 4	4 or 1
3	2	3	4 or 1	1 or 4	3	2
4	1 or 4	4 or 1	2	3	3	2
5	3	2	2	3	4 or 1	1 or 4
6	3	2	1 or 4	4 or 1	2	3

Table 14-02

A six-position selector switch may be used which will allow any of the combinations (AB, BA, BC, etc.) shown to be selected. If the phasemeter used is graduated in quadrants 1 and 4 only, then a rotation of the switch until a reading is obtained ensures that the correct pair of signals will be selected, but ambiguity is now present as between AB and BA, BC or CB, and CA or AC. It is necessary to have all six combinations available on account of the direction of rotation of the meter. Consider a craft navigating a circular course starting from point P in Figure 14-08 and proceeding clockwise about the beacon as center. In sectors 1, the phasemeter reading changes from -90^{O} to $+90^{O}$ if the phase of B relative to A is measured (AB). In sectors 4 however, if the same phase difference (AB) is measured, the meter reading will change in the opposite sense, i.e. from $+90^{O}$ to -90^{O}. To avoid the necessity of having two phase scales reading in opposite directions, it is therefore necessary to have all six combinations available.

The ambiguity between two of the six switch positions may be solved by having a second or subsidiary phasemeter which indicates a reading only in the third (or second) quadrant. This involves the use of a second six-position switch ganged with

Switch Position	Main Meter	Subsidiary Meter
1	AB	AC
2	AC	BC
3	BC	BA
4	BA	CA
5	CA	CB
6	CB	AB

Table 14-03

Switch Position	Main Meter	Subsidiary Meter
1	3	4
2	4	2
3	2	2
4	2	1
5	1	3
6	3	3

Table 14-04
Meter indications for various switch positions, observer in sector 5b (point Q, Figure 14-08).

the first. The connections obtainable in the six positions of the switch, for both main and subsidiary phasemeters, are indicated in Table 14-03. Consider now an observer situated at (say) Q in sector 5b. The quadrants of the phase differences to be indicated by the two phase meters for each of the six switch positions are shown in Table 14-04.

If the main meter is graduated in only the first and fourth quadrants, and the subsidiary meter in only the third quadrant, it will be seen that only position 5 on the selector switch will give a readable indication, and the ambiguity is resolved.

The physical connections from the selector switch to the phasemeters will depend on the type of direct-reading phasemeter used. The procedure to be followed in obtaining a fix would then be as follows:

1. Tune receiver to selected beacon frequency.
2. Adjust output level if necessary.
3. Adjust phasing of rotary switch until meter M (Figure 14-06) reads zero.
4. Rotate six-position selector switch until a reading is obtained on both phasemeters.
5. Read main phasemeter, and note time.
6. The switch position gives the sector number (1 to 6, Figure 14-08) and the main phasemeter reading gives (by reference to a conversion table or chart based on Figure 14-05) the azimuth angle within the sector, yielding a position line.
7. Repeat the above procedure using another beacon. The intersection of the two position lines gives a fix.

It should be possible to make a good deal of the above procedure automatic if suitable control circuits are used.

Since the two lines of position are not obtained simultaneously, running fix technique will be necessary.

Bibliography

Identification	Classification	Title	Issued by
WA 781-6	Secret	Post-Office Engineering Department Radio Report No. 928	British Post-Office, London
WA 781-2	Secret	" No. 929	"
WA 1804-6	Secret	" No. 1077	"
WA 2523-5	Secret	" No. 1085	"

The A-N type of radio range has been very widely used in this country by civil aviation.

Each ground station sets up four tracks or ranges. This is accomplished by using a directional antenna system that can emit two different patterns. In Figure 15-01 these two patterns are indicated as the solid-line pattern and the dashed-line pattern. The transmitter power is keyed alternately from one pattern to the other. The keying is such as to produce A's (.-) from the solid-line pattern and N's (-.) from the dashed-line pattern. This keying is interlaced in such a way that an aircraft on the line OC would receive equal signals from the A and N patterns and a continuous tone would be heard. An aircraft on the line OE would receive an A signal proportional to the length OF and an N signal proportional to the length OG. Thus the A signals would predominate and the pilot would know that he was off course to the right if he is flying toward O.

The patterns of Figure 15-01 can be obtained by using two loops at right angles to each other. One loop will produce the "A" pattern and the other will produce the "N" pattern. These patterns may also be obtained by using four tower antennas located on the corners of a square. The diagonal of the square is small compared to a wavelength. Diagonally opposite towers are fed 180^{0} out of phase from a common feed point. Each diagonally opposed pair of towers will give a field-pattern similar to a loop. This system minimizes high-angle radiation and will therefore considerably reduce the sky-wave errors experienced with the crossed loops.

In Figure 15-01 the opposite courses are 180^{0} apart and the adjacent courses are 90^{0} apart. It is very seldom that four courses having this angular relationship are desired. The 90^{0} angle between adjacent courses may be modified by attenuating the energy fed to one loop or pair of diagonally opposed antenna towers thus yielding a pattern similar to Figure 15-02. The 180^{0} relation between opposite courses may be altered by adding an omnidirectional vertical antenna to the crossed loop system or at the center of the square of the 4-tower system to yield a pattern as shown in Figure 15-03. By proper adjustment these four courses can therefore be made to set up 4 airways leading from a city to other cities.

Most of the present A-N type "ranges" use the five-tower antenna system. The center tower is driven by a separate transmitter whose frequency is 1020 cps different from the transmitter driving the four corner-towers. The transmitter driving the central tower can be voice modulated for transmission of weather information. The voice-channel of the transmitter has a filter to eliminate frequencies of 1020 cps. The radio-range receiver has a 1020-cps band-pass filter which will discriminate against the voice modulation and give only the A-N signals. A 1020-cps band-stop filter in the receiver will reject the A-N signals and permit the voice modulation to be heard. The pilot can thus choose either the A-N signals or the voice modulation.

The radio "range" stations in the United States operate on frequencies between 200 kcps and 400 kcps. These stations are spaced approximately 200 miles apart. Every 30 seconds a code signal identifying the station is sent alternately on the A and N patterns. There are approximately 200 of these "range" stations in the United States.

The A-N type of radio range has been very widely used in this country by civil aviation.

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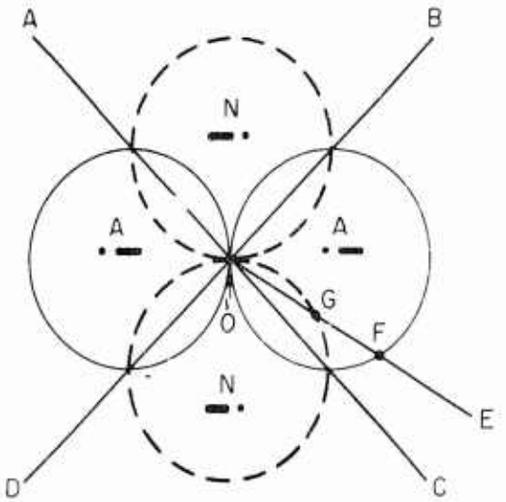


Fig. 15-01 Radiated patterns

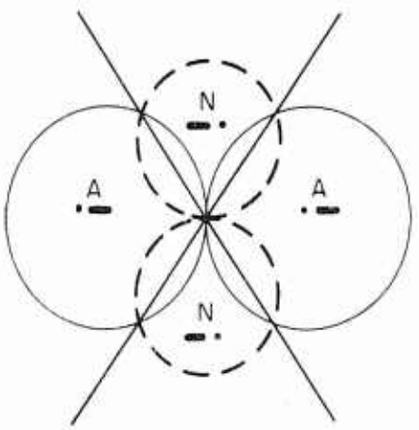


Fig. 15-02 Radiated patterns with course-shifting

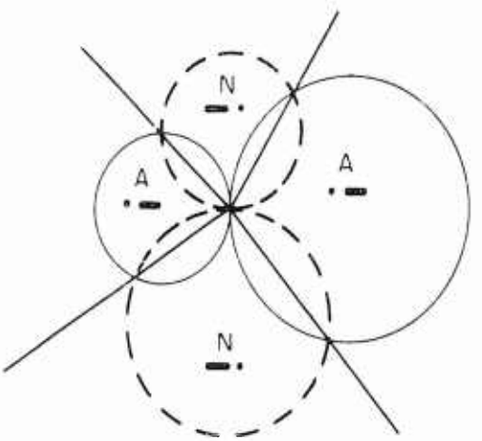


Fig. 15-03 Radiated patterns with course-bending

The multiple courses, bent courses, and night-time sky-wave errors experienced with the LF type of A-N radio range prompted the development of several VHF radio "ranges". Since the ground wave from a VHF radio "range" is attenuated very rapidly, course bends due to diffraction of the ground wave in passing over different terrain are no problem. Waves of this frequency are not reflected by the ionosphere and therefore there are no sky-wave errors. Interference patterns caused by reflections from hills and mountains are not as troublesome at these frequencies as in the LF system since the maxima and minima will be only a few feet apart. They will show up merely as a modulation on the signal.

As in the case of the VHF omnidirectional-beacon, horizontal polarization has been found to give the best results. Alford loops are used as radiating elements.

A four-course aural VHF "range" has been developed. Figure 15-04 gives the field patterns produced. These patterns are more efficient than the crossed figure of 8's produced by the LF "ranges" since the maximum energy is directed near the useful equisignal courses. Figure 15-05 is a block diagram of the system. The direction of the courses is shifted by rotating the whole array. The array is mounted 5/4 of a wavelength above a counterpoise screen 35 feet in diameter. All this is mounted on top of a 30-foot steel tower. The system operates on a frequency between 123 and 127 mcps with a power output of 300 watts. The transmitter is modulated 100% by a 1020-cps audio signal. Some of these VHF "Ranges" were installed on the New York to Chicago airway.

A two-course VHF radio range which gives visual indication to the pilot has also been developed. The antenna field patterns produced are given in Figure 15-06. The signal from the solid-line pattern is modulated with a 90-cps frequency and the signal from the short-dashed-line pattern is modulated with a 150-cps frequency. The output of the aircraft receiver is passed through two filters which select the 90-cps and 150-cps audio signals respectively. These two audio signals can be rectified and applied to the two windings of a differentially-wound zero-center meter to give course indication. Quadrant-identification is possible by the use of the long-dashed-line pattern and the dot-dash-line pattern. A 1020-cps signal is keyed to these two patterns in some specified code so that the pilot can identify which side of the "range" station he is on. A filter in the output of the receiver rejects the 90 cps and 150 cps signals and passes only the 1020 cps signal. The course indication can be used to operate an automatic pilot. It is proposed to install two parallel lines of these "range" stations along busy airways to provide two parallel courses for aircraft flying in opposite directions.

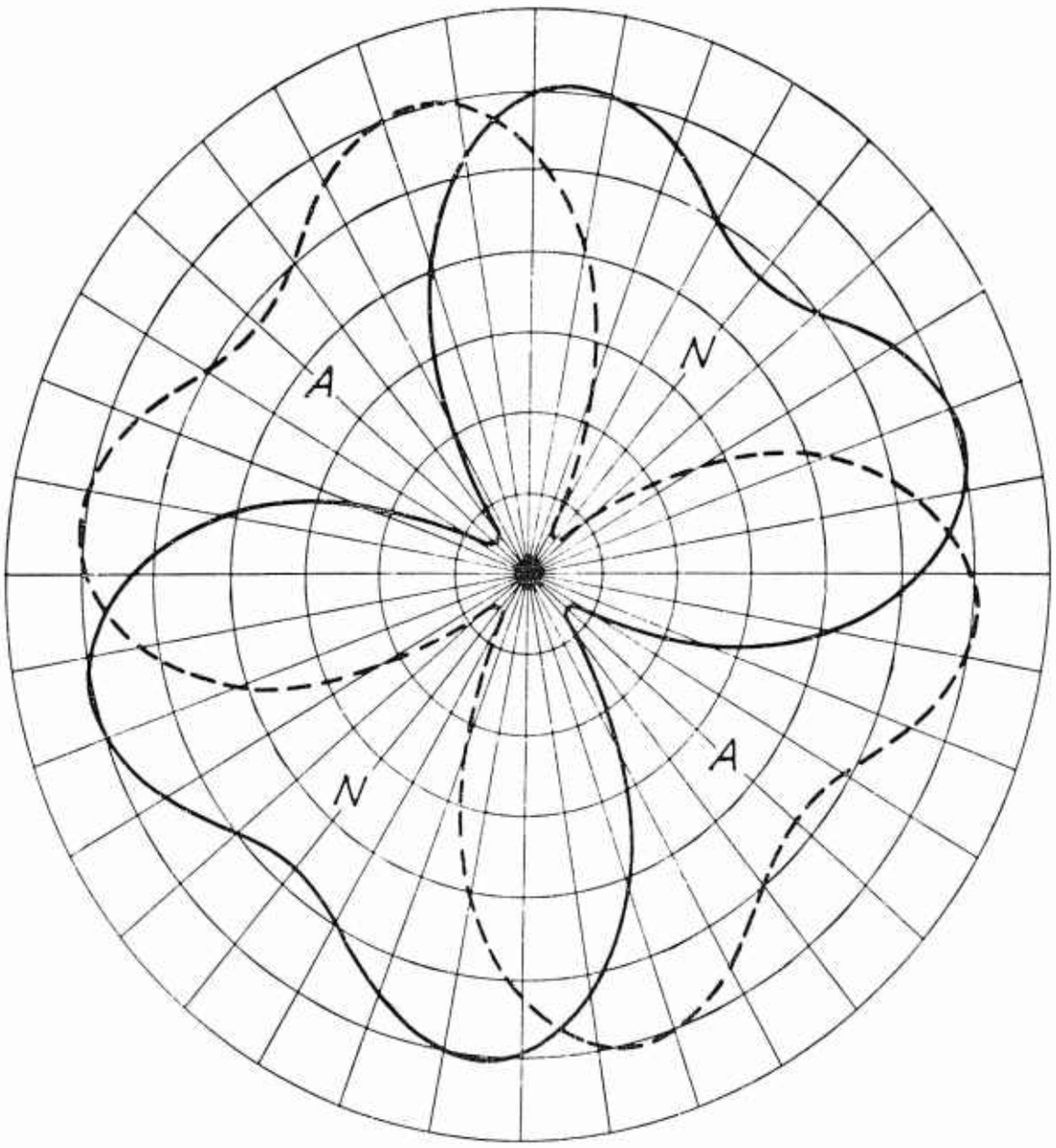


Fig. 15-04 Four-course VHF aural "range"

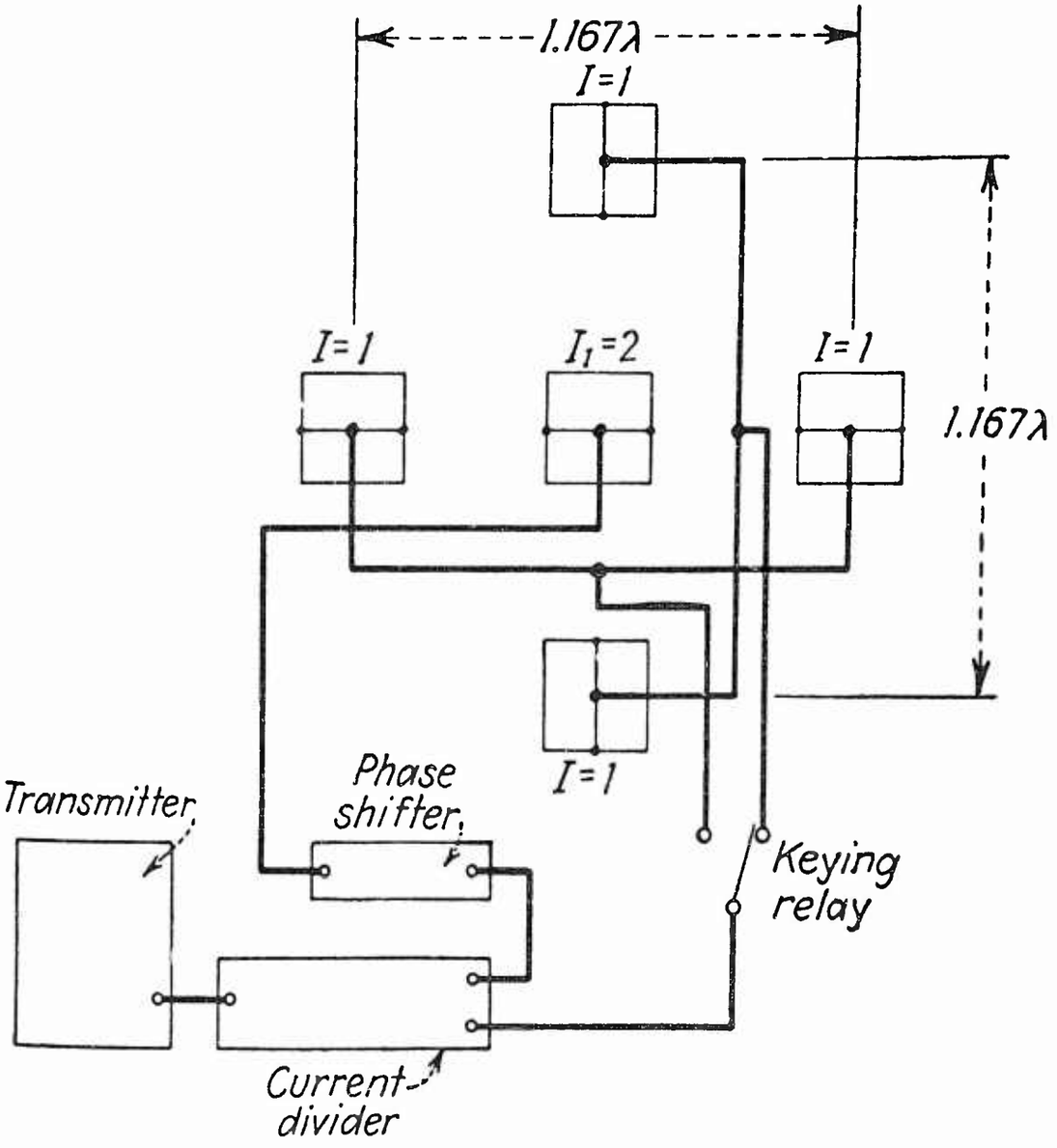


Fig. 15-05 Loop array of VHF aural "range"

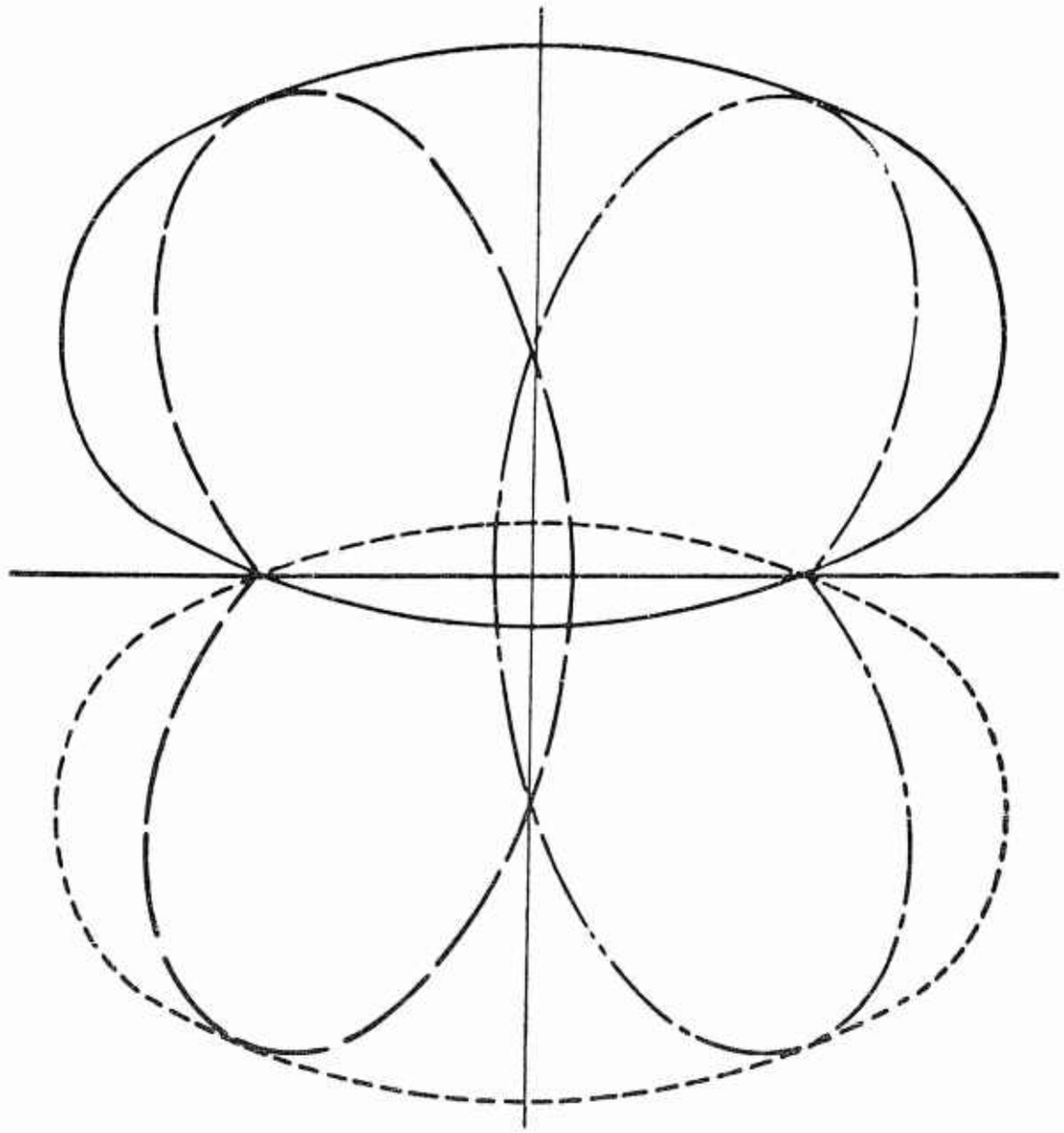


Fig. 15-06 Radiated patterns of two-course visual VHF "range"

CAA A-N Radio "Range"

Sandretto, P. C.: "Principles of Aeronautical Radio Engineering", pp. 24-71, McGraw-Hill Book Company, Inc., New York, 1942.

CAA VHF Radio "Ranges"

Sandretto, P. C.: "Principles of Aeronautical Radio Engineering", pp. 72-105, McGraw-Hill Book Company, Inc., New York, 1942.

There are numerous aircraft direction-finders and homing systems. While these systems could be used on other types of craft they have been used principally on aircraft in the past.

Figure 16-01 illustrates the principle of a homing system. A loop and non-directional antenna are used to give a cardioid response-pattern. The maximum of this cardioid can be shifted from the right side of the craft to the left by reversing the loop connections. The two response patterns obtained are shown as the solid and dotted patterns of Figure 16-02 (a).

The cardioid pattern results from the addition of the signal from the loop-pattern Figure 16-02 (b) and the signal from the non-directional antenna pattern Figure 16-02 (c). However, the signal from the loop is 90^{O} out of phase with the signal from the non-directional antenna. In compensation it is necessary to introduce a 90^{O} phase-shift in one of the channels.

In Figure 16-01 the loop signal is alternately reversed by the action of the motor-driven reversing-switch. The output of the receiver is alternately connected to the two coils of a differentially-wound zero-center DC meter in synchronism with the reversing of the loop input. In Figure 16-02 (a) OA represents the longitudinal axis of the aircraft. If the desired station lies along the line OB the signal when the dotted pattern is switched on will be proportional to OC and the signal will be proportional to OD when the solid pattern is switched on. Thus, a larger signal is applied to one coil of the differential meter than to the other coil. The connections are such that the meter deflects to the right indicating that the desired homing-station lies to the right of the heading of the craft and that the craft should be turned to the right to home on the station.

If the loop is rotatable the system can be used as a manual direction finder

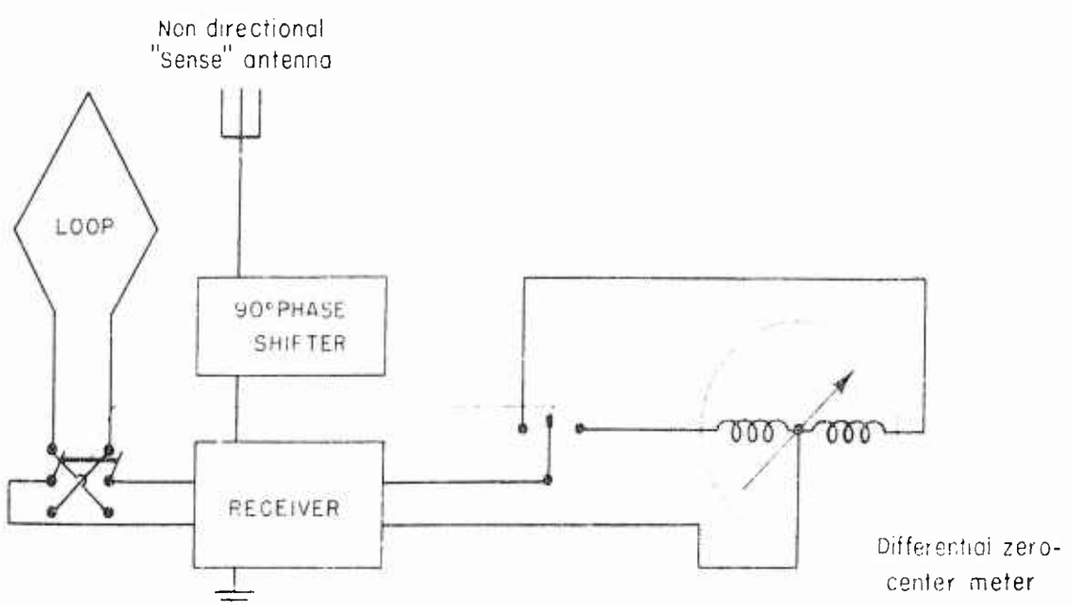


Fig. 16-01 Principle of switched-cardioid homing system

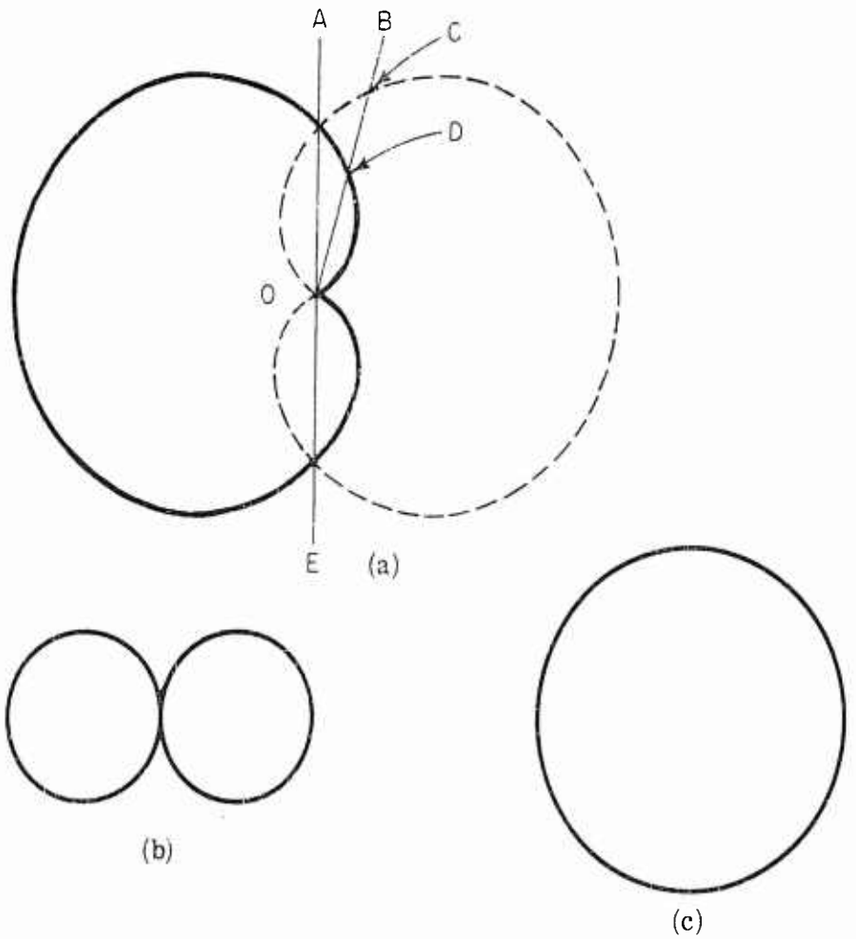


Fig. 16-02 Loop and antenna response patterns

by rotating the loop until the meter reads zero. "Sense" can be determined by noting the relative motion of loop and meter pointer. If a bearing is taken with OA pointing to the station a slight rotation of the loop to the left will give a meter deflection to the right. However, if the station is in the direction OE the pointer will deflect in the same direction as the rotation of the loop.

In practice the mechanical switching-system of Figure 16-01 is replaced by an electronic switching-system similar to Figure 16-03. The loop-signal is amplified by a tuned radio-frequency amplifier. This amplified loop-signal is then applied to a balanced modulator which performs the switching. This switched loop-signal is combined with the signal from the non-directional "sense" antenna which has been shifted 90^{0} in phase and applied to the receiver. The output of the receiver is applied to a directional rectifier (balanced modulator). This circuit is also supplied with audio frequency from the same source that supplies the RF balanced modulator. The output of this directional rectifier operates a zero-center DC meter.

Figure 16-04 is the block diagram of a typical self-orienting automatic direction-finder. The loop-signal is amplified by the tuned-RF loop-amplifier. The amplified loop-signal is applied to a balanced modulator. The output of the balanced modulator, which consists of only the two side-frequencies, is combined

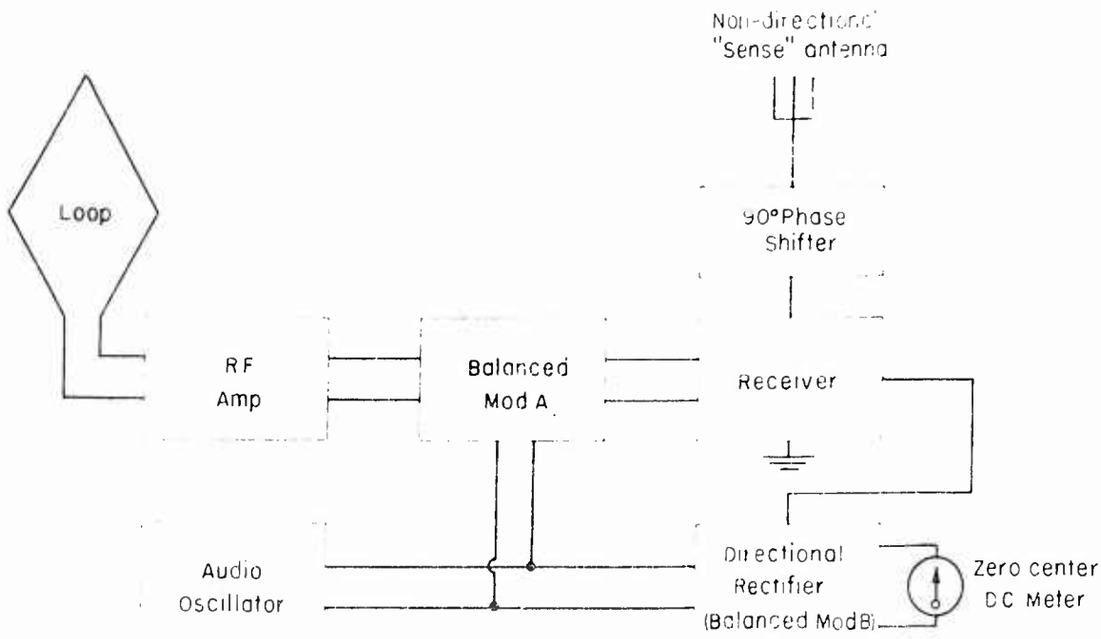


Fig. 16-03 Block diagram of homing system

with the signal from the non-directional antenna which has been shifted 90° in phase. The resulting amplitude-modulated wave is amplified and detected by the receiver. The audio output is filtered by a bandpass filter to remove all modulation frequencies but that produced by the balanced modulator. This is to avoid overload of the motor control circuit by audio modulation and noise. If either of the nulls of the loop are pointing to the station the audio output will be zero. When the loop swings through a null the phase of the audio signal reverses. The audio output and the AC from the same source that supplies the balanced modulator are applied to the motor-control circuit. An antihunt voltage proportional to the derivative of the error is applied in series with the audio voltage. This antihunt voltage is obtained from an armature-reaction rate-generator.* This motor-control circuit controls a reversible two-phase motor which rotates the loop. The direction and speed of the motor depends upon the phase and amplitude of the audio signal resulting from the loop switching. This motor will rotate the loop to a null. Only one of the nulls of the loop will yield a condition of stable equilibrium. The loop position is repeated to the instrument panel by a flexible shaft or synchro-mechanism. This equipment may be used for homing by maintaining zero relative bearing to the station.

Figure 16-05 is the block diagram of an automatic direction finder that employs a rotating loop or equivalent. The loop is rotated continuously by a driving motor. This driving motor also drives a reference-phase generator. The signal from the rotating loop is amplified by a tuned radio-frequency amplifier and is then combined in the antenna coupling-circuit with the signal from the non-directional antenna which has been shifted 90° in phase. The signal from the rotating loop will be amplitude modulated but will contain only the two side-frequencies. Instead of a rotating loop two crossed loops and a goniometer may be used. The rotor of the goniometer is driven by the driving motor.

* See Bond, D. S.: "Radio Direction Finders", pp. 201 ff.

The carrier is re-supplied from the non-directional antenna. This is equivalent to rotating a cardioid response pattern at driving motor speed. The signal supplied to the receiver is an amplitude modulated signal. The phase of the modulation envelope depends upon the direction of the station being received. The audio output phase is compared with the phase from the reference-phase generator in some type of phase-meter or comparator. It would also be possible to use two crossed loops each feeding a balanced modulator. The modulating voltage would be applied to these two balanced modulators 90^0 out of phase. This would give in effect an electronic goniometer.

Two automatic direction-finders could be used to take continuous bearings on two stations and this information might be used in an automatic computer to give a continuous fix. A system of this type is described in Section 18.

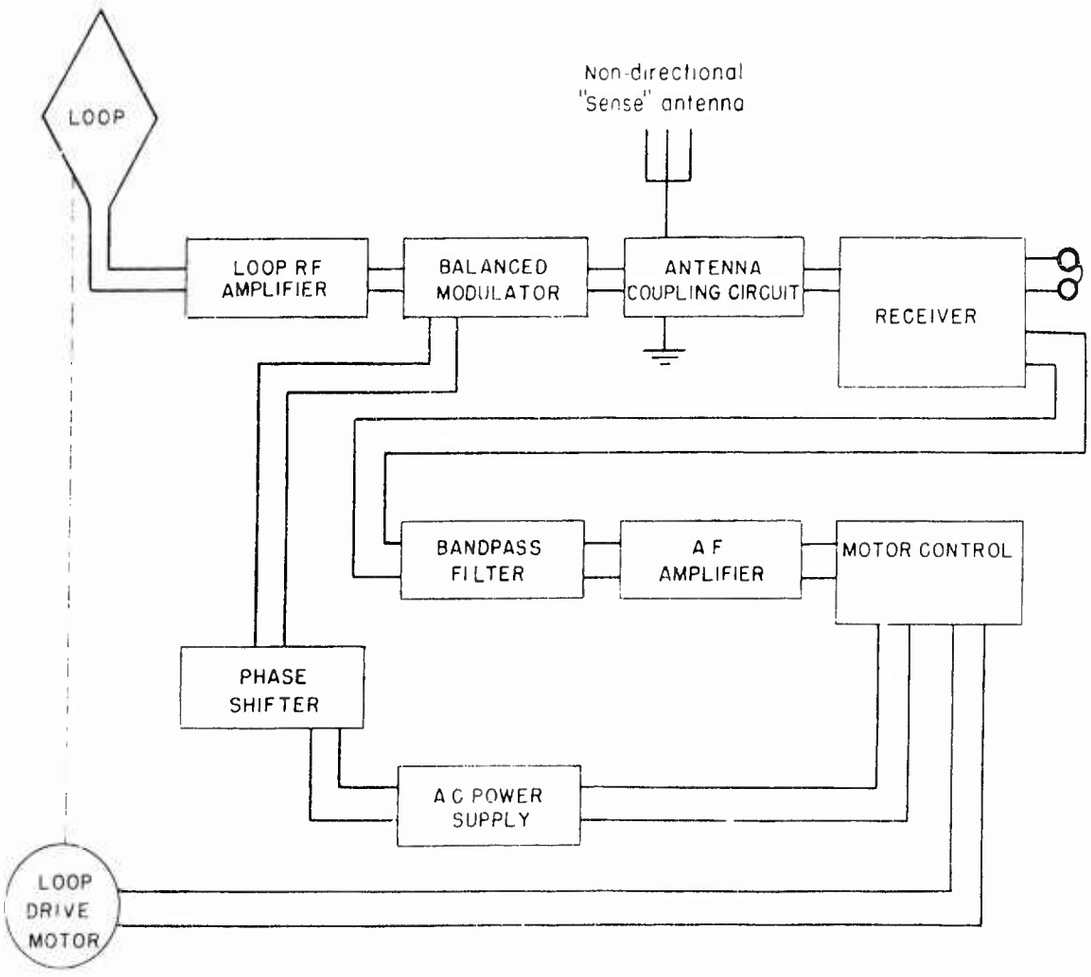


Fig. 16-04 Block diagram of self-orienting direction-finder

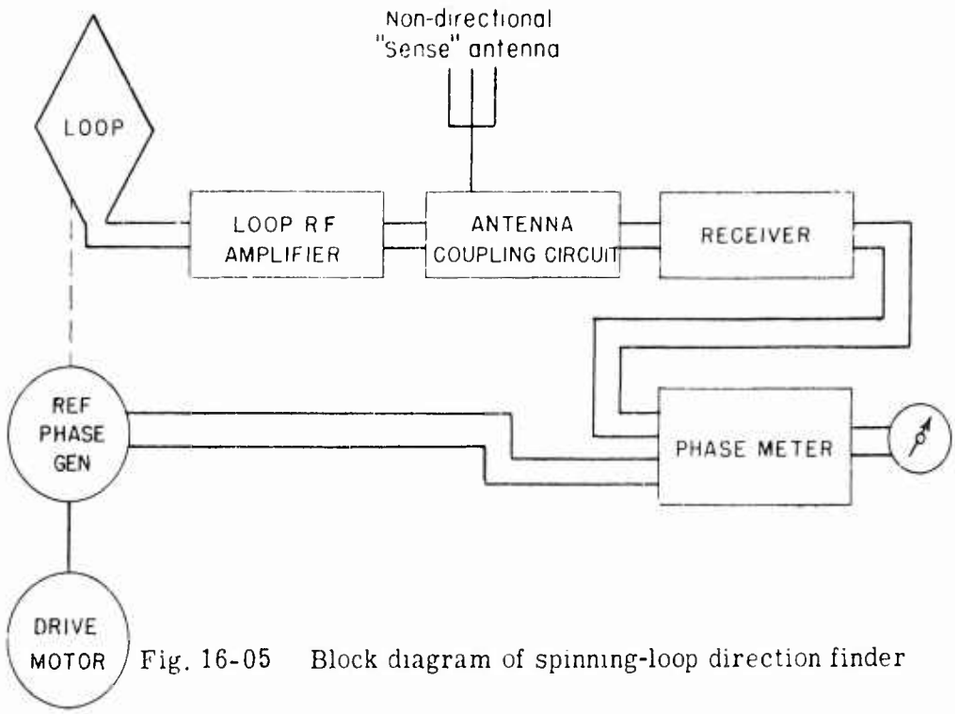


Fig. 16-05 Block diagram of spinning-loop direction finder

Aircraft Direction Finders and Homing Systems

Bond, D. S.: "Radio Direction Finders", pp. 117-149 and pp. 171-230, McGraw-Hill Book Company, Inc., New York, 1944.

Sandretto, P. C.: "Principles of Aeronautical Radio Engineering", pp. 106-142, McGraw-Hill Book Company, Inc., New York, 1942.

SONNE (CONSOL)

Type of System

Azimuth, giving radial lines of position.

Useful Range

Depends on transmitter power and location of craft. Figures based on a number of observations of German transmissions are:

Day 1000 miles
Night 2000 miles } transmitter power 1.5 kw, transmission over water.

Owing to the frequency used, there are no altitude limitations at a distance. However, aircraft close to the source of transmissions will be subject to errors in position due to geometrical considerations. (See Section 1)

Accuracy and Precision

The best theoretical precision is approximately $1/6^{o}$ azimuth in a line of position.

Results of a number of test observations indicate an average operational accuracy of 1.7^{o} by day and 2.3^{o} at night, corresponding to errors of 15 and 20 miles at 1000 miles range in a line of position. Ambiguity exists between alternate sectors, and must be solved by an approximate knowledge of position obtained from dead reckoning based on previous bearings or from D/F observations. Large errors have been observed at sunrise and sunset.

Type of Presentation

Aural. The operator counts the number of dots and dashes during a one-minute cycle.

Operating Skill Required

A feature of this system is that the complexity of the operations and equipment on the craft have been reduced to a minimum. No skill is required beyond the ability to tune a communications radio receiver, plus the ability to listen, count, add, subtract, and use charts.

At the ground installation, skilled monitoring is desirable.

Two minutes are required for determination of a line of position. A fix should be obtainable in four to six minutes.

Equipment Required

At the ground station: Transmitter of about 1.5 kw, specialized phasing and keying gear, two or three antenna towers of height 150 - 350 feet with the necessary transmission lines, monitoring equipment. On the craft: Standard communications receiver.

Frequency

250 - 500 kcps (wavelength 1200 - 600 meters).

Bandwidth Required

Less than that of the usual communications receiver. 1 kcps per ground station.

Present Status

The Sonne system has been used extensively by the Germans during the last two years of the war. The Allied Air Forces have also found the system reliable and

useful. Sonne is considered by many qualified persons to be in certain respects superior to Loran as a long-distance navigational aid for general use. British use of German Sonne transmission is usually referred to as Consol. Prior to the Japanese surrender a modified Sonne system (AN/FRN - 5) was under development for fighter navigation in the Pacific theater.

Principles of Operation

A Sonne station radiates a multi-lobed pattern in which, by phase-switching and phase-shifting of the transmissions from three spaced antennas, certain "equisignal" lines relative to the station are defined. These lines move slowly in position over a period of one minute. By counting the number of dots and dashes heard before and after the passage of the equisignal during this period, the operator at the craft is able to locate himself with regard to the ground station, obtaining a line of position. Another such observation yields a second line of position on a different station, and thus a fix is obtained.

The ground station uses three antennas (A, B, and C in Figure 17-01). The spacings between A and B, and between B and C, are equal and are usually of about three wavelengths. A variety of arrangements as to phasing and amplitude of antenna currents is possible, but that used by the Germans is illustrated in Figure 17-02 (a) and (b). The amplitudes of the currents in antennas A and C are equal, and are one-fourth (other fractions may be used) of that in antenna B. At the start of a one-minute phase-shifting period, the phase relations are as indicated in Figure 17-02 (a). Taking the A current as phase reference, the C current has a phase of 180° with respect to A, while B is at $+90^{\circ}$. At the end of the first 5/6 second of the phase-shifting cycle the phases of A and C are suddenly reversed. After an additional 1/6 second the phases of A and C are suddenly returned to their original positions (ignoring for the moment the relatively slow superimposed phase-sweep described below). This phase-keying sequence is repeated at one-second intervals throughout the one-minute phase-shifting period. At the same time, the phases of A and C are moved slowly and uniformly in opposite directions, so that after 10 seconds, the A and C phases would be as shown in Figure 17-02 (b), and after 60 seconds the A and C phases would each have changed by 180° and would be reversed with respect to their initial positions in Figure 17-02 (a). At the beginning of the next phase-shifting period (after a further interval of one minute) the phases start again from the positions of Figure 17-02 (a). The complete sequence of events in a two-minute cycle is as follows:

Phase-shifting and keying in the manner described	for	60 seconds
Silent period (no transmission)	for	1 second
Steady transmission from the center antenna alone including an identification signal	for	56 seconds
Silent period (no transmission)	for	3 seconds
		120 seconds

The complete sequence therefore lasts for two minutes, and bearings cannot be taken closer in time than this interval.

Considering the radiation pattern at the start of the 60-second phasing period, the current in antenna B leads that in antenna A by 90°, and that in antenna C leads by 180° (Figure 17-02 (a)). The radiated pattern is then similar to Figure 17-03 which is drawn for an antenna spacing of 3 wavelengths, amplitude of A and C currents one quarter of amplitude of B current. If the phases of A and C were reversed the pattern would be as shown in Figure 17-04. It will be seen that maxima in Figure 17-04 occur at the same azimuth angles as minima in Figure 17-03 and vice versa. The pattern is symmetrical with regard to the line of antennas, but not with regard to a line perpendicular to them. If now the phase reversal of the A and C currents

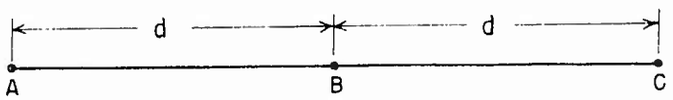


Fig. 17-01 Spacing

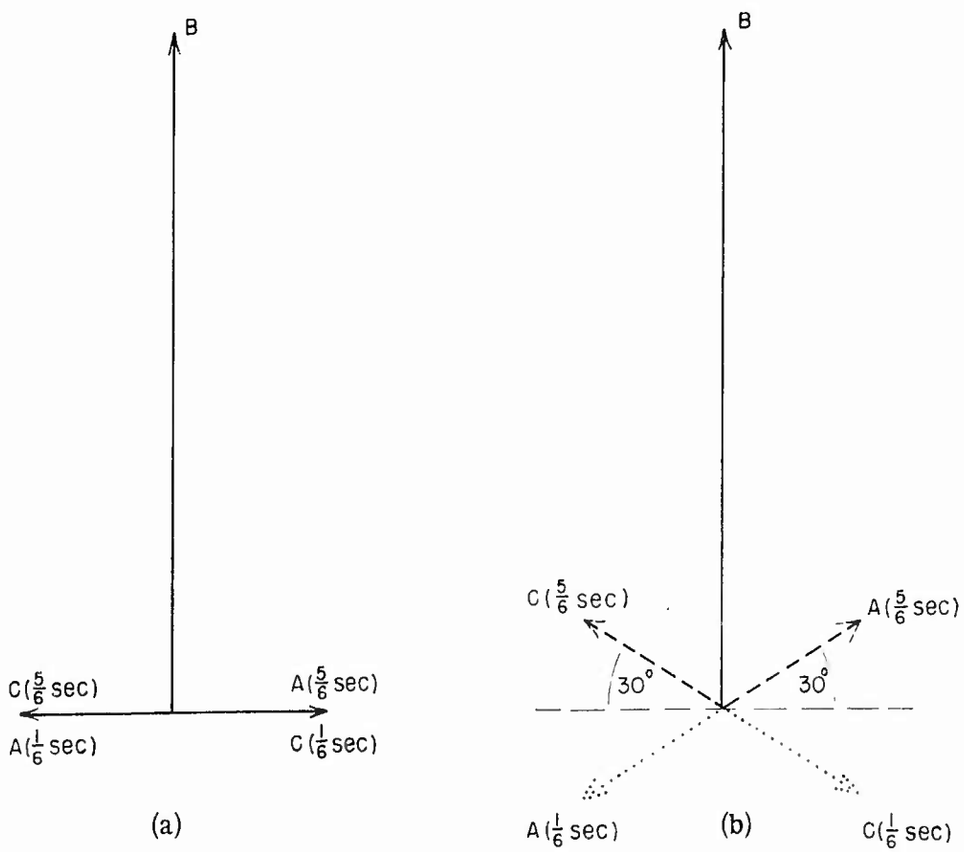


Fig. 17-02 Phasing

were to take place without any change in the phase of B, the patterns of Figures 17-03 and 17-04 would alternate. This is illustrated by Figure 17-05, in which the two patterns are superimposed. (Figure 17-03 contributes the dashed line, Figure 17-04 the full line). Since Figure 17-03 would obtain for 5/6 second intervals and Figure 17-04 for 1/6 second intervals, Figure 17-03 will be referred to as the "dash pattern" and Figure 17-04 as the "dot pattern".

An observer on a craft located at P (Figures 17-03, 17-04, 17-05) will receive stronger signals during the 5/6 second intervals when the dash pattern obtains than during the 1/6 second intervals corresponding to the dot pattern. He will therefore hear a series of dashes. An observer in the direction OQ will hear dots by similar reasoning. In the direction OR, both patterns yield signals of the same strength and

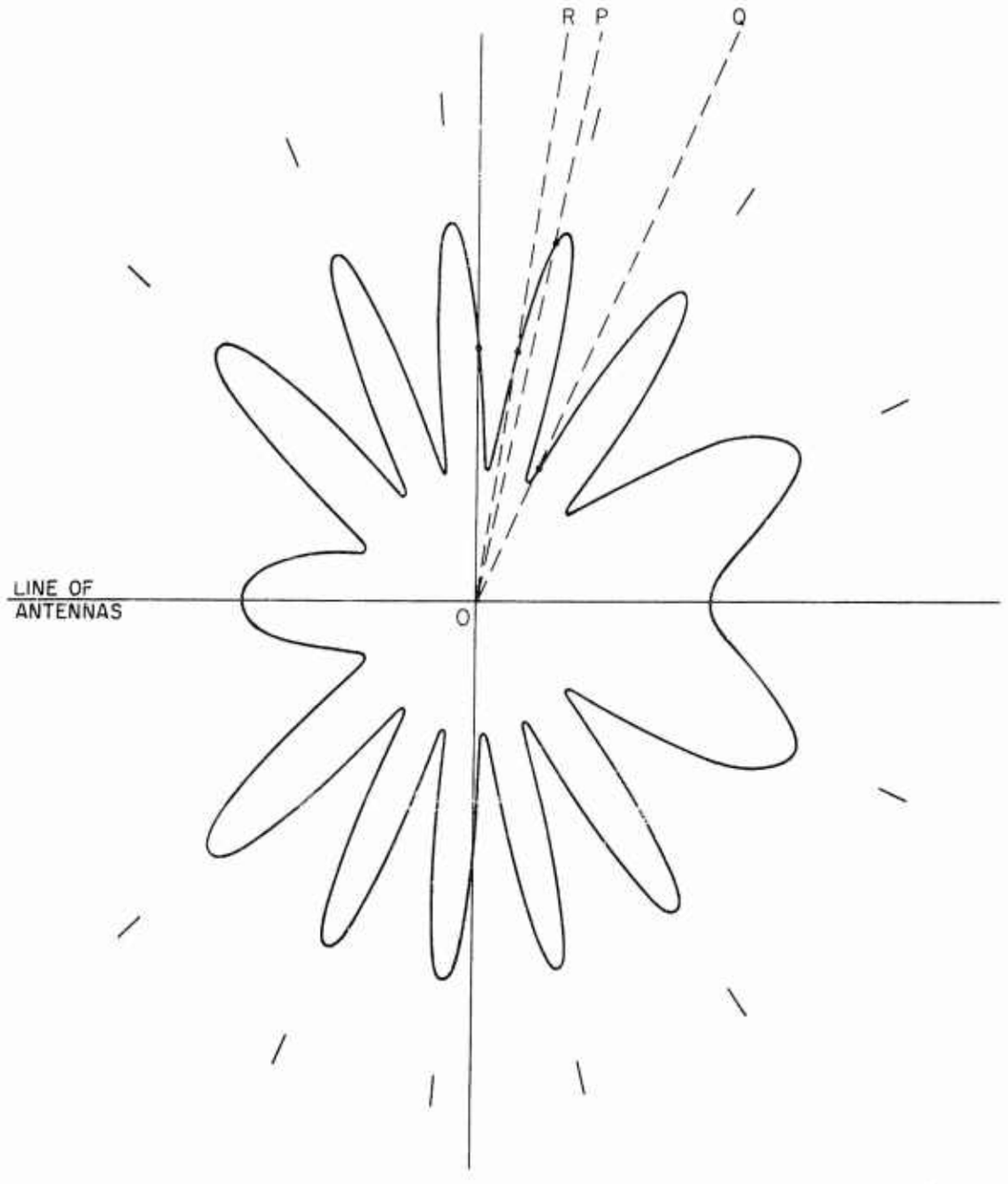


Fig. 17-03 Dash pattern

a continuous signal will therefore be heard. This is referred to as an equisignal. The alternation of the two patterns therefore determines a number of equisignal lines characterized by equal signal strengths from the dot and dash patterns. These equisignal lines are shown in Figure 17-05.

In this relatively simple form, which includes no phase-sweep, the system provides a navigational aid known as Elektra. Elektra was used by the Germans in 1940-41 and Sonne was developed from it. The difference between Sonne and Elektra lies in the slow progressive shifting of the phases of the currents in the two outer antennas. The effect of this slow and uniform phase shift in the A and C currents is to cause a rotation of the equisignal lines. Starting from the beginning of the 60-second phase-shifting period, the equisignals are first as shown in Figure 17-05. The equisignals

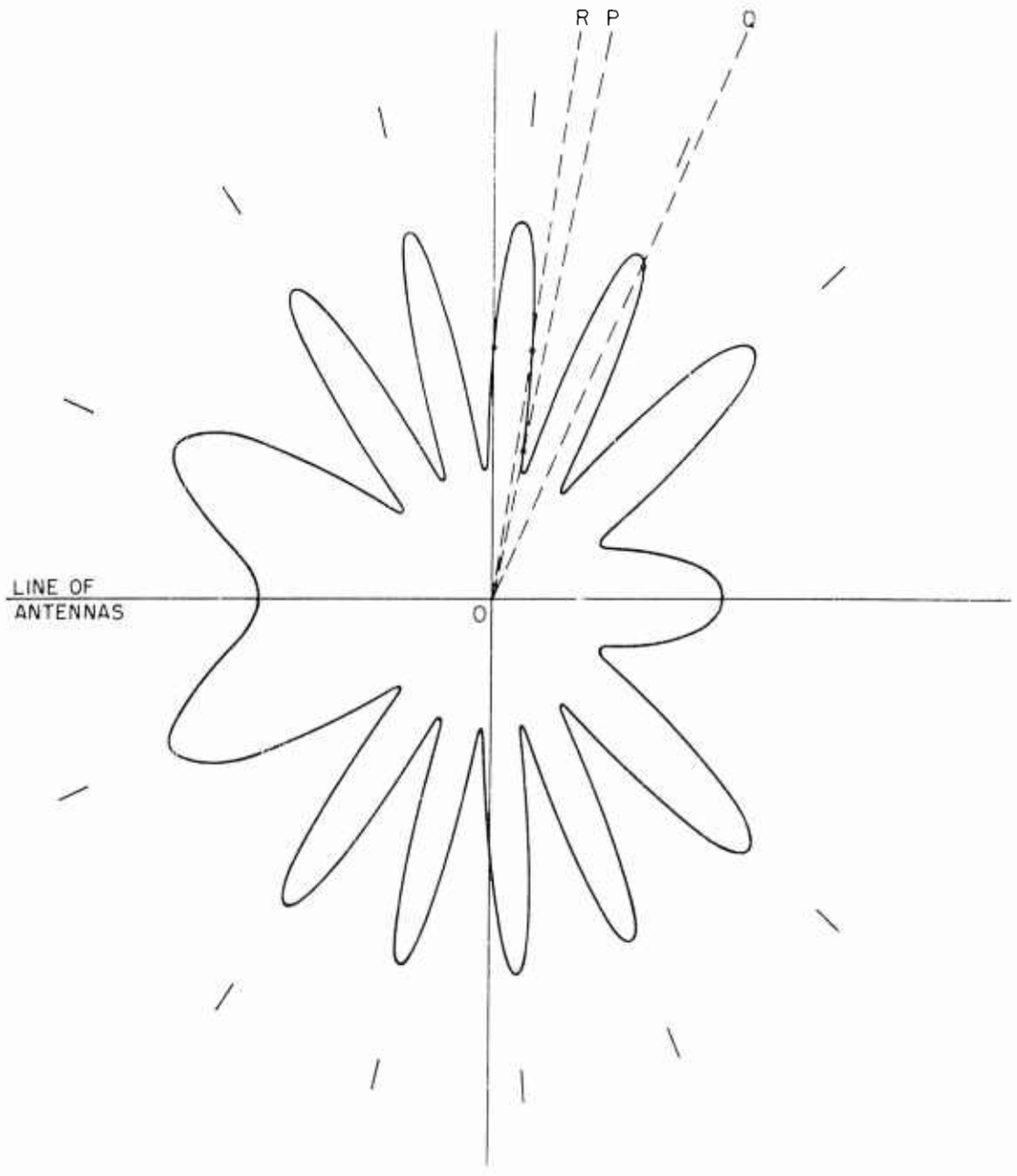


Fig. 17-04 Dot pattern

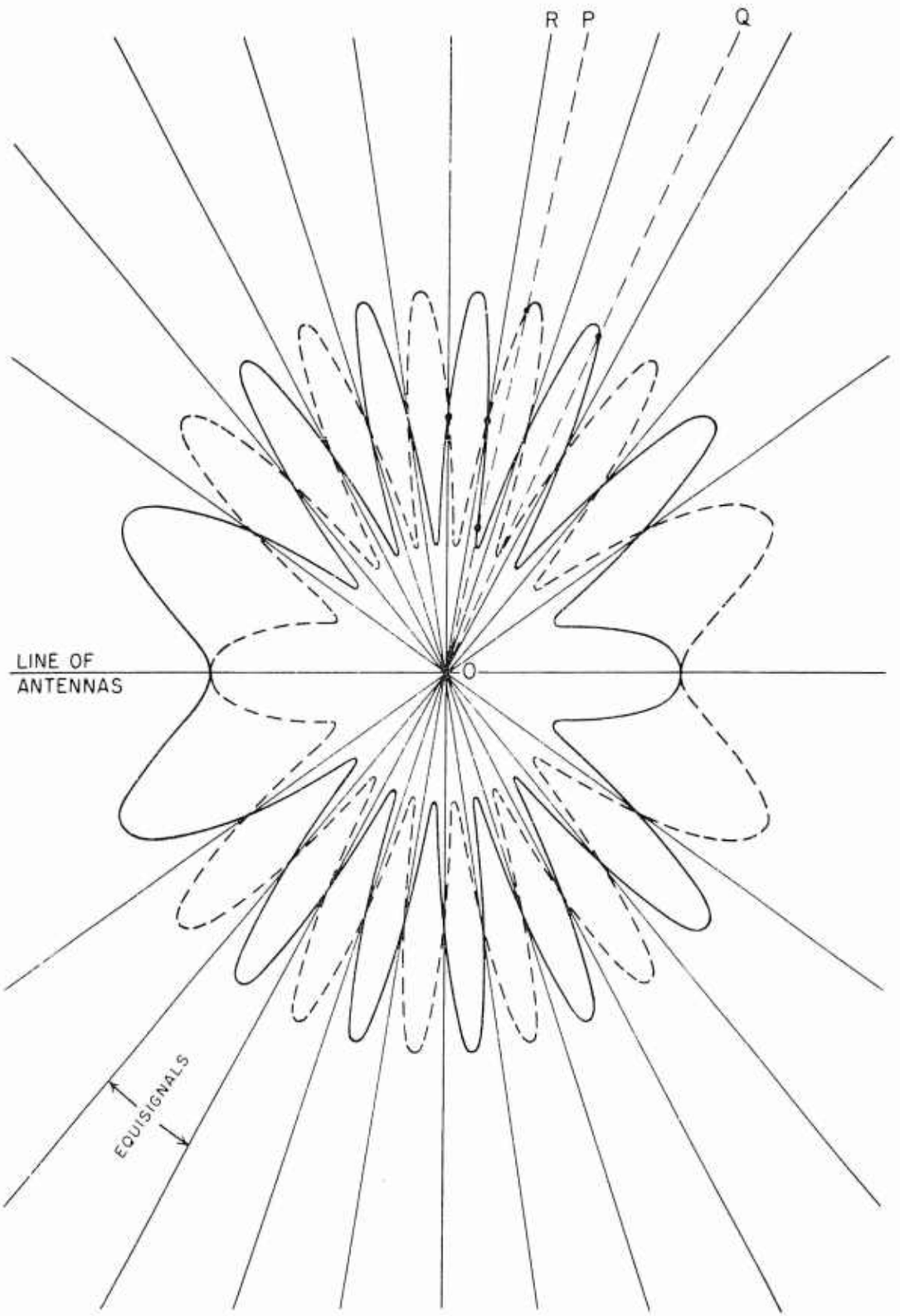


Fig. 17-05 Dot and dash patterns superimposed

in the top half of Figure 17-05 then move clockwise, and those in the lower half counter-clockwise, until at the end of the 60-second period each equisignal now occupies the position originally occupied by the adjacent equisignal to the right. At the left side of the dash pattern, the small lobe expands and divides; and at the right side the two large lobes contract into one small lobe. Corresponding changes take place in the dot pattern, so that at the end of the 60-second period the two patterns have become interchanged.

Considering effect of these changes on an observer situated on (say) OP, the sequence of events will be as follows:

(a) At the start of the cycle, dashes will be heard
(b) Dashes decrease in contrast (5/6 second and 1/6 second signals become more nearly equal) until
(c) Equisignal is heard.
(d) After the equisignal, dots are heard, at first increasing in contrast and then decreasing slightly until the end of the 60-second period occurs.

These changes are graphically represented in Figure 17-06, in which the time intervals are not drawn to scale. During the 3-second silent intervals there is no transmission from any of the antennas, and during the 56-second steady signal, only the center antenna is used.

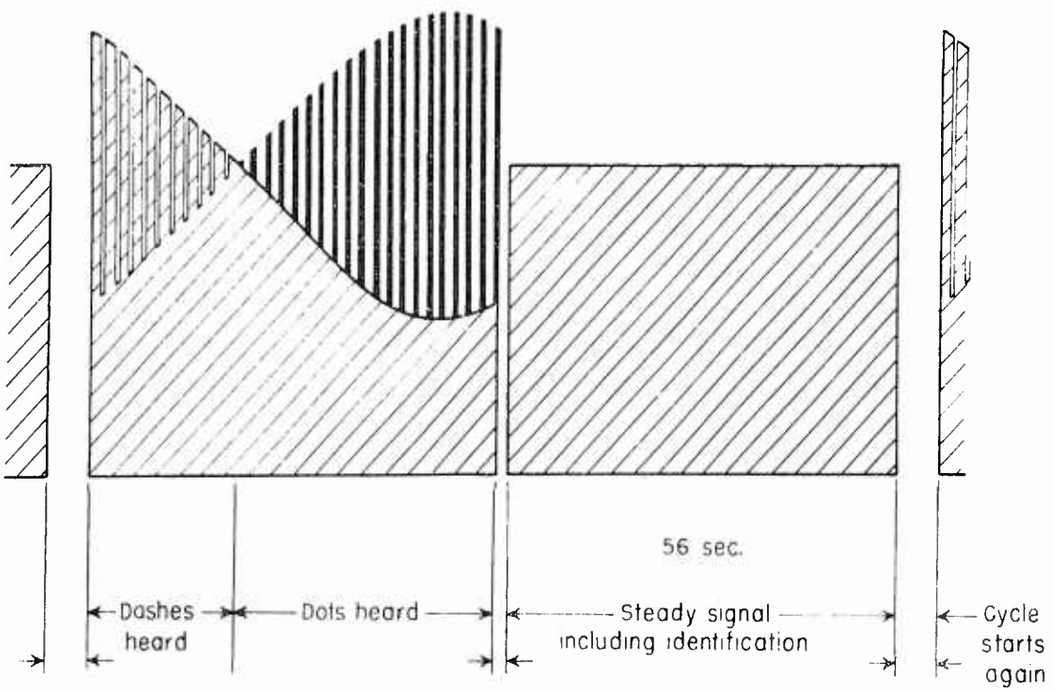


Fig. 17-06 Transmission sequence

Provided the operator knows his approximate position, a knowledge of the number of characters heard (dots or dashes) before the equisignal, and of the initial and final positions of the equisignal concerned, together with suitable means for interpolation, enables a line of position to be determined.

Since in general the equisignal will not be sharply defined, and may appear to last several seconds, the operator counts both (a) the number of dashes (or dots) heard before the equisignal and (b) the number of dots (or dashes) heard after the equisignal. These are added and the total subtracted from 60 (the number of characters transmitted) giving the apparent length of the equisignal. Half of this latter figure is then added to the (a) count so as to determine as nearly as possible the true interval before the equisignal. For example, the observer at P might have counted as follows:

13 dashes
Equisignal
41 dots

The computation is then as follows:

13	60 = characters transmitted
41	54
54 = characters heard	6 = apparent length of equisignal

$13 + \frac{6}{2} = 16$ = true number of characters before equisignal.

Charts are provided on which position lines marked in degrees azimuth from Sonne stations are overprinted in color. Keys or tables are also provided by means of which the azimuth line of position corresponding to a given count within a given sector can be obtained. A sketch of the central portion of such a key is shown in Figure 17-07. The advantage of this procedure is that if it should become necessary to change the phasing of the antenna currents in order to modify the pattern for security or other reasons, only new keys and not new charts are required.

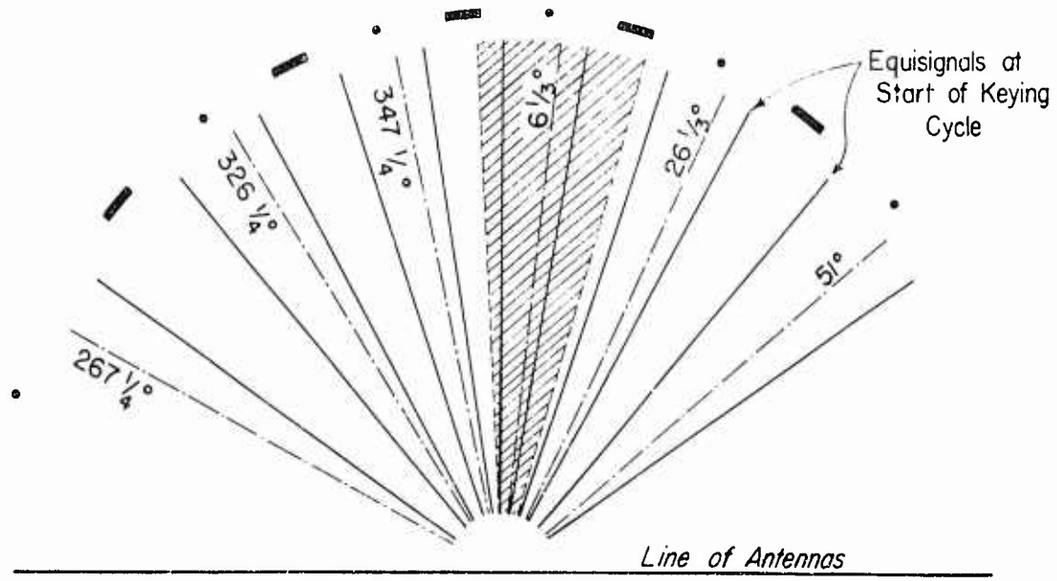
It will be seen that ambiguities exist. The above count could have been obtained in any of the dash sectors of Figure 17-05. In the patterns shown, the minimum angular separation between equisignals is 9.6°. The ambiguity is thus between position lines whose minimum separation is 19.2°. It is therefore necessary for the craft to know its bearing on the Sonne station to within 9.6° or better. This may be done by a rough D/F measurement on the steady 56 sec. signal or the position may be approximately found by dead reckoning, a knowledge of the existing course and speed since a previous observation then being necessary. Regarding the extent of the ambiguity, adjacent dash sectors (or adjacent dot sectors) are separated by a minimum angle of about 19°. The maximum error permissible in the D/F measurement used to solve the ambiguity is however only half this figure. A consideration of Figure 17-07 will illustrate this point.

Suppose that a navigator makes a count of 40 dots preceding the equisignal and 20 dashes following it. The fact that the dots were heard first locates him in a dot sector. The fact that 40 dots were heard locates him at a particular azimuth within a dot sector. This azimuth is read from a key or table attached to the actual chart. The central portion of such a key, somewhat compressed in scale and with the finer markings omitted, is shown in Figure 17-07 (b). On an actual key, azimuth angles corresponding to the line of antennas of the particular Sonne station are read from the angular scale direct. In Figure 17-07 (b), it is assumed for convenience that the line of antennas runs from west to east, so that the central equisignal points due north.

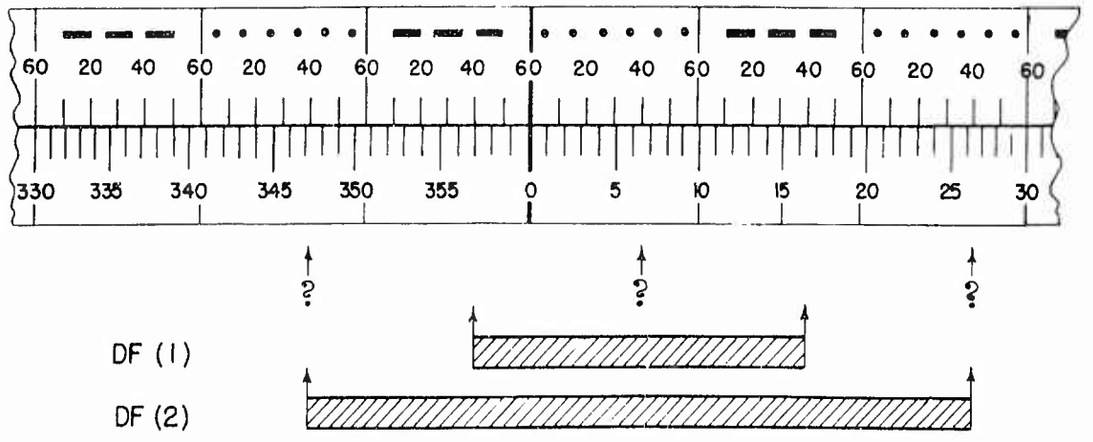
The count obtained therefore gives the navigator the following choices in line of position on the north side of the pattern.

$$6\tfrac{1}{3}^{\circ},\ 26\tfrac{1}{3}^{\circ},\ 51^{\circ},\ 267\tfrac{1}{4}^{\circ},\ 326\tfrac{1}{4}^{\circ},\ 347\tfrac{1}{4}^{\circ}$$

These lines of position are shown as dashed lines in Figure 17-07 (a).



(a)



(b)

Fig. 17-07 Sector ambiguity

Suppose further that the maximum error to be expected in the D/F observation is the same as the angle of ambiguity, i.e., 19°. Then the situation may be represented at (2) in Figure 17-07 (b), where the D/F reading might give an azimuth indication anywhere within the shaded range. Remembering that the D/F reading may give the extreme values of $347\frac{1}{4}^{o}$ or $26\frac{1}{3}^{o}$, and that the navigator has only one reading at his disposal and will take the position line nearest this reading, it is seen that he might easily choose $347\frac{1}{4}^{o}$ or $26\frac{1}{3}^{o}$ as the final reading. If however, the maximum error to be expected in the D/F observation is reduced to $9\frac{1}{2}^{o}$, the situation will be as represented in the shaded area of Figure 17-07 (a) or at (1) in Figure 17-07 (b). Even an extreme D/F reading will indicate to the navigator that his correct azimuth bearing is $6\frac{1}{3}^{o}$. The maximum allowable error in the D/F reading is therefore one half of the minimum angle of ambiguity.

Since observations cannot be taken closer in time than two minutes, running fix technique may be necessary.

It should be noted that Sonne transmissions as here described are unmodulated (C.W.). The receiver used should therefore include a beat-frequency oscillator. If receivers without beat-frequency oscillators are to be used, then provision for modulation at the transmitter must be made.

This concludes the general discussion of the system. Some notes on the geometry of the radiation pattern, and on factors affecting it, will now be given, together with information as to the transmitting equipment used, a discussion of transmitter errors and tolerances, and an outline of a proposed two-antenna system.

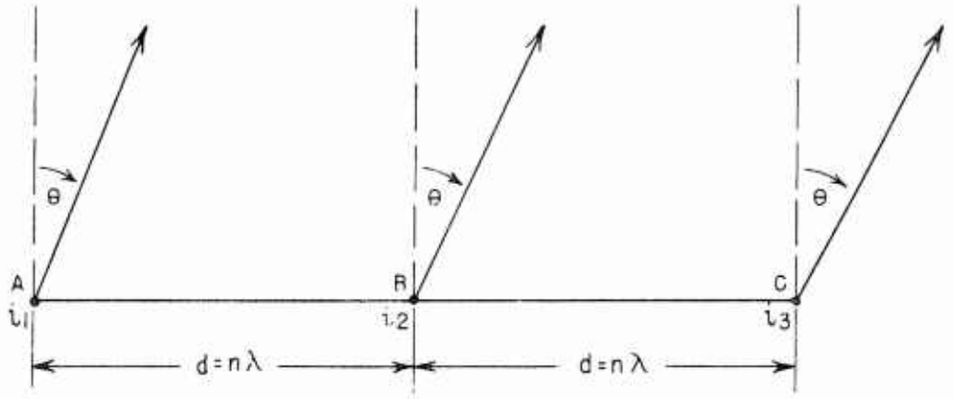


Fig. 17-08 Three-antenna Sonne

$i_1 = \pm A \sin(\omega t + \phi)$ $\quad i_2 = B \cos \omega t$

$i_3 = \mp A \sin(\omega t - \phi)$

$B/A = p$ $\quad$ spacing $= n\lambda$

$\phi = (\frac{\pi}{60})t$ radians, t measured in seconds

Field strength at a distant point P of azimuth angle θ

$E = k.\cos \omega t. [B \pm 2A \sin(\phi - 2\pi n \sin \theta)]$

where k is a constant determined by the distance of P from the array and by propagation conditions.

The radiation pattern of Sonne

Many arrangements yield multi-lobed patterns of the type described. Two basic arrangements are here discussed:

(1) three antennas, equally spaced, equal currents in the two outer antennas, phased as indicated in Figure 17-03. This is the system used by the Germans.
(2) possible two-antenna arrays yielding the same results as (1).

Three antenna Sonne

Let the spacing $d = n\lambda$. Note that n need not be integral. The currents in the three antennas are $i_1 = \pm A \sin(\omega t + \phi)$; $i_2 = B \cos \omega t$; $i_3 = \mp A \sin(\omega t - \phi)$. (See Figure 17-08). The + and - signs in i_1 and the - and + signs in i_2 yield the dash and dot patterns quoted previously if the upper sign obtains for 5/6 sec. and the lower sign for 1/6 sec. The phase-shift ϕ in the outer antennas is given by $\phi = (\frac{\pi}{60})t$ radians where t is measured in seconds from the start of the phase-shifting period. The ratio of the current amplitudes is denoted by $B/A = p$.

There are two physical variables:
(1) n (2) p

The following factors relating to the pattern are of interest:

(1) total number of equisignals in the pattern.

(2) minimum angle of ambiguity. One half of this is the maximum tolerable error in the D/F measurement required to solve the ambiguity of sector, as already noted. It should be as large as possible, that is, a value of 360° would indicate complete certainty of sector.

(3) The ratio $\frac{\text{equisignal field}}{\text{maximum field}} = \rho$. For most economical use of a given radiated power to obtain large useful range, ρ should be as near unity as possible. This ideal condition is not realizeable in practice with either two- or three-antenna arrays.

(4) Absolute field strength at equisignal. This determines the maximum useful range.

(5) Rate of change of field strength with azimuth in the region of an equisignal. This is a factor in determining the discrimination with which a bearing may be observed (that is, the theoretical accuracy obtainable).

(6) The number of db. difference in level between the dot and dash signals for 1° azimuth departure from an equisignal.

The way in which these five factors depend on the variables (current amplitude, antenna spacing) is summarized in Table 17-01.

Table 17-01

	Current Amplitudes	Spacing
total number of equisignals in pattern (1)	no influence	equals $8n$ (1)
minimum angle of ambiguity (2)	no influence	decreases as n increases (equal to $2 \sin^{-1} 1/2n$)
$\rho = \frac{\text{equisignal field}}{\text{maximum field}}$ (3)	$\rho = \frac{p}{p+2}$	no influence
absolute field strength at equisignal (4)	proportional to B only	no influence
rate of change of field strength with azimuth ($dE/d\theta$) at equisignal (5)	proportional to A only	proportional to n
	also proportional to $\cos\theta$	
db. difference (6) between dot and dash signals per degree azimuth departure from equisignal = α	$\alpha = 20 \log_{10} \frac{1 + 0.22\,(n/p)\cos\theta}{1 - 0.22\,(n/p)\cos\theta}$	
Equation determining equisignal positions	$\sin\theta_e = \frac{1}{2n}\left(\frac{t}{60} \pm m\right)$, where m is any integer including zero	

Notes on Table 17-01

1. If the spacing d is an integral number of half-wavelengths (that is, if n = 0.5, 1.0, 1.5, 2.0, 2.5, etc.), equisignals occur at $\theta = \pm 90^{o}$, and by symmetry the number of equisignals in the pattern is always even, whatever the value of n. If n is some other number (e.g. 2.3), the number of equisignals will be the next even number above 8n (e.g 20). This is not however, the number of useful equisignals. In the pattern drawn, it will be noted that the accuracy will be very poor near $\theta = \pm 90^{o}$, so that a safe rule for the number of useful equisignals is 8n - 2.
2. The angle of ambiguity is the angle between the equisignal concerned and the next but one adjacent to it. This is a minimum (requiring the greatest accuracy of approximate D/F observation) at $\theta = 0^{o}$. (Equisignals occur at $\theta = 0^{o}$ and $\theta = 180^{o}$ in all patterns covered by this analysis). Since equisignals occur where sin $(2\pi n \sin \theta) = 0$, the angle concerned is $2 \sin^{-1} 1/2n$ for the first pair of equisignals either side of $\theta = 0^{o}$. In the pattern shown in Figure 17-05, n = 3 and p = 4, so that there are twenty-four equisignals in all, occurring at the following approximate values of θ: $0^{o}, \pm 9\frac{1}{2}^{o}, \pm 19\frac{1}{2}^{o}, \pm 30^{o}, \pm 41\frac{3}{4}^{o}, \pm 56\frac{1}{2}^{o}, \pm 90^{o}, \pm 123\frac{1}{2}^{o}, \pm 138\frac{1}{4}^{o}$, $\pm 150^{o}, \pm 160\frac{1}{2}^{o}, \pm 170\frac{1}{2}^{o}, 180^{o}$. The minimum angle of ambiguity is therefore about 19^{o}.
3. With the phase relationships here assumed, the pattern may be thought of as made up of (a) a uniform component due to the central antenna, (b) a component due to the two outer antennas which varies in phase and in magnitude as θ is varied, causing increments and decrements to the uniform component. Thus in the example given B = 4A (p = 4) and the ratios of maximum field, equisignal field and minimum field are as (B + 2A) : B : (B - 2A), that is, as 6 : 4 : 2 or as 3 : 2 : 1.
4. Since at the equisignals the fields due to the two outer antennas exactly cancel, the equisignal field depends only on that due to the center antenna.
5. Analysis shows that $\frac{dE}{d\theta}$ in the region of an equisignal is given by $4k\pi A \cos \theta$ units per degree azimuth where k is a propagation constant depending on the distance of the observer from the transmitter. This gives the slope of either the dot or the dash pattern at the equisignal.
6. Of more interest than $\frac{dE}{d\theta}$ is the number of db. difference in signal strength between the dash and dot patterns per degree azimuth departure from equisignal. This is given by $\alpha\,(\text{db}) = 20 \log_{10} \left[\frac{E + \frac{dE}{d\theta}}{E - \frac{dE}{d\theta}}\right]$, where E is the equisignal field (of magnitude kB) and $\frac{dE}{d\theta}$ is measured in units per degree and is evaluated at the equisignal. This reduces to $\alpha\,(\text{db}) = 20 \log_{10} \left[\frac{1 + 0.22 \frac{n}{p} \cos \theta}{1 - 0.22 \frac{n}{p} \cos \theta}\right]$ decibels per degree azimuth.

   This expression is characteristic only of the geometry of the radiation pattern and does not depend on propagation factors or on distance from the array. Applying this result to the example previously used (n = 3, p = 4), the maximum change in signal strength per degree is obtained at $\theta = 0^{o}$, under which condition α (db) = $20 \log_{10} \left[\frac{1 + 0.165}{1 - 0.165}\right] = 2.9$ decibels per degree azimuth. If it be assumed that an operator under average conditions can detect a 1 db. change in audible signal level, then the position of the central equisignal ($\theta = 0^{o}$) can be observed directly to about $\pm 1/3^{o}$ azimuth. However, since the technique of counting dots and dashes both before and after the equisignal is used, greater discrimination than this may be obtained, and the limiting factor under these conditions is not in practice the change in signal strength per degree azimuth but is concerned with the

number of characters transmitted per minute. This is further considered later under the heading Theoretical Accuracy.

In general it is to be noted that the change in the signal strength per degree azimuth at equisignals varies as follows:

Maximum at $\theta = 0$, decreasing to zero at $\theta = \pm 90^{o}$
Increases as n is increased.
Decreases as p is increased.

Two-antenna Sonne

It has been pointed out that similar results may be had if only two antennas are used. The spacing between antennas is $n'\lambda$ and the currents are $i_1 = A \sin(\omega t + \phi)$ and $i_2 = \pm B \cos \omega t$ (Figure 17-09), and $\phi = (\frac{\pi}{60})t$. The equisignals occur at azimuth angles where the magnitudes of the dash and dot fields are equal, that is, where $\sin(\phi - 2\pi n' \sin\theta) = 0$. Since this is the same equation as that which determines equisignals in the three-antenna pattern, the equisignals will occur at the same azimuth angles if $n = n'$, and the 2 antenna pattern will be similar to the 3-antenna pattern.

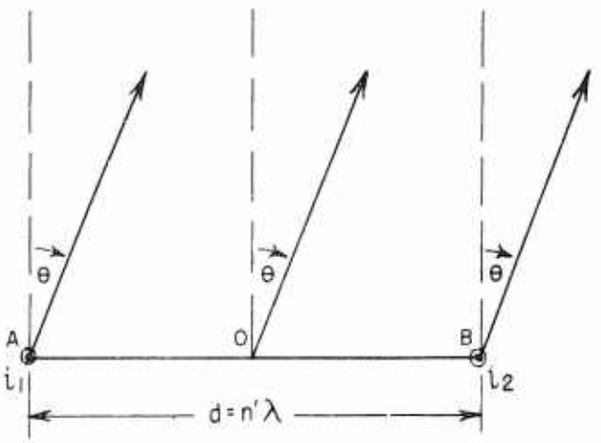


Fig. 17-09 Two-antenna Sonne

$i_1 = A \sin(\omega t + \phi)$
$i_2 = \pm B \cos \omega t$
$\frac{B}{A}$ = ratio of amplitudes = p'
spacing = $n'\lambda$
$\phi = (\frac{\pi}{60})t$ radians, t measured in seconds

Field strength at a distant point P of azimuth angle θ is $E = kA\sqrt{1 + p'^2 \pm 2p' \sin(\phi - 2\pi n' \sin\theta)}$ where k is a constant representing the distance of point P from the array and the propagation conditions.

In Table 17-02 the features of the pattern and their dependence on physical variables ($p' = B/A$ and $n' = d/\lambda$) are listed.

Table 17-02

	Current Amplitudes	Spacing
total number of equisignals in pattern (1)	no influence	equals $8n'$ (or next higher even number if $8n'$ is not even)(1)
minimum angle of ambiguity (2)	no influence	decreases as n' increases ($=2 \sin^{-1} 1/2n'$)
$\rho' = \frac{\text{(equisignal field)}}{\text{(maximum field)}}$ (3)	$\rho' = \frac{\sqrt{1+p'^2}}{1+p'}$	no influence
absolute field strength at equisignal (4)	$\alpha = k\sqrt{A^2+B^2}$ or $kA\sqrt{1+p'^2}$	no influence
Rate of change of field strength with azimuth at equisignal (5)	proportional to $\frac{Ap'}{\sqrt{1+p'^2}} = \frac{AB}{\sqrt{A^2+B^2}}$	proportional to n'
	also proportional to $\cos\theta$	
db difference (6) between dot and dash patterns per degree azimuth departure from equisignal = α'	$\alpha' = 20 \log 10 \left[\frac{1+p'^2+0.11\,p'n'\cos\theta}{1+p'^2-0.11\,p'n'\cos\theta}\right]$	
equation determining equisignal positions	$\sin\theta_e = \frac{1}{2n'}\left(\frac{t}{60} \pm m\right)$, where m is any integer including zero.	

Notes on Table 17-02

1. Equisignal considerations follow from the same equation as for the three-antenna case. The equisignals at $\theta = \pm 90^0$ (in the case where $n'\lambda$ is an integral number of half wavelengths) are not useful and in this case the number of useful equisignals will be $8n' - 2$.

2,3 The same considerations apply as in the three-antenna case.

4. Since at the equisignals the magnitude of the field is unaffected by the choice of +B or - B, equisignals only occur at positions such that the received A and B signals are in phase quadrature.

5. $\frac{dE}{d\theta}$ in the region of an equisignal is given by

$\frac{2kAp'\pi n'\cos\theta}{\sqrt{1+p'^2}}$ units per radian or $\frac{0.11\,kAp'n'\cos\theta}{\sqrt{1+p'^2}}$ units per degree azimuth

where k is constant for any one position of the observer.

6. Analysis shows that, for any given value of n' and $\cos\theta$, α' will have its maximum value when $p' = 1$, that is, when the amplitudes of the two antenna currents are equal. Further, if $p' = 1$, and $n' = 3$, and $\cos\theta = 1$, $\alpha' = 2.9$ db per degree azimuth. Comparing this with the result for the 3-antenna Sonne quoted on page 17.12, it is seen that the two- and three-antenna Sonnen give very closely corresponding pattern features.

Theoretical Accuracy of the System

Assuming no errors in phasing at the antennas and no errors due to propagation conditions, the accuracy of a Sonne bearing depends upon the following:

(1) The rate at which signal strength changes with azimuth in the region of the equisignal. This has been discussed above.

(2) The effect of the counting technique used, which is to reduce (we hope) any errors due to a slow rate of change in (1) above.

(3) The number of characters transmitted per minute. This is assumed to be 60. It is doubtful whether this number could be increased without danger of errors in the actual count. The cycle might be lengthened to (say) 90 characters transmitted in $1\frac{1}{2}$ minutes, but this would involve either increasing the interval between possible readings, or decreasing the length of the steady transmission available for D/F observations.

Three points may be noted with regard to the sizes of the errors due to these causes:

(a) Since the count cannot in any case be made to within less than one character, we are limited to an accuracy determined by the angle through which the equisignal sweeps in 1 second. For the central sectors in the example given in Figure 17-05, this is approximately 1/6 degree azimuth. In the same example, the error due to a one-decibel limit of dot-dash discrimination, $\pm$ 1/3 degree azimuth, when modified by the results of the counting technique, probably amounts to less than this figure so that factor (3) above is likely to be the limiting one. These figures would of course be modified if the constants p and n had been given different values.

(b) Errors due to factor (1) above increase as θ increases, being inversely proportional to $\cos\theta$. However, the increase will not be large until θ approaches $75 - 80^{o}$, in which zone the utility of the system is not considered great.

(c) Errors due to factor (3) above also increase as θ increases, since the angular separation of equisignals is larger at the sides of the pattern, causing the angular speed of movement of the equisignals to increase also at larger values of θ. The constants of the German system appear to have been well-chosen since the errors due to both (1) and (3) are of about the same magnitude, and since a given Sonne beacon has a reasonable coverage arc over which the maximum theoretical error will not exceed twice the value at $\theta = 0^{o}$.

German Transmitting and Phasing Equipment

Details have recently become available concerning the standard German phasing equipment. A simplified circuit diagram is shown in Figure 17-10. The RF power from the transmitter (1.5 kw) is divided between the center antenna, which receives 8/9 of the total power (if B = 4A), and the end antennas. Switch S and the divided primary of T_1 allow reversal at 5/6 and 1/6 second intervals. The loop fed from the secondary of T_1 is tuned to resonance, as is the next loop including the primary of T_2. P is a phase shifter which is preset and controls the exact phasing of the end antenna currents with respect to the current in the center antenna. The loop fed by the secondary of T_2 is also tuned to resonance and includes the rotor coil (1) of the goniometer G. The two stator coils (2,3) are mutually at right angles. The voltages induced in them have the same phase, but are of magnitudes proportional respectively to the sine and cosine of the angle through which the rotor has turned. Thus when coil 1 is parallel to coil 2, E_2 will be a maximum and E_3 zero. As the rotor turns, E_2 decreases and E_3 increases, these voltages remaining in phase. The primary of T_3 being tuned to resonance, the voltage E_4 induced in its secondary is in quadrature with E_3.

The voltages E_2 and E_4, which are therefore in quadrature, are applied at ab and cd respectively to the condenser network Q which functions as a mixer. All eight condensers are of equal capacitance (about 1030$\mu\mu$f). Outputs are taken at ef (E_5) and gh (E_6). E_5 is therefore proportional to the vector sum of E_2 and E_4, and E_6 to their vector difference. These two output voltages, developed in loops which are tuned to resonance, are applied to the 600-ohm open-wire transmission lines which feed the two end antennas.

The phase-relationships at various times in the phase-shifting cycle are represented in Figure 17-11. At t = 0, $E_2 = 0$ and E_4 has its maximum value, denoted by E. E_5 and E_6 are therefore equal to E in magnitude and are opposite in phase. At t = 15 sec, coil 1 has rotated through 45°, E_2 and E_4 are equal in magnitude and are 0.707 E. E_5 and E_6 have therefore remained equal to E in magnitude, but have shifted their phases by 45° in opposite directions. At t = 30 sec, $E_2 = E$ and $E_4 = 0$, so that E_5 and E_6 are now in phase. At t = 45 sec, $E_2 = 0.707E$ and E_4 has changed sign. It will be seen that the two output voltages are always of equal magnitude and that their phase shifts due to the rotation of the goniometer are equal and opposite.

The effect of the keying at S is to reverse all phases, including that of the two output voltages. During the second 180° of rotation of coil 1, no power is supplied to the phase-shifting system (56 sec. omni-directional signal from center antenna alone), and at the end of the two minute cycle the phases are again in their original relationships.

Circuits of monitoring and protective equipment are not given here.

Two-antenna Sonne

Figure 17-12 shows a block diagram of a scheme proposed by Commander E.N. Dingley, Jr., U.S.N.R. for the phase-shifting and keying of a two-antenna Sonne.

The crystal oscillator (1) of frequency f_1 drives a phase-shifter of the three-phase capacitor-goniometer type (2). The output from the phase-shifter is continuously variable in phase and is applied to a mixer (6) by way of a buffer amplifier (3). The other input to the mixer is from a second crystal oscillator (4) of frequency f_2, using a buffer amplifier (5). A band-pass filter (7) selects the output component at the sum frequency ($f_1 + f_2$). A relay (8) and adjustable attenuator (9) are inserted between this output and the transmission line to one of the two antennas. At the antenna mast, the frequency is divided by two (10) and the resulting signals drive a power amplifier (not shown) and thence the antenna (11).

The second antenna is fed in the same way, except that the input to the buffer amplifier (16) is taken direct from the crystal oscillator (1) and not from the output of the phase shifter.

The outputs from the two antennas are therefore of frequency $\frac{f_1 + f_2}{2}$, and the signals passed over the transmission lines are of twice this frequency. By this means it is expected that the effect of radiation from the transmission lines upon the main radiation pattern will be reduced. Furthermore, the phasing of antenna no. 1 with respect to antenna no. 2 is $\theta/2$, if θ is the phase-shift introduced by the phase shifter (2). This makes it possible to use one complete rotation of the phase shifter ($\theta = 360°$) to produce a phase shift of 180° as required in the transmission from antenna no. 1.

Keying and phase-shifting are accomplished by a synchronous motor which

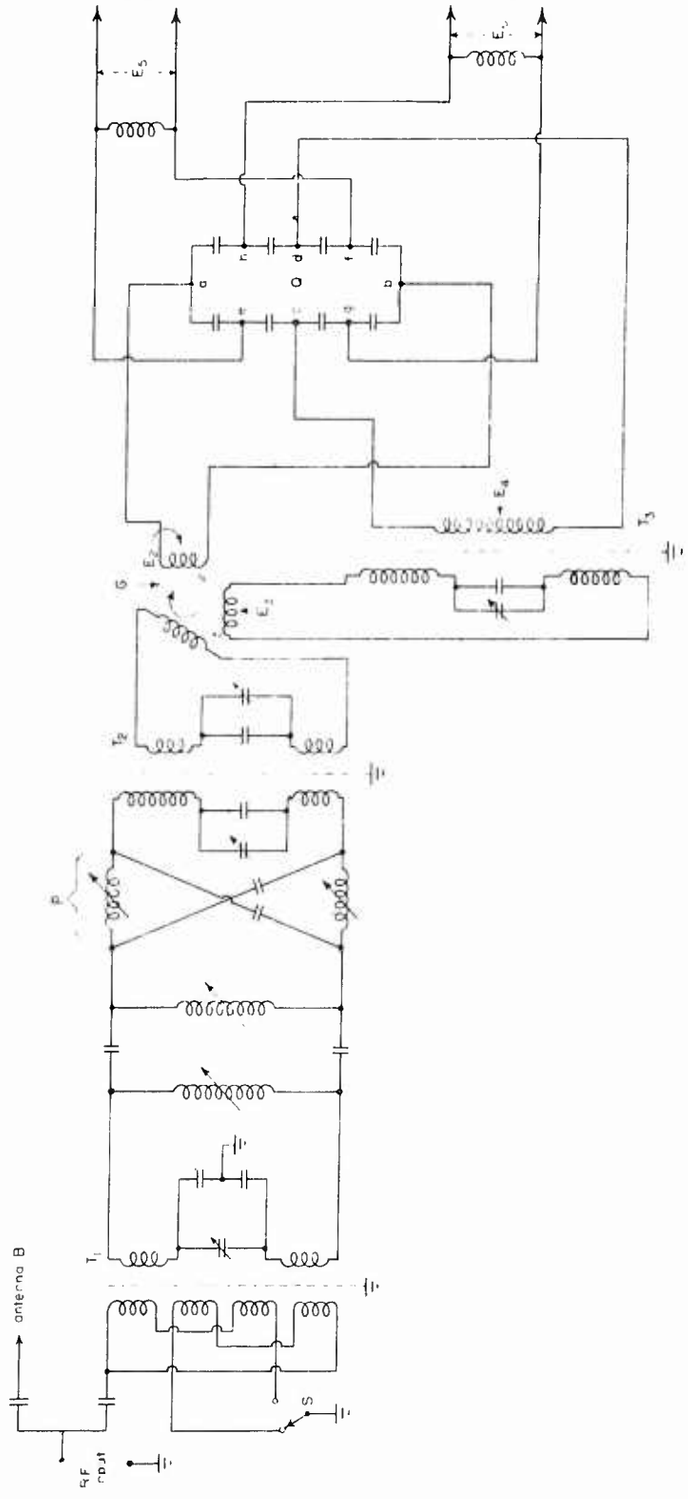
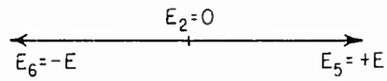
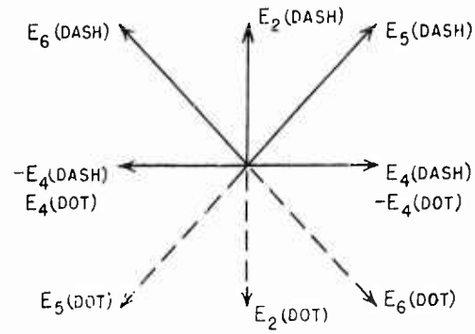


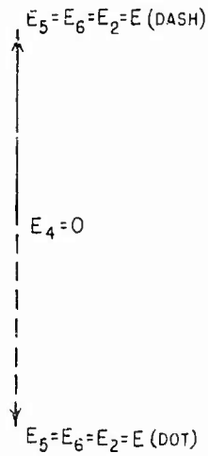
Fig. 17-10 German phase shifting circuits



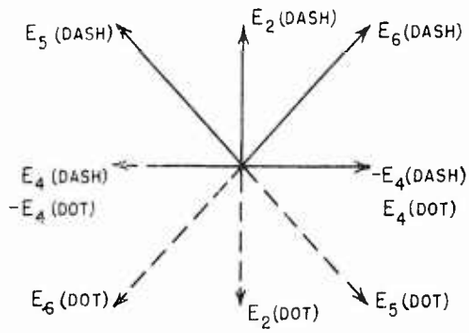
t=0



t=15 sec.



t=30 sec



t=45 sec.

$$E_5 = E_2 + E_4$$
$$E_6 = E_2 - E_4$$

Fig. 17-11 Vector diagram illustrating German method of phasing

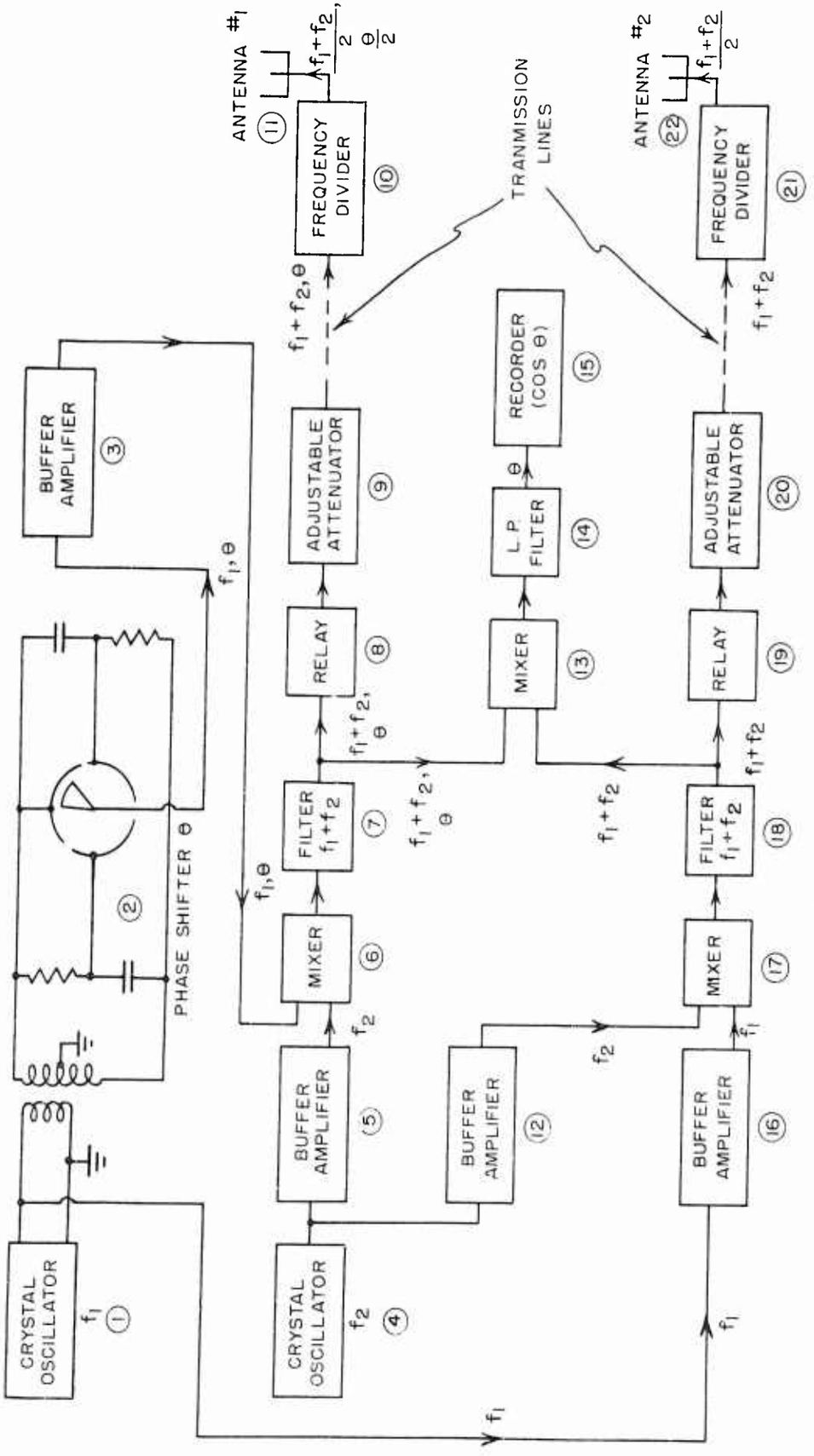


Fig. 17-12 Block diagram, two-antenna Sonne

is made to operate the phase shifter (2) through reduction and differential gearing, and also operates relays (8) and (19). The following cycle is proposed:

0-60 sec.	both relays closed
60-64 sec.	both relays open
64-116 sec.	relay (8) open, (19) closed
116-120 sec.	both relays open
120-180 sec.	both relays closed
180-184 sec.	both relays open
184-236 sec.	relay (8) closed, (19) open
236-240 sec.	both relays open

repeat cycle

At all times the phase-shifter (2) rotates at a uniform angular speed of 360° per minute. It is assumed that the phase-shifter is so constructed that 1° of rotation produces 1° of phase shift at all angles. Further, there is a phase-reversing relay (which reverses the polarity of the leads) connected between the output of the frequency-divider and the input to the transmitter at antenna no. 2. This relay is operated (5/6 sec. in one position and 1/6 sec. in the other) over a control line from a contact controlled by the same synchronous motor.

It will be noted that the omnidirectional signal radiated during the 52 second period is transmitted alternately by the two antennas. This permits the current amplitudes to be checked, by means of a monitoring receiver fitted with a calibrated output meter and located exactly mid-way between the two antennas. This also allows the monitoring operator to check the time-position in the cycle of the equisignal. If this is not correct, or if it is to be altered, the setting of the rotor of the phase-shifter (2) relative to the driving shaft is changed by means of the differential gears. The uniformity of the change of phase with angle of rotation is checked by the recorder (15) operated by the mixer (13) and low-pass filter (14). This is arranged to give a record (on a moving tape) of the cosine of the phase angle θ. This record is compared with a standard cosine curve.

Another advantage claimed for this arrangement is that the crystal oscillator (1) and phase shifter (2) are standard equipment for all Sonne stations, the oscillator being of standard frequency and the phase shifter of standard design. Sonnen of different frequencies are accomodated by choosing different values for f2, the frequency of the oscillator (4).

Transmitter errors and tolerances

Errors in the magnitudes or phasing of the antenna currents will distort the Sonne radiation pattern. The results of this may be classified under three headings:

(1) Actual shift in the angular positions of the equisignals at the start of the phase-shifting cycle. The navigator determines his apparent line of position by reference to a key or table on which the azimuth positions of equisignal lines at the start of the cycle are shown. If the equisignals do not lie in the marked positions, there will be a corresponding error in the line of position obtained. This error will be of the constant type, predictable if the nature and extent of its causes are known.

(2) Loss of discrimination. If the change in signal strength per degree azimuth angular shift from an equisignal becomes smaller for any reason, the theoretical precision of a reading decreases. Such errors will be of the random type, averaging out among a very large number of readings.

(3) Loss of uniformity in the speed at which equisignals sweep in azimuth during the phase-shifting cycle. To obtain a line of position, the navigator refers to the table or key which shows the relation between the number of dots (or dashes)

preceding the equisignal and the corresponding bearing on the Sonne transmitter within the sector on the chart identified by D/F or dead reckoning. This table or key is based on the fact that $\sin(\frac{\pi}{60}t - 2\pi n \sin\theta) = 0$ at equisignals. The relation between t (time in seconds from start of phase-shifting period) and θ (azimuth of equisignal at any instant) is therefore sinusoidal. Any errors in phasing which result in a departure from this sinusoidal relationship amount to errors in position-line interpolation in time within the sector used, even though the initial and final values of θ which determine the sector may themselves be correct.

The most serious error is that identified in (1) above. In general, most effects which produce appreciable errors of the second and third types will also produce much more serious errors of the first type. A number of possible departures from ideal conditions at the transmitter will now be mentioned for both two- and three-antenna Sonnen, together with their effect (if any) on the angular positions of the equisignals at the start of the phase-shifting period. Errors due to propagation conditions are not peculiar to the Sonne system and are separately discussed elsewhere (see Section 1). It is to be noted that each possible cause of error is considered separately. The simultaneous consideration of two or more sources of error cannot be generalized, and the number of possibilities is therefore too large for inclusion here. A factor which by itself does not produce any equisignal shift may operate to increase or decrease errors due to some other factor. Two factors which separately produce no appreciable error may give rise to considerable errors when combined simultaneously.

(a) Three-antenna Sonne

1. Currents in the outer antennas are not equal in magnitude. This condition is represented, 20 seconds after the start of the keying cycle, in Figure 17-13 (a), which shows the current vectors at the transmitter. Figure 17-13 (b) shows the components of the received field at a point whose azimuth angle corresponds to the first equisignal, at this particular instant. The effect of placing the receiver at some azimuth other than zero is that the distances from the receiver to the three antennas are not equal. This is illustrated in Figure 17-13 (d). Considering the B component of the received field (Figure 17-13 (b)) as phase reference it will be seen that the A component is made to lag by an amount proportional to Ap and the C component to lead by the same amount since the antenna spacings are equal. If θ is such that the lag and lead thereby introduced in the received field components exactly compensates for the lead and lag introduced by phase shifting at the transmitter, the field components at the receiver will be as shown in Figure 17-13 (b) for a dash, and in Figure 17-13 (c) for a dot. It is seen that the resultant field R is equal in magnitude for the dot and dash fields, although the dot and dash phases are not the same.

   The equality in magnitude of the dot and dash fields is not affected by inequalities of the A and C antenna currents. Therefore equisignals are observed at the same positions and times no matter whether the A and C currents are equal or not, and no errors result. If the A and C currents had been equal, the phases of the received fields would also have been identical. The relative magnitudes of the current vectors in Figure 17-13 are purposely not drawn to scale.

2. The phase-shifts of the currents in the outer antennas are not equal. This is illustrated in Figure 17-14 (a), in which the phase-shifts are ϕ_1 and ϕ_2 for the A and C currents respectively. To obtain an equisignal, the observer must shift to an azimuth such that the lag and lead thereby introduced into the A and C field components is $\frac{\phi 1 + \phi 2}{2}$. This is illustrated in Figure 17-14 (b) (dash) and Figure 17-14 (c) (dot). Since the A and C fields cancel, an equisignal is obtained. This equisignal would have occupied a slightly different position if ϕ_1 had been equal to ϕ_2. The difference is small if ϕ_1 and ϕ_2 are not too unequal. A difference of 10° between ϕ_1 and ϕ_2 shifts the position of the central equisignal by only 16', if n = 3 (see Figure 17-05).

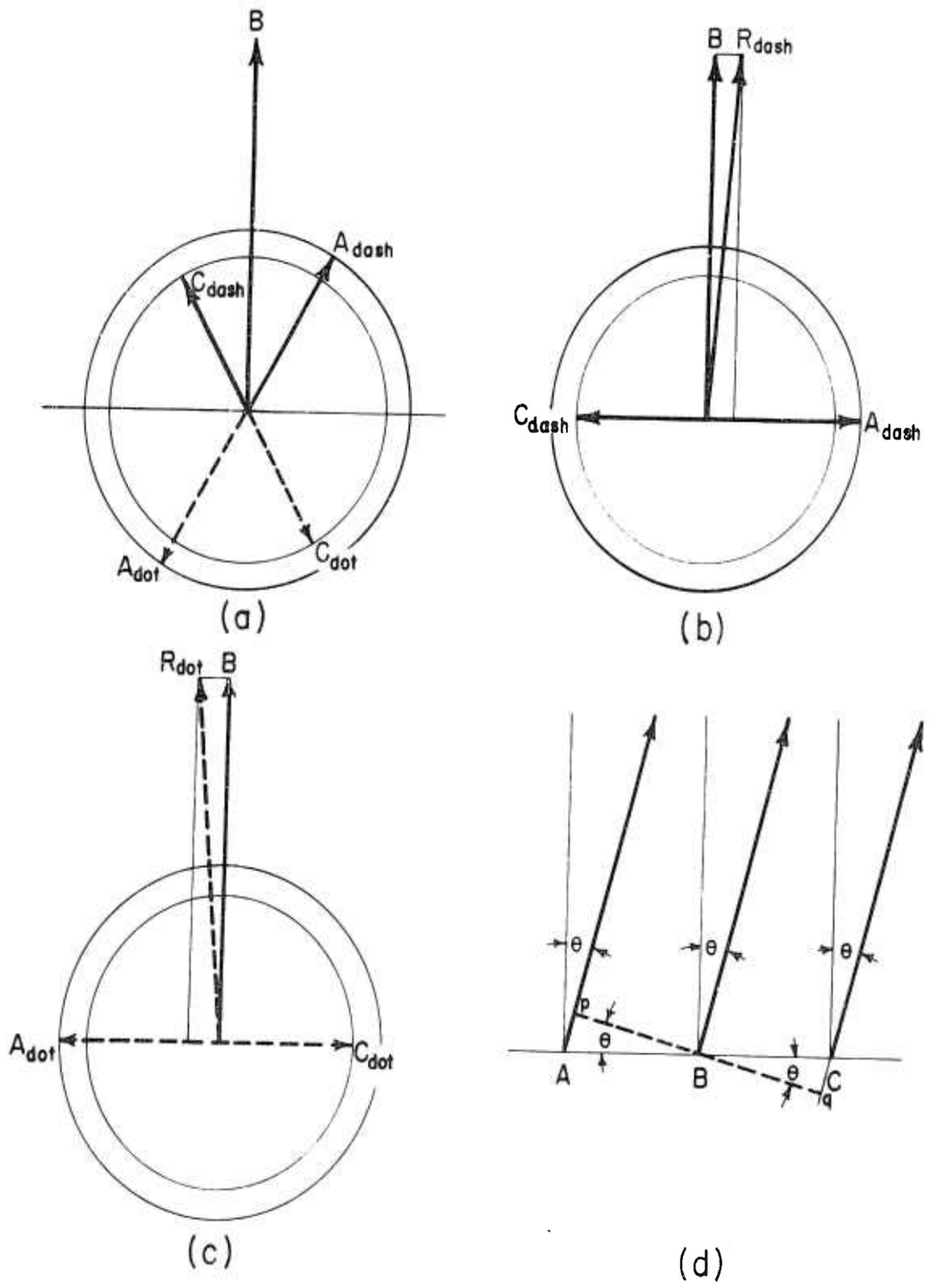


Fig. 17-13 Vector diagrams illustrating incorrect amplitude

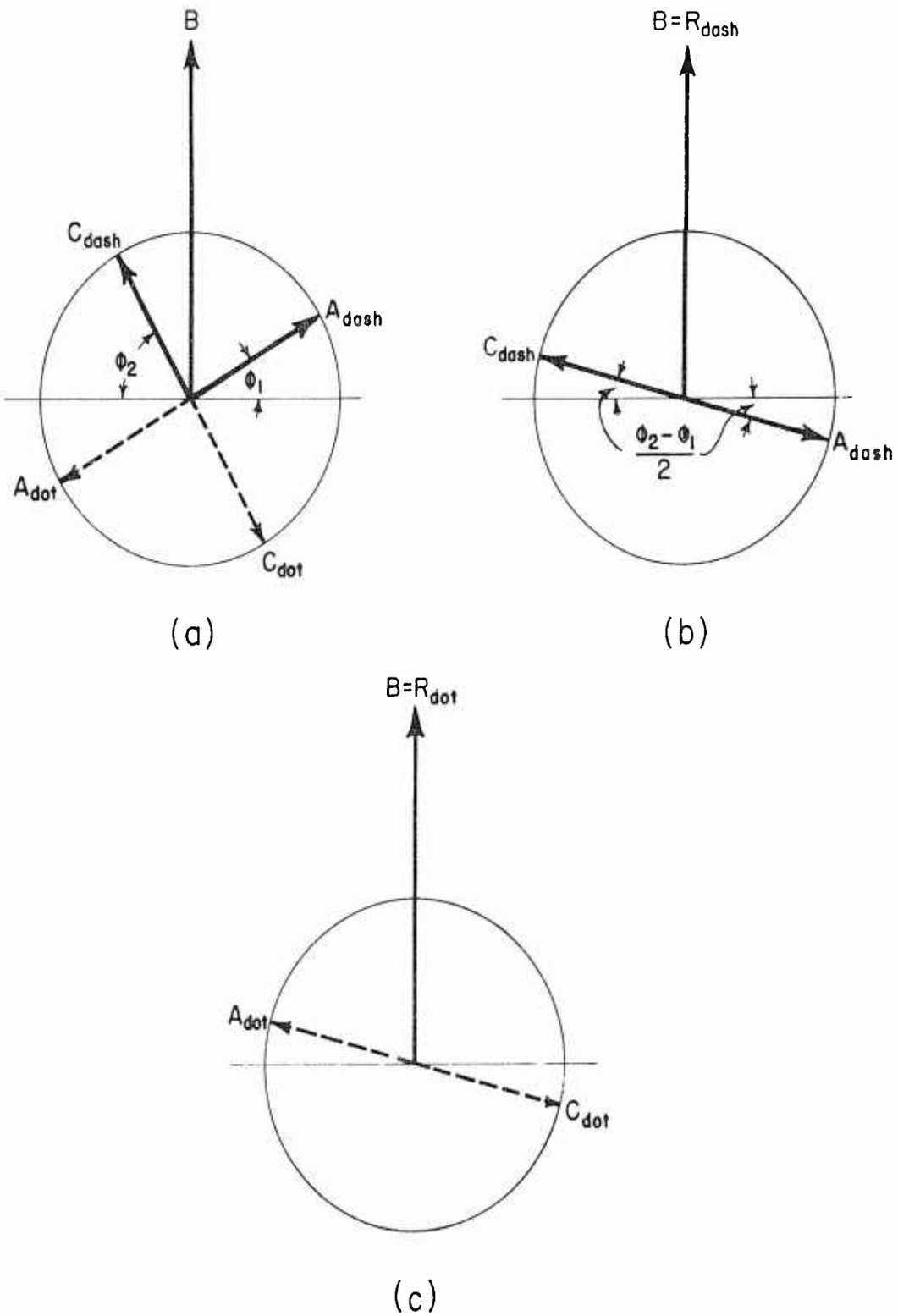


Fig. 17-14 Vector diagrams illustrating incorrect phasing

3. Change in frequency or in antenna spacing. These are equivalent as far as the radiated pattern is concerned, since the pattern geometry depends on $n\lambda$. A change in frequency will of course have profound effects if the antenna tuning circuits (and any other tuned circuits) have not been realigned, but it is presumed that this has been done and that the frequency change was made for some definite reason--e.g. to avoid jamming. Small errors in siting the transmitting antennas are also covered under this heading.

   Analysis shows that the center equisignal will not be shifted at all by such a change or error, and the others slightly. The shift increases as θ increases, being proportional to $\tan\theta$. Taking $n = 3$ and the least favorable case (fifth equisignal at $\theta = 56\frac{1}{2}^{\circ}$), this equisignal is shifted by only $\frac{1}{12}^{\circ}$ or by $5'$ for a 0.1% frequency change or a 0.1% error in antenna spacing.

4. The phases of the A and C antenna currents are correct, but that of the B antenna current is incorrect. This is equivalent to inequality of phase shift of the outer antenna currents, discussed under (2) above. The central equisignal will be shifted by $16'$ if the phasing of the B antenna current is incorrect by 10°. Other equisignals are shifted by proportional amounts, the shift being proportional to $\frac{1}{\cos\theta}$.

5. The magnitude of the B antenna current, or of the A and C antenna currents, departs from its assigned value. This amounts to a change in the value of $p = \frac{B}{A}$, and it will be noted from Table 17-01 that the number and disposition of the equisignals is not affected.

6. The phase-shift applied to the outer antenna currents is not linear with time. The effect of this error is that the actual phasing of the transmitted signals at some instant t seconds after the start of the phasing cycle is that which should have existed at a different instant t' seconds after the start of the phasing cycle. This is the same effect as would be produced by an error in the counting of dots and dashes. The error in azimuth angle thereby introduced is a minimum for the central equisignal at $\theta = 0^{\circ}$, for which a phase departure of 10° from the proper value corresponds to an error of 3 characters in the count, which in turn produces an error of $29'$ in the line of position obtained. For other equisignals the error is larger, being proportional to $\frac{1}{\cos\theta}$.

(b) Two-antenna Sonne

1. The magnitudes of the currents in the two antennas depart from their assigned values. This is a change in the value of $p = B/A$. From Table 17-02, it is seen that although such an error will affect the sharpness of discrimination, the number and position of the equisignals will not be affected.

2. The phase of the B antenna current during a dot (or dash) period departs from its assigned value. This results in a shift of the equisignals. If the phase is in error by $\Delta\phi$ degrees, the equisignals are shifted by an amount $\Delta\theta$ (degrees) $= \frac{\Delta\phi}{2\pi n \cos\theta}$. For the central equisignal and an antenna spacing of three wavelengths a 10° phasing error produces an equisignal shift of $32'$. Other equisignals will be shifted further, the shift being proportional to $\frac{1}{\cos\theta}$.

3. Change in frequency or antenna spacing. Assuming the phasing of all currents to remain correct, and considering only the change in $n\lambda$ as it affects the radiated pattern, the effect of this change is precisely the same as in the three-antenna case. That is, a 0.1% change in frequency or in spacing shifts the fifth equisignal by $5'$ for $n = 3$, the central equisignal not at all.

4. The initial phase of the A antenna current departs from its assigned value. That is, $\phi \neq 0$ at $t = 0$. The effect of such an error with the 2-antenna Sonne is the same as an inaccuracy in the phasing of the dot or dash B-antenna current, discussed under (2) above.

5. The shift in phase during the cycle is not linear with time. The same remarks apply here as in the three-antenna case. (See (a), 6 above.)

Comparison of two- and three-antenna Sonnen

1. Siting. The site of a Sonne station should be free from directional non-uniformities over a considerable area, and should also be flat. Other conditions being equal, a two-antenna Sonne should be easier to site than a three-antenna Sonne.

2. Cost. In any low-frequency system, the outlay on antenna-towers and on the ground system represents a sizeable part of the capital cost. This consideration therefore favors a two-antenna design.

3. Power rating of transmitters. Using the numerical values for spacing and current ratio already taken as typical ($n = 3$, $p = 4$ for three-antenna Sonne and $n' = 3$, $p' = 1$ for two-antenna Sonne) the equisignal field strength at the same distance in the two cases is proportional to B for the three-antenna station and to $\sqrt{2}B'$ for the two-antenna station. If these equisignal field strengths are to be equal B' should equal 0.707 B. The total power radiated is proportional to $B^2 + 2A^2 = \frac{9}{8}B^2$ for the three-antenna case and to $2B'^2 = B^2$ for the two-antenna case. Therefore, if the two-antenna and three-antenna designs are to produce equal equisignal field strengths at equal distances, the three-antenna Sonne must radiate $12\frac{1}{2}\%$ more power than the two-antenna Sonne.

4. Power-Handling capacity of phase shifter and keyer. With the two-antenna design, one-half of the total power must be keyed (for dot and dash patterns) and phase-shifted (for pattern rotation), if the antenna currents are equal and if the phase-shifting and keying is done at high power-level. Under the same conditions, only one-ninth of the power must be keyed and phase-shifted with the three-antenna design. If high-level keying and phase-shifting are used, this point appears to be a conclusive argument in favor of three antennas as opposed to two, and probably represents the main answer to the question of why the Germans used the three-antenna design.

5. Key clicks. With the three-antenna phasing and keying arrangement used by the Germans, there is no change of RF phase at equisignals between the dot and dash fields, since the equisignal field is due to the steady current in the center antenna alone. With the two-antenna design, the RF field changes phase by 90° at the equisignal if the antenna currents are of equal magnitude. Using a receiver containing high-Q RF circuits, key clicks would probably be more severe with two-antenna transmission for this reason.

6. Sharpness of equisignal discrimination. Using equal currents in the two-antenna Sonne, a current ratio $p = 4$ with the three-antenna Sonne and equal antenna spacings of three wavelengths, it has been already noted that equal discrimination is obtained in the two cases.

7. Susceptibility to errors in the phasing and keying circuits. From the considerations of transmitter tolerances and errors already given, it may be seen that the two-antenna system is slightly more susceptible to equisignal shifts than is the three-antenna system. Exact comparison under this heading will of course depend on the circuits used to realize the required results

Bibliography

Identification	Classification	Title	Issued by
JEIA 8416	Secret	Aids to Navigation Memo no. 8 Consol plotting chart, Faeroes	Coastal Command
JEIA 6826	Secret	German Long-range Navigational system: Notes on Sonne Navigational beacon system: Consol as an aid to Navigation	Intelligence Div. C.N.O.
G 30984	Secret	Observations of the German Sonne system	Toronto Conference
JEIA 7072	Secret	Instructions for plotting radio fixes by the G.A.F. Radiobeacons "Elektra Sonne".	Intelligence branch, O.C.S.O.
S 67-5	Secret	M.I.T. comments on the Sonne (Consol) Navigation System	N.L.O. Div. 14 NDRC
JEIA 7080	Secret	Investigation of Loran, Sonne and Decca navigational aids.	Intelligence Div. C.N.O.
S-935-17	Secret	Sonne	BUSHIPS
WA-4099-3	Secret	An investigation to find a suitable method of checking the stability of the position-line given by Sonne	P.O.E.D., London
JEIA 7944	Secret	Theoretical comparison of the two- and three-aerial Sonne systems	O.C.S.O. Washington
WA-4312-3	Secret	German Sonne navigational air radio station, investigation of, 12/14/44	C.I.O.S. SHAEF
JEIA 2809	Secret	Consol Range and Accuracy Trials	Intelligence Div. CNO
VA 2/5260	Secret	Circuit diagram of German phasing equipment for Sonne transmitters.	Watson Labs
Report no. 9	Secret	Interim report on the Sonne (Consol) Navigation System	Watson Labs
JEIA 10908	Confidential	"Elektra-Sonne" (Translation of Lorenz description and Operating Instructions for Sonne 8 HF-Rack 111)	Air Ministry, London

Bendix Automatic Position-Plotter

Type of system

Azimuth

Useful range and coverage area

Depends on power of ground beacons, also on height of navigated craft.

Accuracy

The accuracy of a fix obtained by this system is limited by the accuracy of the automatic direction-finders used. A fairly conservative estimate would be $\pm 3^{o}$ azimuth in either of the lines of position which yield the fix.

Type of presentation

Visual. Continuous and automatic indication of position is given visually on a chart.

Operating skill required

(a) Craft: Two automatic direction-finders of standard type, flux-gate compass, specialized computer (automatic in operation), plotting board with special attachments. (b) Ground: Two beacons required for a fix. For coverage of a large area, a number of beacons would be required.

Radio-frequency spectrum allotments necessary

Each beacon transmits on a different frequency. The automatic direction-finder as at present used covers the frequency range 100 kcps - 1600 kcps. Unless other information were to be transmitted by the beacons, no modulation would be necessary and each beacon would require only a single frequency.

Present status

The specialized computer and plotting board attachments are now being developed experimentally and a working model is expected to be in operation at the Bendix Company's development laboratory in a few months. Flux-gate compasses and automatic direction-finders are standard equipment already.

Principle of Operation

Referring to Figure 18-01, suppose that the craft is at R and the two ground beacons at P and Q. The craft is headed in the direction RH, and RN represents magnetic north. The flux-gate compass on the craft provides continuous readings of the angle A between the heading and magnetic north. The two automatic direction-finders give continuous indications of B and C, the angles of the beacons Q and P with respect to the heading. The computer therefore receives three channels of information: A, B and C. It performs two functions:

(a) By means of differential synchros, the angles ϕ_1 and ϕ_2 are computed. These are the magnetic bearings of the beacons with respect to magnetic north. The magnetic deviation is set into the computer as a constant, so that from these angles the true bearings are obtained. In Figure 18-01, no distinction has been made between true and magnetic north, for the sake of simplicity.

(b) If the positions of P, Q and R are specified by rectangular coordinates with respect to axes OX and OY, then it will be realized that by the application of trigonometry, the coordinates x and y of the craft can be computed in terms of the constants $x_1 x_2 y_1 y_2$ and the observed angles ϕ_1 and ϕ_2. This the computer does.

The plotting board has a small carriage ("bug") to which may be attached a pointer, source of light or recording pen. This carriage is supported on, and moved by, a framework running on two long threaded lead screws parallel to OX and OY. The lead screws are rotated by means of small motors driven by suitable amplifiers, into which are fed error voltages which represent the differences between the output of the computer (x, y) and "position" voltages which are proportional to the coordinate distances by which the carriage is displaced from the origin of coordinates. These "position" voltages are obtained from long wire-wound potentiometers supported below and parallel to the threaded lead screws, contact springs being mounted on the screw heads which propel the carriage in the x and y directions.

The block diagram of Figure 18-02 illustrates the method by which these results are obtained.

Referring to Figure 18-02, the two automatic direction-finders provide data as to the angles B and C in Figure 18-01. The flux-gate compass gives the angle A. By means of differential synchros, the angles α and β are fed to the computer, in the form of physical rotations.

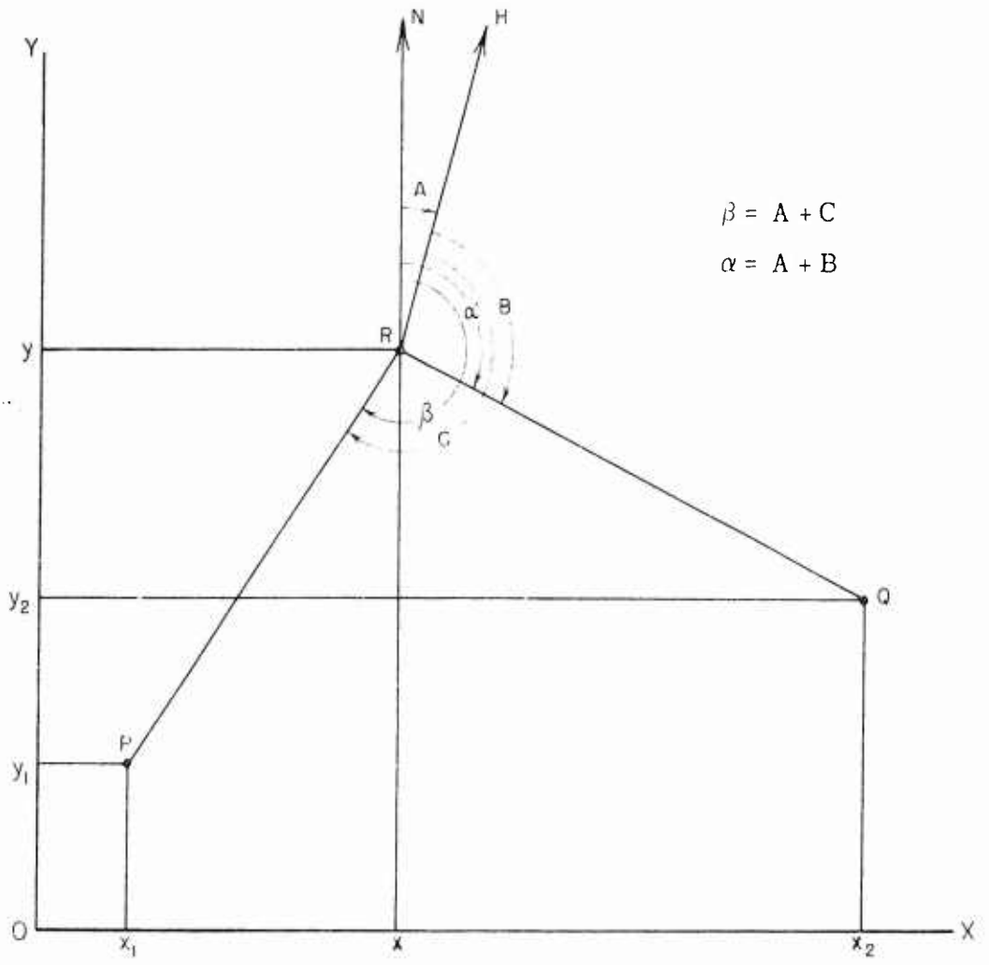


Fig. 18-01 Angular relations

It may be shown that the coordinates x, y of the craft are given by the following equations, in which the quantities $x_1\, x_2\, y_1\, y_2\, \alpha$ and β have the significance indicated in Figure 18-01.

$$x = x_1 + \frac{\sin \beta}{\sin (\alpha - \beta)} \cdot \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \quad (1)$$

$$y = y_1 + \frac{\cos \beta}{\sin (\alpha - \beta)} \cdot \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \quad (2)$$

Assuming that voltages proportional to x and y could be generated, and that voltages proportional to x' and y', representing the actual position of the cursor at any time, are obtained from the long wire-wound x and y potentiometers, then $x' - x$ and $y' - y$ would represent error voltages which, when suitably applied to the x and y driving motors, would correctly position the cursor so that $x' - x = y' - y = 0$. However, the operation of multiplying by $1/\sin (\alpha - \beta)$ cannot be adequately performed since this quantity varies between 1 and ∞. Therefore the above equations are multiplied by $\sin (\alpha - \beta)$, giving

$$x \sin (\alpha - \beta) = x_1 \sin (\alpha - \beta) + \sin \beta \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \quad (3)$$

$$y \sin (\alpha - \beta) = y_1 \sin (\alpha - \beta) + \cos \beta \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \quad (4)$$

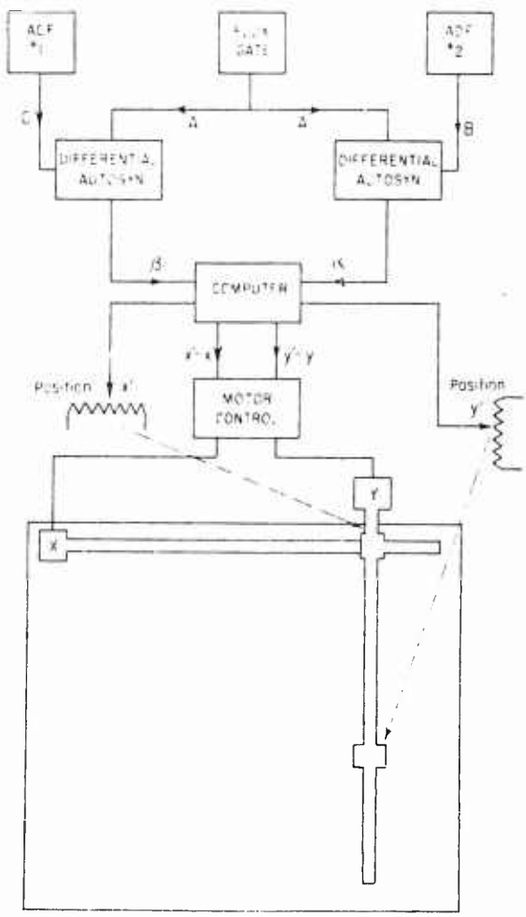


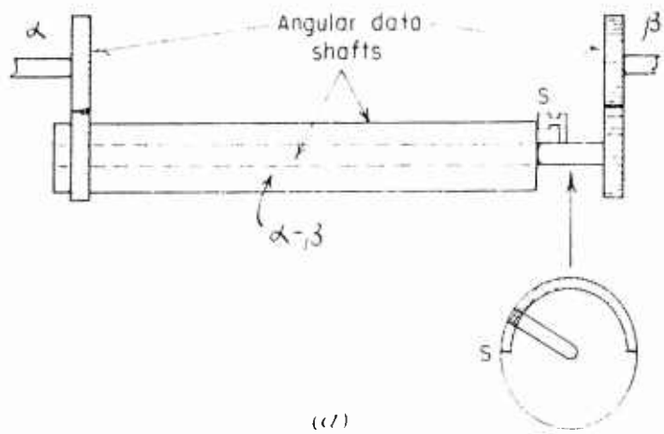
Fig. 18-02 Block Diagram

This means that the voltages x' and y' must also be multiplied by $\sin(\alpha - \beta)$. The error voltages which drive the x and y motors will then be given by

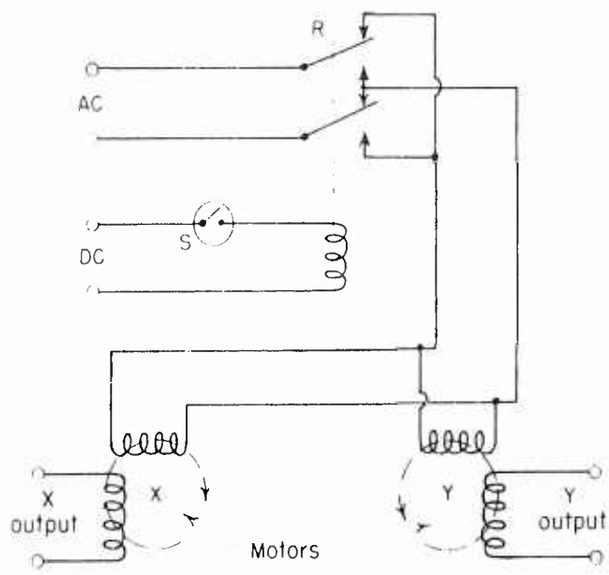
$$x' \sin(\alpha - \beta) - \left\{x_1 \sin(\alpha - \beta) + \sin\beta \left[(x_1 - x_2)\cos\alpha + (y_2 - y_1)\sin\alpha\right]\right\} \qquad (5)$$

$$y' \sin(\alpha - \beta) - \left\{y_1 \sin(\alpha - \beta) + \cos\beta \left[(x_1 - x_2)\cos\alpha + (y_2 - y_1)\sin\alpha\right]\right\} \qquad (6)$$

These therefore are the operations which must be performed by the computer. It should be noted that when $(\alpha - \beta) = 0^0$ or 180^0 (on the line joining the beacon transmitters and on the extensions of this line) the error voltages will be zero. There is therefore a region of low accuracy adjacent to the base line and its extensions. Furthermore, if the aircraft crosses the base line, $\sin(\alpha - \beta)$ will change sign. If the error voltages are to maintain the correct direction of drive, both driving motors must be reversed at this point.



(a)



(b)

Fig. 18-03

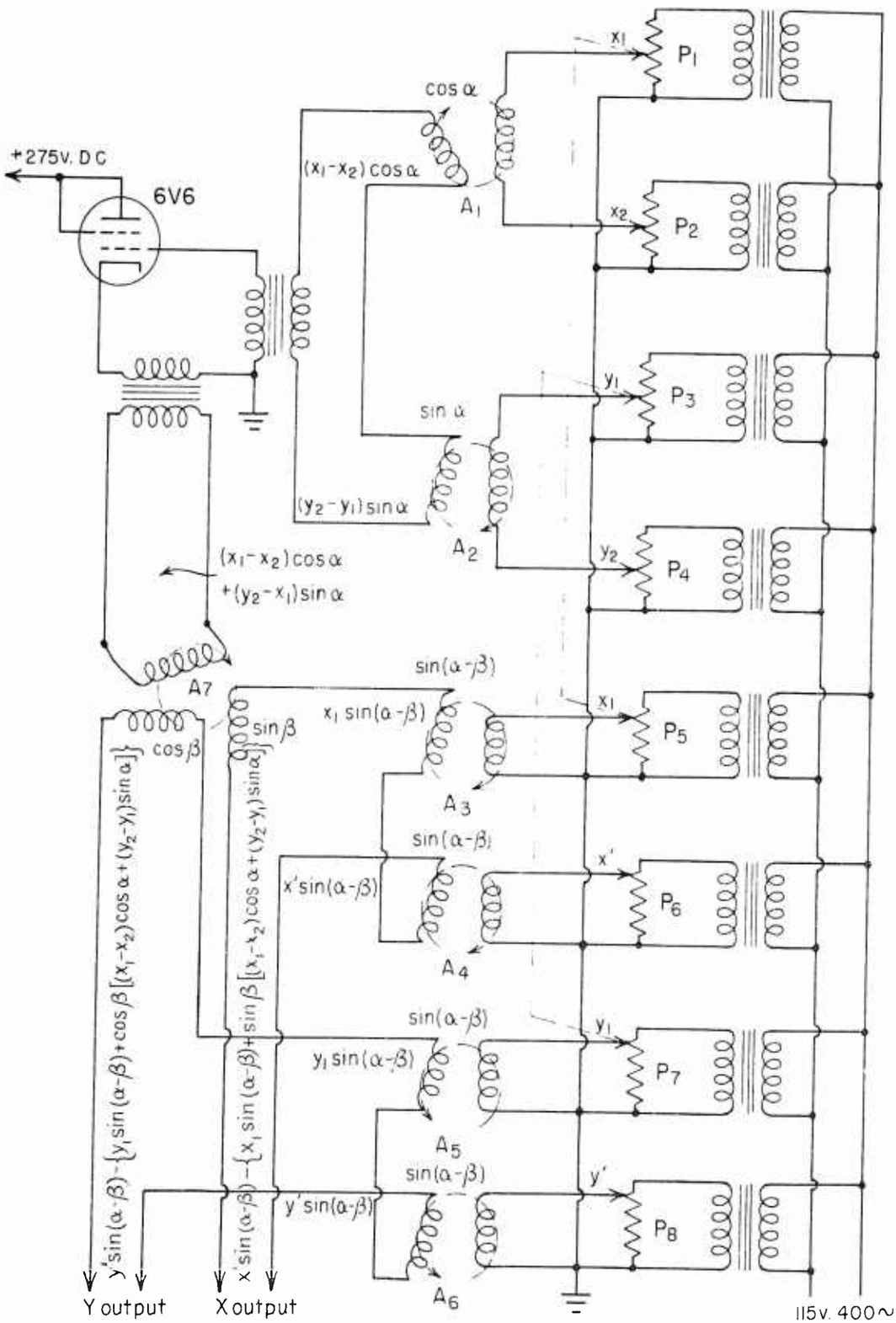


Fig. 18-04 Computing circuits

Referring to Figure 18-03 (a), the differential drive shown makes the angle $(\alpha - \beta)$ available as a physical rotation. The switch S, which is closed when $0 < (\alpha - \beta) < 180^{\circ}$ and open when $180^{\circ} < (\alpha - \beta) < 360^{\circ}$, performs the required reversal of the motor drive as indicated in Figure 18-03(b), where AC motors are used and the sense of the stator fields is reversed by the reversing switch R.

Referring now to Figure 18-04, AC voltages at 400 cps frequency are taken from the secondaries of the eight transformers at the right and are applied to eight potentiometers P_1 - P_8. The x_1, x_2, y_1 and y_2 coordinates (constants for the two beacons and particular chart used) are preset into P_1, P_2, P_3, P_4, P_5, and P_7 as indicated. It is suggested that this operation might be ganged with the tuning controls of the two automatic direction-finders, so that push-button station selectors could be used to cover the area within which this type of navigational coverage is provided. P_6 and P_8 are the "position" potentiometers parallel to the x and y axes on the plotting board.

The outputs of P_1 and P_2 are placed in series with the stator of A_1, which is a goniometer so constructed that the output from its rotor is proportional to the cosine of the angle through which the rotor has been turned. Since the rotor is driven from the α angular data shaft, the output from it will be a 400-cycle AC voltage whose magnitude is proportional to $(x_1 - x_2) \cos \alpha$.

In a similar way, P_3, P_4 and A_2 yield an AC voltage whose magnitude is proportional to $(y_2 - y_1) \sin \alpha$, the A_1 and A_2 rotors being at right angles and both driven from the α angular data shaft.

These two voltages are combined in series and applied to the 6V6 torque amplifier. The rotor of A_7 therefore receives a current proportional to $(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha$.

A_3, A_4, A_5 and A_6 are all driven with their stators attached to the α angular data shaft and their rotors to the β shaft. Each of them therefore multiplies its input voltage by a factor $\sin (\alpha - \beta)$. The outputs of A_3 and A_4 are placed in series and applied to one stator coil of A_7. The rotor of A_7 is driven by the β angular data shaft. The current in the x output circuit is therefore proportional to

$$x' \sin (\alpha - \beta) - \left\{x_1 \sin (\alpha - \beta) + \sin \beta \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \right\}$$

which is of the required error form.

The second stator coil of A_7 is at right-angles to the first, and therefore multiplies the rotor input by $\cos \beta$. The y output is therefore proportional to

$$y' \sin (\alpha - \beta) - \left\{y_1 \sin (\alpha - \beta) + \cos \beta \left[(x_1 - x_2) \cos \alpha + (y_2 - y_1) \sin \alpha \right] \right\}$$

which is also of the required form.

Thus if the cursor is not at the correct position, it will be driven there by two error voltages (or currents) whose magnitudes decrease as the correct position is approached. Anti-hunt features are not included: it is presumed that they will not be required.

Type of system

Azimuth (radial).

Useful range

50 miles at 1000 feet. Coverage area - 50-mile circle around station.

Accuracy

(a) Ideal or best theoretical $\pm$ 2.8°.
(b) Actual $\pm$ 5° (may be improved).
(c) 180° ambiguity easily resolved.

Type of presentation

Right-left zero-center meter and azimuth selector. Neon light indicates 180° error.

Operating skill required

(a) At ground installations: May operate unattended. VHF transmitter, side-frequency generator and control equipment to be serviced.
(b) In navigated craft: Very little skill required.
(c) Time to obtain a fix: 20 seconds.

Equipment (Complexity and Weight)

(a) At ground or control point: Transmitter and antenna system, fairly complex. Weight not in excess of 1000 to 2000 pounds.
(b) In craft: Receiver employs standard VHF practices. Converter fairly complex. Weight about 25 pounds.

Frequency

125 mcps.

Wavelength

2.4 meters.

Bandwidth

About 24 kcps.

Present status

Experimental.

Description of system

This system is based upon the use of a rotating horizontal-antenna directivity pattern. This pattern which is a limacon is produced by an antenna array consisting of four elements mounted at the corners of a square and a fifth element located at the center of the square. The center element is fed with 125-mcps energy which is amplitude modulated with a 10-kcps frequency. The 10-kcps frequency is frequency-modulated by 60 cps from the power line. The 125-mcps energy supplied to the center element can also be voice-modulated for communication purposes. The other four elements are fed with energy in the following manner. Diagonally opposed pairs of elements are connected to a common feed point but with different lengths of transmission line so that one element is 180° out of phase with the diagonally opposite element. The second diagonally opposite pair are phased in the same way. Each diagonally opposed pair is fed from a side-frequency generator. The modulation envelope of one pair of elements is 1/4 period different in phase from the modulation envelope of the other pair of elements. The side frequencies produced are (125 mcps - 60 cps) and (125 mcps + 60 cps). No 125-mcps carrier voltage is pro-

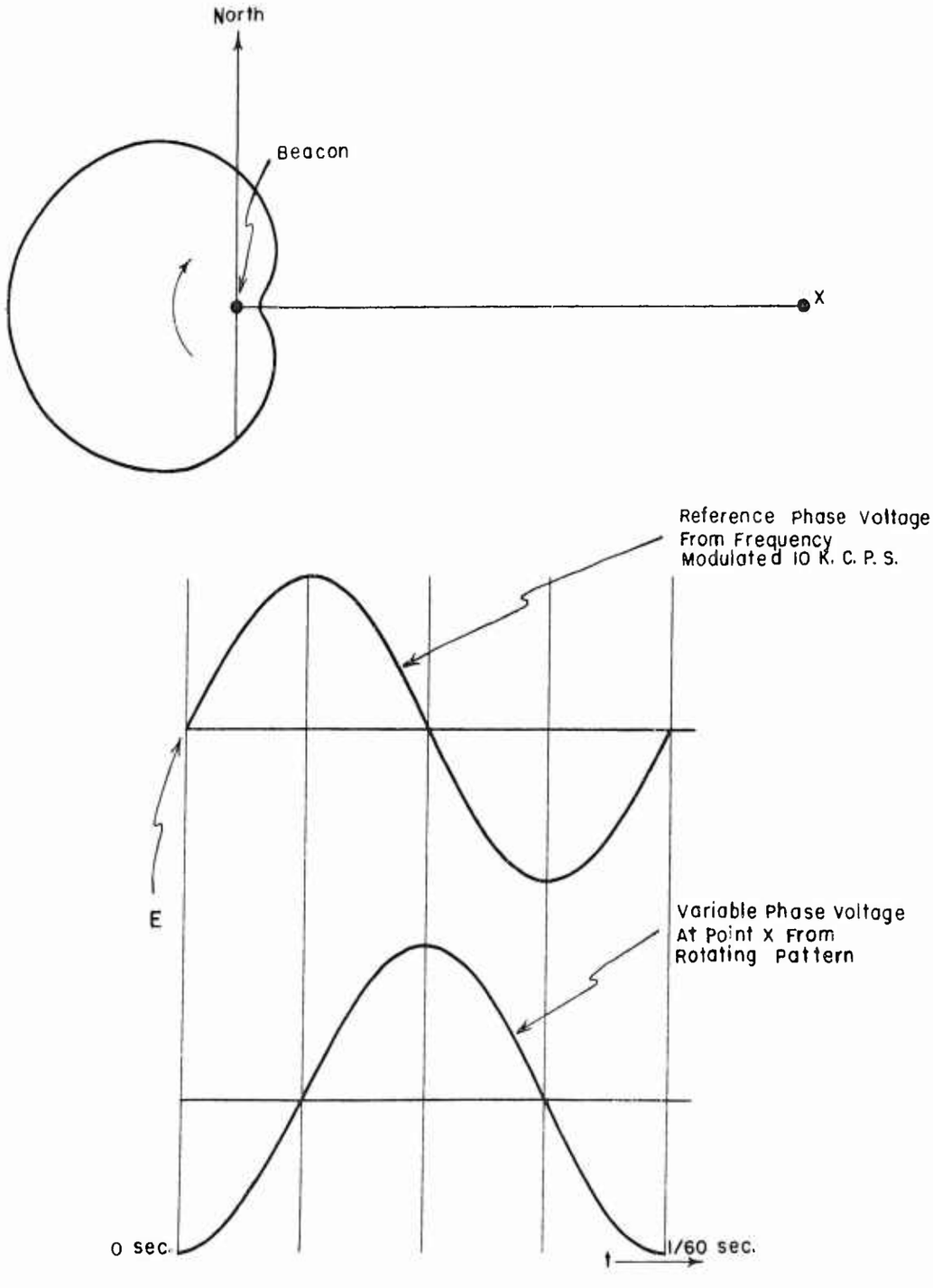


Fig. 19-01 Principle of operation of omnidirectional beacon

duced by the side-frequency generators. These side-frequency generators may be either balanced modulators or a rotating-capacitor modulator. At any given point in space one will receive a 60-cps-modulated 125-mcps signal. The absolute time phase of the 60-cps modulation depends upon the azimuth angle with respect to the beacon of the receiving point. As one moves about the beacon in azimuth the phase of the 60-cps modulation changes. It is thus possible to determine azimuth if some phase reference voltage is available. This reference phase is provided by the 60-cps frequency modulation of the 10-kcps sub-carrier.

Figure 19-01 illustrates the operation of the system. It is here assumed that the amplitude of the reference voltage passes through a maximum at the same instant that the maximum of the rotating pattern passes through North. At the point X the variable-phase voltage passes through a maximum 90° later than the reference-phase voltage. This indicates that the point X is at an azimuth angle of 90° from the beacon. Thus azimuth angles are presented as a phase angle between the variable-phase voltage and the reference-phase voltage.

Two radiating systems have been tried. One consists of five vertical half-wave dipoles placed over a circular metal counterpoise. The other radiating system consists of five "Alford loops"* placed above a circular counterpoise. These loops are placed in a horizontal plane to give horizontal polarization. It was found that reflections from trees, telephone poles and so forth interfered with the accuracy of the radiated pattern when the vertical dipoles were used. This distortion of the radiation pattern was minimized by using horizontal polarization. The only practical omnidirectional elements that can produce horizontal polarization and can be closely spaced are Alford loops. Surrounding this array of loops is a vertical polarization filter consisting of a cylindrical cage of vertical wires.

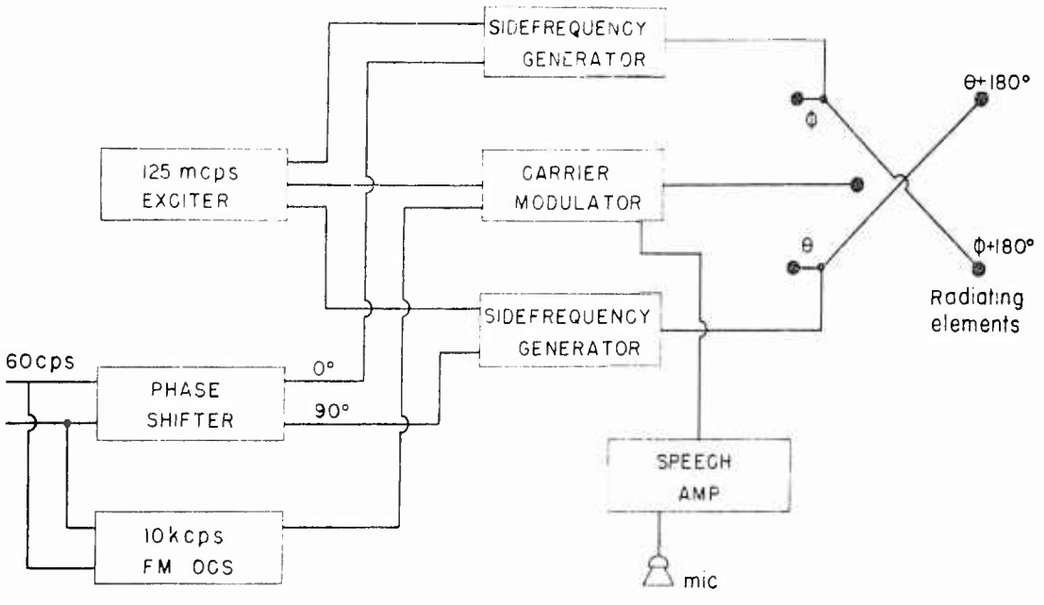


Fig. 19-02 Block diagram of system using electronic side-frequency generators

*See Figure 19-08 (a)

Figure 19-02 is a block diagram of the beacon transmitter using electronic side-frequency generators. A 125-mcps exciter supplies energy to the two side-frequency generators and to the carrier modulator. The modulating voltage for the two side-frequency generators is supplied from the 60-cps power line. The 60 cps supplied to the one side-frequency generator is shifted 90^{0} with respect to that supplied to the other side-frequency generator. The modulation envelopes of these two side-frequency generators are thus 90^{0} out of phase. The carrier modulator is supplied with a 10-kcps signal which is frequency-modulated at 60 cps to a deviation ratio of 8. In other words, the frequency swings between 9520 to 10480 at a 60-cps rate. It was found that frequency modulation of the 10-kcps sub-carrier gave better results and less cross modulation than when amplitude modulation of this sub-carrier was used. A speech amplifier and microphone are used so that the center element can also be voice-modulated.

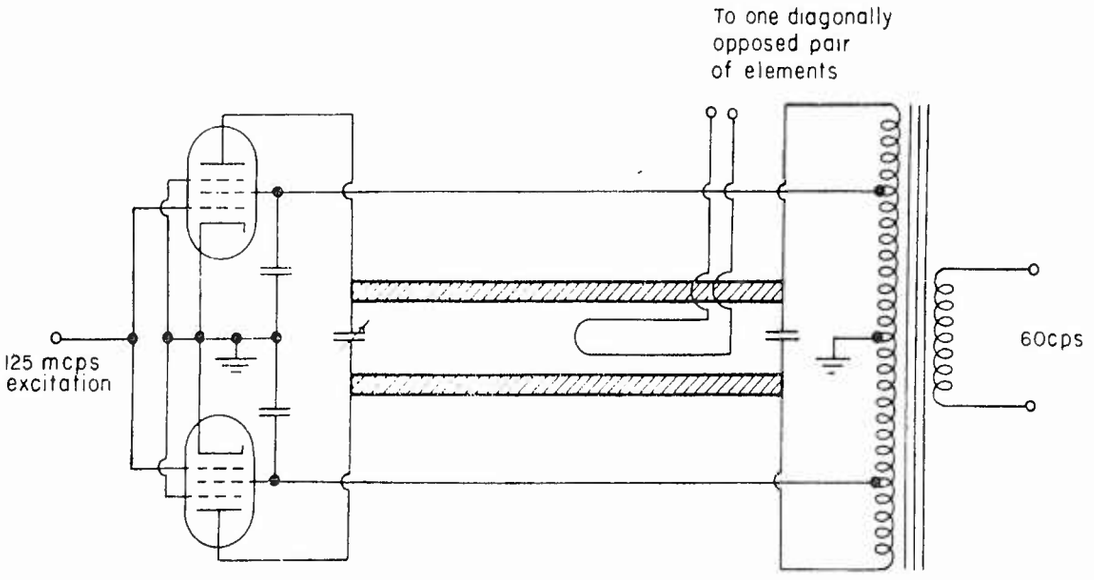


Fig. 19-03 Electronic side-frequency generator

Figure 19-03 is a simple diagram of one of the side-frequency generators. It is a balanced modulator using parallel input of the 125-mcps to the two tubes. The plates are connected to the output circuit in push-pull and the 60 cps is applied to the two plates and screens in push-pull.

Figure 19-04 is a diagram of the 10-kcps sub-carrier generator. It is a delay-line or phase-shift type of oscillator using a 6SG7 amplifier followed by a 6J5 cathode follower. The output of the cathode follower is fed back to the input of the 6SG7 amplifier through a four-section delay line. One of the shunt elements of the delay line is made electronically variable by being connected to the two 6J5s connected in series. The effective resistance of the 6J5s is varied by the 60-cps input.

Figure 19-05 is a block diagram of the beacon transmitter using a rotating-capacitor side-frequency generator. Both the carrier modulation and the side-frequency modulation are done at the final output level. The rotating-capacitor side-frequency generator is driven by a synchronous 60-cps motor running at 3600 rpm.

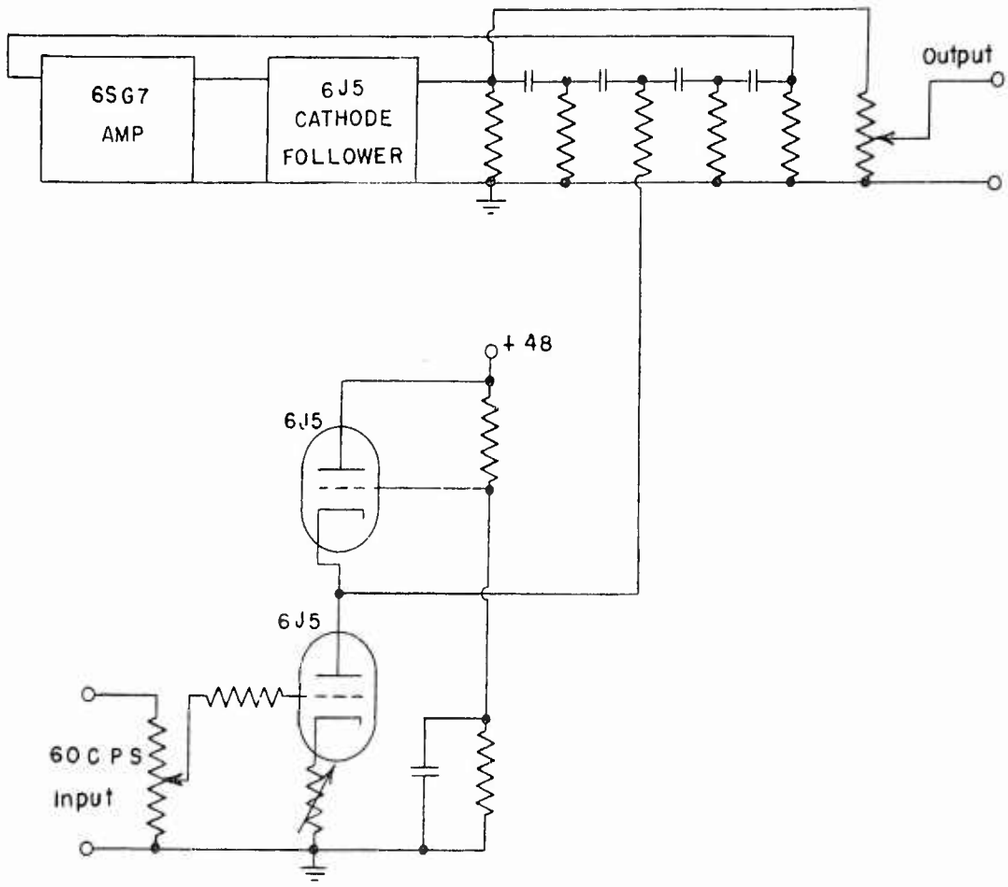


Fig. 19-04 Frequency-modulated oscillator

This motor also drives a two-pole AC generator which supplies the 60-cps reference frequency to the 10-kcps FM oscillator. The carrier modulator is a $\lambda/4$ line type.

Figure 19-06 illustrates the principle of the rotating-capacitor side-frequency generator. It has a rotor consisting of two electrodes supplied with energy from the transmitter and two stators mounted at right angles to each other. The rotor electrodes are half-cylinders with the ends tapered off. When rolled out flat the shape of each side is a double half-sine-wave. Each stator consists of two half-cylindrical shells. The two sets of shells are mounted so that the slits are at right angles.

Figure 19-07 is a developed (rolled-out-flat) diagram of the side-frequency generator.

Figure 19-08 (a) shows the design of the Alford loops used. The current distribution on two sides is also shown.

Figure 19-08 (b) shows the top view of the array of five loops.

Figure 19-08 (c) is a side view of the array of loops.

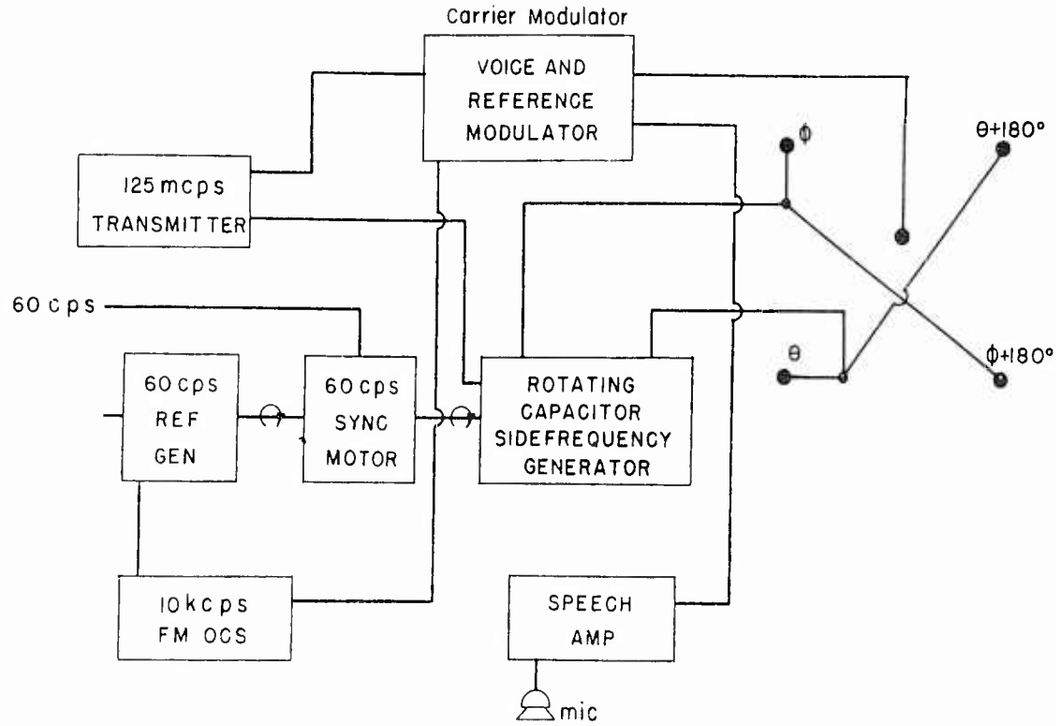


Fig. 19-05 Block diagram of system using rotating-capacitor side-frequency generator

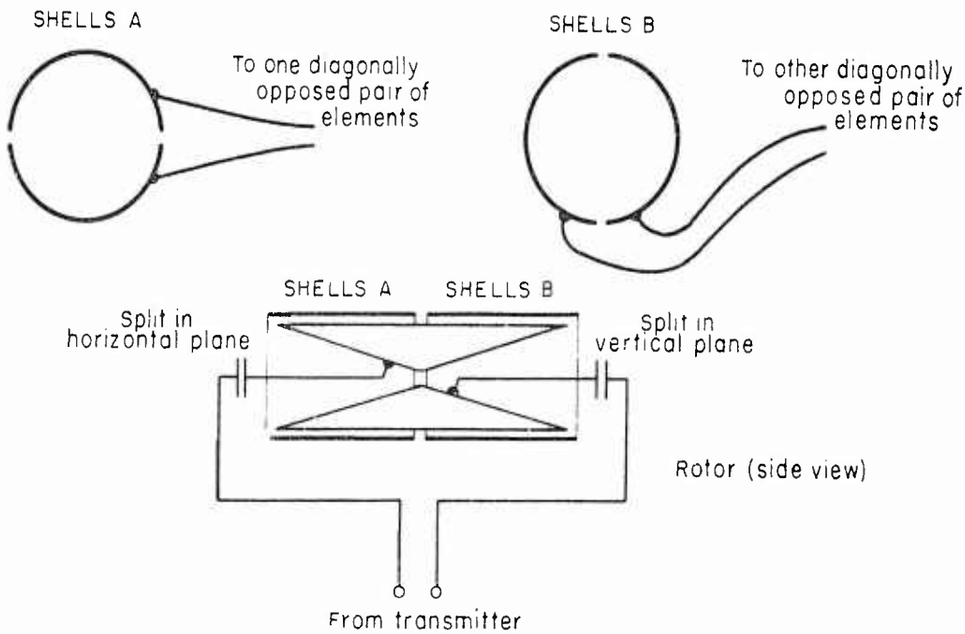


Fig. 19-06 Rotating-capacitor side-frequency generator

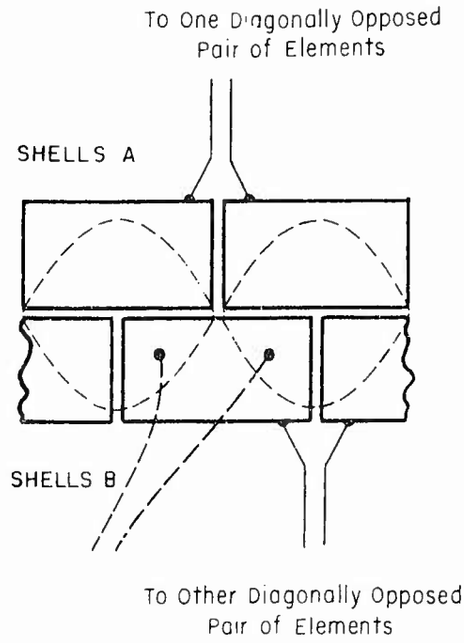


Fig. 19-07 Developed diagram of rotating-capacitor side-frequency generator

Figure 19-09 is a block diagram of the converter used in the receiving installation. A 125-mcps superheterodyne receiver is used to receive the transmissions. The converter consists essentially of two channels, a phase shifter and a phase comparator. The upper channel contains a high-pass filter and amplifier to select and amplify the 10-kcps sub-carrier. This frequency-modulated sub-carrier is then applied to a discriminator (shown in Figure 19-10) which recovers the 60-cps phase-reference voltage. This 60-cps voltage is applied to a phase splitter and then to the two stators of a goniometer-type phase shifter. The lower channel contains a low-pass filter and amplifier to select and amplify the 60-cps variable-phase voltage. The output of the phase shifter and of the lower channel are applied to a

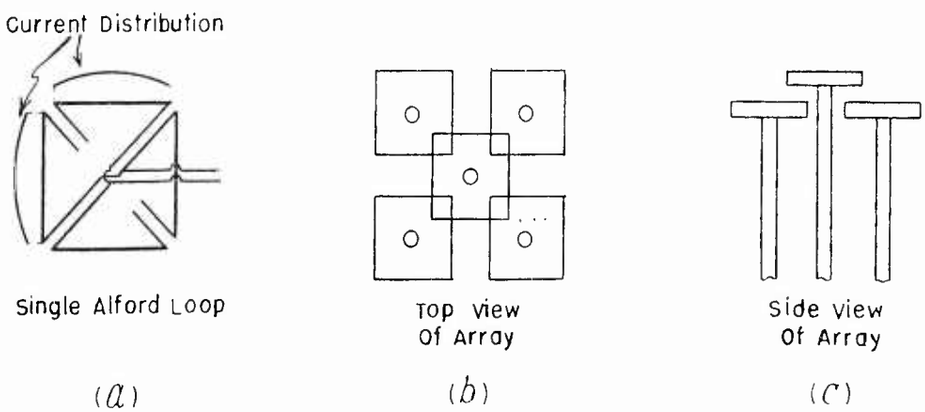


Fig. 19-08 Alford loop and loop array

phase-comparator circuit. This phase-comparator circuit (shown in Figure 19-11) is a wattmeter circuit. The zero-center meter will indicate zero current when the voltages are 90° out of phase. This allows a 180° ambiguity, so an ambiguity-resolving circuit is used. The output from the phase shifter is shifted +45° in one phase shifter and the output of the variable-phase channel is shifted -45° in another phase shifter. These two voltages are applied to a mixer amplifier and then to a neon lamp. When the phase shifter is adjusted to give a zero indication on the left-right meter the voltages applied to the mixer will be either in phase or 180° out of phase. The correct setting is that which gives in-phase voltages and therefore lights the neon lamp. Thus the lamp serves to indicate ambiguity, the beacon code, and proper operation of the system.

Figure 19-12 is a complete circuit diagram of the latest model of azimuth converter.

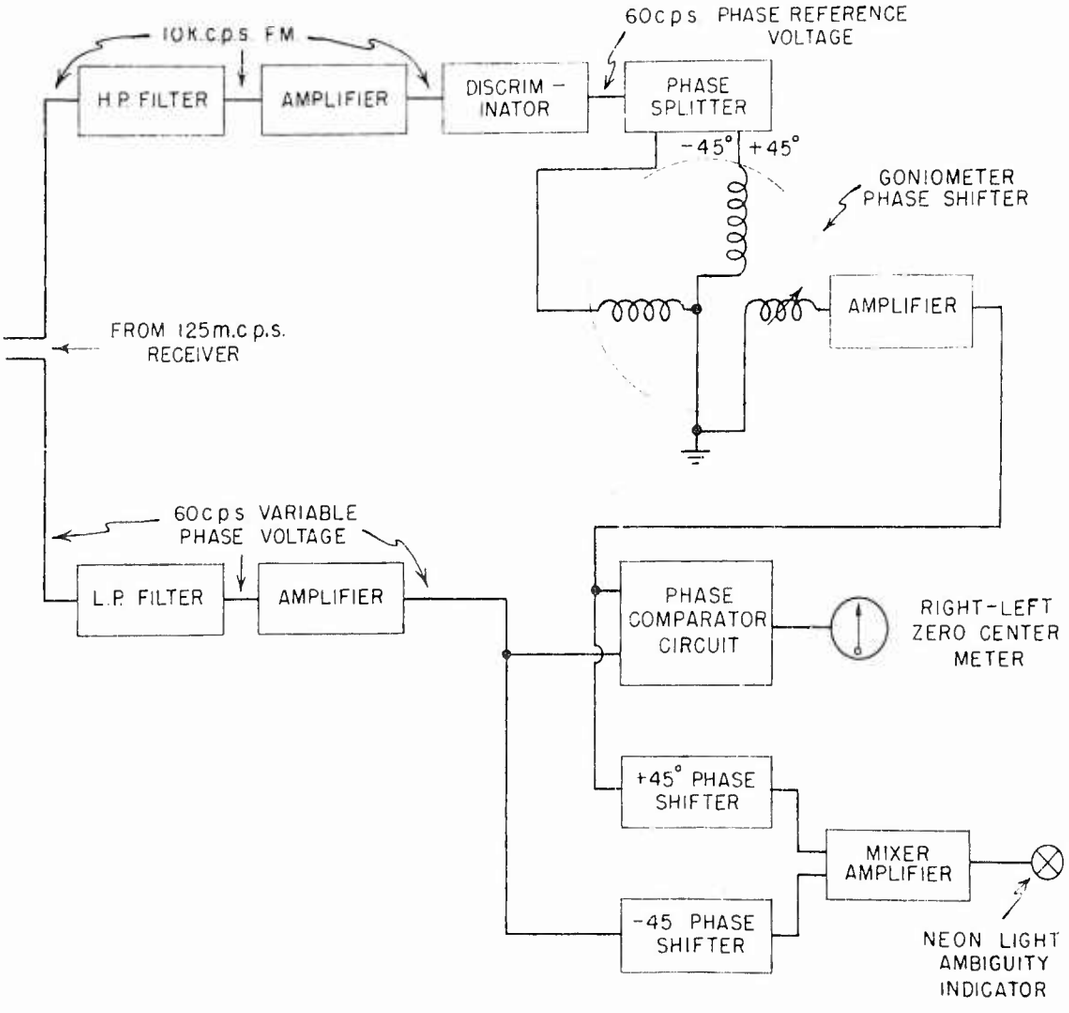


Fig. 19-09 Block diagram of azimuth converter

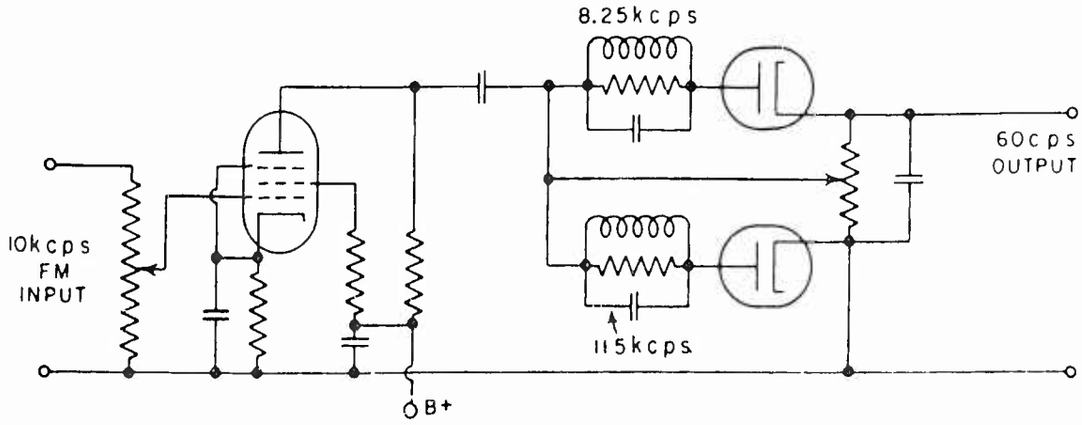


Fig. 19-10 Discriminator

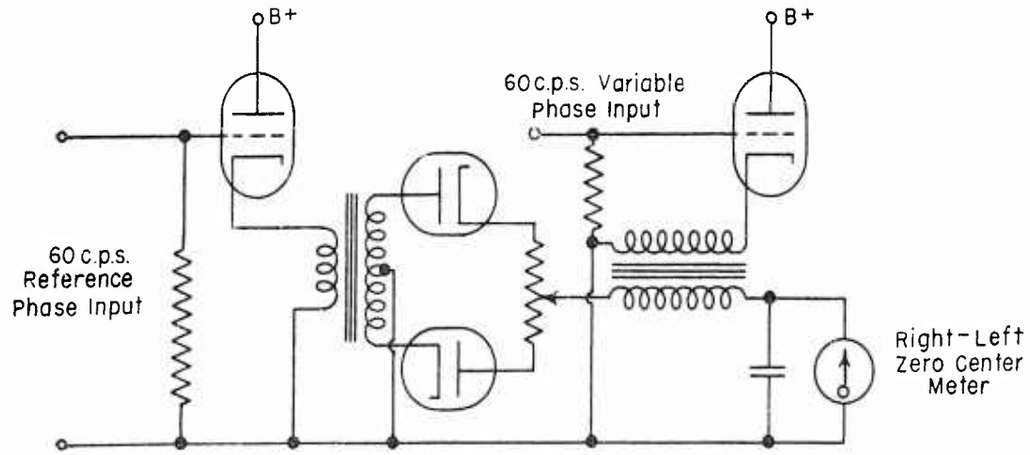


Fig. 19-11 Phase comparator

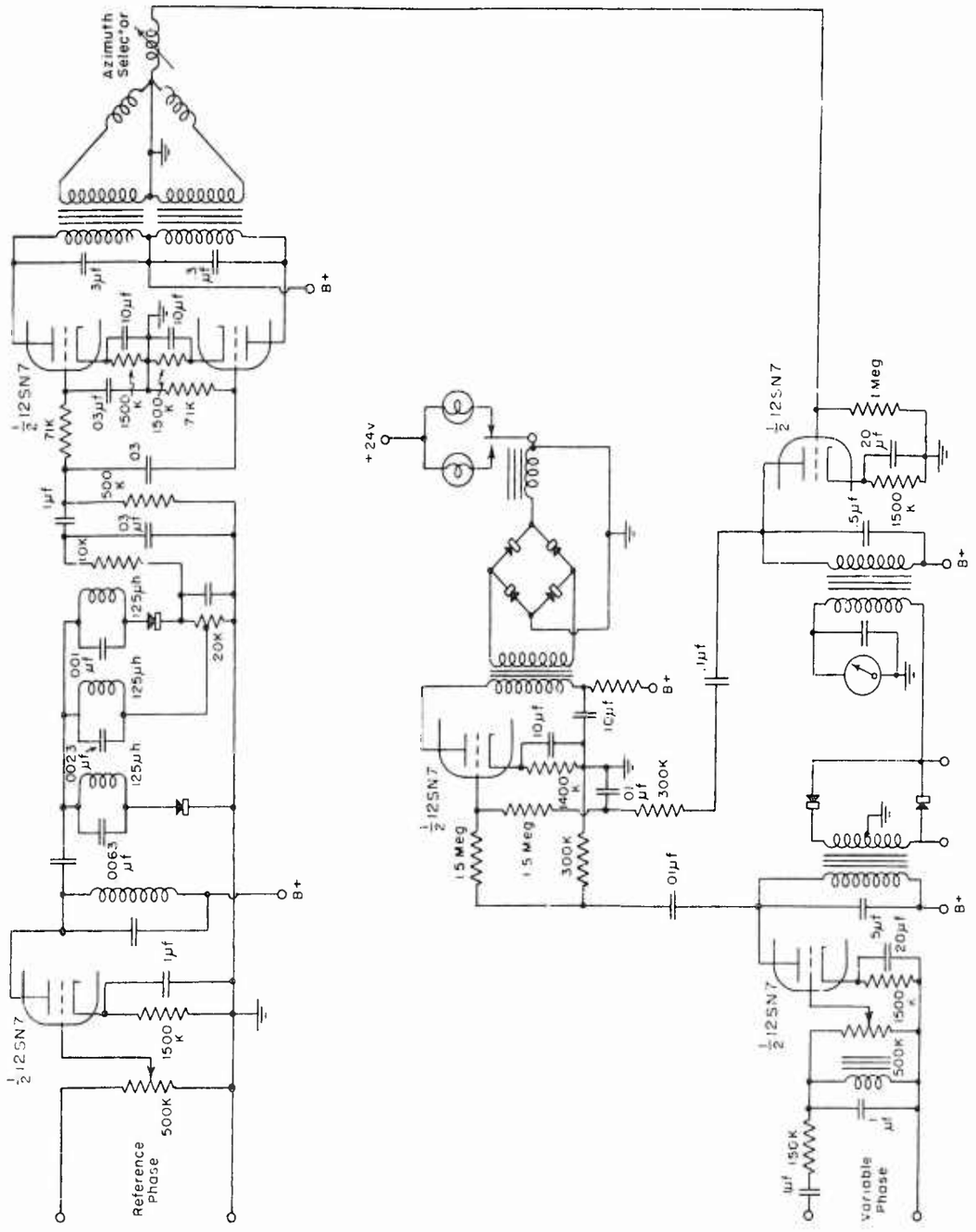


Fig. 19-12 Circuit diagram of azimuth converter

The Civil Aeronautics Authority is constructing an experimental low frequency omnidirectional beacon. The principle of operation is the same as that of the CAA VHF omnidirectional beacon described in Section 19. Five tower antennas will be used instead of the Alford loops used in the VHF version. The frequency will be somewhere between 200 kcps and 400 kcps. Because of the low frequency, the sub-carrier on the center antenna will be 1000 cps rather than the 10,000 cps used on the VHF beacon. Since a rotating-capacitor side-frequency generator is not practical at this low frequency it is proposed to use a rotating inductive-goniometer type of side-frequency generator. The azimuth converter used with the VHF beacon can also be used with this LF beacon if the discriminator is changed.

Type of system

Azimuth.

Useful range

Day - 1500 miles

Night - 1500 miles.

Accuracy

Ideal - Calculated accuracy assuming attenuator accuracy of 1%.

Accuracy in best direction

$1/5^{O}$ = 5.2 miles at 1000 miles

Accuracy 10^{O} from direction of least accuracy

$1\text{-}1/2^{O}$ = 39 miles at 1000 miles

Actual - Not known

Ambiguities - Unresolvable ambiguity between sectors spaced equi-angular from 90^{O} and 270^{O}. Accuracy in 90^{O} and 270^{O} directions is very poor, therefore ambiguity between closely spaced sectors on either side of 90^{O} or 270^{O} is not serious since system is not useful there anyway.

Presentation

Visual (meters and control knobs). Knobs must be varied to give specified meter indication and then line of position is read from dials. Line of position can be obtained in 1/2 to 1 minute.

Skill

Ground: Operator to check phase and amplitudes of currents fed to two antennas.

Craft: Intelligent use to avoid blind faith to readings.

Equipment required

Ground: 65-kw (max.) CW transmitter, phase-shifting equipment, two high and expensive antennas spaced $\lambda/2$ apart. Relatively simple and could be automatically monitored.

Craft: Receiver and indicating equipment. Fairly complex. Special charts.

Radio-frequency spectrum allotments required

Frequency: 70 kcps to 76 kcps

Wavelength: 4280 meters to 3950 meters

Bandwidth: Receiver - 15 cps

Transmitter - 70 cps.

Present status

Proposed.

This system is based upon the use of a fixed station which transmits energy in four different directivity patterns in succession. The signal received at the craft will have four amplitudes corresponding to these four directivity patterns. By proper interpretation of these values, the azimuth from the fixed station may be determined. Let us first consider only two of the four radiated patterns as shown in Figure 21-01. Pattern X— is obtained when the two antennas A and B are driven in phase. Pattern Y--- is obtained when two antennas A and B are driven 180^{O} out of phase. If the craft were located at the point f along the line ad the X and Y signals would be equal. This would be called an equisignal path since the X and Y signals would both correspond to the length ad. Let us now consider the craft at the point

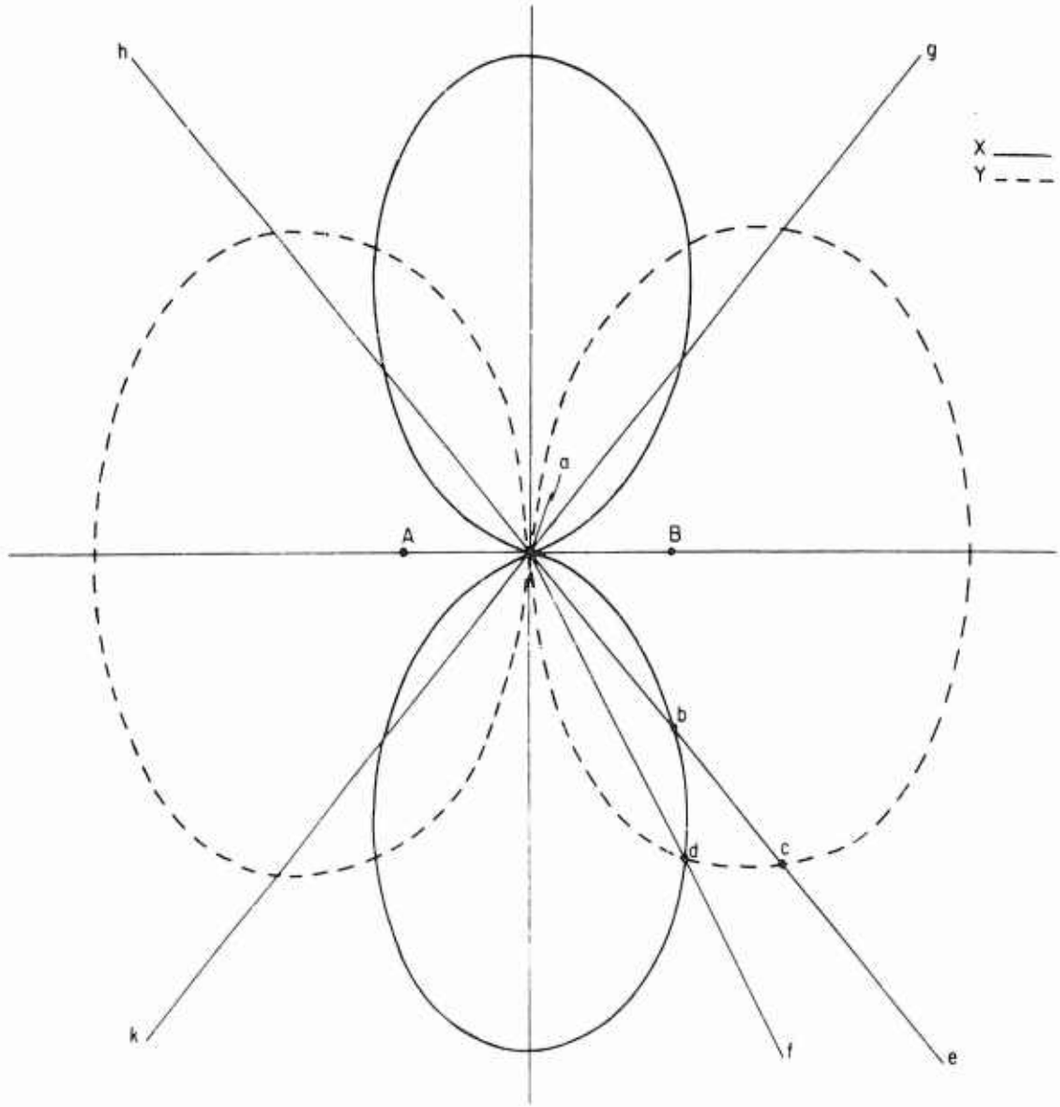


Fig. 21-01 Radiated patterns for 0^{O} and 180^{O} phase of antennas

e on the line abc. The Y signal will correspond to the length ac and the X signal will correspond to the length ab. If the equipment in the craft can measure the ratio of the X signal to the Y signal (X/Y = ab/ac) then it has determined the fact that it may be on the line abce. It might also lie on the lines ag, ah, or ak. This ambiguity can be reduced from 4 possible lines to two possible lines by making use of the other two radiated patterns. In the above case the ratio X/Y would be measured by gating the Y signal (ac) through a calibrated attenuator and reducing its amplitude to equal that of the unattenuated X signal ab. The value of attenuation necessary may be read from the attenuator thus giving the line of position on the special chart.

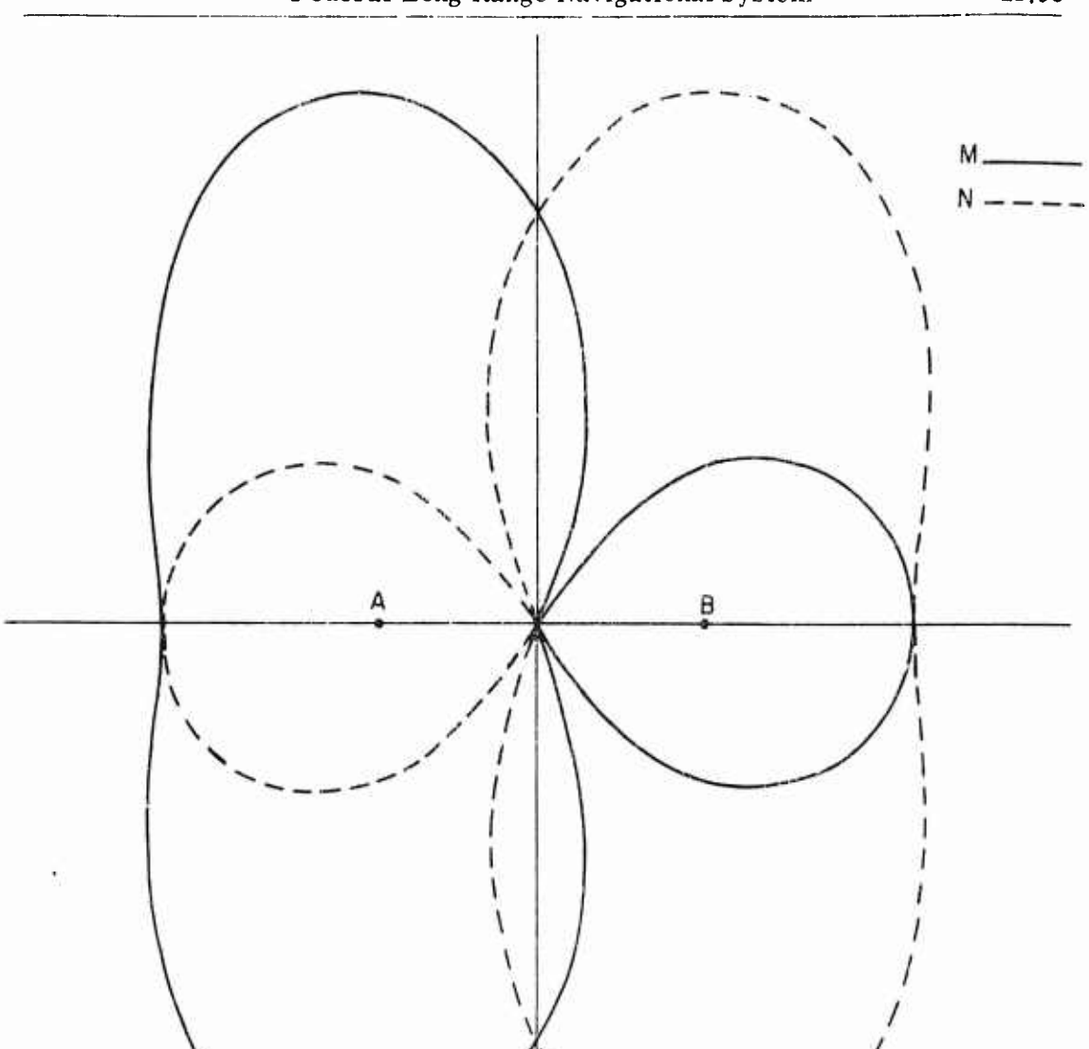


Fig. 21-02 Radiated patterns for 90^{O} and 270^{O} phase of antennas

In the simplified explanation given using only two antenna patterns, a limited number of azimuths in four general directions can be determined since the X/Y or Y/X ratio cannot be measured accurately if the weaker signal is too weak. In order to overcome this fault four antenna patterns are used. Figure 21-02 gives the two additional antenna patterns that are used. Pattern M—— is obtained when the current in antenna B leads the current in antenna A by 90^{O}. Pattern N--- is obtained when the current in antenna B leads the current in antenna A by 270^{O}. Thus all four of the patterns given in Figure 21-01 and Figure 21-02 may be obtained from the two antennas by supplying them with currents of equal magnitude and varying the phase of one current in four steps of 90^{O} with respect to the other. In order to be useful in measuring azimuth, some means of synchronizing the ratio-measuring circuit in the receiver must be used. In order to accomplish this an omnidirectional signal is transmitted once each cycle of four directivity patterns.

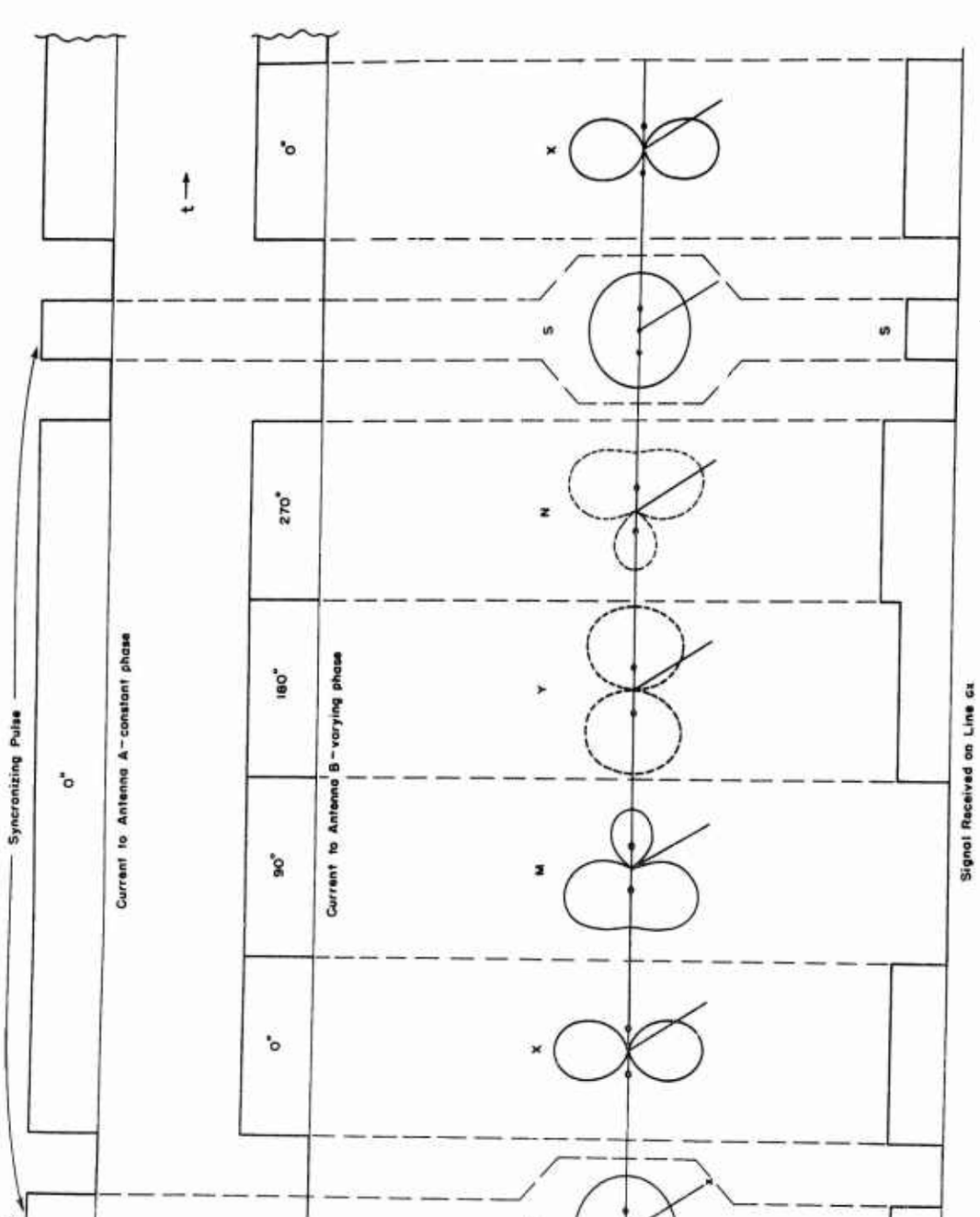


Fig. 21-03 Cycle of system

Figure 21-03 is a diagrammatic presentation of the currents supplied to each antenna and of the directivity patterns that result. The first line represents the current supplied to antenna A. This current is constant in phase but varies in amplitude as shown. The second line shows the current supplied to antenna B. Its amplitude and phase vary as shown. The phase angle indicated is taken with respect to the current in antenna A. The third line indicates the antenna directivity patterns obtained with the indicated phases. The fourth line indicates the signal that would be received along the line ax. The synchronizing signal S is received equally well in all directions. This cycle has a period of approximately 1 second.

The upper part of Figure 21-04 is a rectangular plot of the four radiation patterns of the ground antenna system. The bottom part of this figure is a plot of the X/Y, Y/X, M/N, and N/M ratios. From this it can be seen that a ratio less than 0.4 need never be used. Between the two plots the useful ratios and the sector symbol assigned to them are given. It will be noticed that there are two sectors in which the same X/Y ratios occur. This ambiguity can be resolved by use of the M/N or N/M ratios since they will not be the same for these two ambiguous sectors. The ratios used for sector resolution or check are shown above the sector symbol. It will be noted that sectors equi-angular distant from 90^{0} and 270^{0} are ambiguous and that this ambiguity cannot be resolved.

Figure 21-05 is a block diagram of the receiver-indicator system. Only the IF amplifier of the receiver is indicated. An auxiliary detector is fed from the output of the IF unit. The output of this detector corresponds to the entire cycle of signal strengths. This output is fed to the synchronizing-signal selector which selects only the synchronizing signal. This signal (pulse) is used to synchronize a stable sine-wave oscillator. This oscillator serves as a time base to operate the gating circuit. The output of this sine-wave generator is fed to a phase-shifting circuit. The output of this circuit consists of two sine waves that are roughly 90^{0} out of phase (the actual phase relation proposed is 113^{0}). One of these sine waves is used to control a gating-pulse generator. These gating pulses gate an IF amplifier stage and therefore pass only part of the X and Y signals, or the M and N signals. The other sine wave is fed to a half-wave rectifier. The output of this rectifier energizes a nonpolarized relay. The rectifier can be switched to pass either the positive or the negative halves of the sine wave supplied to it. As a specific example, let us assume that the sine wave of the correct phase to gate the X and Y signals to the detector is used. The other sine wave is half-wave rectified and the pulses operate the relay. The relay can thus be pre-set, by the rectified pulses of current, to pass the X signal through the attenuator and released to pass the Y signal direct. The actual duration and timing of the X and Y signals is not determined by the relay timing but by the gating pulse generator. By reversing the direction of the relay rectifier the Y signal may be passed through the attenuator and the X signal passed directly. This permits either the Y/X ratio or the X/Y ratio to be measured. By reversing the roles played by the two out-of-phase sine waves the M signal and N signal may be gated to the detector and the relay rectifier switch permits one to select either the M/N or the N/M ratio. The attenuated and unattenuated signals are applied to a differential zero-center meter through two reversing switches and a damping filter. Since this system may be used for homing, one reversing switch is used to reverse the sense of the meter indication depending upon whether the craft is moving toward or away from the fixed station. The second reversing switch is used to give the correct sense of indication when the ambiguity check is made. This second reversing switch, the relay rectifier reversing switch, and the phase distributor switch are all ganged together and called the sector selector switch. This switch has eight positions, two for each of the following ratio

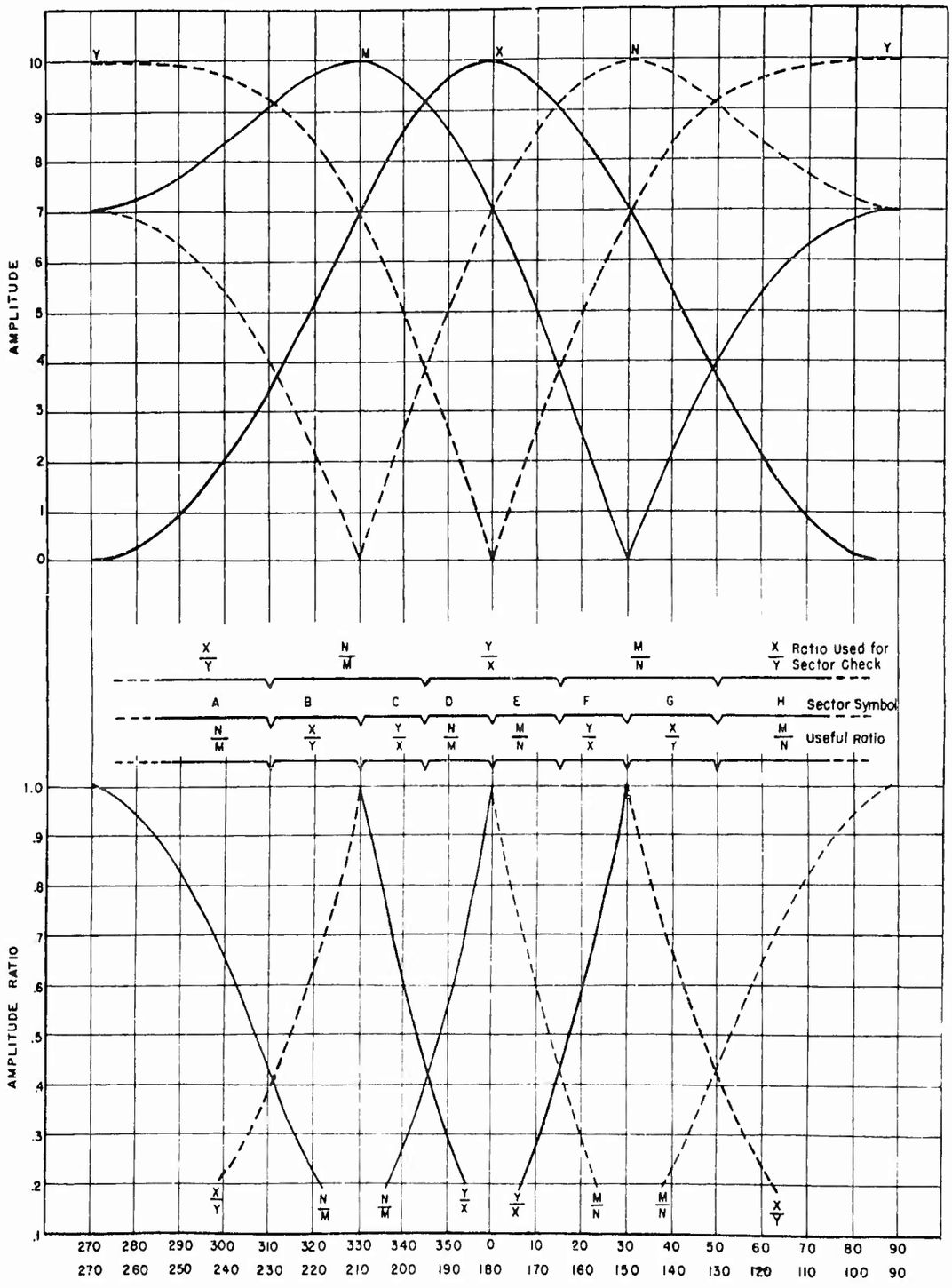


Fig. 21-04 Radiated patterns and ratios used for measurement

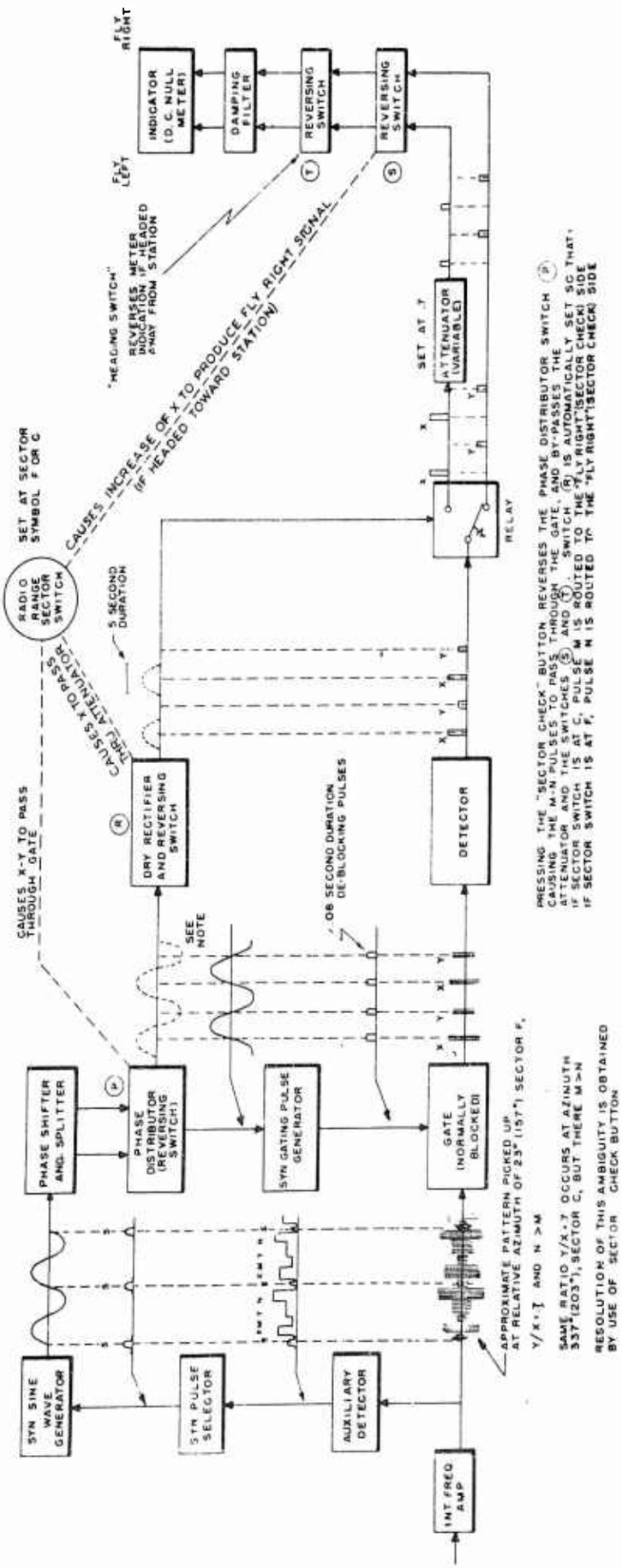


Fig. 21-05 Block diagram of azimuth unit

measurements: X/Y, Y/X, M/N, N/M. For a given value of any one of the four ratios given there exist four radial lines of position. By checking the value of the ratio obtained from the other pair of patterns this ambiguity can be reduced to two lines of position equi-angular distant from the 90^{o} - 270^{o} axis. By referring to Figure 21-04 it can be seen that a given value of Y/X ratio can be obtained in sectors C and F. The N/M ratio in sector C is less than one and is greater than one in sector F thus permitting the ambiguity between sectors C and F to be resolved by a check on the N/M ratio. On the indicating panel a push button is provided to do the necessary switching to make this check. This irreducible ambiguity is not too serious since the system does not give accurate lines of position close to this axis anyway. It is suggested that this ambiguity could be reduced by taking bearings from other stations or by use of a DF system on the craft.

The calculated accuracy assuming an attenuator accuracy of 1 % is:

Pattern	Azimuth	Angular error	Lateral error at 1500 miles
M-N	0^{o} (180^{o})	$1/5^{o}$	5.2
M-N or X-Y	15^{o} (345^{o}, 165^{o}, 195^{o})	$1/3^{o}$	8.7
X-Y	30^{o} (330^{o}, 150^{o}, 210^{o})	$1/4^{o}$	6.5
M-N or X-Y	50^{o} (310^{o}, 130^{o}, 230^{o})	$1/2^{o}$	13
M-N	70^{o} (290^{o}, 110^{o}, 250^{o})	$5/8^{o}$	16
M-N	80^{o} (280^{o}, 100^{o}, 260^{o})	$1\text{-}1/2^{o}$	39
M-N	90^{o} (270^{o})	6^{o}	157

Some errors might be caused by the fact that the ratio of the field strengths is not measured instantaneously but the two fields are sampled in succession. The presence of noise or rapid fading would require a very long time-constant in the meter damping filter to average out such effects.

Bibliography

Identification	Classification	Title	Issued by
Proposal No. 235	Confidential	Universal Communications, Airport Control, Traffic Control, and Aerial Navigation System (Part III - Aerial Navigation)	Federal Telephone and Radio Corporation

There are a number of airborne radar sets which are designed to perform one or several different functions such as: search, general navigation (by beacons, landscape, etc.), bomb release, identification, interception, early warning, gun-laying, collision prevention, measurement of altitude, etc. Brief descriptions of the various pieces of radar equipment which are available to perform some of the above functions may be found in Section 1 of the U.S. Radar Survey. H2X (AN/APS-15 or AN/APQ-13) equipment is among the most useful airborne radars for purposes of general navigation, and has been in operational use for several years. AN/APS-15 is typical of H2X equipment. The following pages of this section contain a description of the AN/APS-15 set and the NOSMO attachment to it. The Micro-H attachment for H2X is described separately in Section 5. AN/APS-15 is X-band airborne radar equipment with PPI presentation and facilities for making accurate range measurements to range-coded beacons.

Description of Radar Set AN/APS-15 (H2X)

Type of System

Combination of range and azimuth.

Useful Range

0-90 miles for search operation, 0-250 miles for beacon operation (radar line-of-sight), 1000-36,000 feet for precise altitude measurement. Battleships can be detected at a maximum reliable range of 60 miles, destroyers at 45 miles, surfaced submarines at 10 miles, and ground targets such as cities at a maximum range of 30-60 miles.

Accuracy and Precision

(a) Range accuracy: For beacon interrogation, $\pm$ 200 yards; for high altitude bombing $\pm$ 200 yards; for normal search operation, $\pm$ 500 yards on 5-mile sweep, $\pm$ 5,000-10,000 yards on 90-mile sweep; for high altitude search, $\pm$ 200 yards on computer, $\pm$ 500 yards on 5-mile sweep, $\pm$ 2000 yards on 20-mile sweep.

(b) Azimuth-angle accuracy, $\pm$ 3^{o}; azimuth-angle accuracy with azimuth stabilization, $\pm$ 6^{o}.

Presentation of Data

Visual on PPI.

Operating Skills Required

One skilled radar-operator and possibly also a navigator in the aircraft. Ground beacons are unattended. Time for a navigational fix with beacons: less than a minute.

Equipment Required

Weight of H2X aircraft equipment is about 370 pounds. An X-band beacon such as AN/CPN-6 or equivalent is suitable as ground beacon equipment for use with H2X.

Radio-Frequency Spectrum Allotments Required

Aircraft Radar, f = 9335 to 9415 mcps λ = 3.2 cm. B.W. = 2.5 mcps.
Ground Beacons, f = 9310 mcps

Present Status of Development

Fully developed, in production, and in operational use.

Brief Non-Technical Description of H2X Equipment

Although the primary use of H2X equipment is to locate land objectives and to time the release of bombs for area bombing, it is also an extremely useful aid

for general navigation. H2X equipment provides means for:

(1) Blind navigation and homing through beacon reception.
(2) Normal radar search operation with PPI presentation.
(3) Control of high-altitude bombing.
(4) Determination of altitude.
(5) Instantaneous determination of true or relative bearing.
(6) Determination of drift angle.

The essential components of the set are shown in the block diagram of Figure 22-01.

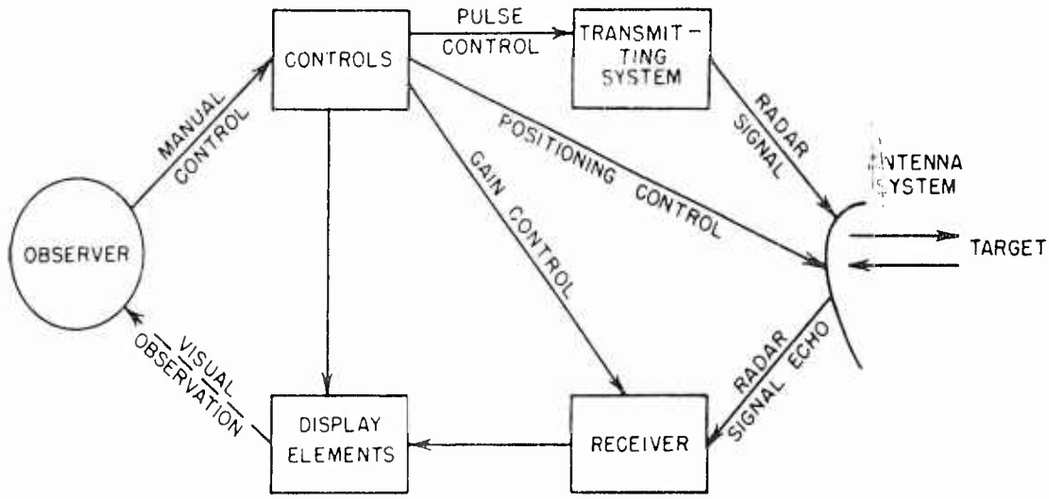


Fig. 22-01 Simplified block diagram for H2X radar set

The PPI gives a map-like presentation of a large circular area (or sector thereof) of the earth's surface, and superimposed upon this may be indications of other aircraft in the vicinity. During navigation by beacons, only beacon response signals and an adjustable range marker appear on the PPI screen.

The map-like character of the PPI presentation makes it extremely useful as a general navigational aid especially near coastal regions where characteristic irregularities of coastline are easily recognizable. The top of the PPI screen may be chosen to represent either true north or the heading of the aircraft.

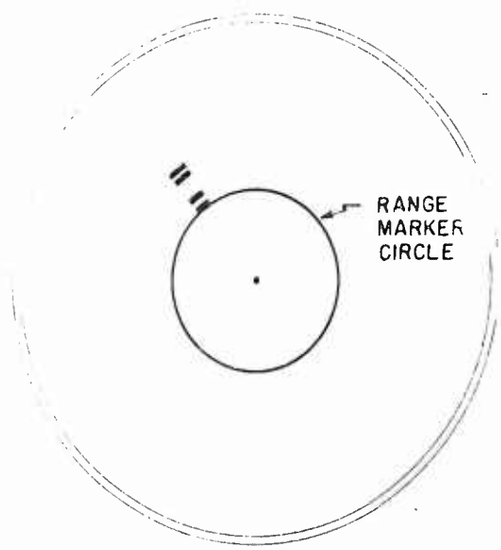


Fig. 22-02 Example of beacon code signal

The altitude of the aircraft is obtained from the time required for a pulse signal to travel from the aircraft to the ground and back. Two signals must be aligned visually on a separate cathode-ray-tube indicator (A-scan) with the aid of a variable time-delay circuit the adjustment of which controls the position of a direct-reading altitude-indicator.

Radar responder beacons (racons) may be interrogated from the aircraft, and range-coded response signals observed on the PPI screen as illustrated by Figure 22-02. The beacon response signals are coded for the purpose of beacon identification. The range to any beacon may be obtained from dial indications after setting an adjustable slant-range marker circle for coincidence with the first (inner) beacon response on the PPI. From the altitude and slant range, and ground range may be easily determined. (See Figure 22-03). Ground range determinations on two beacons enable the navigator to determine a fix (See Figure 22-04).

The PPI may be set so that the top of its screen represents the heading of the aircraft. It is then a simple matter for the pilot to direct the craft so as to "home" on a beacon.

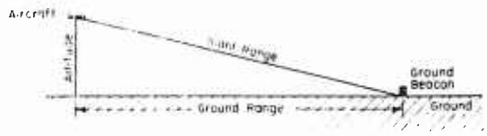


Fig. 22-03 Range and altitude relationships

The stationary circumference of the PPI screen is marked off in degrees with zero at the top. A fine ruled line on a transparent rotatable cover may be set to any desired azimuth. When the flux-gate compass and associated azimuth-stabilization equipment is used to keep the true-north direction at the top (0^{O} position) of the PPI screen, the adjustable azimuth line on the transparent cover may be conveniently used to obtain the true bearing of any target appearing on the screen. A bright radial line on the PPI is available if desired to indicate the heading of the aircraft. If the azimuth stabilization equipment is not used, then the top of the PPI image represents the heading of the aircraft; and the adjustable azimuth line may then be used to determine the relative bearing of any target with respect to the heading of the aircraft. The use of the adjustable azimuth line to determine drift angle will be discussed later.

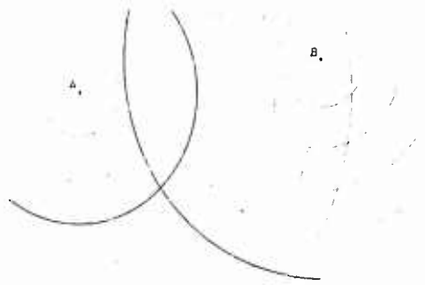


Fig. 22-04 Navigational fix obtained from range measurements to two beacons

Although this survey is not primarily concerned with bombing-run procedure, in the present instance an outline of the high-altitude bombing operation provides a convenient illustration of techniques which are also applicable to general navigational problems. In this operation, a preliminary determination of wind velocity must be made early in the mission before the start of the actual bombing run. This may be accomplished by determining the air velocity and ground velocity during a short straight flight. The air velocity is obtained from the direction of flight (PPI indicator) and an air-speed indicator dial, the reading of which must be corrected for altitude and temperature. The ground velocity may be most easily determined with the aid of ground beacons. Two successive navigational "fixes", taken a short time apart, will give the ground velocity (ground speed and course bearing). A vector diagram such as that shown in Figure 22-05 enables the navigator to determine the wind velocity.

As soon as the target is located (within 50 miles of the aircraft) the pilot heads the aircraft toward the target and the navigator calculates as quickly as possible what the air speed and heading should be in order that the plane's course pass directly over the target. This trigonometric calculation is simply a second applica-

tion of a vector diagram similar to that of Figure 22-05, except that now the desired ground velocity toward the target is known; and from the predetermined wind speed the navigator can calculate the required air speed and heading of the aircraft. Temperature and altitude corrections must be applied to the true air speed in order to obtain the indicated air speed to which the pilot must hold the aircraft.

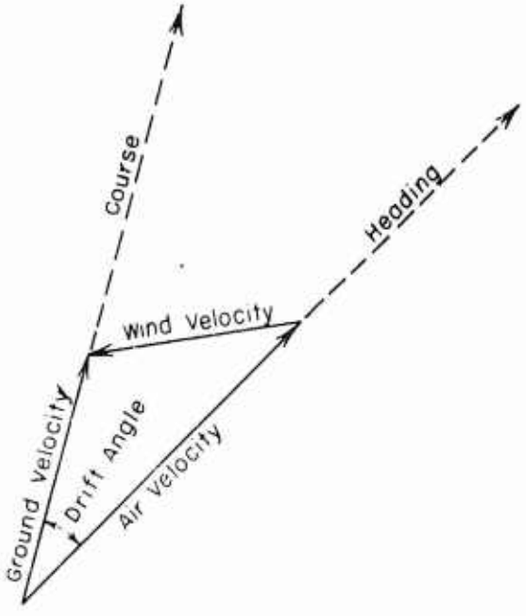


Fig. 22-05 Determination of wind velocity

If the center line of the sector scan corresponds to the heading of the aircraft then the top of the PPI screen indicates the craft heading; and the adjustable azimuth line if set at the proper drift angle indicates the aircraft's course over the PPI map. All objects on the PPI screen tend to drift parallel to the adjustable azimuth line underneath which the target should appear. However, during the bombing run it is more convenient to have the top of the PPI screen correspond to the aircraft course through the target as shown in Figure 22-06. An azimuth adjustment is therefore provided so that the center of the sector-scan may be displaced from the heading of the aircraft.

For a given type of bomb, corresponding altitude and slant ranges have been determined for several values of ground speed. This information is presented graphically upon a drum chart, the vertical and horizontal scales of which are altitude and slant range. Adjustment of a slant-range cross hair for coincidence with an intersection of an altitude cross hair with the chosen value of aircraft ground speed, automatically places the adjustable slant-range marker-circle on the PPI at the proper slant range required for bomb release. The bombs are released at the instant that the target crosses tne slant-range marker-circle.

Brief Technical Description of the AN/APS-15 (H2X) Radar Set

The type AN/APS-15 radar set has been chosen as typical airborne equipment. A brief description of the type and function of each component is presented first. Then a number of more specialized functional block-diagrams with some waveforms and time charts are discussed. A few circuit diagrams of special interest are given; but for detailed mechanical and electrical information the reader is referred to the Handbook of Instructions for Radio Set AN/APS-15 (H2X) prepared by the MIT Radiation Laboratory. Space does not permit a detailed description of each and every circuit of the H2X system. More space is allotted to the description of the timing circuits than to more standard components such as IF amplifiers, wave

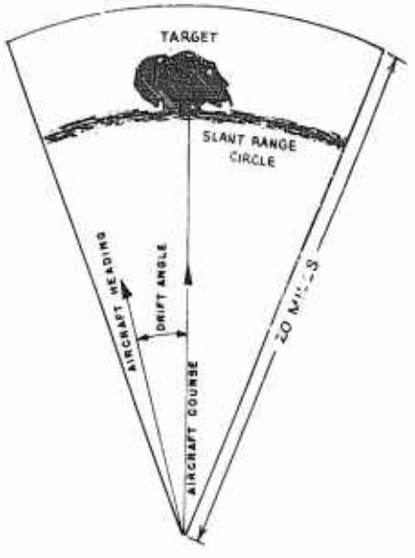


Fig. 22-06 Setting of precise slant range marker

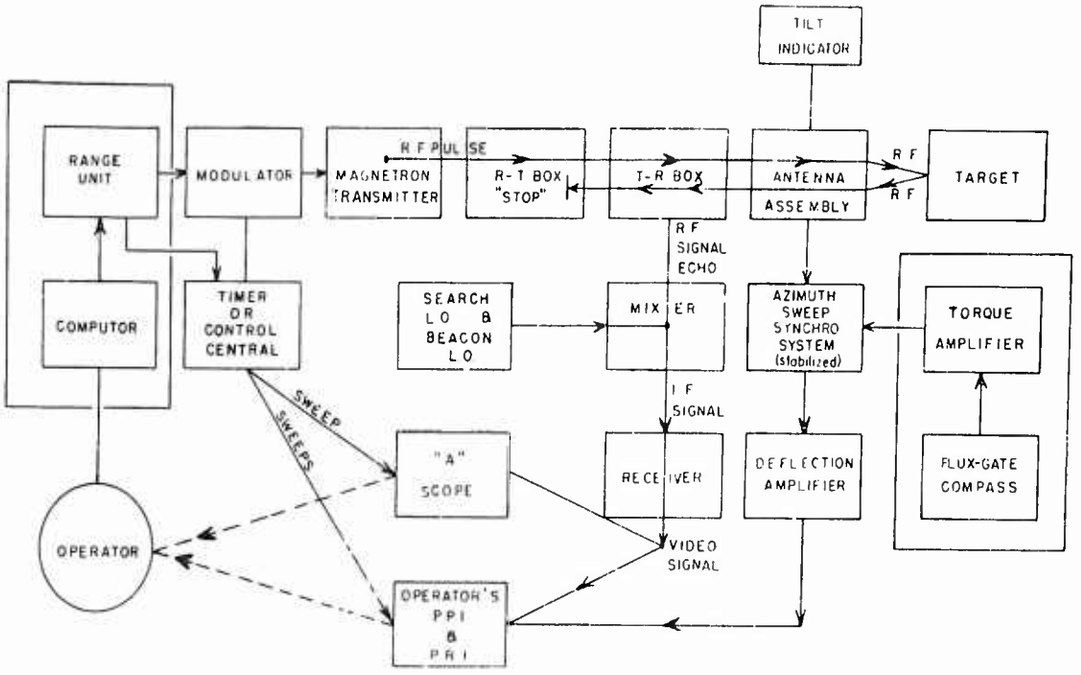


Fig. 22-07 Functional block diagram of the AN/APS-15 equipment

guides, etc. For a description of the more or less standard radar-set components and special UHF techniques involved in the operation thereof, the reader is referred to any of the Army or Navy radar instruction manuals or to other similar books such as "Principles of Radar" by the staff of the MIT Radar School.

Figure 22-07 is a functional block diagram of the AN/APS-15 equipment. Referring to Figure 22-07, the timer or control central, the computer, and the range unit are the components of greatest interest in a discussion of the functional operation of H2X equipment. The consideration of these timing circuits is postponed until a brief description of the other components of the system has been completed.

Sweep Circuits

The "A" scope may be used for a variety of purposes such as checking the dividing ratio of a frequency-dividing circuit, checking signal strength and overload of the receiver, or other alignment problems; but the operational use of the "A" scan is primarily for matching a delayed marker pip with the first ground-return signal for the determination of altitude. The sawtooth voltage sweep generator for the "A" scope is a conventional RC hard-tube circuit in which the desired sweep is generated while a normally conducting tube is cut off by a negative gate from the timing oscillator. The same negative gate is used to "unblank" the "A" scope during the sweep.

The trapezoidal voltage necessary to cause a sawtooth current-wave in the magnetic deflection coils of the PPI tube is generated by a circuit very similar to that of the "A"-scope sweep-generator. The required trapezoidal voltage is fed through slip rings to the rotor of the sweep synchro which rotates in synchronism with the antenna system (See Figure 22-08). Two mutually perpendicular sets of secondary stator windings each pick up a trapezoidal voltage and apply it through a push-pull synchronized clamping-circuit to a correspondingly oriented set of magnetic-deflection coils on the PPI tube. The rotary motion of the synchro rotor is relatively slow, so that its change in angle during the short time of any one trapezoidal sweep voltage cycle is negligibly small. Consequently the voltages induced in the two mutually perpendicular sets of secondary stator coils are in time phase with one another, but in general differ in magnitude, depending upon the position of

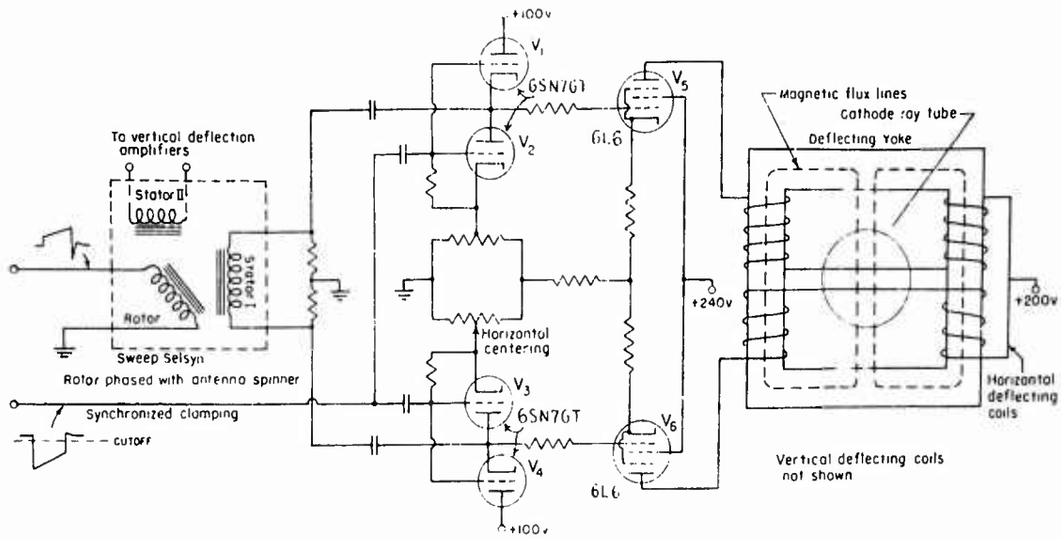


Fig. 22-08 Horizontal deflection amplifier with synchronized clamping

A similar circuit connected to stator II provides for vertical deflection. The normally conducting tubes V1 and V2 act as a voltage divider to clamp the control grid of V5 to a definite potential except during the time of the sweep when a negative gate cuts off V1 and V2 allowing the tropezoidal signal to be amplified by V5. The lower half of the push-pull circuit acts in a similar manner. Horizontal centering is accomplished by balancing the DC plate currents of V5 and V6.

the rotor. The magnitudes of the two secondary voltages vary slowly throughout the cycle of rotation of the antenna spinner (12 or 24 r.p.m.); the magnitude of one varying sinusoidally and that of the other cosinusoidally with respect to the angular position of the rotor. These voltages provide a radial sweep (from the center to the outer edge of the screen) the azimuth of which changes in synchronism with the direction of the antenna beam. The top of the PPI presentation corresponds to the heading of the aircraft unless azimuth stabilization is used, in which case the position of the sweep-synchro stator coils relative to the aircraft heading may be oriented by means of a flux-gate compass and servo-system (including magnetic deviation correction) so that the true north direction appears at the top of the PPI screen.

RF Components

The modulator, transmitter and receiver-preamplifier (converter) are located in a pressurized chamber directly above the radome. The input pulse to the driver or pulse-forming circuit is shown in Figure 22-09 and has a peak amplitude of about 120 volts. This voltage is divided between an artificial line, a transformer secondary S, and the grid-cathode space of the pulse-forming amplifier tube shown in Figure 22-10. The transformer has three suitably damped windings with the primary and secondary windings regeneratively connected. The tube is normally biased beyond cut-off, but upon application of the positive pulse, the regenerative action turns on the plate current suddenly. The rise of plate current is, however, quite linear, result-

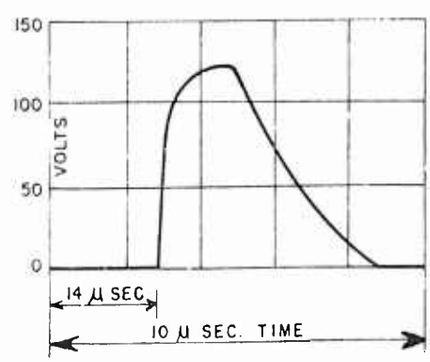


Fig. 22-09 Input pulse to the driver

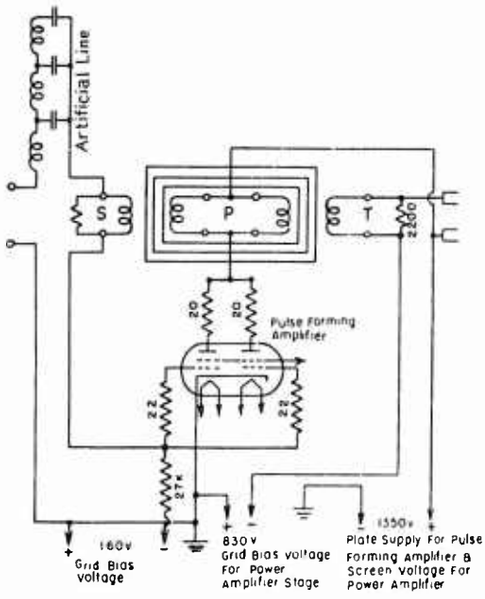


Fig. 22-10 Transmitter driver pulse forming circuit

ing in constant secondary and tertiary voltages. The uniform rise of plate current continues until the input pulse returns as an in-phase reflection from the end of the artificial line, at which instant the grid is driven negative and regenerative action abruptly stops the flow of plate current. A typical rectangular output voltage pulse of the tertiary winding is shown in Figure 22-11. The time width of the output pulse of course depends upon the delay introduced by the artificial line. Three artificial lines are available for generating 0.5, 1, and 2 microsecond pulses.

Application of the positive, rectangular pulse to the grid of a power-amplifier stage, delivers a 14,000 volt negative pulse to the cathode of the magnetron oscillator, the plate of which is at ground potential.

The short train of SHF electromagnetic waves constituting a signal pulse is transmitted from the magnetron to the antenna through the radio-frequency system, consisting of the magnetron coupling unit, T-R and R-T boxes, several lengths of rectangular waveguide (1" x 1/2"), azimuth-rotating and tilt-rotating joints. The antenna consists of the antenna feed system and specially-shaped reflector. A block diagram of the pressurized RF system is given in Figure 22-12. The function of the T-R box is to protect the crystal of the sensitive receiving-system from the high-power transmitted pulse. The output circuit of the magnetron

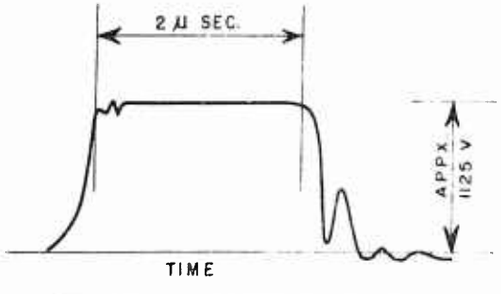


Fig. 22-11 Driver output pulse during beacon operation

when inoperative is prevented by the R-T box from absorbing much energy from the weak radar echo signals.

The wave guide terminates in two "windows" at the focal point of the reflector. The radiation from the windows is gathered by the reflector and focused into a narrow, fan-like beam of about 3^{O} angular width in the horizontal plane, and about

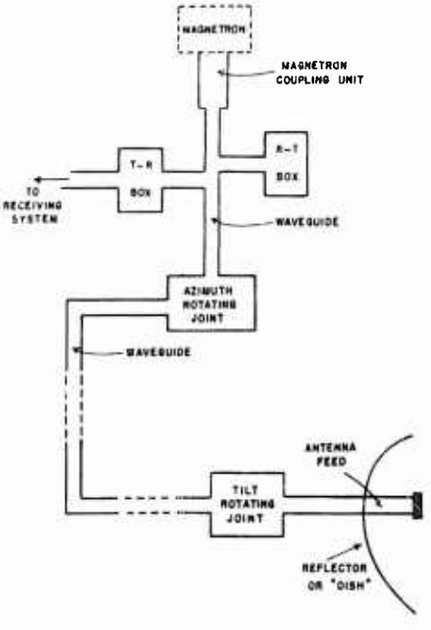


Fig. 22-12 Block diagram of the RF system

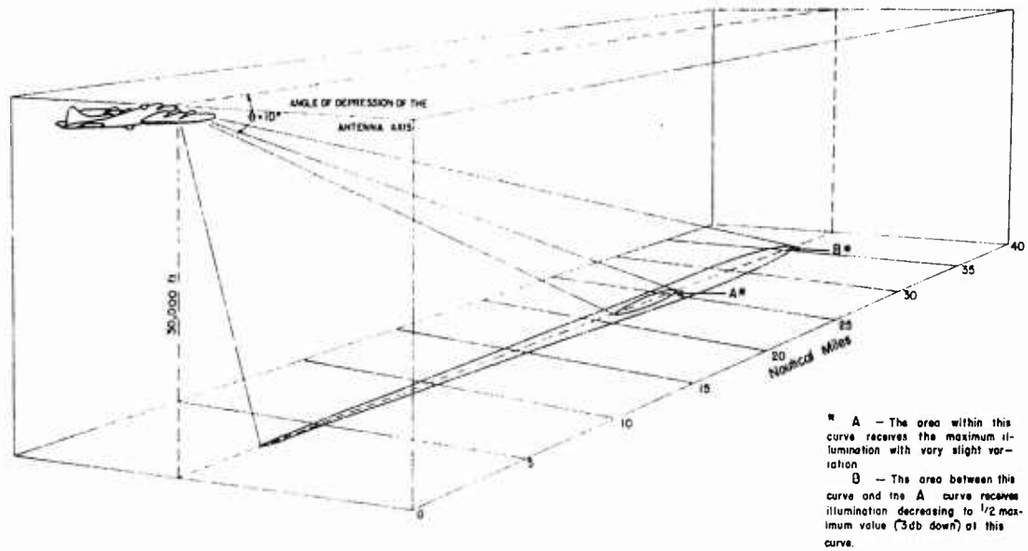


Fig. 22-13 Perspective drawing of antenna beam pattern

60^{o} angular width in the vertical plane (assuming the aircraft in level flight). Figure 22-13 illustrates the illumination of the ground when the reflector is in its normal position with the aircraft in level flight. The small area within curve A receives the maximum illumination with very slight variation. This small area is at an angle of depression θ of about 10^{o} from the horizontal (See Figure 22-14). The illumination decreases gradually between curves A and B until at curve B it has fallen to one-half of its maximum value (3 db down). This type of beam pattern is sometimes referred to as a "cosecant squared" type, since over a considerable range of θ the field strength in a vertical plane containing the aircraft and its line of flight is directly proportional to $\text{cosecant}^{2}\theta$. The reflector may be tilted in the vertical plane by $\pm$ 20 degrees from its normal position in order to permit a more favorable illumination of a particular target area. The antenna system may be rotated continuously to provide for a 360^{o} PPI presentation, or it may be wobbled back and forth to provide for a 56^{o} sector scan.

Echo signals may be received only from the direction in which the reflector is "looking". Reflected wave trains are collected by the reflector and focused upon the windows in the end of the wave guide which act as a receiving system to driv. the wave guide. Such a reflected signal traverses the RF system in the opposite direction from that of the transmitted pulse. At the junction leading to the T-R box however, the received signals are diverted through the T-R box to the converter of the receiving system.

Flux-gate Compass System

The heading of the aircraft relative to true or magnetic north is determined by the gyro flux-gate compass system which depends for its operation upon the horizontal component of the earth's magnetic field. The flux-gate element consists of three soft iron cores, each carrying primary and secondary windings and arranged as the legs of an equilateral triangle as indicated in Figure 22-15. It is located out in one wing of the aircraft, as far as possible from any ferrous-metal parts, and is

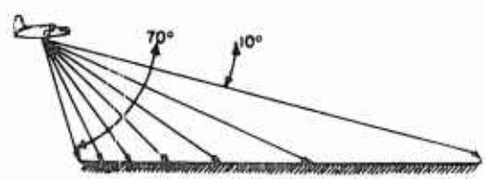


Fig. 22-14 Approximate antenna radiation pattern for constant target contrast

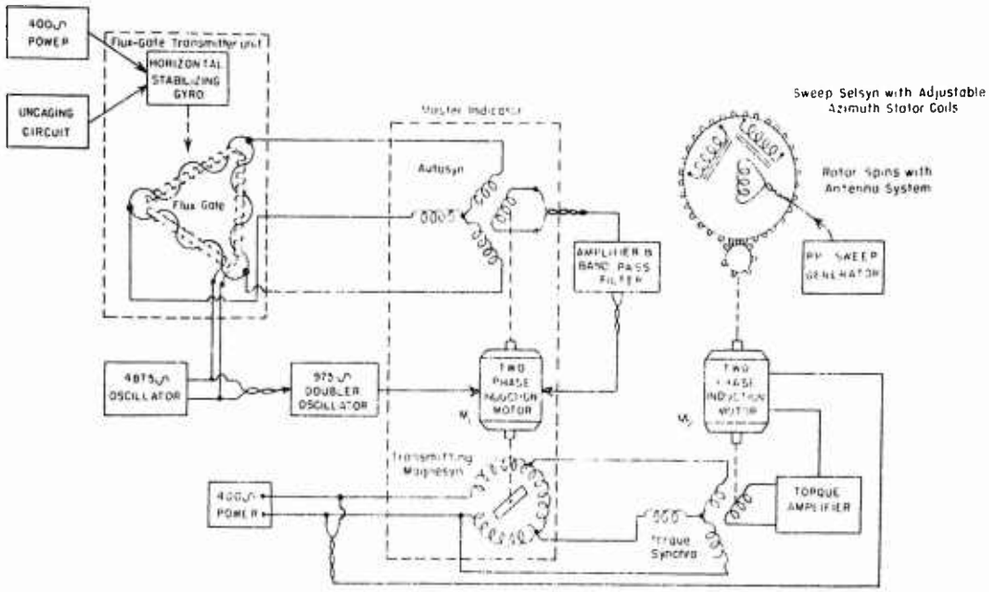


Fig. 22-15 Schematic diagram showing essential elements of azimuth stabilization system

stabilized in a horizontal plane by a vertical-seeking gyroscope, the electric driving-motor of which is powered by the 400 cps supply of the aircraft.

A 2.5 volt sine wave from the 487.5 cps oscillator is impressed upon the primary winding of the flux gate. This signal is sufficiently large to saturate the cores so that the only significant rate of change of flux occurs twice a cycle when the primary current is near zero. The primary current which saturates the cores serves to gate the effect of the earth's magnetic field in such a way that the earth's field can exert its influence only during two short periods in each cycle, hence the name "flux gate". If the earth's magnetic field were non-existent, the three secondary voltages would all be identical, and would consist of alternate positive and negative pulses occurring whenever the primary current passed through zero. The presence of the earth's magnetic field or a component thereof parallel to one of the cores will cause an increase in the secondary voltage pulse of one polarity and a decrease in the size of the pulse of opposite polarity. The presence of alternate positive and negative pulses of unequal magnitude is essentially equivalent to a large second-harmonic component in the secondary voltage. The second harmonic content of the voltage pulses in the three secondary windings will in general be different for each of the windings, and will depend upon the direction of the earth's horizontal field relative to the fixed orientation of the flux-gate element in the aircraft. If the earth's magnetic field were non-existent, the equal secondary voltages of the flux gate applied to the stator of the autosyn would produce no resultant magnetic field to act on the rotor; but with the earth's field acting on the flux gate, the unequal voltages applied to the stator of the autosyn produce an alternating field having a definite direction dependent upon the direction of the earth's field linking the flux gate. The rotor of the autosyn picks up a voltage, the 975 cps component of which is selected by an amplifier and band pass filter and applied to one phase of a two phase induction motor, the other phase being fed by a 975 cps signal from a doubler oscillator. The motor turns until the rotor of the autosyn reaches a null position in which no voltage is picked up to drive the motor further. The rotor is geared to a dial pointer which indicated the heading of the aircraft. Provision is made so that the magnetic variation may be set in manually so that the dial pointer

of the master indicator reads the heading of the aircraft relative to true north instead of magnetic north. Mechanical screwdriver adjustments are provided every 15 degrees around the circumference of the dial to correct the pointer reading for errors introduced by the distortion of the earth's field due to magnetic material in the aircraft. The calibration adjustments are made at a selected ground site after installation of the equipment.

In order that the top of the PPI screen shall always represent the north direction, as the aircraft heading changes, the movement of the sweep-synchro stators must follow the rotation of the autosyn rotor. This is accomplished by means of another servo link. A permanent magnet rotor of a transmitting magnesyn is geared to the pointer of the master indicator. 400 cps power is fed to the saturable core stator windings of the transmitting magnesyn and also to one phase of a two phase induction motor M_2. The voltage distribution in the three stator windings of the magnesyn as determined by the position of its rotor is transmitted to the stator windings of the torque synchro and sets up an alternating field in a direction corresponding to the position of the permanent magnet rotor of the transmitting magnesyn. The rotor coil of the torque synchro picks up an error voltage which is amplified by the torque amplifier and applied to the second phase of the motor M_2. The motor runs, rotating both the sweep synchro stator assembly and the rotor coil of the torque synchro until the coil reaches a null position in which no voltage is picked up to drive the motor further.

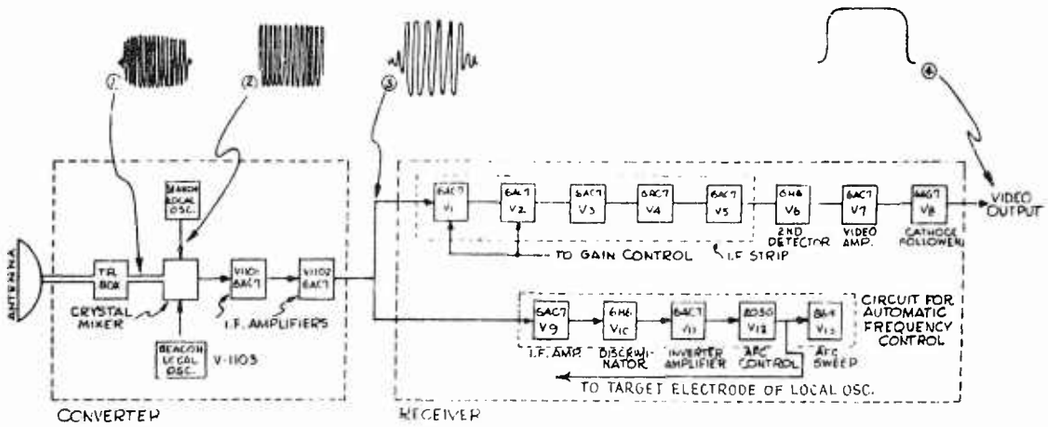


Fig. 22-16 Block diagram of the receiver showing signal path

Receiver Components

A block diagram of the receiver is shown in Figure 22-16. The frequency used for the beacon reply signals is slightly different from that of the magnetron transmitter, and it is convenient to provide two local oscillators, one for use in normal search operation and one for use in beacon navigation. The receiver is divided into two main parts as indicated in the figure. The T-R box, converter, and first two IF amplifier stages are located near the antenna system in the same pressurized container which houses the transmitting magnetron and pulse-shaping components. The receiver proper is located in the Receiver-Indicator unit in front of the radar operator at some distance from the antenna system. The receiver proper contains five IF stages, 2nd detector, two video-stages and also a circuit for automatic frequency-control of the local oscillator.

RF and local-oscillator signals are fed into the converter or mixer which is a section of wave guide terminated by a crystal. Both echo and beacon local-oscillators employ the 723-A Shepherd-Pierce tube, a velocity modulated tube of the reflex type. The local oscillator frequency is 30 mcps higher than the RF frequency and

is maintained at the correct frequency by an automatic frequency-control circuit which feeds back a DC control-voltage to the target electrode of the local oscillator tube.

A typical IF stage is shown in Figure 22-17. All IF stages are of the "single-tuned" type with slug tuning of the inductors in the grid circuit. The input and output capacitances of the tubes comprise the major part of the circuit capacitance.

A conventional diode-detector and two video-amplifier stages are used, the second video-stage being a cathode-follower, controlling the PPI beam intensity. Range-marker pips may be mixed with the signals at the input to the first video stage.

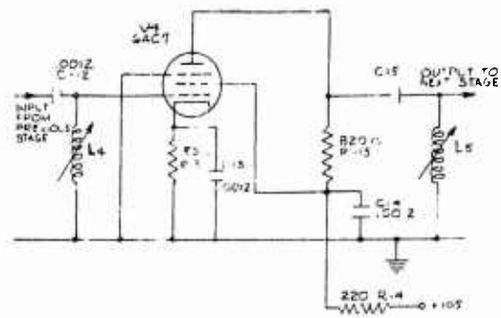


Fig. 22-17 Typical intermediate-frequency stage

Timing Circuits

Referring to Figure 22-07 the timer, or control central, is that part of the radar set which initiates and controls the timing of pulse transmission, indicator sweeps, gates, range markers, etc., that is, it acts as the stop watch of the system. The main component of the control central is a master multivibrator or timing oscillator which may be either "free running", or synchronized by every 70th or 320th pulse originating in a crystal oscillator running at 80.86 kcps located in the range unit. The repetition rate of the synchronizing pulses is stepped down from that of the crystal oscillator by two frequency-dividing circuits of the blocking-oscillator type in steps of 10:1 and then either 7:1 or 32:1 depending upon whether the set is being used for high-altitude search or beacon navigation. During beacon observation the pulse repetition rate must be low in order to allow sufficient time for a beacon response to return from a distance which may be as great as 250 nautical miles.

Three separate gate-signals are taken from the multivibrator to initiate and control certain system functions to be described shortly. The frequency or overall period is constant, but four choices of relative conducting times of the two triode-sections of the multivibrator are available for the 5, 20, 50, and 90-mile sweeps. The timing circuits of the range unit are each described in turn before any functional block diagrams of the system as a whole are described.

Figure 22-18 is a block diagram of the control central and indicators. A few typical voltage waveforms are shown for the 20-mile sweep. Gating voltages from the timing oscillator (master multivibrator) simultaneously initiate and control the time duration of the "A" scope sweep generator, the "A" scope unblanking circuit, and the PPI sweep generator circuits. Due to time delays in the sweep synchro, the unblanking of the PPI sweep must be delayed by 12 microseconds in order to allow time for the sweep to get started. The delay and pulse forming is accomplished with two triodes shown in Figure 22-19. A negative exponential grid-waveform from the master multivibrator cuts off one triode which is normally conducting. A capacitor C_1 connected between its plate and ground charges toward B+ through an adjustable plate load resistor. The plate of the first triode is directly connected to the grid of a second triode which is normally cut off. The grid voltage of the second triode rises exponentially and reaches cutoff in about 12 microseconds. The exponential change of grid voltage is amplified and the plate voltage used to gate both the PPI unblanking circuit and the ringing circuit of the range-mark generator. The initial rate of change of plate voltage on the second triode is sufficiently great so that it may be differentiated by R_2C_2 to form a pulse. The pulse is then amplified and coupled through a cathode follower to trigger the modulator,

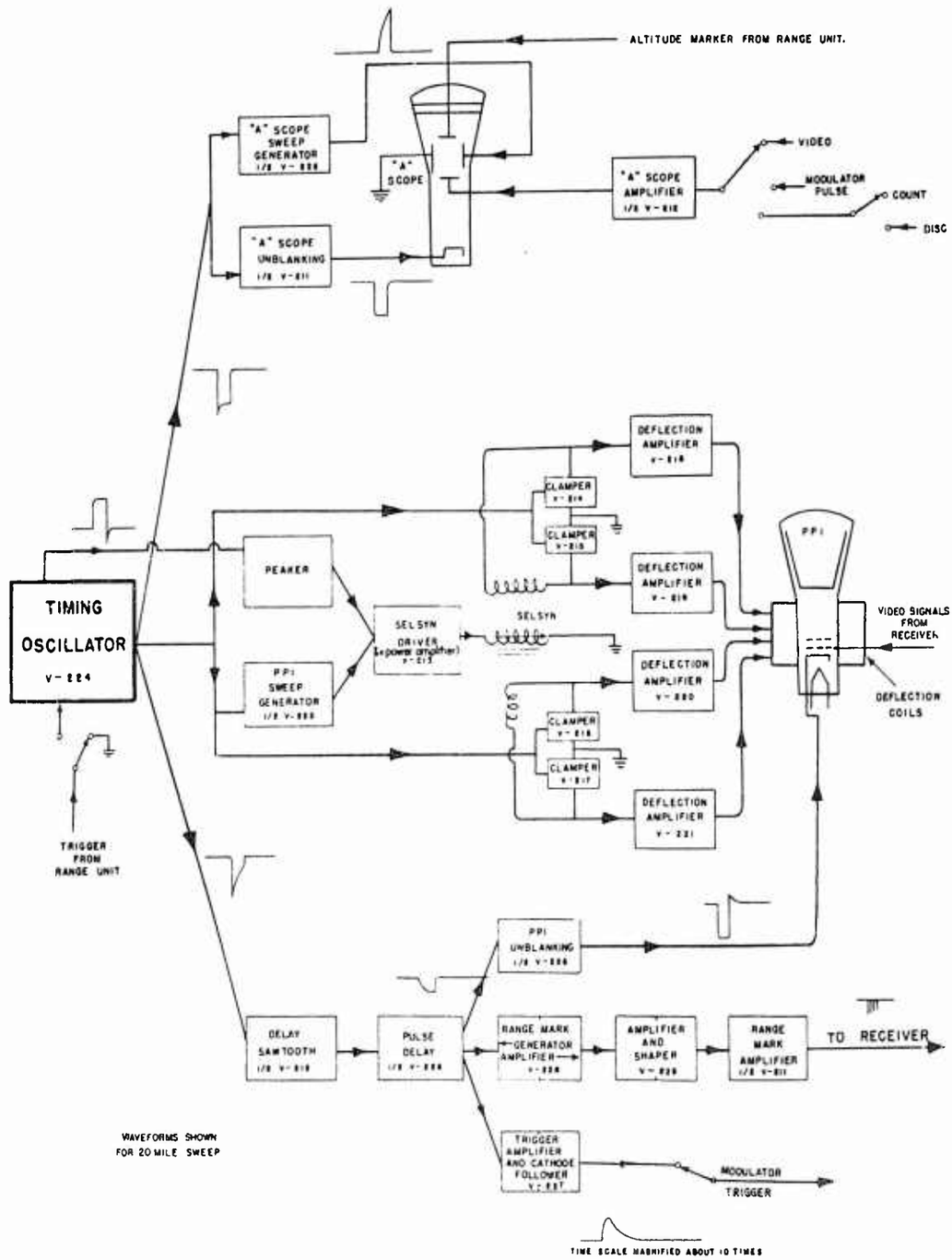


Fig. 22-18 Block diagram of control central and indicators

the operation of which has already been covered. As described later, the modulator may also be triggered off by a pulse from the range unit whenever the sweeps are delayed by the altitude delay circuit, or by both the altitude and beacon delay circuits.

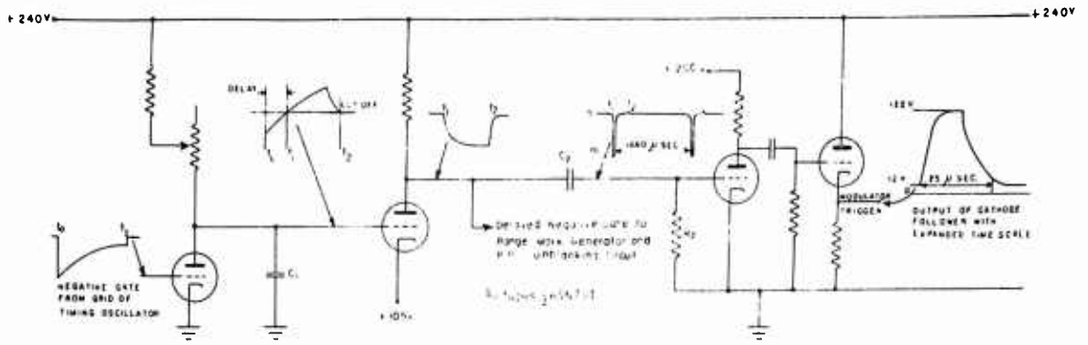


Fig. 22-19 Delay control circuit

The range-mark generator shown in Figure 22-20 employs a conventional ringing circuit. During the quiescent period near the end of each cycle when the grid of the first triode is at ground potential, it conducts a steady plate current

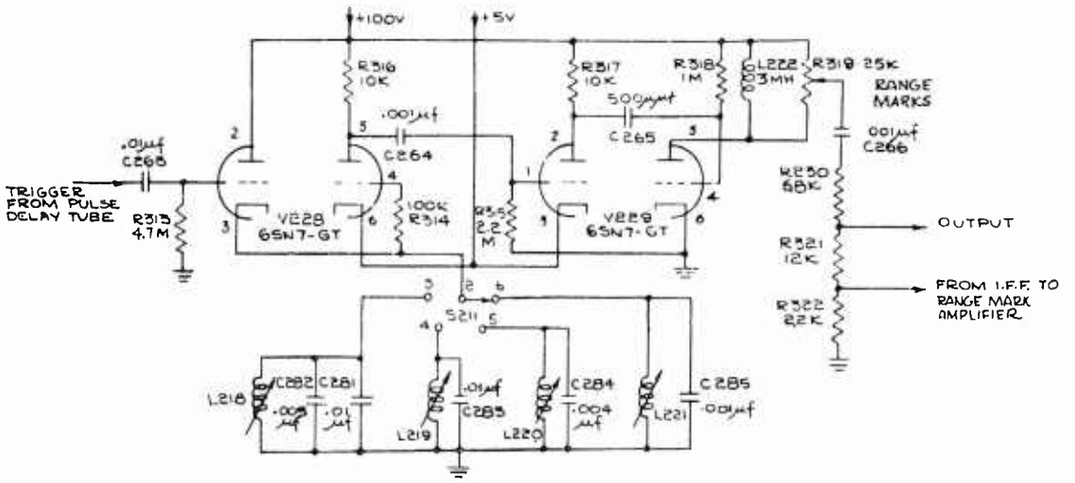


Fig. 22-20 Range mark generator and amplifier

which passes through the inductor of any one of four available tuned cathode circuits. No oscillations can take plate at this time because the tuned circuits are highly damped by the very low output-impedance of the first tube. Upon the application of a negative gate (from the pulse-delay circuit previously described) to the grid of the first triode section of the range-mark generator, the plate current is cut off; and the energy stored in the inductance of the tuned circuit initiates a train of damped oscillations. The damped oscillations appearing at the cathode of the first triode (see Figure 22-21), are amplified, clipped, and differentiated in the remaining triode sections of the range-mark generator, the differentiation occuring in the inductive plate-circuit of the last triode section. The range-mark pips are amplified in a single stage and mixed with the echo signals in the video amplifier which feeds the intensifier grid of the PPI tube.

The negative gate from the 12-microsecond pulse-delay tube is used to unblank the PPI during the sweep period. The unblanking circuit and PPI operating circuits are shown in Figure 22-22.

Figure 22-21 shows the time coincidence of some of the more important

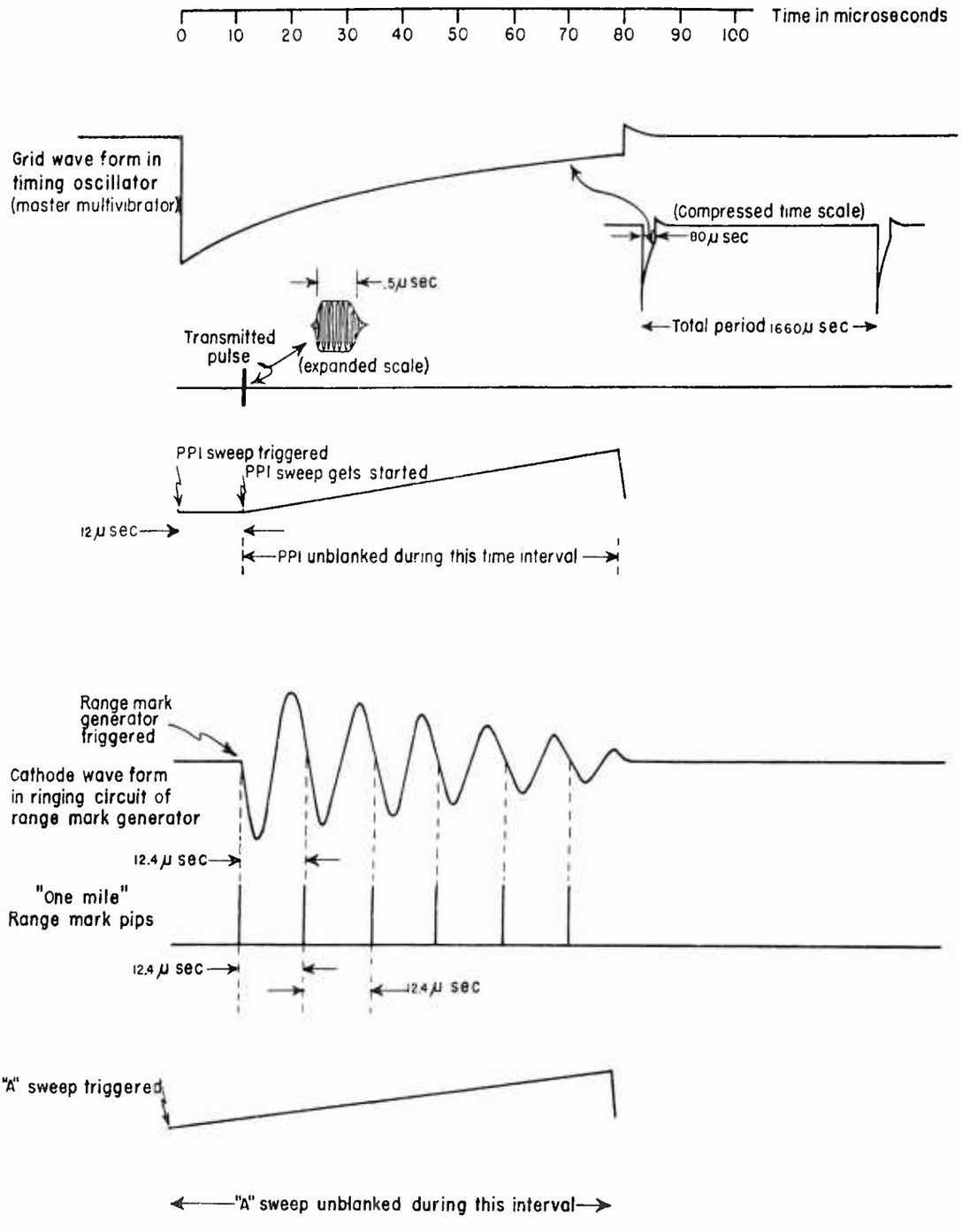


Fig. 22-21 Time diagram for five mile sweep

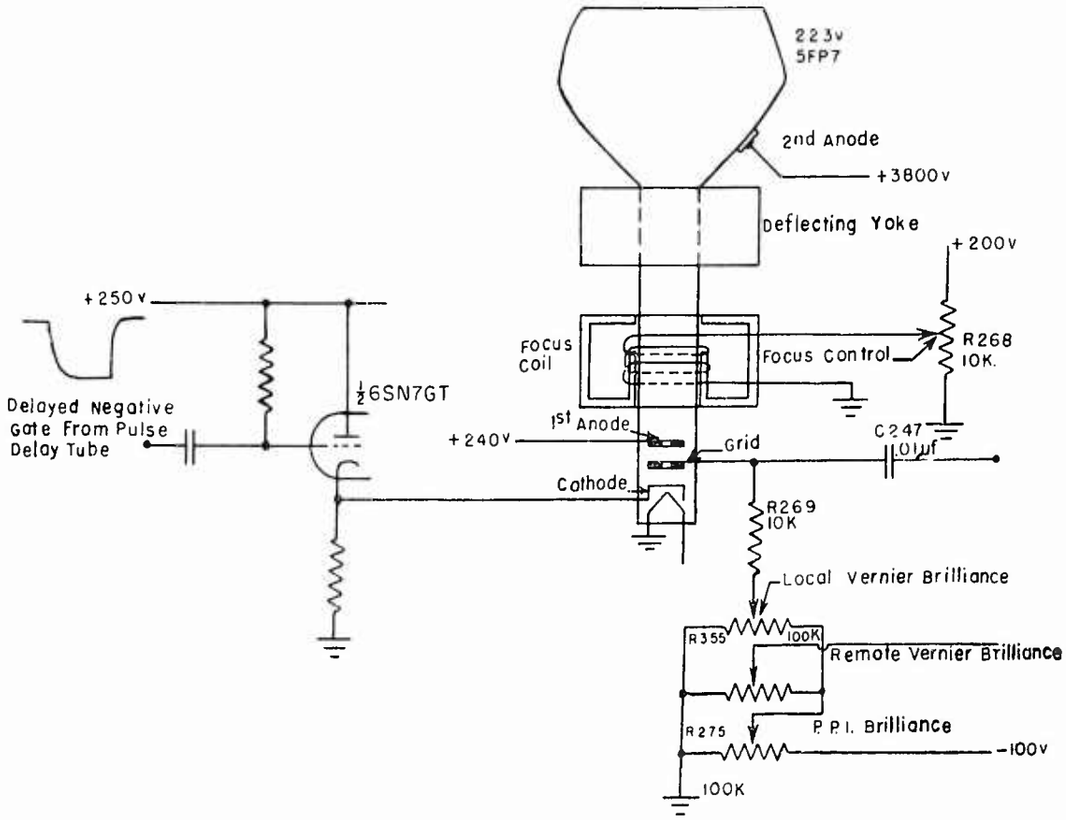


Fig. 22-22 PPI operating circuits

events occurring in normal search operation. The five-mile sweep was chosen for convenience in plotting. 5, 20, 50, and 90-mile sweeps are available. Figure 22-23 is a "stop watch" diagram showing for the 90-mile sweep the sequence of events occurring in normal search operation.

With the aid of the ordinary equally-spaced range-marks on the PPI, measurement of range can be interpolated with a precision of $\pm$ 500 yards. The precision of range measurement is increased to $\pm$ 200 yards by the use of a precise range-marker of adjustable range. The additional timing-circuits necessary to control the precise range marker are contained primarily in the range unit, but partly in the computer and control unit.

The period of an 80.86 kcps signal corresponds to the time required for an electromagnetic wave to travel one nautical mile and return. An 80.86 kcps triode crystal oscillator (V-1 of Figure 22-24) is the source of all timing pulses in the range unit. The operation of the crystal oscillator is class C, and the plate current pulse serves to trigger the blocking-oscillator pip-generator. The phasing of the pulse is such that the oscillator plate-current-pulse causes the grid of the blocking oscillator to swing in the positive direction and the plate to swing in the negative direction. The natural period of the blocking oscillator is of course slightly longer than that of the crystal oscillator so that the blocking oscillator grid potential will not have risen to cut-off potential by the time the triggering pulse arrives.

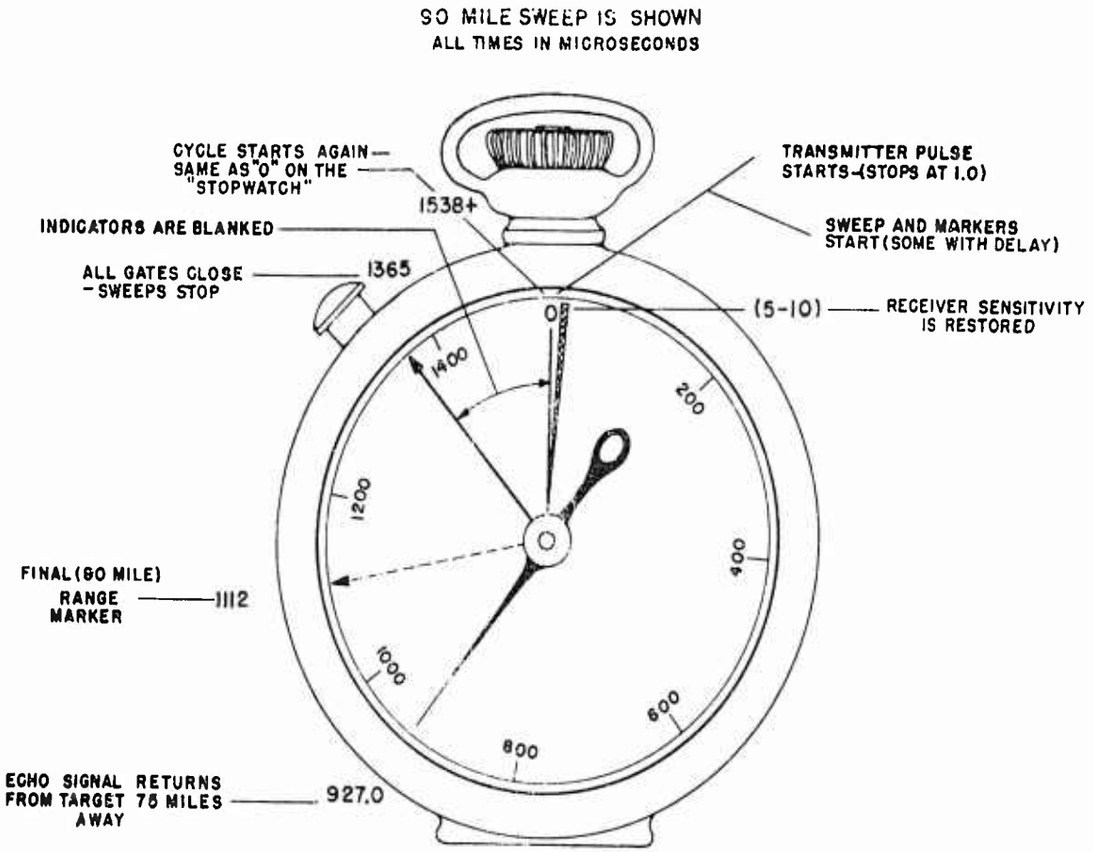


Fig. 22-23 "Stop-watch" diagram of operating sequences in normal search operation

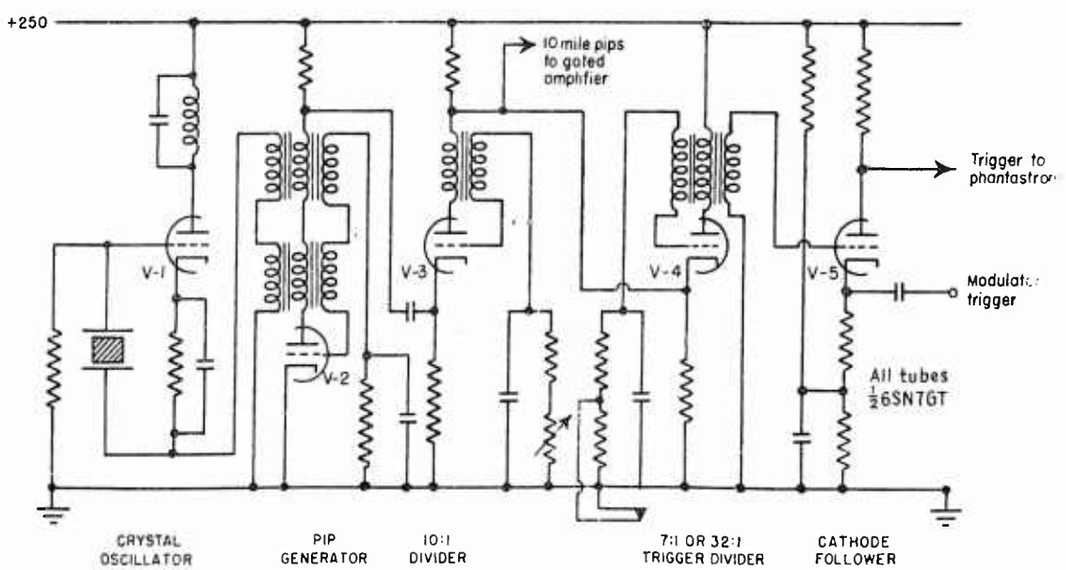


Fig. 22-24 Crystal controlled timing circuits

The negative output pulse from the pip generator serves to trigger the 10:1 frequency-dividing circuit which is also of the blocking-oscillator type. The output of the 10:1 divider feeds 10-mile pips to a gated amplifier yet to be described and also triggers the final frequency-dividing circuit which divides in either a 7:1 or 32:1 ratio depending upon whether the bottom resistor in the grid circuit is shorted or not. The output of the final frequency-divider is coupled through a cathode follower to a cable leading to the modulator in the transmitter unit. A voltage divider from B+ to ground through a portion of the cathode circuit provides sufficient bias to keep the cathode-follower tube cut off until the pulse from the frequency-divider circuit reaches a certain level. This arrangement eliminates the first, slowly rising portion of the applied signal and results in an output pulse with a much steeper wavefront. A negative pulse to trigger the phantastrons is taken from the plate of the combination amplifier and cathode follower stage.

The Phantastron Delay Circuits

A phantastron delay circuit is a voltage-controlled, medium precision, aperiodic delay-system designed for range measurement. The control voltage is effective over a 200 volt range, and the time delay or "gate width" introduced by the phantastron is accurate to within 0.1 microsecond corresponding to the time required for an electromagnetic wave to travel about 30 yards. This is equivalent to 15 yards of measured range (allowing for go-and-return). The accuracy of range measurement is about ± 15 yards ± 0.1 percent of the range measured as far as the phantastron circuit alone is concerned; but the full capabilities of the circuit are not realized in the H2X system in which the operational accuracy of range measurement is considerably less than the above figure because the signal matching for range measurement is done on a rather limited PPI sweep. The output of the phantastron is free from jitter to within ± 5 yards for delays less than 200,000 yards, the delay time being practically independent of the repetition frequency as long as the delay does not exceed 90 percent of the period.

The advantage of the phantastron over a multivibrator is that the delay time is almost independent of the supply voltage, and depends instead upon a ratio of voltages determined by the setting of a potentiometer connected across the supply

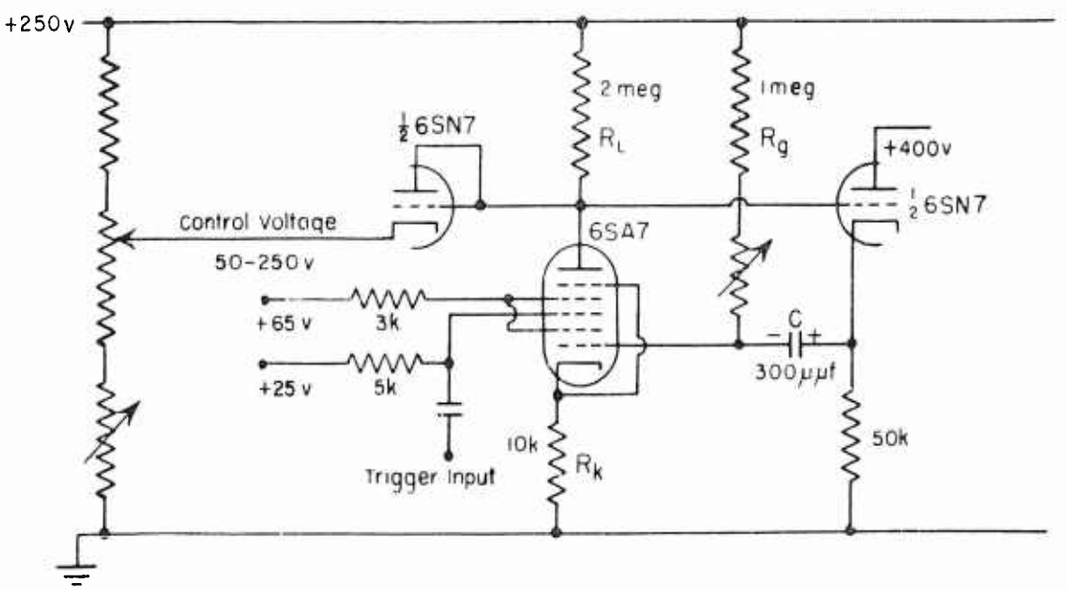


Fig. 22-25 Phantastron delay circuit

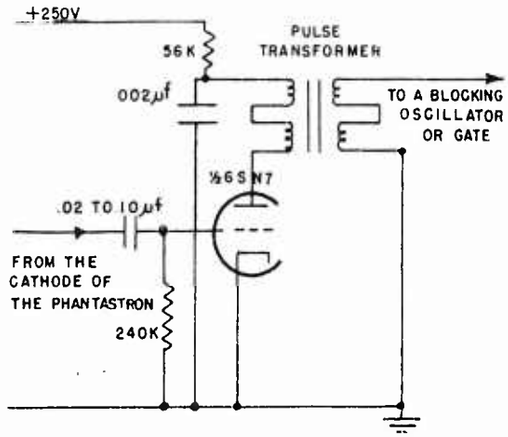


Fig. 22-26 Pulse amplifier used between a phantastron delay circuit and a circuit to be triggered by it

voltage. The delay time also depends upon one temperature-controlled RC time constant. However, the phantastron does not turn off as sharply as a multivibrator and so the output must be amplified in order to obtain an output signal useful for triggering.

A phantastron delay-circuit is diagrammed in Figure 22-25. It may be triggered in several different ways, but the input triggering-pulse is usually applied to the number three grid as a positive pulse. The output voltage, taken from the cathode of the 6SA7 phantastron, is used to control a pulse amplifier of the type shown in Figure 22-26. The amount of time delay introduced by the phantastron is determined by the setting of the control-voltage tap on the potentiometer at the left of Figure 22-25. The triode cathode-follower on the right is used to provide a path for the quick charge of condenser C at the end of the delay cycle, thus shortening the recovery time so that the circuit may accept another triggering impulse. Since the gain of the cathode follower is essentially unity, the phantastron circuit is equivalent to the simplified diagram of Figure 22-27 which is convenient for visualizing the circuit operation.

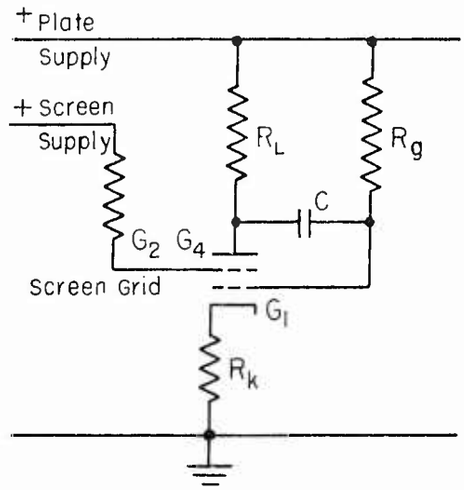


Fig. 22-27 Simplified phantastron circuit

For purposes of explanation, the operation of the circuit may be conveniently divided into six stages. A few typical voltage wave-forms are given in Figure 22-28.

Stage VI is the quiescent stage in which the phantastron circuit is waiting for a triggering impulse to start a cycle of operations. In this stage there is considerable screen current (mainly from the inner screen G_2) and very little plate current. During this stage the plate potential of the phantastron (6SA7) is determined

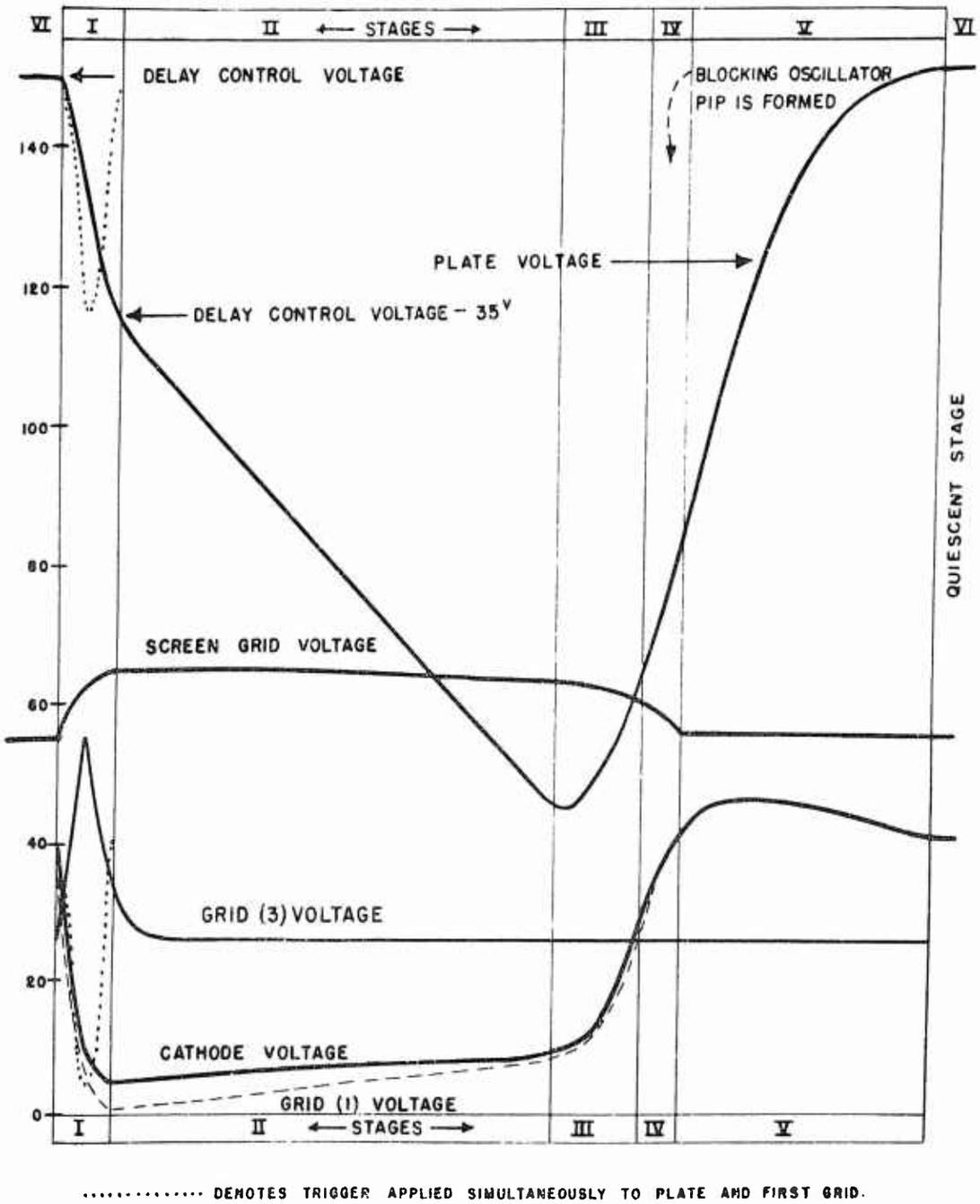


Fig. 22-28 Waveforms of phantastron delay voltages with respect to ground

by the setting of the control voltage potentiometer tap. Grid current flows through R_g and keeps the potential of G_1 approximately at cathode potential which is about 40 volts above ground for the case illustrated in Figure 22-28.

Upon the application of a positive triggering pulse to G_3 or a negative triggering pulse to the plate or to the plate and G_1, the current flowing to the screen grids (G_2, G_4) is suddenly shifted to the plate circuit. The plate potential drops by some 30 or 40 volts during stage I due mainly to the increase of plate current through resistor R_L, and the left-hand diode of Figure 22-25 stops conducting. The voltage on capacitor C does not change appreciably during this period, and the amplification ratio of the cathode follower is very nearly unity; so that the potential of G_1 follows quite closely the change in plate voltage during stage I, and the grid current to G_1 stops immediately at the start of stage I.

During stage II the potential of G_1 rises slowly toward B+ potential, and would do so with a time constant of R_gC if the tube were not present. However, the voltage amplification from G_1 to the plate causes the rise of G_1 potential to be very much slower than it otherwise would be. The rise of G_1 potential results in a fall of plate potential which is transferred by means of capacitor C back to the grid, thus reducing the net amount of its potential rise. The discharging of C through R_g takes place with an effective time-constant of approximately μR_gC where μ (of the order of 1000) is the amplification factor of the phantastron tube. During stage II the plate potential drops quite linearly until at a certain point there is a rather sudden loss of amplification in the tube. Although the loss of amplification occurs suddenly enough to produce accurate timing of the cycle of events, the end of the cycle (which takes place in stages III, IV and V) contains no abrupt voltage changes comparable to those in a multivibrator circuit.

After the loss of amplification, the potential of G_1 rises toward B+ potential with unhindered, simple time-constant, R_gC. The cathode potential follows the rise of grid potential with the screen grid taking most of the additional space current. The drop in screen grid voltage does not divert current to the plate circuit because the increasing negative bias of G_3 offsets this effect. Finally (at the end of stage III) the increased bias on G_3 starts to shut off the plate current quickly and causes the plate potential to rise.

During stage IV the plate potential rises and the grid and cathode voltages also rise rapidly due to the regenerative effect. The screen-grid potential drops sharply since it takes the additional space current, and finally drops so low that the screen current no longer increases. At some point during stage IV the rise in cathode potential triggers the pulse amplifier of Figure 22-26.

Stage V is the recovery stage in which the plate potential rises with time constant R_LC_{stray} until it is caught by the left hand diode at the control voltage level. The circuit is then ready to be triggered again.

Delayed Sweep for Beacon Observation

In order to avoid the use of an excessively long sweep when viewing responses from distant beacons, it is necessary to delay the start of the PPI sweep until the beacon signal has nearly arrived. With a shorter sweep length, it is possible to obtain greater precision of setting the adjustable slant-range marker to the beacon response signal. During beacon operation it is usually most convenient to use the 20-mile sweep, the start of which is delayed from the triggering of the transmitter by a time interval corresponding to any desired integral number (0 to 23) of ten-mile distances. The necessary wide-range time-delay in 10-mile steps cannot be determined to the desired accuracy by means of a phantastron circuit alone. A

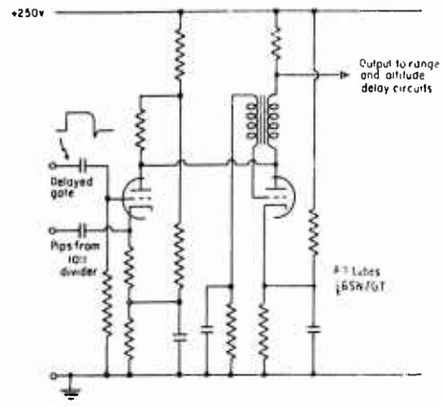


Fig. 22-29 Gated amplifier coincidence circuit and trigger blocking oscillator

phantastron and gate generator are used to produce a voltage gate 8 to 12 miles in width and centered as nearly as possible at a time corresponding to the desired range-delay of n x 10 miles after the triggering of the "main bang" by one of the 10-mile pips from the crystal oscillator. In normal beacon-operation the transmitter is triggered by every 32nd 10-mile pip. The delayed gate from the phantastron and the output of the 10-mile pip generator are applied to the grid and cathode respectively of an amplifier tube biased well beyond cut-off (See Figure 22-29). Neither the positive gate on the grid nor the negative pulse on the cathode is alone sufficient to cause conduction of plate current. However, a 10-mile pip occuring at any instant while the 8-mile gate is on the grid will cause a pulse of plate current through the tube. The negative pulse at the plate of the gated amplifier serves to trigger the "single-shot" blocking-oscillator, which in turn triggers off the range and altitude delay-circuits.

The 8-mile gate is generated in a multivibrator circuit similar to that described previously for obtaining a 12 microsecond delay time. The circuit with waveforms is shown in Figure 22-30 along with a triggering circuit controlled by the cathode-output voltage of the phantastron circuit.

Combined Functioning of the System Components

The combined functioning of the component parts of the system will now be discussed with the aid of block diagrams and timing diagrams. Figure 22-31 is a time diagram for the events in the range unit, transmitter, and indicators when the system is used for high-altitude search or bombing; and Figures 22-32 and 22-33 are functional timing and block diagrams respectively of the range unit, also for the case when the system is used for high-altitude search or bombing. Referring to Figure 22-33 the 10:1 and 7:1 frequency dividers following the one-mile pip generator controlled by the crystal oscillator, allow every 70th one-mile pip to initiate a transmitter pulse. The repetition period is about 865 microseconds corresponding to a pulse-repetition-frequency of about 1155 cps. Since during high-altitude search or bombing, the PPI sweep is delayed by an amount corresponding to the altitude of the aircraft, the modulator is triggered by the cathode follower at the end of the chain of frequency dividers instead of by the delayed output of the timing oscillator. The instant at which the output of the cathode follower triggers the modulator is taken as zero reference time for Figures 22-31 and 22-32. In order to delay the PPI sweep by an amount corresponding to the altitude the adjustable-delay-phantastron shown in block dia-

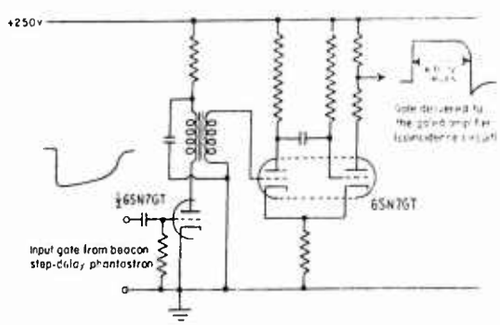


Fig. 22-30 Delayed trigger amplifier and selector-gate generator

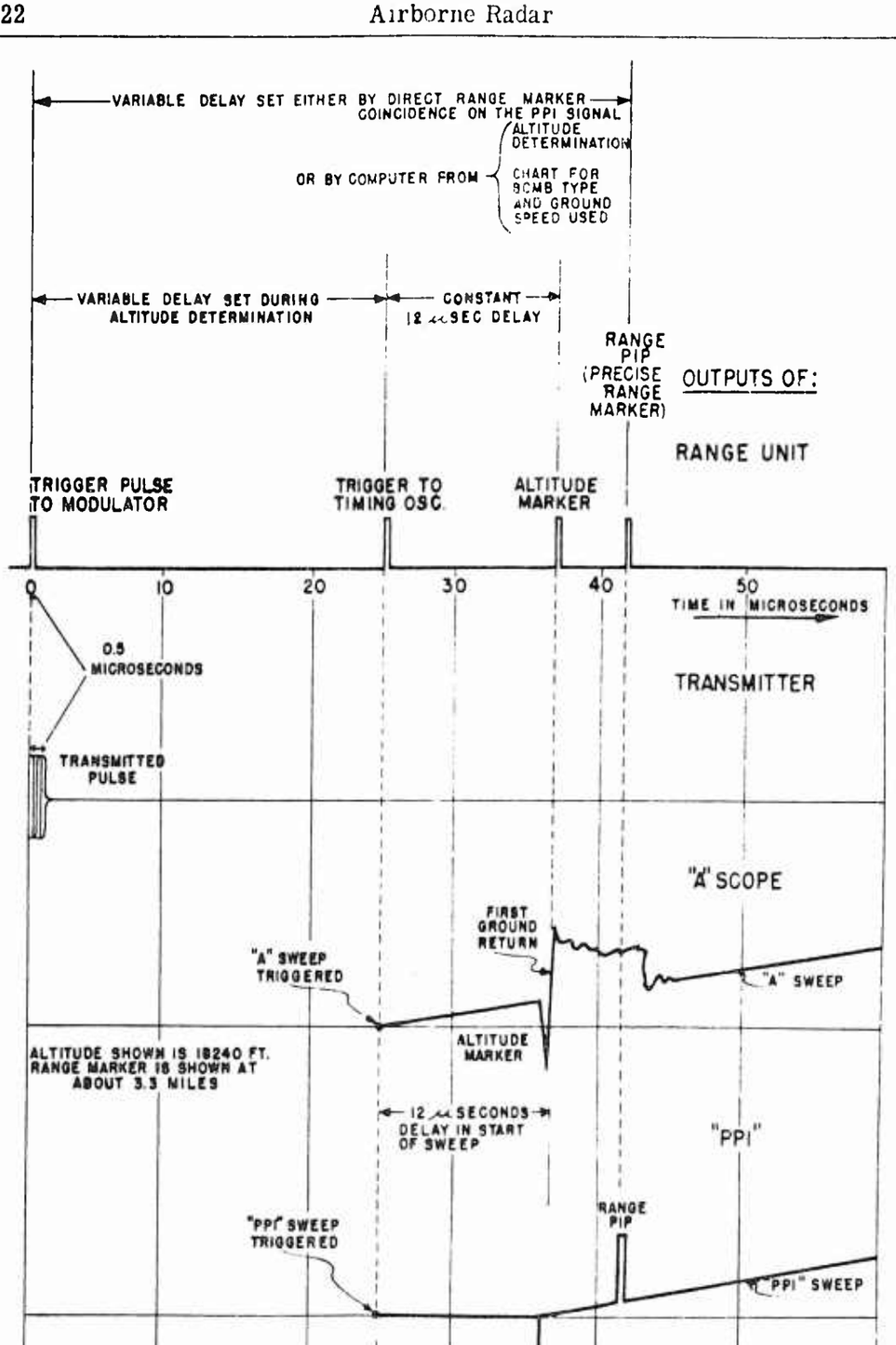


Fig. 22-31 Timing diagram for events in the range unit, transmitter, and indicators, when the system is used for high altitude search and bombing

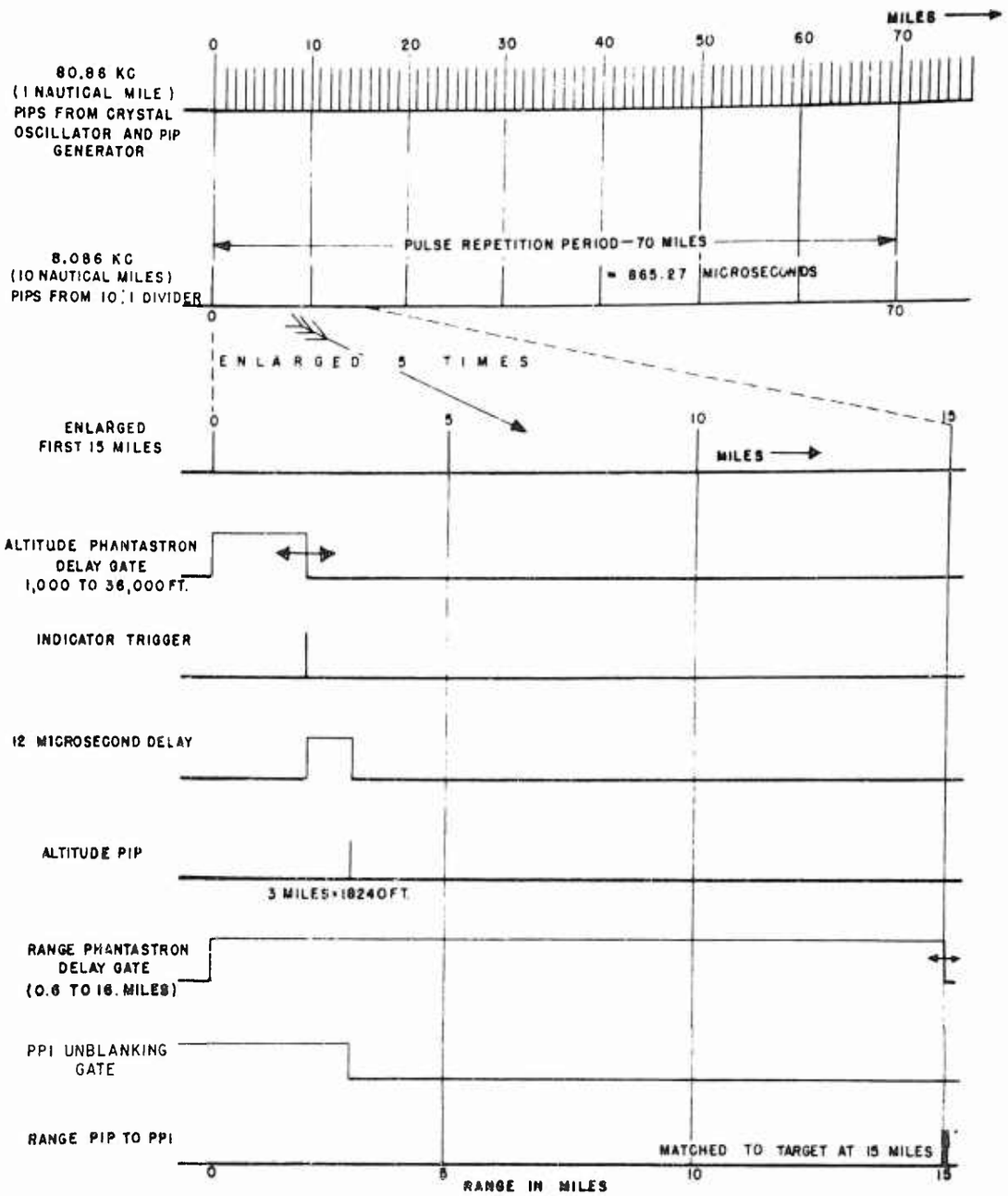


Fig. 22-32 Timing diagram of range unit as used in high-altitude search and bombing

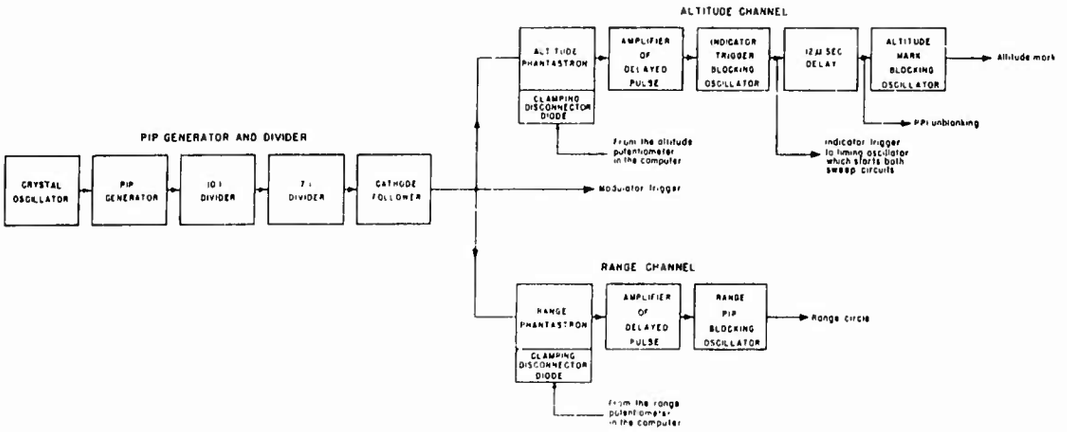


Fig. 22-33 Functional block diagram of the range unit during high-altitude search or bombing

gram form in Figure 22-33 delays the triggering of the timing oscillator and sweep circuits by an amount which is 12 microseconds less than the time required for an electromagnetic signal to travel from the aircraft to the ground and return. Although the "A" scope sweep starts immediately upon being triggered,

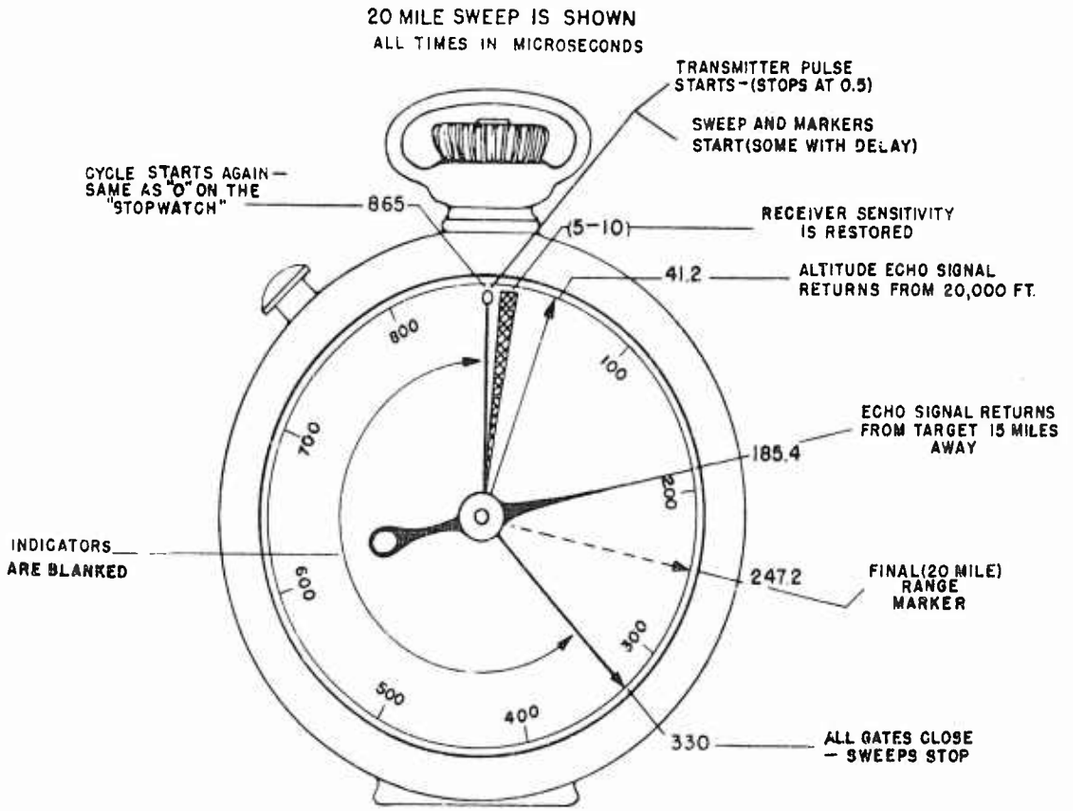


Fig. 22-34 "Stop-watch" diagram of operating sequences in high-altitude search and bombing

the PPI sweep does not get started until 12 microseconds after triggering as illustrated in Figure 22-31. An altitude marker to be matched to the first ground return is generated 12 microseconds after the triggering of the sweep circuits and corresponds in time to the effective starting point of the PPI sweep (See Figures 22-31, 22-32, and 22-33). A gate from the 12 microsecond delay circuit unblanks the PPI after the 12 microsecond delay. In Figure 22-31 both indicator and respective sweep signals are superimposed schematically on the vertical scale. The pip which marks a portion of the precise slant-range marker-circle, at a given instant in each sweep, is generated in the range-pip blocking-oscillator, which is triggered by the adjustable 0.6 to 16 mile, range-delay phantastron.

Other timing diagrams which may be helpful in visualizing the operating sequences used in high altitude search and bombing are shown in Figures 22-34 and 22-35.

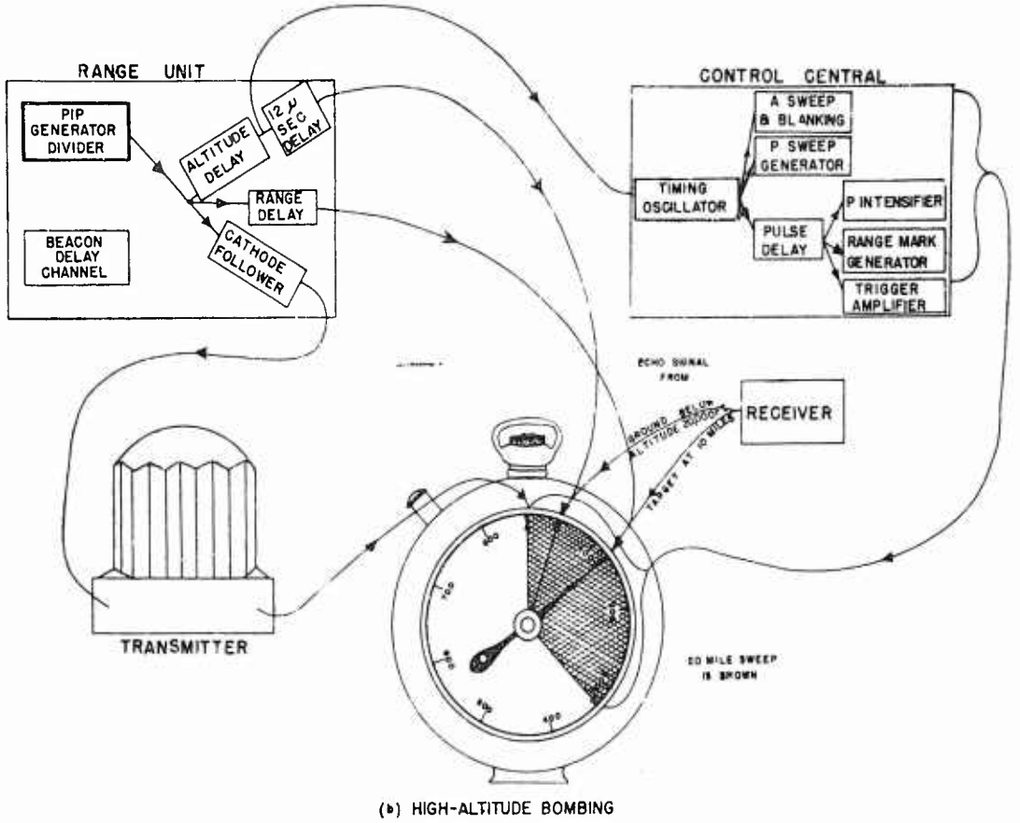


Fig. 22-35 Block diagram of "stop-watch" correlation with the basic timing functions in high-altitude search and bombing

Figure 22-36 is a functional block diagram of the range unit during navigation by beacon, and Figure 22-37 is the corresponding time diagram. Figures 22-38 and 22-39 are "stop-watch" and block diagrams respectively for the basic timing functions during navigation by beacon. The pulse repetition frequency is of necessity much lower than that used in high-altitude search and bombing because of the large time-delays required when observing beacons which may be as far

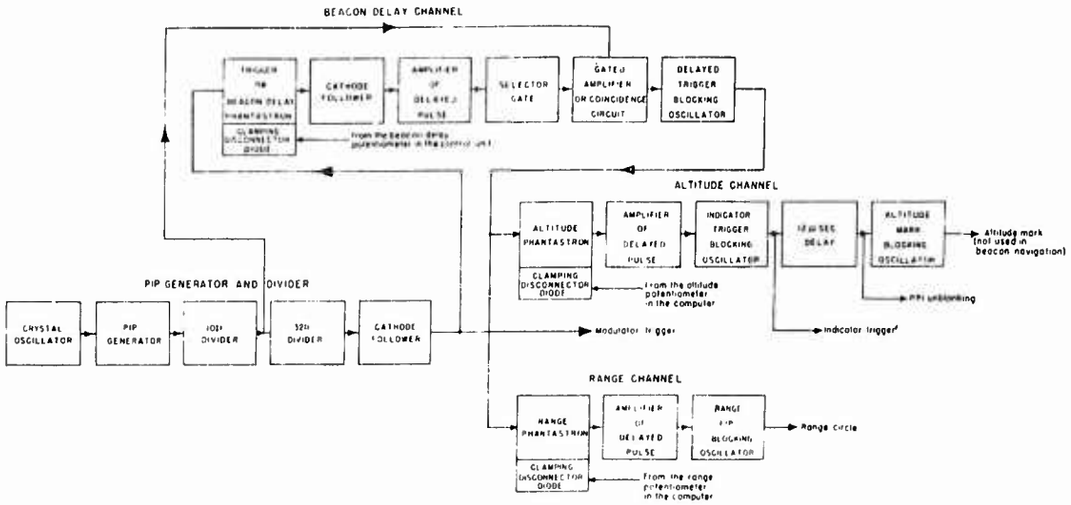


Fig. 22-36 Functional block diagram of the range unit during navigation by beacon

distant as 250 miles. 10:1 and 32:1 frequency dividers following the crystal oscillator allow every 320th one-mile pip to trigger the modulator. The PPI sweep is delayed a suitable number of ten-mile intervals by the trigger step-delay phantastron. The 10-mile pips (output of the 10:1 frequency divider) and the selector-gate output of the trigger-delay phantastron are mixed in the coincidence circuit in order to obtain crystal accuracy in the beacon delay time. The output of the coincidence circuit initiates the operation of both altitude and range channels as shown in the block diagrams. The calibrated range phantastron in the range channel allows the pip for the adjustable range marker circle to be delayed by an amount suitable for matching to the beacon signal. When the range marker circle is properly matched to the beacon response signal, the range to the beacon is the sum of the ranges corresponding to the delays introduced by the beacon step-delay channel and the range channel. During navigation by beacon, the setting of the altitude phantastron is of no consequence since the matching of the range marker circle to the beacon echo does not depend upon the time at which the sweep starts. The operation of the altitude channel is the same as previously described except that during beacon navigation, no use is made of the altitude mark appearing on the "A" scope.

Bibliography

Identification	Classification	Title	Issued by
135-c	Confidential	Handbook of instructions for radio set AN/APS-15 (H2X)	MIT Rad. Lab.
AN-05-15-16	Restricted	Gyro-Stabilized Flux-Gate Compass System	*see below

* Joint authority of Commanding General Army Air Forces, the Chief of the Bureau of Aeronautics and the Air Council of the United Kingdom.

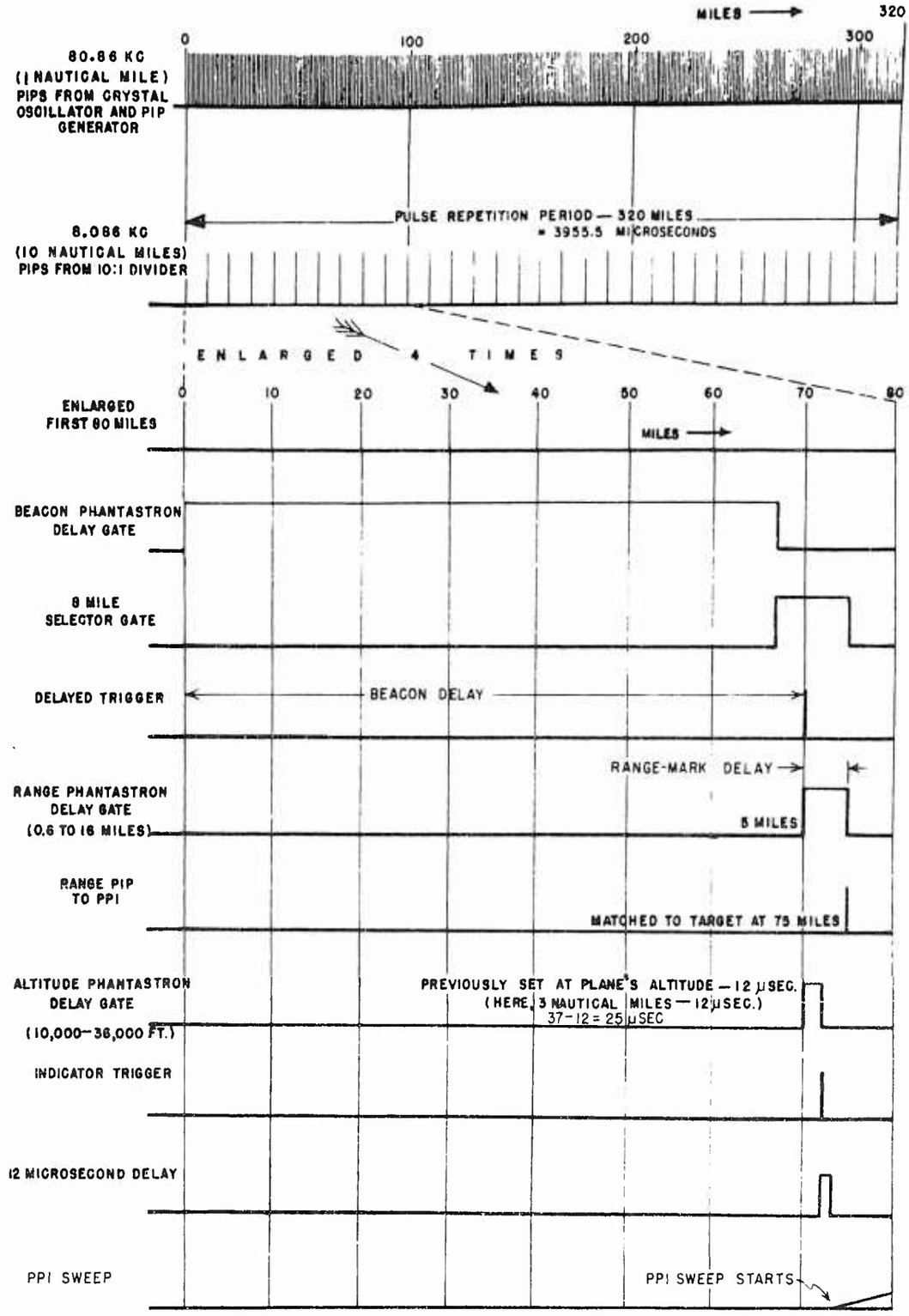


Fig. 22-37 Timing diagram of range unit as used in navigation by beacon

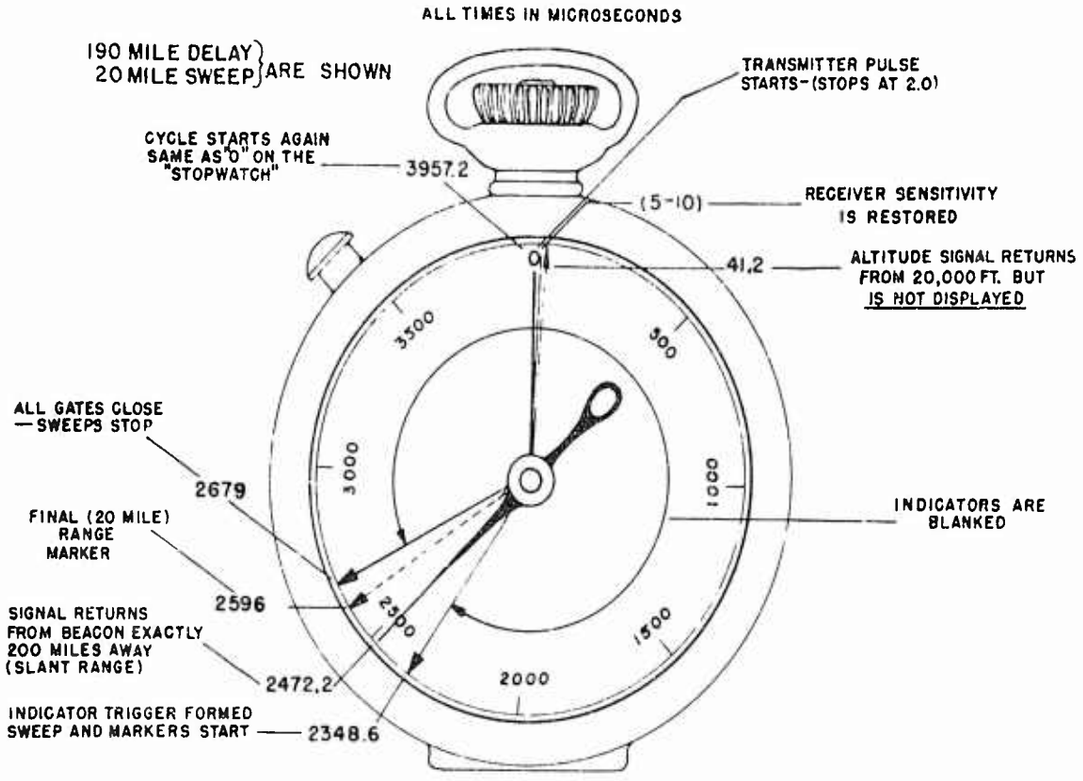


Fig. 22-38 "Stop-watch" diagram of operating sequences during navigation by beacon

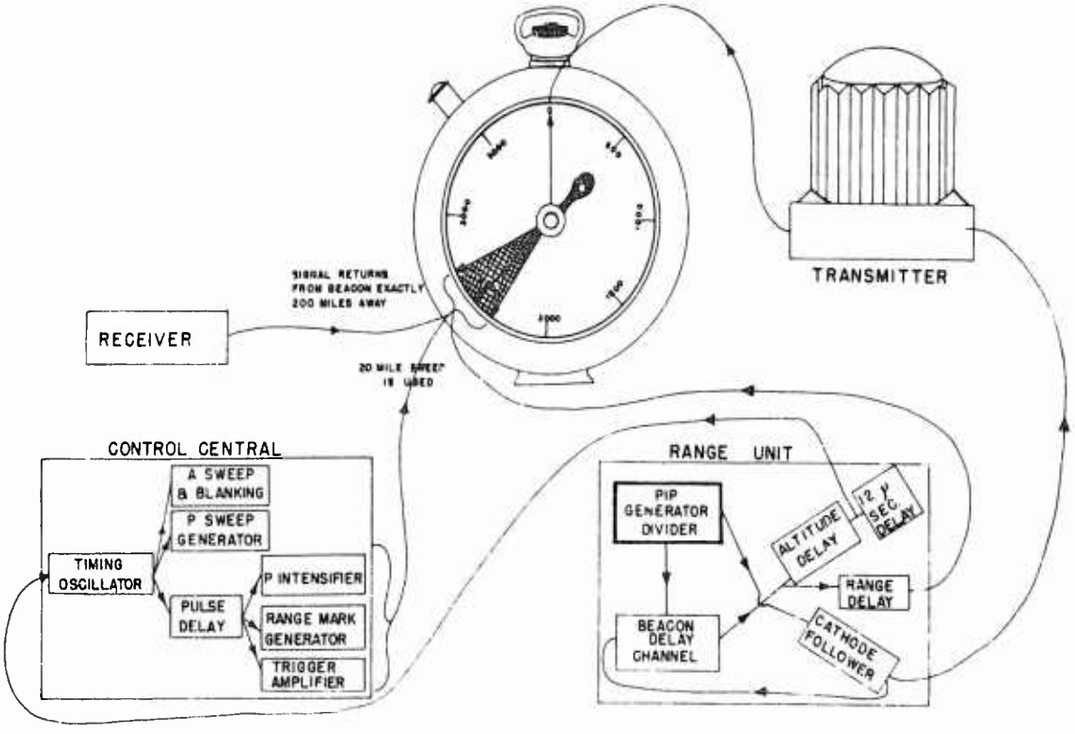


Fig. 22-39 Block diagram of "stop-watch" correlation with the basic timing functions during navigation by beacon

The H3X attachment for airborne radar

H3X is an H-type system similar to Micro-H. It is an X-band radar attachment that provides automatic range-tracking of two beacons giving out continuous range information. The computing circuits permit the flying of either a hyperbolic course or a cat-mouse course. H3X has been developed but since it is more complicated than Micro-H and gives accuracy not significantly greater than that of Micro-H, it is no longer being worked on.

Bibliography

Identification	Classification	Title	Issued by
71-7/19/44	Confidential	H3X (Centimeter-H): A Beacon Blind Bombing Attachment for Airborne X-band Radar	MIT Rad. Lab.

The NOSMO Attachment for AN/APS-15

The AN/APA-46 (NOSMO) equipment is an attachment for AN/APS-15 or -15A airborne radar sets although it can also be used with AN/APQ-13 if a special control-box is provided. By means of this attachment it is possible to use the radar information of target range and bearing to synchronize the Norden bombsight in range. This permits bombing with the Norden sight either in case the radar target echo should break up before reaching the bombing circle, or possibly to take advantage of any last minute visibility in which there would be insufficient time to synchronize the bombsight by normal optical methods. As a navigational aid, the NOSMO equipment provides for pulse-Doppler drift determination, which allows a quick determination of drift angle and ground track without the use of a reference point and without turning the aircraft. Only the navigational function will be described here.

In general, whenever an observer and a source of wave motion are either approaching or going away from one another, the number of waves received per second by the observer (i.e. the frequency of the received waves) is increased or decreased respectively. The change in frequency is proportional to the relative velocity between source and observer.

In the case of a moving aircraft transmitting and receiving radar signals, the change in frequency is multiplied by a factor of two because the waves make a round trip. The frequency received by an aircraft from radar echo-points lying anywhere along a line passing through a point directly beneath the aircraft and making an angle θ with the aircraft's ground track is given by $f_t + \frac{2v_g \cos\theta}{\lambda}$ where f_t is the transmitted frequency, λ is the wavelength corresponding to the transmitted frequency, and v_g is the groundspeed of the aircraft along its ground track. The radar beam is of finite width (about 3^o for H2X sets) and each transmitted pulse has a finite duration. Due to the very slow variation of the $\cos\theta$ function about $\theta = 0$, radar echos from all points lying within the 3^o beam near $\theta = 0$ have approximately the same frequency; and hence the output of the non-linear frequency converter contains frequencies which produce a very low beat or rate of flutter of the video signal. On the other hand when the radar beam is at an angle with respect to the ground track, the variation in $\cos\theta$ within the 3^o width of the radar beam is considerably greater than when $\theta = 0$ so that the composite radar signal returned to the aircraft will contain components having a greater spread of frequencies. The eye can detect rapid fluc-

tuations in intensity at frequencies below about 20 cps, above which frequency the image appears blurred. The flutter of the video signals due to the Doppler effect is visible within a sector of about seven degrees on the PPI screen. Since a yellow filter makes it difficult to observe rapid variations in signal strength, a sector or wedge-shaped blue filter is used in order to eliminate the persistence of the tube in the region within which the Doppler measurements are being made. During the Doppler measurements the antenna spinner may be aimed or "search lighted" in any desired azimuth. If the radar beam is slowly and smoothly positioned in the vicinity of the ground track, it is possible to locate with an accuracy of $\pm 1^{\circ}$ the position of minimum beat frequency or rate of flutter of the signal intensity. The effect is most clearly seen on homogeneous ground clutter and optimum sweep length is about 15 miles. The appearance of the null varies somewhat with the terrain, and is not sufficiently clear cut for measurement over water.

The position of the antenna spinner which gives the minimum amount of signal flutter indicates the direction of the ground track of the aircraft. Either a dark or light line may be caused to occur on the PPI screen at this ground track azimuth. The drift angle is then the angle between the ground track indicator and the lubber line which gives the heading of the aircraft, and this angle may be read directly upon a drift angle dial on a control box.

The NOSMO attachment contains computing equipment necessary to provide for measurement of groundspeed by synchronous tracking of a clear-cut echo on the ground track of the aircraft. The AN/APA-46 (NOSMO) equipment, provides for a highly accurate determination of wind velocity by means of a double drift, double groundspeed, or drift and groundspeed diagram plotted on an army type E6B pocket computer. From about 30 seconds to a minute is required for this determination. The NOSMO equipment weighs about 50 lbs. installed.

Bibliography

Identification	Classification	Title	Issued by
M-227	Confidential	Preliminary Handbook of Operating and Maintenance Instructions for Model AN/APA-46 Aircraft Radar Equipment	MIT Rad. Lab.
63-2/17/45	Confidential	Recommended Operational Procedure for use of Nosmo Over a Complex Target	MIT Rad. Lab.

Airborne Radar for Navigation

An airborne radar set such as AN/APS-15 is suitable for navigation either by means of beacon reception or through recognition of familiar radar echos from the landscape below. Attachments such as NOSMO, Micro-H, and GPI increase the usefulness of an airborne radar as a general navigational aid; but undoubtedly lighter and more efficient airborne radar equipment could be obtained by an entirely new design incorporating all of the features of the above mentioned attachments. Navigation by radar is simplest over terrain containing railroads, large steel structures, land-water boundaries, etc., which provide easily recognizable echo patterns. Navigation over very flat inland terrain from which few strong echos are obtained is in general difficult without the use of responder beacons or suitably positioned corner reflectors. The details of Map-PPI Superposition (Radar mapping) are discussed in Section 26. The accuracy, range, usefulness for special services, etc., of airborne radar is compared with that of other types of navigational aids in Section 31.

High-definition ground (or ship-based) search radar may be used as a navigational aid since it will give the position of all craft within range. It is possible for any craft within range to get a fix by communication with the radar station. Identification of the particular craft requesting a fix is somewhat of a problem. There are several ways that this identification can be accomplished. One of the simplest methods and one that requires no additional equipment is for the craft to execute a specified maneuver that the radar operator can identify. This is slow and inefficient and not workable when many craft are requesting fixes. In many applications this is not a serious problem since the craft is continuously tracked or the track of many craft may be plotted on a plotting table. If the craft carries a responder beacon the problem of identification is somewhat simpler since some type of beacon coding may be used to identify the craft requesting identification. It appears that the most satisfactory coding is range coding. The beacon in the craft gives the further advantage of greatly increasing the range of the radar set. Two other systems that are covered elsewhere in this report are possible. One involves the relaying of the ground PPI presentation to the craft within range. Thus the navigator or pilot in each craft sees the same PPI presentation that the ground radar operator sees. He can identify his own response on the oscilloscope by any of the methods mentioned above. This system is described further in section 25 on the Federal Traffic control system. The second method involves the transmission of the ground PPI presentation to the craft by television. In this system it is also possible to transmit a map of the region and much additional information to the craft. This system is further described in section 27 on the RCA Televised Radar System.

It is the purpose of this section to describe briefly two of the typical radars that are suitable for navigational purposes. The most successful radars to date for the purpose are the MEW (AN/CPS-1) and SCR 584. Of these two the MEW has the greatest range and versatility. The MEW was originally designed as a microwave early-warning radar. Its great range and high definition have ideally fitted it for navigation and fighter-direction purposes.

MEW (AN/CPS-1)

Type of system

Combination range and azimuth system.

Useful range

Maximum range (theoretical 266 miles).
Single large aircraft at 20,000 to 30,000 feet - 175 miles.
Single small aircraft at 10,000 feet - 100 miles.
Smallest aircraft can be seen up to radar horizon if equipped with beacon.
Minimum range - 1/2 mile.

Accuracy and precision

Range $\pm$ 1 mile
Azimuth $\pm$ 1^{o}

Resolving power

Range 1/2 mile
Azimuth $1/2^{o}$.

Presentation - visual

PPI scope, B scope, off-center PPI.

Operating skills required

Trained operators to interpret scope presentation. Time required to get fix - Position available continuously on long persistence scopes but is only correct when beam swings by aircraft. Rotational speeds of beam of 1, 2, and 4 revolutions per minute are available.

Equipment required

Weight - about 66 tons (crated for shipment).

Complexity - This is one of the most complex radars made, both as to the complexity of individual circuits and the number of circuits used.

Service and maintenance requirements - highly trained personnel.

Radio-frequency spectrum allotments required

Frequency - 2700 to 2900 mcps.
Wavelength - 10.3 to 11.2 cm.
Bandwidth - 3 to 4 mcps.

Present status

Operational.

The MEW is a long-range microwave search-radar system. Its high angular definition is obtained by the use of a very large antenna system. The antenna system consists of two cylindrical parabolic dishes placed back to back. These are fed by arrays of 106 dipoles fed by a wave guide. One of these dishes gives a low-angle beam for detecting low-flying aircraft or aircraft at long ranges. The other dish gives a high-angle cosecant-squared beam for detection of near, high-flying aircraft. The half-power beam-width of both beams in the horizontal plane is 1.5°. The low-beam dish is 25 feet long and 8 feet high and the high-beam reflector is 25 feet long and 5 feet high. Experimental dishes 50 feet long have been built. Each dish has two transmitters and receivers. Each transmitting magnetron is on a slightly different frequency. The two transmitters in use are driven in parallel by a single modulator.

The indicating equipment normally furnished consists of five 12-inch PPI scopes and five 7-inch B scopes. One 5-inch expanded A range scope mounted on a dolly is provided. This can also be used for general servicing.

The PPI scopes have 60-, 80-, and 100-mile sweeps and have a variable delay adjustable from 0 to 200 miles. 10-mile range circles with every fifth one being intensified and 10° azimuth markers with every third one wider are provided. A recent modification is the provision for off-centering the presentation. It can be off-centered by as much as 2 radii.

The B scopes can cover an azimuth sector of 40° to 100° and have 10° azimuth markers. The sweeps cover 30, 80, and 100 miles with a delay from 0 to 200 miles. 10-mile range markers are provided.

The A scope has sweeps of 5, 50 and 200 miles. Any of these scopes can present the signal from either the high-beam antenna or the low-beam antenna.

Ground clutter (the reflections from fixed reflecting objects on the ground) is always a problem in any microwave radar using a low angle beam. A method of decreasing this ground clutter has been devised. MTI (moving target indication) lessens ground clutter by suppressing the responses from fixed targets. Targets having a radial component of velocity will produce a doppler-effect change of frequency in the reflected signal. In order to make practical use of this effect (which is quite small), a beat method is used. The radar receiver must employ a very stable local oscillator. A beat oscillator working at intermediate frequency is used. This is rephased by every transmitted pulse. This is necessary since there is no consistent phase relation between successive transmitted pulses. With these modifications the response from stationary targets will be constant and those from targets with a radial component of velocity will flutter. That is, the pulses will vary from positive to negative at the beat frequency rate. In order to make effective use of this moving target flutter some sort of storage device is necessary. A liquid delay line has proven very effective for this purpose. Electronic storage tubes may also be used to store the responses from a transmitted pulse. The delay of the line is made equal to the pulse repetition period. The delayed signal from this line is mixed in opposite phase with the output from the receiver. The response from a fixed target will therefore be cancelled out since it is of constant amplitude. The response from a moving target will vary from pulse to pulse and will therefore not be completely cancelled out. An MTI modification kit for the MEW is being developed.

Two new methods have been developed which deal with the method of presentation. Photographic Projection PPI (called P^4I) consists of photographing the PPI scope, developing the film and then projecting an enlarged image on a screen from the film. This process has been developed to the point where the film can be exposed for one revolution of the PPI and then processed and be ready for projection in 10 seconds. If the antenna is making one revolution per minute an exposure can be made for each rotation. The film provides a permanent minute-to-minute record. The film may be projected in reverse on an 8-foot translucent screen. It can therefore be viewed from the side opposite from the projector. Plotting may be done directly on this screen.

In many applications it is desirable to have a simple map or check points superimposed on the PPI presentation. This has been done by marking directly on the face of the scope with a china pencil. This method has the disadvantage that the scale or sector cannot be shifted without voiding the marking. An electronic method of superimposing a map and reference marks on the PPI presentation has been developed. The map to be superimposed is scanned radially by a beam of light in synchronism with the radar pulse rate and antenna rotation. The reflected light is focused on a photocell and the signal from this cell is amplified. This signal is mixed with the video signal from the radar receiver. After the initial registration has been made, change of sweep range, centering, or sector presentation will not affect the map superposition since it will move with the scope presentation. In effect this is really a television technique.

SCR 584

Type of system

Combined range and azimuth.

Useful range

Maximum search range - 40 miles.
Maximum tracking range - 18 miles.
Minimum range .28 mile.

Accuracy and precision

Automatic tracking accuracy
Range ± 15 yards (.0085 mile)
Azimuth ± .034
Elevation ± .034°
Search accuracy
Range ± 1500 feet.
Azimuth ± 2°.

Presentation

Search - Visual PPI
Tracking - Azimuth and elevation dials.
Aided manual range tracking on J-scope (circular sweep), dial indication.

Operating skills required

Trained operators.
Time required to get fix: time to read PPI when searching. Time to read dials when tracking.

Equipment required

Weight - 10 tons (installed in trailer)
Equipment is quite complex.
Service and maintenance requirements - highly-trained personnel required.

Radio-frequency spectrum allotments required

Frequency - 2700 to 2900 mcps
Wavelength - 10.3 to 11.2 cm.
Bandwidth - 3 to 4 mcps

Present status

Operational.

The SCR 584 is a microwave radar designed for anti-aircraft gun-laying. It automatically tracks an aircraft in elevation and azimuth and has aided manual tracking in range. It can also be used for general search. It is not very well suited for general search since its beam is very narrow in a vertical plane as well as in a horizontal plane. It scans a 20°-elevation sector by using a helical scan. In other words, the elevation angle of the beam increases as the antenna rotates through 6 revolutions. It takes about one and a half minutes to make one complete scan. If it is desired to automatically track a selected echo the automatic search is stopped and the antenna is set on the echo manually by watching the PPI scope.

The SCR 584 is not well suited to following the movements of many individual aircraft or groups of aircraft but it is well suited to tracking one aircraft or group of aircraft.

The indicating equipment consists of one 7-inch PPI with sweeps of 35,000 yards (20 miles) and 70,000 yards (40 miles). Range-marker circles spaced 10,000 yards (5.7 miles) apart are provided. An azimuth scale is provided around the edge of the PPI tube face. Range is measured accurately by the use of two 3-inch J scopes. One of these is the coarse range scope. One turn around the circle on it equals 32,000 yards (18.2 miles). One turn around the fine range scope equals 2,000 yards (1.14 miles). The azimuth and elevation angle of the beam is indicated on two respective dials.

An MTI modification kit is being developed for the SCR 584.

Identification	Classification	Title	Issued by
TM11-1544	Confidential	Radio Set AN/CPS-1 Service Manual: Theory, Trouble-Shooting, and Repair	War Dept.
TM11-1524	Confidential	Radio Set SCR-584 Service Manual: Theory, Trouble Shooting, and Repair	War Dept.
"Radar" No. 10 30 June 1945	Secret	Off-center PPI pp.20 and 21 Kits for the MEW pp. 55-57	OSRD under direction of the Air Communication Officer

Type of system

Combines range, azimuth and DF (homing) on aircraft.

Useful range

100 miles (line of sight).

Accuracy and precision

Not known.

Presentation

3 meters indicating range (distance), homing and track.

Operating skill required

(a) At ground or fixed installation: can operate unattended.
(b) In the navigated craft: very little skill required.
(c) Time to obtain readings: instantaneous

Equipment required

(a) At ground beacon: Fairly complex transponder beacon and two-lobe antenna system. Highly trained personnel to service beacon.
(b) In the navigated craft: Fairly complex interrogator-responser; highly trained personnel to service equipment.

Radio-frequency spectrum allotment required

Frequencies around 220 mcps. About 4 or 5 mcps bandwidth required for interrogator and beacon.

Present status

Experimental.

Description of system

This equipment supplies three types of information. It measures the range (distance) from the aircraft to the beacon, it determines if the aircraft heading points to the beacon; and it determines if the aircraft is on a given track.

The equipment on the craft is essentially an interrogator-responser using a two-lobe antenna system and lobe switching. The equipment on the ground is a responder beacon feeding a two-lobe antenna system. The beacon responses are switched from one lobe to the other at a switching frequency of 10 cps. The pulse length is varied for the two lobes, long pulses being sent out from the right lobe and short pulses from the left lobe. In the aircraft equipment the responses from the right and left lobes may be separated by two pulse-length discriminators. These pulses may be integrated and applied to a left-right meter to indicate track. An automatic range-tracking follow-up system will stay locked on to the returning responses and provide range information. A manual range-search must be used initially to lock the follow-up on the desired beacon response. The lobe switching at the aircraft is done at a much higher rate than at the ground beacon. The output of the receiver is switched in synchronism with the lobe-switching and applied to a differential meter which indicates homing angle.

Figure 24-01 illustrates the system. Aircraft 1 is headed toward the beacon and therefore the amplitudes from its two lobes are equal. It is not on the track however and therefore the long pulses have a greater amplitude than the short pulses. Aircraft 2 is on track so the long and short pulses have equal amplitude. The aircraft is not headed toward the beacon though, and therefore the amplitude of the response from the right lobe is greater than the amplitude of the response from the left lobe.

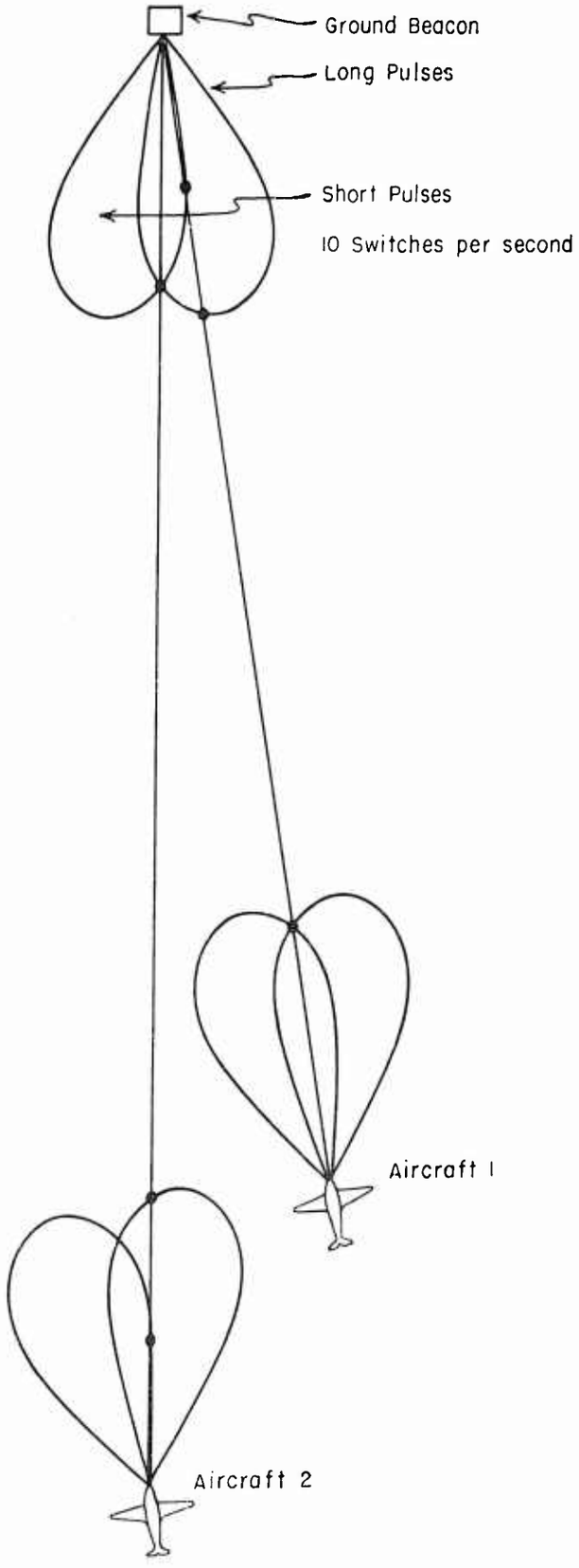

Ground Beacon
Long Pulses
Short Pulses
10 Switches per second
Aircraft 1
Aircraft 2

Fig. 24-01

Type of system

Combined range and azimuth (Radar).

Useful range and coverage area

Line of sight.

Accuracy

Not known.

Type of presentation

PPI presentation on cathode-ray tube centered about ground installation. Self-identification of craft provided; PPI presentation on ground.

Operating skill required

At ground station: Highly trained operators to maintain search radar plus additional complex equipment. On craft: Operational training in interpretation of PPI presentation. Little technical skill required. Time to obtain a fix: Instantaneous.

Equipment required

At ground station: Microwave search radar, UHF pulse transmitter and receiver, and fairly complex control circuits. In craft: Microwave receiver, UHF receiver, UHF pulse transmitter, cube-law sweep-curving circuits and cathode-ray tube circuits.

Radio-frequency spectrum allotments required

Frequency: Microwave channel - 3,000 to 10,000 mcps.
UHF channel - 500 to 1,000 mcps.
Wavelength: Microwave channel - 3 cm. to 10 cm.
UHF channel - 30 cm. to 60 cm.
Bandwidth: Microwave channel - 6 to 8 mcps.
UHF channel - 4 to 6 mcps.

Present status

Proposed.

Description of system

This system makes use of two different types of radar systems, simultaneously. Since these systems could work separately it is simpler and more convenient to describe them separately. The two systems used are the three-path radar, hereafter referred to as 3PR and the rotating lighthouse system, hereafter referred to as RLS.

In the 3PR system a powerful microwave search-radar transmitter and antenna are used. All planes are assumed to be equipped with responder beacons consisting of a microwave receiver and an UHF pulse-transmitter. As the microwave search-radar beam sweeps past a given plane its beacon responds to each microwave radar pulse by transmitting an UHF pulse. At the ground station this UHF pulse is received by the UHF receiver. The output of this receiver triggers off the microwave pulse-transmitter which radiates these echo responses omnidirectionally. Transmitted simultaneously with each directional radar pulse is an omnidirectional UHF synchronizing pulse. Figure 25-01 represents the ground station and two aircraft. At the moment represented the search-radar antenna is directed toward aircraft 2. Let us consider the signals that are received at aircraft 1. At the ground station the microwave radar pulse and the omnidirection-

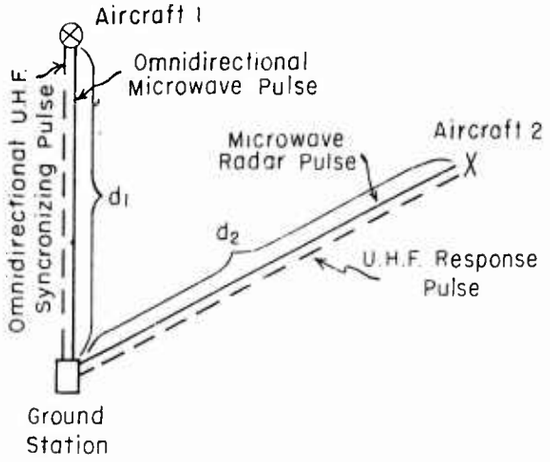


Fig. 25-01 Principle of three-path Radar

al UHF synchronizing pulse are simultaneously transmitted. The omnidirectional UHF pulse travels the distance d_1 and arrives at aircraft 1 at the time t_1. The microwave radar pulse travels the distance d_2 to aircraft 2. The beacon in aircraft 1 responds with an UHF response pulse. This UHF pulse travels the distance d_2 back to the ground station and arrives there at a time t_2; at the ground station the UHF response is retransmitted as an omnidirectional microwave pulse. This experiences an additional delay and arrives at aircraft 1 at a time $t_1 + 2t_2$. Thus the difference in time of arrival at aircraft 1 of the UHF synchronizing pulse and the omnidirectional microwave pulse is $(t_1 + 2t_2) - t_1 = 2t_2$. This is the same delay that is observed at the ground station between the directed microwave radar pulse and the UHF response pulse. If the cathode-ray sweep in aircraft 1 is started by the UHF synchronizing pulse then the omnidirectional microwave pulse will be displayed at the correct point to form a PPI presentation centered about the ground station. One other requirement must be met to produce a true PPI presentation on aircraft 1. The rotating deflection system of the cathode-ray tube must be synchronized with the rotating radar antenna at the ground station. This is accomplished by having the UHF synchronizing-pulse transmitter transmit a special pulse of different width as the radar antenna swings through north.

Since this radar system receives beacon responses on a different frequency than its own pulses it will "see" only responder beacons. Natural obstacles, runway ends, etc. can be indicated by the use of ground beacons. All aircraft within range including aircraft 1 itself will be shown on aircraft 1's PPI. Since there is no difference between the aircraft's own response and that of other aircraft on the PPI, self-identification is not provided. It would be possible to identify your own plane by interrupting your beacon's response for a few seconds and noting which spot disappears from the PPI.

In the RLS (Rotating Lighthouse System) a high-powered microwave pulse transmitter feeds a rotating directional antenna. This can be the same combination as used in the 3PR system. The function of this microwave system is to illuminate all objects within range of the ground station.

In Figure 25-02 the ground station, two aircraft, and a natural obstacle are represented. The omnidirectional UHF synchronizing pulse and the microwave

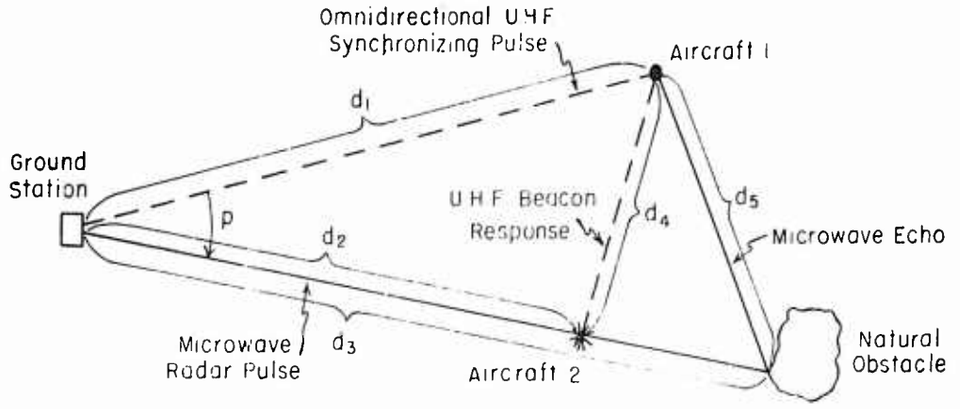


Fig. 25-02 Principle of Rotating Lighthouse System

radar pulse are emitted simultaneously. The UHF synchronizing pulse travels the distance d_1 to aircraft 1 and upon arriving there starts the sweep. The microwave radar pulse is assumed to be directed out toward aircraft 2 and the natural obstacle at the instant represented. The microwave radar pulse travels the distance d_2 to aircraft 2 and triggers off the responder beacon which radiates an omnidirectional UHF pulse. This pulse travels the distance d_4 to aircraft 1. The microwave radar pulse also travels the distance d_3 to the natural obstacle and some of this energy is reflected to aircraft 1 along the path d_5. Thus at aircraft 1 beacon responses may be received on an UHF receiver and direct reflections may be received on a microwave receiver. This system is therefore equivalent to a radar system in which the receiving equipment is at a distance from the transmitter. If the rotating deflecting system of the cathode ray tube of aircraft 1 is kept synchronized with the direction in which the radar antenna is pointing then the angular indication on aircraft 1's PPI will be correct if this PPI is centered about the ground station. The directional indication will be correct since only those objects in the path of the radar beam can produce responses. In order to give correct distance indications a nonlinear sweep must be used on the cathode ray tube in aircraft 1. The shape of this sweep is a function of the distance d_1 and the angle p. The angle p may be determined from the time when the microwave radar beam sweeps past the aircraft. The distance d_1 may be determined by the three path radar indication. For a small angle p as shown the sweep would move the cathode ray spot very rapidly at first and then slower. (See Figures 25-03 and 25-04). The fact that d_1 and p must be known to give a correct RLS indication means that the self-position of the plane must be known. By combining this RLS with the 3PR system a valuable check is obtained since the 3PR system does give a presentation correct in azimuth and range. It is proposed to use alternate pulses of the microwave radar transmitter for the RLS and 3PR functions. The two presentations would be superimposed on the same cathode ray tube. Figure 25-05 gives the appearance of the RLS display. Self-position is indicated by the ellipse. The end of the ellipse at the center of the PPI indicates the ground station and the outer end indicates self-position. The ellipse is a blind area. No objects can be seen in it by the RLS function. This is not serious however since the 3PR system will give indications of planes in this area.

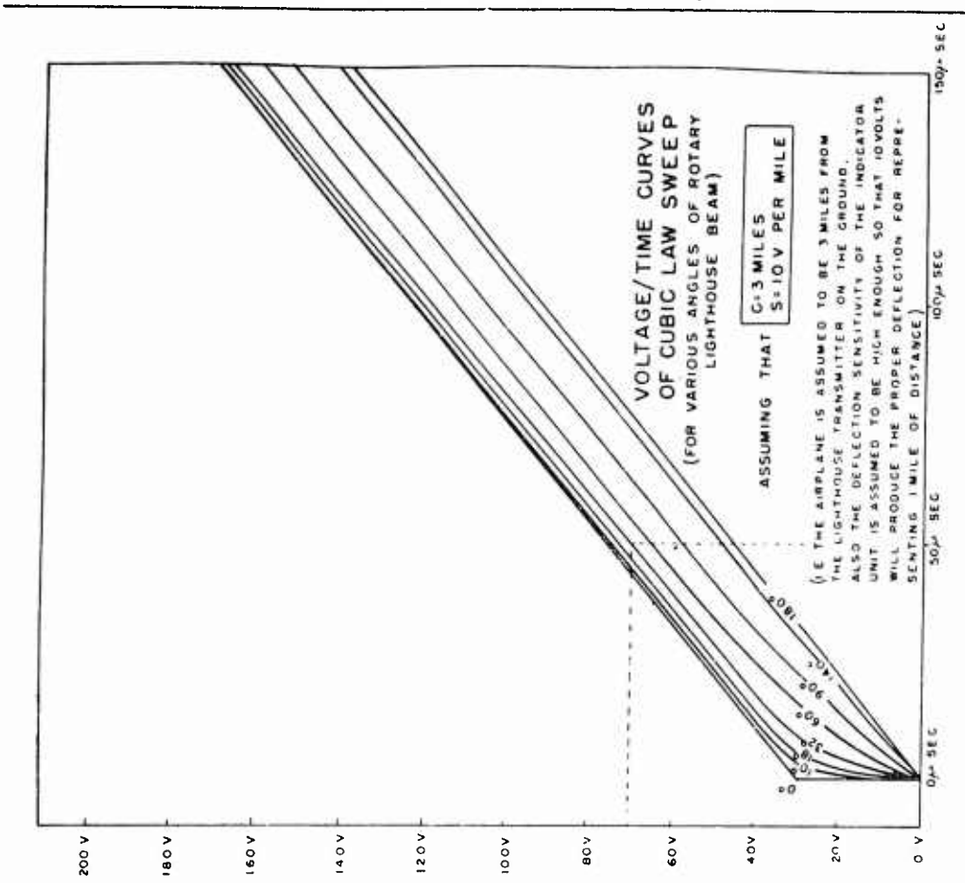


Fig. 25-04 Sweep waveforms for aircraft at 3 miles from lighthouse

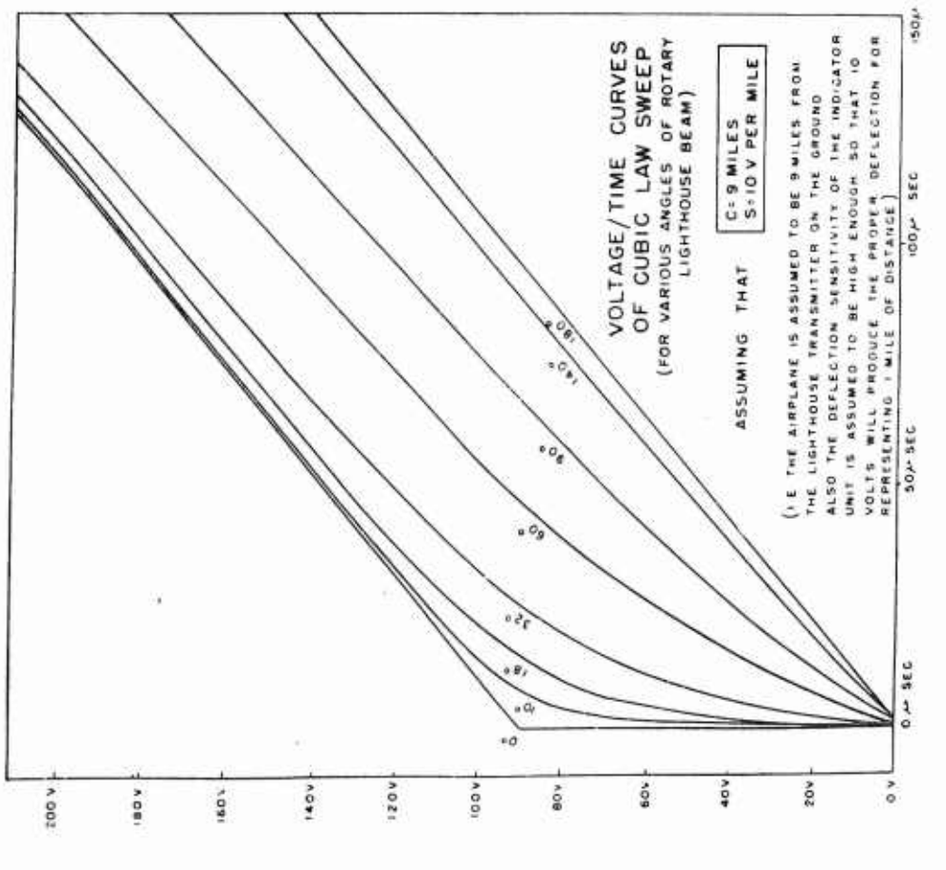


Fig. 25-03 Sweep waveforms for aircraft at 9 miles from lighthouse

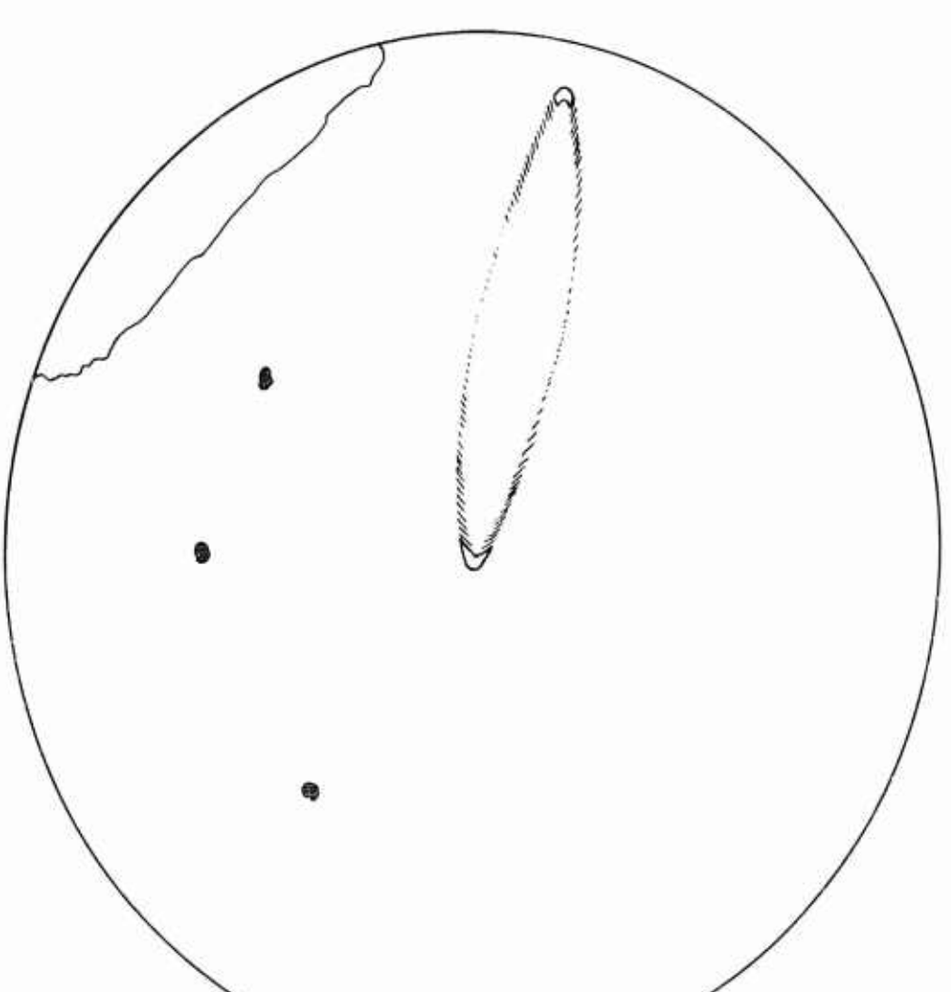


Fig. 25-05 Rotating Lighthouse Presentation

Identification	Classification	Title	Issued by
Proposal No. 287	Confidential	Three-path Rotating Lighthouse System for Airport Control	Federal Telephone and Radio Corporation

Part I General Information

The signal pattern on a PPI is a map-like presentation of echo signals received from surrounding artificial and topographical features of many kinds. Even though the radar set be located at a considerable altitude above the earth's surface, by proper design and adjustment of the PPI sweep circuits the echo signals may, with a high degree of accuracy, be made to appear at the correct ground range and azimuth from the radar set. With the possible exception of a small area at the center, the relative positions of all signals with respect to one another are shown on a PPI with sufficient accuracy to enable a chart of the same territory to be fitted by superposition to the PPI signals. A navigational fix is thus obtainable from the position of the center point of the PPI upon the superimposed chart.

Direct superposition in the form of an overlay is undesirable because of parallax (due to thickness of the glass in the tube face) and distortions produced by electrostatic charge on the operators hands. Successful superposition may be accomplished by an optical method which produces a virtual image of the chart in the plane of the cathode-ray tube face. One of the simplest forms which the apparatus may take is shown in Figure 26-01. Such an arrangement is called a Virtual PPI Reflectoscope, usually abbreviated as VPR. The VPR apparatus does not make use of any lenses and it is enclosed in a frame which also acts as a light-hood. The map or chart to be used is placed upon the illuminated chart table at P. Rays of light from the chart are reflected from the mirror at R, and at D from the unfilmed side of the glass plate G. The operator sees the chart as a virtual image in the plane of the cathode-ray tube face (distance PR + RD + DC is equal to the distance PE). The observer also sees the PPI tube face through the filmed glass without loss of clearness.

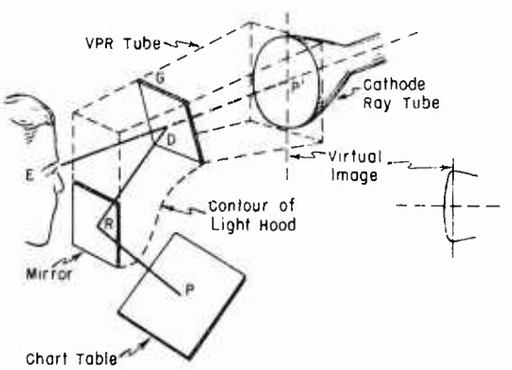


Fig. 26-01 Essential parts of the VPR

The chart which is prepared with white lines on black is readily shifted about by hand, and the chart table is also movable in its plane by two screws at right angles to one another.

In some types of shipborne radar equipment 6 and 12-mile sweeps are available on the PPI tube and two corresponding sizes of charts must be provided for superposition. The charts to be used are prepared in advance of their operational use and may have characteristics and markings of special usefulness for matching purposes.

35 mm. microfilm may be used instead of a paper chart. The NMP (Navigational Microfilm Projector) apparatus is similar to that of the VPR just described except that the chart table is replaced by a diffusing screen which receives the image of the map by optical projection from below.

Another type of projector called the Autofocus Microfilm Projector has an adjustable range of magnification. This arrangement enables a chart to be matched to the sweep length of a number of different radar sets. The essential parts of the Autofocus Microfilm Projector are shown in Figure 26-02.

As manufactured by the Spencer Lens Co., the apparatus has a few additional features. For measurement of azimuth, the shadow of an adjustable protractor may,

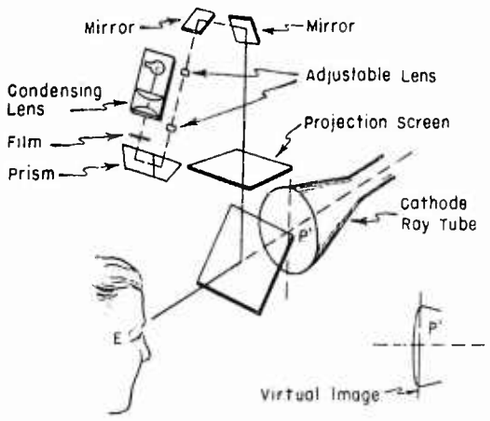


Fig. 26-02 Essential parts of the Autofocus microfilm projector

if desired, be cast upon the projection screen with red light which does not appreciably dilute the normal white light illumination of the map. The relative position of the PPI screen and the superimposed chart is adjustable in the north-south and east-west directions by means of two micrometer screws carrying reset counters which can be set to zero at any convenient reference point on the chart which may be desired as an origin of coordinates. The counters read the x and y coordinate distances to the nearest hundred yards, with the possibility of estimation to the nearest 50 yards. The information on the counters is given by the radar operator to the navigator who works on standard size navigational charts.

Still another type of projection system somewhat similar to the VPR is under development in which the image of the PPI scope is projected onto the table top upon which the navigator works.

In the various types of Map-PPI superposition equipment, azimuth stabilization is almost always used so that true north is as the top of the PPI screen. After the radar operator has matched the chart to the PPI pattern in a manner consistent with the topography of the area and straight line propagation of the radiation, a navigational fix may be obtained by any of several methods. With the Spencer Autofocus type of equipment, a navigational fix may be obtained with the shadow protractor alone by taking bearings on any two known points of the chart. Alternatively a fix may be obtained by measurement of both bearing and range of a single known point on the chart with the aid of the protractor and range marks. A fix may also be obtained from the readings of the north-south and east-west counters. In the VPR system a fix may be obtained by reading off the position coordinates of the center of the PPI scope upon whatever grid of coordinate lines is reflected with the chart upon the screen of the cathode-ray tube.

Television techniques are utilized in a new electronic method of Map-PPI superposition. The map and reference marks to be superimposed upon the radar signals are scanned radially by a beam of light which is synchronized with the radar pulse rate and antenna rotation. The reflected light is detected by a photocell and amplified. This signal is then mixed with the video signal from the radar receiver and the two sets of signals appear superimposed upon the PPI. After the initial registration has been made, change of sweep range, centering, or sector presentation will not affect the map superposition since it will move with the scope presentation.

For presenting a scope picture to a large number of people, a Photographic Projection PPI (called P^4I) has recently been developed The P^4I method consists of photographing a PPI presentation, developing the film, and then projecting an enlarged image upon the back of a translucent screen. Plotting may be done directly on the front side of the translucent screen. This process has been developed to the point where the film can be exposed for one revolution of the PPI, and then processed so as to be ready for projection in 10 seconds. The processed film provides a permanent record of the operations.

A PPI pattern may not bear too great a resemblance to a map because of

antenna beam width, shadowing, $1/R^4$ effects, etc. Greater definition may be obtained by using narrower beams and shorter pulses. The gain of the receiver may be varied throughout the sweep so that equal targets at different ranges produce approximately equal signals. The use of improved sweeps (linear for surface craft and hyperbolic for aircraft) and either rotating coil or electrostatic PPI's help to eliminate map distortions. Little can be done about shadowing effects except to become familiar with expected PPI patterns, through previous experience and study of stereo-pair photographs or model relief maps. A good indication of expected PPI patterns may be had through a preliminary study of a model relief map, which may be illuminated from different angles with special flash lights.

A number of topographical features show up on radar PPI scopes. Some of the features which are most useful in radar mapping are shorelines, islands, hills, etc. Groups of tall buildings have corner-reflector characteristics and give good reflections from all directions. Large lakes, lagoons, valleys, and rivers give useful blanks.

The advantages of Map-PPI Superposition are:

(1) The amount of quantitative information which can be presented graphically upon a small area is very great.
(2) Appraisal by eye is quickest means of comparison of two sets of data of this type.
(3) Radar signals cannot in general be effectively camouflaged or damaged. The navigator is not dependent upon the proper functioning of any person or apparatus not aboard his own craft.

Several sources of data for radar mapping are available such as the 1:80,000 U.S. Geodetic Survey navigation charts (local mercator projections) and U.S. Geological topographic maps. The best source of data for radar maps is an up-to-date aerial survey with complete "stereo-pair" coverage. The stereo-pairs show height on an exaggerated scale. Standard methods of photogrammetry are employed to prepare a radar map showing the features in their correctly projected positions. For sweeps of 12 miles or less the distortion of the mercator charts is not appreciable, but whenever possible, conic projection should be used. All charts issued by the U.S. Hydrographic Office are also available on microfilm.

Part II The NALOC (Navigational Aids to Landing Operations Committee) System of Map-PPI Superposition

Type of System

Combination of range and azimuth (PPI presentation).

Useful Range

Approximately 10 miles for accurate radar mapping.

Accuracy and Precision

The location of the craft is known to within about $\pm$ 100 yards.

Presentation of Data

Visual presentation on PPI.

Operating Skill Required

A radar operator trained in Map-PPI Superposition (Radar Mapping).

Time for Fix

Several minutes for an independent fix starting from scratch, but as many as 3 fixes per minute are possible when navigating on a course.

Equipment Required on LCC

(1) Shipborne X-band or K-band radar set with gyro compass for stabilization of PPI, VPR or NMP mapping equipment.
(2) QBG sound head (underwater sound directional receiver).
(3) Marine Odograph with reversed plotting head (dead reckoning recorder).
(4) Recording Fathometers - types NK-2 and NJ-8.
(5) Three type TCS radios for communications.
(6) Type ZB/RU short wave radio directional receiver.
(7) Miscellaneous equipment such as magnetic compass, clocks, etc.

RF Spectrum Allotments Required

K-band or X-band. Bandwidths about 1-2 mcps.

Present Status

Operational.

The NALOC system of navigation has been designed primarily for naval landing operations in which a highly technical vessel manned by skilled navigating personnel leads a wave of troop carrying vessels to within a few hundred yards of a target beach. The problem is to direct the wave of landing craft so that a landing may be made within ± 200 yards of a target point on the beach in zero-zero visibility and with a range accuracy corresponding to an error of ± one minute in time of arrival.

The landing control craft is equipped with a number of navigational aids so that several methods of navigation are available for use in any landing operation. One of the most commonly used systems makes use of optically superimposing a map upon a PPI presentation. The details of this method have been discussed earlier in this section. As the superposition technique is used in NALOC, a fix is determined from the position of the center point of the PPI presentation upon the superimposed map. If VPR (Virtual PPI Reflectoscope) type of apparatus is used, two sizes of charts are provided to match the 6-mile and 12-mile sweeps of the PPI tube. The charts used are prepared in advance of the landing operation and usually contain only information which is useful for matching it to the PPI pattern. As previously mentioned, the NMP (Navigational Microfilm Projector) type of equipment uses 35 mm. microfilm instead of charts.

There are several types of coordinate systems which may be more convenient to use in landing operations than ordinary latitude and longitude. The terminal objective or target point on the beach is often a convenient origin of coordinates. Two typical coordinate systems are shown in Figures 26-03 and 26-04. The range in Figure 26-04 designated in minutes is of course the actual distance divided by the normal speed of the operation. The particular network of coordinate lines used in an operation is laid out both upon the chart or film used in the projection system and upon the larger charts used by the navigator.

For security reasons it is sometimes necessary to observe complete radar silence during all or the greater part of a landing operation, so other means of navigation must also be provided. The LCC (Landing Craft, Control) is equipped with an underwater-sound directional receiver (QBG sound head) to provide for navigation by means of sonic buoys. For landing operations, sonic buoys are laid one to two

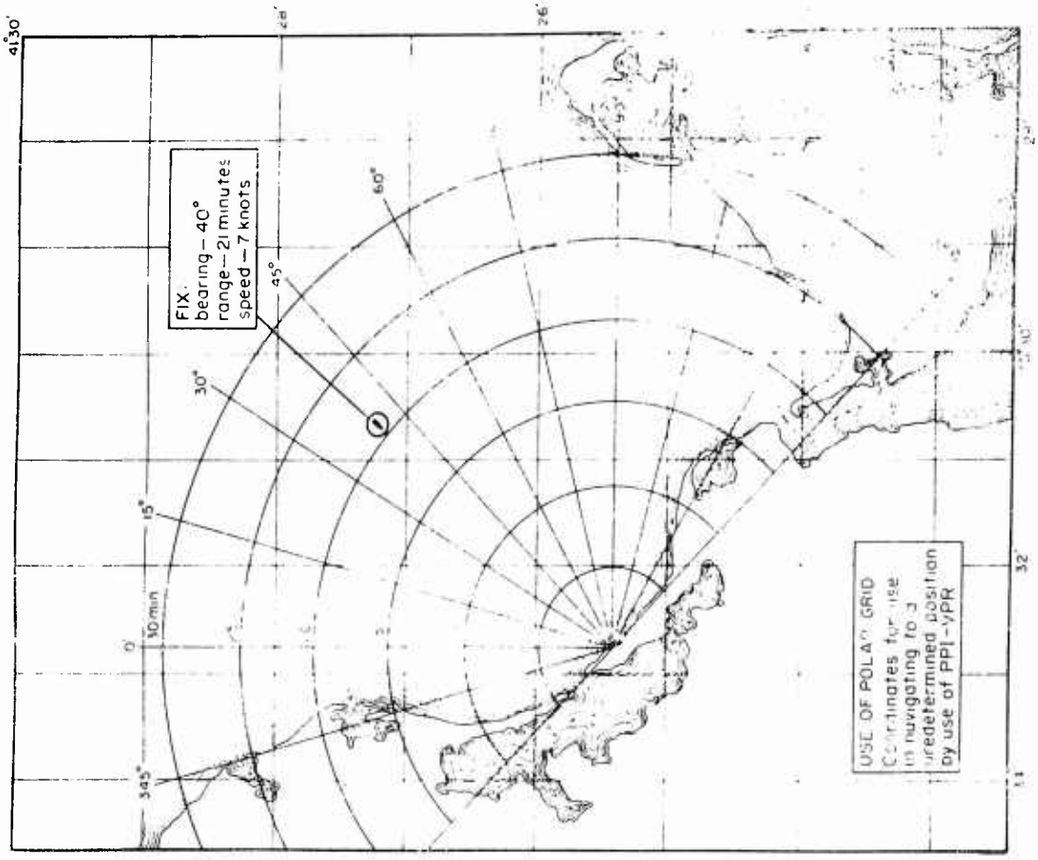


Fig. 26-04

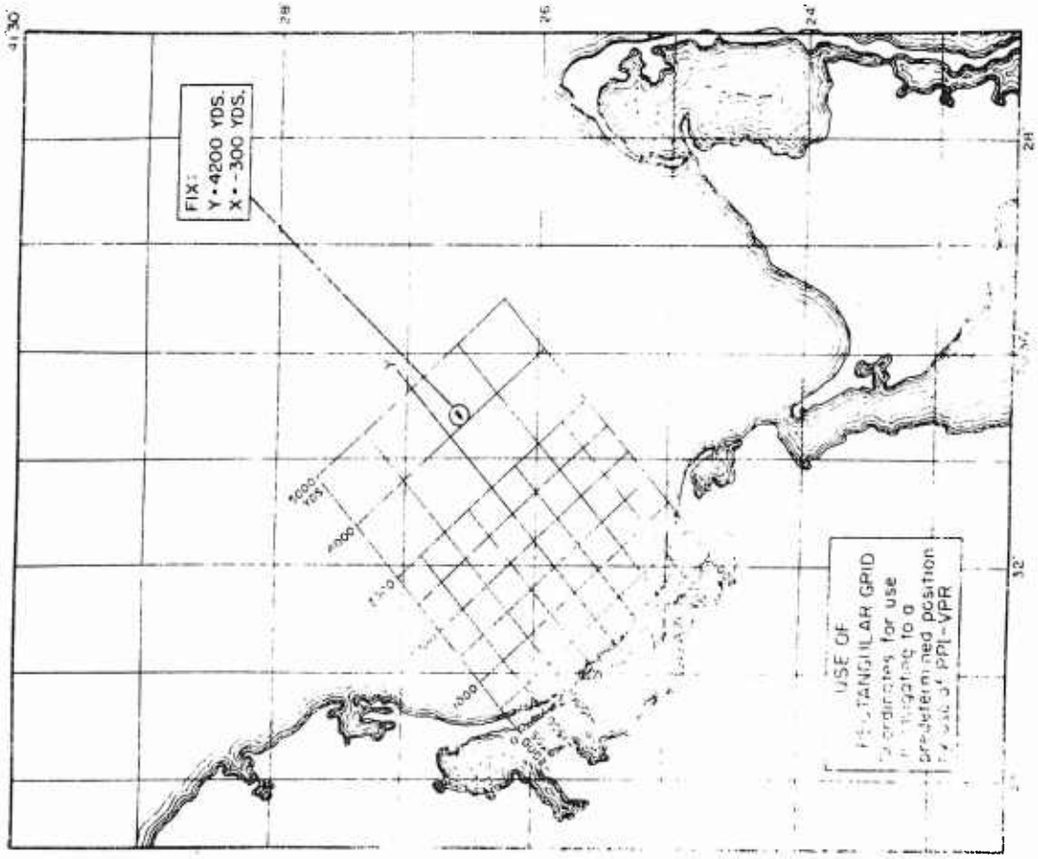


Fig. 26-05

miles apart in a straight line about 10 miles offshore. The buoys are laid by submarine one to three days early and are timed so as to transmit coded signals for an eight hour period centered on H-hour, and then scuttle themselves. They are anchored at least 125 ft. below the surface of the water and are designed to keep within a radius of ± 200 yards of the anchor. The sound gear along with a recording fathometer and odograph (dead-reckoning tracer) may be used for the entire landing operation, but they are more commonly used while navigating seaward of the buoy line, and the radar mapping method is then used for the final 10-mile run to the beach.

Although the sonic buoys may usually be heard up to 10 miles or more, under very adverse conditions it may be impossible to hear the buoys at distances greater than 1500 yards, or roughly one mile. It is also difficult under some conditions to lay a line of buoys by submarine with very great accuracy. In such cases it may therefore be desirable to navigate entirely by radar.

Since the range of some Map-PPI Superposition equipment is limited to about 12 miles, navigation by suitably positioned corner reflectors may be used during the early part of a landing operation. Boats with coded corner reflectors may be anchored at suitable positions off the coast line. With the aid of such reflectors it is possible to navigate by means of "backward ranging" radar and thus preserve radar silence toward the shore until the last 10 miles of the operation when the radar may be beamed shoreward for navigation by radar mapping.

Bibliography

Identification	Classification	Title	Issued by
503	Secret	Precise navigation by means of a radar map superposed on the PPI	MIT Rad. Lab.
658	Confidential	A microfilm chart projector for radar navigation	MIT Rad. Lab.
No. 10 June 1945	Secret	"Radar" magazine, page 57	OSRD under the direction of the Air Communications Officer
NALOC Progress Reports No. 1 - No. 7	Secret	Progress Report, NALOC to Chairman NDRC	MIT Rad. Lab.

RCA TELEVISION-RADAR SYSTEM

Type of system

Combination range and azimuth.

Useful range and coverage area

Approximately 200 miles, depending on height of craft (Line of sight). Day and night coverage identical.

Accuracy

The accuracy of position indication is that given by the type of ground search-radar used.

Type of presentation

Visual. (a) At ground station, several PPI indicators, each covering a predetermined altitude range; also inserted information including maps of airways, airports, data regarding weather, etc. (b) At craft, a televised image is presented which reproduces the ground PPI picture corresponding to the altitude range desired, superimposed on the inserted information.

Operating skill required

This system is intended for traffic control, collision prevention, blind-landing approach and general navigation. (a) At the ground station, a permanent staff including traffic controllers, PPI and television operators, power plant attendants, etc., would be required. The skill required is determined by the function of each member of the personnel. (b) In the craft, the only operations required are the tuning of a television receiver to the desired channel, the normal adjustment of intensity required with any cathode-ray indicator, and ability to interpret the composite picture seen. (c) A fix is indicated continuously and automatically by the position of the craft as given in the picture with respect to fixed ground objects, airport runways, etc.

Equipment required

(a) At ground station: ground search-radar set (MEW or SCR 584 and/or GCA), a number of PPI indicators, optical projection systems, television cameras, television transmitters, plotting facilities, telephone and radio communications gear, etc. (b) In craft: beacon transponder with adjustable code, barometric altimeter (standard equipment), television receiver. Normal VHF communication equipment is a useful adjunct.

Frequency requirements

Two S- or X-band radar channels are required. The band-width depends on the degree of oscillator stabilization realized in the craft beacon transmitter and in the ground search radar transmitter. Several television channels are also required.

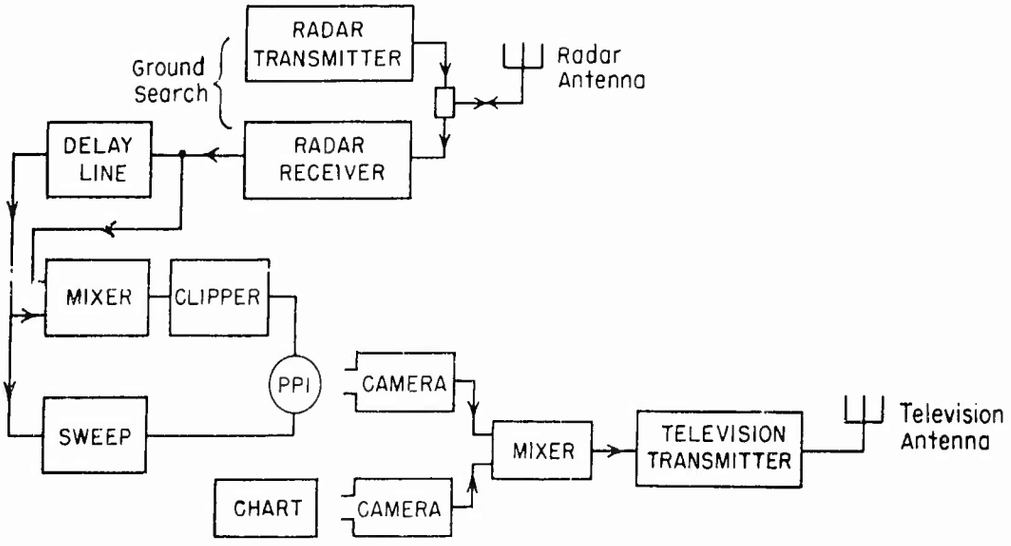
Present status

RCA has made proposals which outline the scheme, but so far as we are aware complete equipment design has not been worked out. Inasmuch as the system uses components which have already been developed, the amount of new circuitry to be developed is not too large.

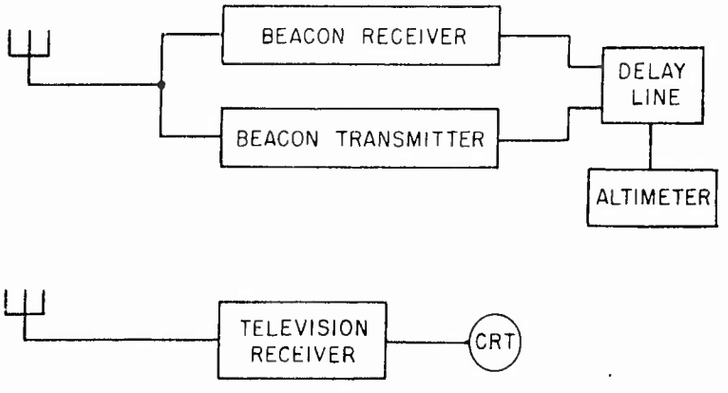
Principle of operation

The block diagram of Figure 27-01 is functional only, and does not indicate a specific arrangement of the equipment. The ground search radar transmitter presents a PPI picture which is televised and transmitted to the craft where it is received and displayed. A second television camera enables a chart to be super-

imposed on the presentation, so that airways, information as to wind direction and velocity, traffic control and other special instructions, data as to obstacles, etc., may be temporarily or permanently superimposed on the pattern. It will be seen that this arrangement is extremely flexible and that a pointer might momentarily be used to designate pictorially areas or objects which are the subject of conversations over the VHF communications equipment. It is understood that television from ground to plane is well established and that the weight of an airborne television receiver may be kept within a reasonable limit. It is proposed that a projection-type PPI display be used on the ground, and an ordinary CRT display in the craft.



(a) Ground equipment



(b) Craft equipment

Fig. 27-01 RCA Televised radar system--Block diagram

Separation of different altitude levels

The beacon receiver in the craft picks up the search pulses from the ground station, and the beacon transmitter radiates its response. This consists of two pulses. The first of these is assumed to be radiated with negligible delay. The second is coded by the plane's barometric altimeter. That is, the time interval between the first and second beacon pulses is controlled by a delay-line which is interlocked with the altimeter, the length of the delay time being a function of the height of the craft. It is proposed that the delay should be variable in steps, each step representing a certain range of altitude. The altitude ranges would overlap slightly.

At the ground receiver, an identical delay-line is used, and signals with and without delay are mixed and clipped. This results in the automatic selection (at the ground station) of responses from all craft in the altitude range for which the

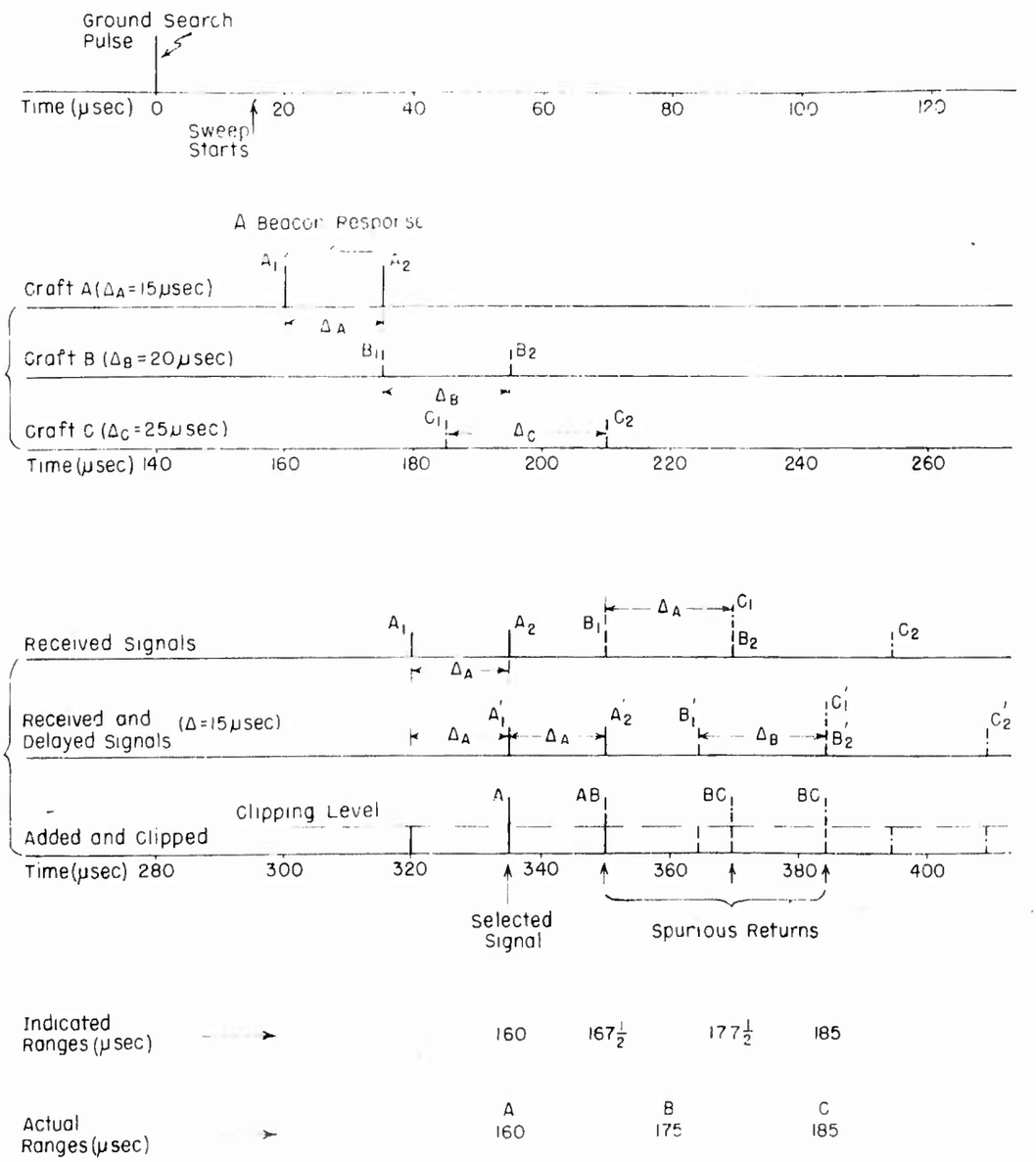


Fig. 27-02 Time relationships

ground delay-line is set. This principle is illustrated in Figure 27-02, in which a time scale starting from the emission of a ground pulse is shown. It is assumed for purposes of illustration that the coding time (Δ) for the particular altitude of craft A is 15 microseconds and that the distance of the craft from the ground station corresponds to a one-way transit time of 160 microseconds. At 320 microseconds and 335 microseconds the return pulses are received. The delayed received pulses occur at 335 and 350 μsec. The second direct pulse and the first delayed pulse coincide in time and add up, so that after clipping, the 320 and 350 microsecond pulses will not appear, the only signal transmitted to the PPI being at 335 microseconds. It will be seen that there can be no coincidence between the direct and delayed pulses from any one craft unless the delay time at the ground station is the same as that at the craft. Thus by selection of the appropriate delay line on the ground, responses from planes in a given altitude layer are selected and displayed on a particular PPI.

In order for the correct range to be indicated, the sweep at the ground station indicator must also be delayed. This is easily accomplished by triggering the sweep with that part of the ground search pulse which has also traversed the delay line. Thus the range indicated for craft A would be $\frac{335 - 15}{2} = 160$ microseconds.

However, there is a possibility of spurious responses. Craft B (range 175 microseconds, delay 20 microseconds) and craft C (range 185 microseconds, delay 25 microseconds) produce overlapping returns as illustrated by the dotted lines. It is seen that there are three spurious returns from the two extra craft: two of these returns give incorrect ranges and all three give incorrect altitude layers. This condition will only arise if a number of craft happen to be within the same cone (as seen from the ground) corresponding to the dimensions of the search beam, at the same time; and unless these craft maintain the same spacing for a period of several search sweeps, the returns will be erratic, fading and changing position. This condition corresponds to dense traffic, would be relatively rare and could probably be recognized; nevertheless it appears to be a disadvantage and will no doubt be eliminated by careful design if this system is to be developed.

Disposition of ground stations

In regions where this type of control and navigation is to be utilized, ground stations would be established in suitable locations, perhaps 100 - 200 miles apart. The overlay or chart televised at one station would include printed instructions at appropriate points at its outer edge for retuning the craft receiver to the frequency used in the next area of control. The pilot of the craft sees his position in relation to other craft in the same altitude layer and to ground terrain. It would appear that heavy traffic under conditions of zero visibility might be handled by this method.

Identification

In order that the craft pilot may identify his own craft on the display, it is proposed that the pulses from the craft transponder be made to brighten the craft television display for a time corresponding to one or two television frames. This will in effect brighten the televised image of the PPI sweep while it is pointing in the direction of the craft. Thus the pilot will see a bright line pointing at his position. If there is only one craft response along this line, he has identified himself. If there are several craft at the same level and azimuth, several responses will be visible along this line and in this case more distinctive identification such as momentary transponder coding by depressing a push-button switch, might have to be provided.

Adaptation of the system to blind approach

Where facilities must be provided for giving a pilot a precise indication of glide path, a modification is proposed. The craft equipment remains as before, the

display being televised. The ground station consists of a GCA (ground-controlled approach) radar set, or simplified GCA omitting the "talk-down" feature, located just to one side of the far end of the runway. Azimuth and elevation sector-scan PPI indicators are necessary, as well as television cameras and transmitting facilities.

The normal displays on the separate azimuth and elevation indicators fed from the GCA radar are shown in Figure 27-03. GO is the desired line of azimuth

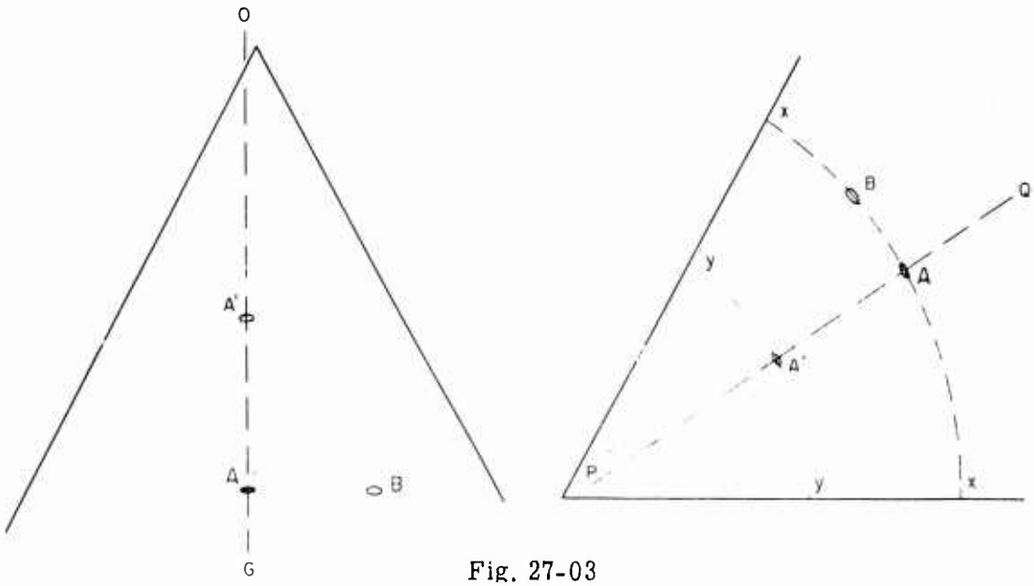


Fig. 27-03

(a) Azimuth scan

(b) Elevation scan

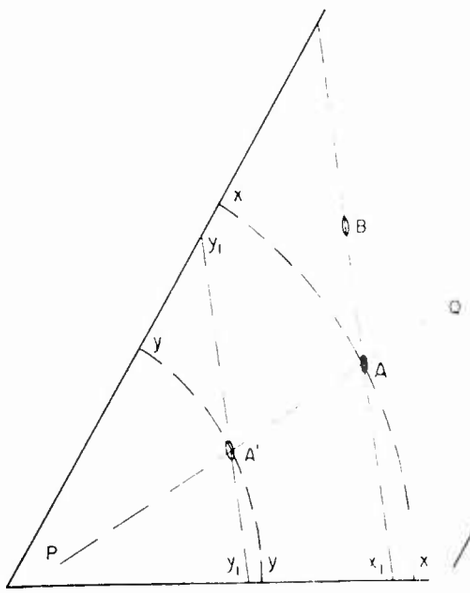


Fig. 27-04

Modified elevation scan

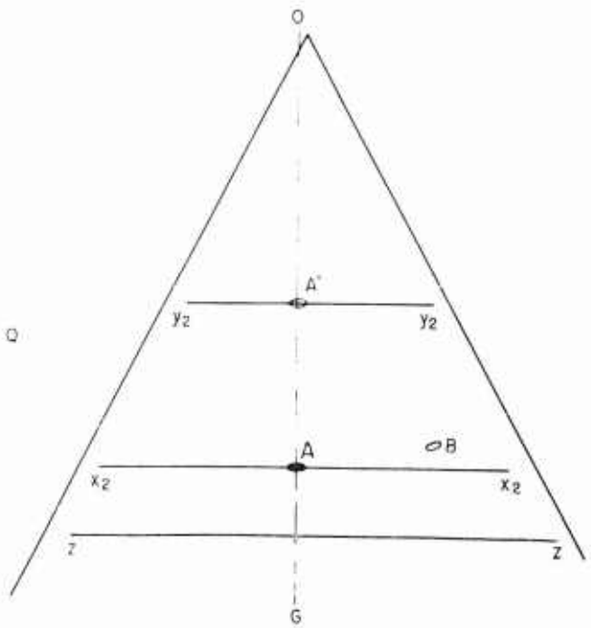


Fig. 27-05

Azimuth and modified elevation scans superimposed

approach, QP is the projection of the desired glide path in a vertical plane. The craft A is correctly navigating along the glide path; at a later time it will have arrived at A'. The arcs xx and yy in Figure 27-03 are drawn for illustration only and are not part of the display. Craft B is too far to the right and too high, although at the same range as A.

In Figure 27-04 is shown a modified elevation display, wherein the amplitude of the sweep is modulated by the magnitude of the angle of elevation of the search beam at any instant in such a manner that the arcs xx and yy in Figure 27-03 now become the straight lines x_1x_1 and y_1y_1 in Figure 27-04. That is, the length of the sweep trace in Figure 27-04 is larger than in Figure 27-03 when the sweep is above QP, and smaller when it is below. It is presumed that suitable circuits can be designed to perform this modulation. Note that the distance between a response pip and the apex of the elevation display will now be equal to the corresponding distance in Figure 27-03 (a) or Figure 27-03 (b) only if the craft has the correct elevation.

By suitable rotation of Figure 27-04 about its apex (in the plane of the paper), and by superimposing Figure 27-03 (a) with Figure 27-04 (rotated), Figure 27-05 (which is the display as seen by the pilot in the craft) is obtained. The display of Figure 27-03 is scanned by one television camera and that of Figure 27-04 (rotated) by another. Between the display of Figure 27-04 and its camera there is placed a cylindrical lens, so oriented that points in Figure 27-04 appear as horizontal straight lines in Figure 27-05. Point A in Figure 27-04 gives rise to the line x_2x_2 in Figure 27-05, and point A' to the line y_2y_2. The "on course" indication is therefore the coincidence of the "elevation" line x_2x_2 and the "azimuth pip" A with a point on the glide path GO. If the pilot navigates in such a way that this coincidence is always maintained as A proceeds through A' towards O, he will remain on the desired glide path. Plane B, which is too high, will give rise to the line zz and the response B in Figure 27-05. The pilot, identifying himself with the response B, sees that he is too high (above the horizontal line zz) and too far to the right. As he approaches the correct glide path, B will move to the left towards OG and will continue to rise, but zz will rise faster, coincidence being obtained as for craft A. The pilot therefore has continuous indication of his position in space relative to the desired glide path and in relation to the airport, and may navigate accordingly.

This system is not a full blind-landing system. If visual contact is obtainable at (say) 50 to 100 feet altitude, the blind approach procedure is followed until this "drop-out" level is reached. Otherwise some other scheme adapted specifically for blind landing must take over after the approach has been completed. The indication is like that of a crossed-pointer meter except that the "crossed pointers" move upward on the "meter" as the airport (top of the "meter") is approached. Furthermore the positions of other aircraft making blind approaches are always shown. Also pictorial transmission of airport runways, obstructions, etc., can easily be added to the picture as transmitted from the ground. A number of aircraft can be making approaches at one time and all can be correctly indicated.

The two modifications here described (control in the vicinity of large airports, blind approach) seem well adapted to handle large amounts of air traffic if they can be realized effectively. The considerable expenses involved should be justified by the volume of traffic that can be controlled under any conditions of visibility.

Bibliography

Identification	Classification	Title	Issued by
Eng. Memo PEM-16C	Confidential	Preliminary Analysis of Radar Navigation Aids	RCA
Eng. Memo PEM-17C	Secret	Memorandum on Radar-Television System of Air Navigation	RCA

Sperry Omnidirectional Range and Distance Indicator

Type of system

Combined azimuth and range (radial lines of position combined with circular lines of position).

Useful Range

Azimuth: 100 miles at suitable height (line of sight)
Range: 24 miles without ambiguity

Accuracy and Precision

(a) Azimuth measurement, about $\pm 3^{o}$ (estimated).
(b) Ambiguity in range at over 24 miles. No ambiguity in azimuth.

Presentation and use of data

Altitude and range would be given by dial indication. Electrical data would also be available for automatic navigation on a preselected course.

Operating Skill Required

(a) At ground installations, where all equipment is automatic, only monitoring and occasional checking would be required. (b) In the craft, the only operations necessary are the tuning of azimuth and range receivers. (c) Since continuous indications of distance and azimuth are given, a fix is constantly available when the craft is within 24 miles of the ground station. Between 24 and 100 miles, azimuth only is available.

Equipment required

(a) At ground station: 50 - 100 watt C-band transmitter for rotating beacon transmission, antenna with dish reflector. Rotation or phase-shifting gear. Omnidirectional transmitter and antenna for phase reference. Beacon transponder for distance indication. (b) At craft: C-band receiver and specialized timing circuits and indicator for azimuth. Transmitter and receiver with specialized phase-matching and indicating circuits for range.

Radio-frequency Spectrum Allotments Required

One C-band channel (5000 mcps) for azimuth measurement and two other channels (frequency undetermined) for range. Frequency stabilization of transmitters and receivers is proposed, so that the bandwidth required for the C-band channel would be of the order of 250 kcps; for the range channels considerably less.

Present Status of Development

The Sperry Gyroscope Company has made proposals which are here outlined, Although various units in the system have been developed to the flight-testing stage, the system as a whole has not been integrated, nor have methods and equipment been frozen to a particular design.

Principles of Operation

1. Azimuth Indication: The ground C-band transmitter is to be crystal controlled, frequency-multiplier klystrons being used in the final multiplier stages. A frequency stability of 1 part in 10^{6} is thereby obtained. This means that many channels can be used within a small part of this band. Part of the energy from this transmitter, modulated at 3 or 4 kcps, is radiated from the omnidirectional antenna and is keyed at some definite repetition rate. The remainder of the energy at this frequency is transmitted as a fairly wide beam from the directional antenna. This is

arranged to give a directional pattern consisting of two intersecting lobes, modulated at different audio frequencies. The directional beam is caused to rotate uniformly in azimuth at a speed of perhaps 2 revolutions per sec., by mechanically rotating the antenna and dish. Alternatively, some scheme of electrical rotation may be used (phase shifting), in which case the rotation could be somewhat faster. The keying of the omnidirectional transmission is synchronized to the rotation of the directional pattern, so that pulses from the omnidirectional antenna constitute a definite azimuth reference.

At the craft, the indicator essentially measures the time interval between the arrival of the omnidirectional azimuth reference pulse and that of the rotating directional beam, which is marked by the sharp change in modulation frequency as the intersection of the two differently-modulated lobes sweeps by the craft. This time interval characterizes a definite line of position in azimuth. The method by which the time intervals are measured and translated into a meter indication has not been definitely determined. Several mechanical and electronic timers are available.

2. Distance Indication: The craft transmitter sends out a signal modulated at 3750 cps. This is received in the receiver section of the ground repeater and retransmitted (on a different frequency) by the transmitter section, the modulation being preserved. At the craft, this ground repeater response is received and the phase of the modulation in the received signal compared with that of the modulation in the original transmitted signal. The difference in phase gives information as to the distance from craft to ground station.

Since a change in phase of 360° at the modulation frequency of 3750 cps corresponds to a craft-ground station distance of 24.8 miles, there will be an ambiguity in the indicated range at distances larger than this. The method of phase comparison proposed is by synchro, with a suitable error-voltage and follow-up system.

It is proposed that this modulation and phase comparison should be effected for short periods of 1/50 second, once every second. Thus by means of suitable switching and filtering circuits, the same channel could be used for communications purposes.

It is understood that the various units involved in these proposals have been developed and tested. Detailed circuits and methods for integrating the system are, however, not available. The basic idea in the thinking of the Sperry Company regarding this and other electronic communications and navigation systems is that of narrow channels, with transmitters and receivers accurately stabilized in frequency to permit multi-channel operation and to improve signal-to noise ratios. The system described is intended to be of moderate range, filling the gap between long-range systems (such as Loran) on the one hand, and specialized glide-path and blind-landing systems on the other. It is understood that the equipment used would be closely coordinated with other communications and navigational-aid equipment carried by aircraft at the present time, or proposed for future use.

Type of System

The GPI is an automatic dead reckoning computer the operation of which is checked by the tracking of a reference radar echo appearing on a PPI scan. The auxiliary radar system is a combination of range and azimuth prototypes.

Useful Range

Up to ± 1000 miles from a reference point.

Accuracy and Precision

The accuracy of the AN/APA-44 Ground Position Indicator attachment for X-band or K-band search radars is ± 3%

Presentation of Data

North-south and east-west rectangular coordinate information of position relative to a fixed ground reference point is presented on dials provided that previous adjustments have been made to cause an electronic crosshair to stay on a reference radar echo appearing on a PPI.

Operating Skill Required

Unless a separate radar operator is provided, the navigator must be skilled in the interpretation of a radar PPI presentation. The GPI dial indications give an instantaneous navigational fix.

Equipment Required

The AN/APA-44 ground position indicator attachment for AN/APQ-7 or AN/APQ-34 search radars weighs about 175 lbs.

Radio Frequency Spectrum Allotments

The GPI attachment is designed for either X or K-band search radars.

Present Status of Development

In production.

The AN/APA-44 ground position indicator is a radar navigational aid and blind-bombing device with which one may (1) navigate with precision to a predetermined reference point or target; (2) approach a target from any direction taking evasive action if desired to within a few seconds of the time of bomb release; (3) bomb a target whether or not it can be seen on the PPI screen. It is essentially an automatic dead-reckoning device which provides for a step-by-step method of navigation.

The equipment consists of a combination of computers, a pilot direction indicator (PDI), a "time-to-go" meter, and other supplementary apparatus designed for use with the search radars AN/APQ-7 and AN/APQ-34. This combination of units illustrated by the block diagram of Figure 29-01 provides an electronic index for the PPI (the intersection of a circular slant range marker and a radial azimuth marker) such that the index automatically follows a radar echo across the face of the PPI once the index is set on the echo by means of "fix" knobs. Any easily distinguishable radar echo of known location may be used as a convenient reference point for ground position coordinates. The aircraft's airspeed vector is resolved into north-south and east-west components to which are added the corresponding components of wind velocity. The resulting components of ground velocity are integrated with respect to time and added to the initial settings of the GPI to give the N-S and E-W position coordinates of the reference point relative to the aircraft. The position coordinates are indicated on counter dials. These coordinates are

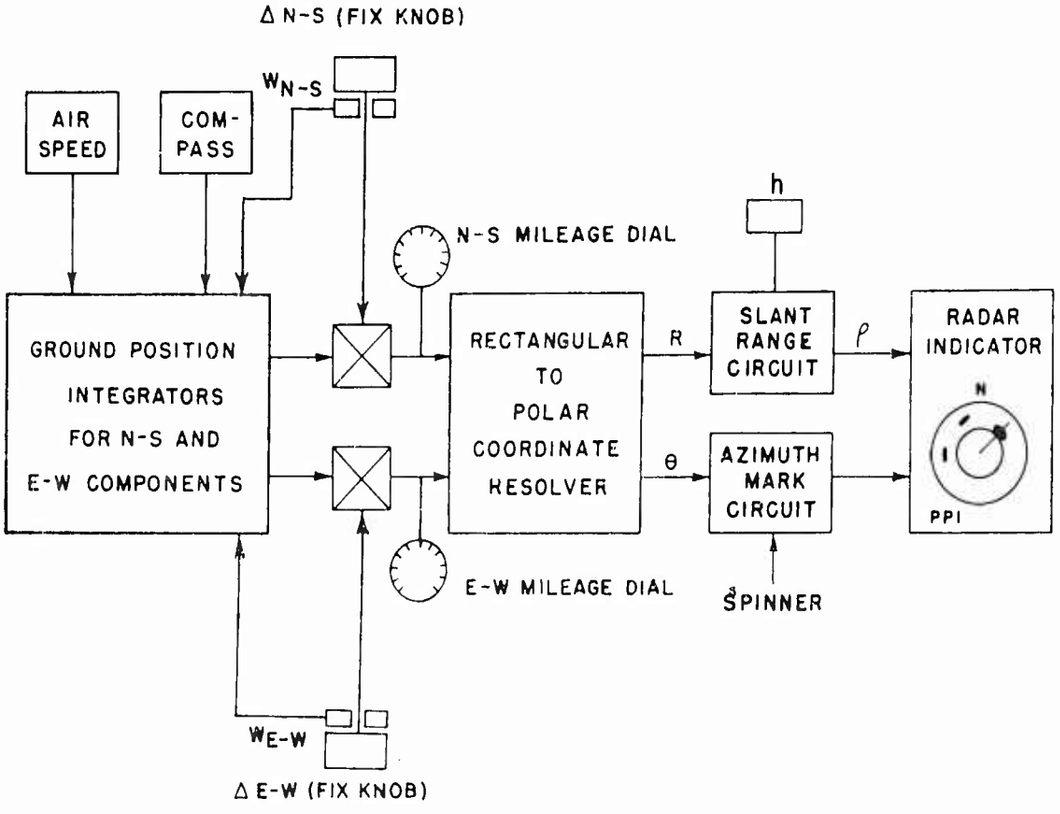


Fig. 29-01 Functional block diagram of the GPI as used for navigation

converted into polar form to give the ground range and true bearing of the reference point from the aircraft. The ground range is combined with altitude information to control a slant range ring on the PPI. The true bearing information controls an azimuth mark on the PPI. If the correct wind data are set in, the electronic index will follow the reference radar echo on the PPI. If the marker drifts off the echo, the wind and position controls can be used to reset it at any time up to six minutes after the first fix. This automatically corrects the wind data, and the marker index should thereafter follow the radar echo unless there is a change in wind velocity. Even after the index and radar echo have moved off the face of the PPI (± 20 mile limits), the dials continue to indicate the position of the reference point relative to the aircraft up to ± 1000 mile limits.

For step-by-step navigation, the electronic index on the PPI may be shifted to a new known reference point by proper resetting of the dials. The process can be repeated until the destination or target area is reached.

For bombing, the index may be set either on the target or on a predetermined reference point for offset bombing. "Time-of-fall" and "trail" dials are adjusted for the proper altitude. The pilot flies on two meters--the "pilot direction indicator" and the "time-to-go" meter. Evasive action may be taken until the "time-to-go" meter approaches zero. The bomb release may be automatic or not, as desired.

The fundamental principles of operation of the Ground Position Indicator as used for navigation are discussed briefly. A block diagram of the GPI as used for navigation is shown in Figure 29-02, and one component circuit of the GPI is

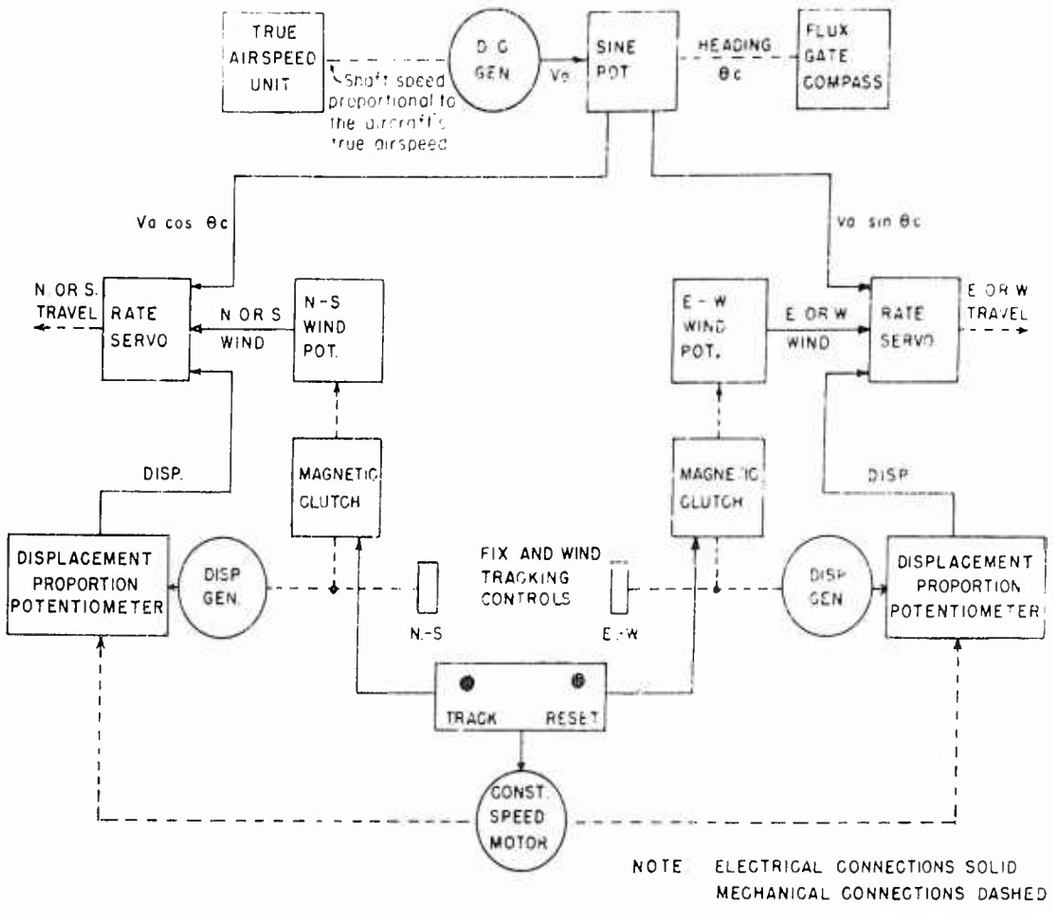


Fig. 29-02 Block diagram of the GPI as used for navigation

illustrated in Figure 29-03. Referring to the diagram of Figure 29-02, a DC voltage which is proportional to the craft's true airspeed is impressed upon a sine potentiometer. The position of the rotor shaft of the sine potentiometer is determined by the heading information from a gyrosyn compass system. The output of the sine potentiometer therefore consists of two DC voltages proportional respectively to the north-south and east-west components of airspeed.

To each of these airspeed-component voltages is added a corresponding voltage proportional to the north-south (or east-west) component of the wind velocity. The two resulting voltages are thus proportional to the north-south and east-west components of ground velocity. These two ground-speed component voltages are fed to rate-servos each of which yields a shaft speed proportional to the applied DC voltage. Ideally in a given time interval the amount of rotation of one of the rate-servo shafts is proportional to the net north-south ground travel of the aircraft, and the amount of rotation of the other rate-servo shaft is proportional to the total east-west ground travel during the same interval. In practice, minor corrections are introduced by the "displacement generator" described below.

Figure 29-03 illustrates the addition of the east-west wind-speed to the east-west air-speed. This component circuit is a direct-current series loop, including a sine potentiometer, a wind-component potentiometer with its own floating voltage-source, a displacement generator with its shunting potentiometer, and a

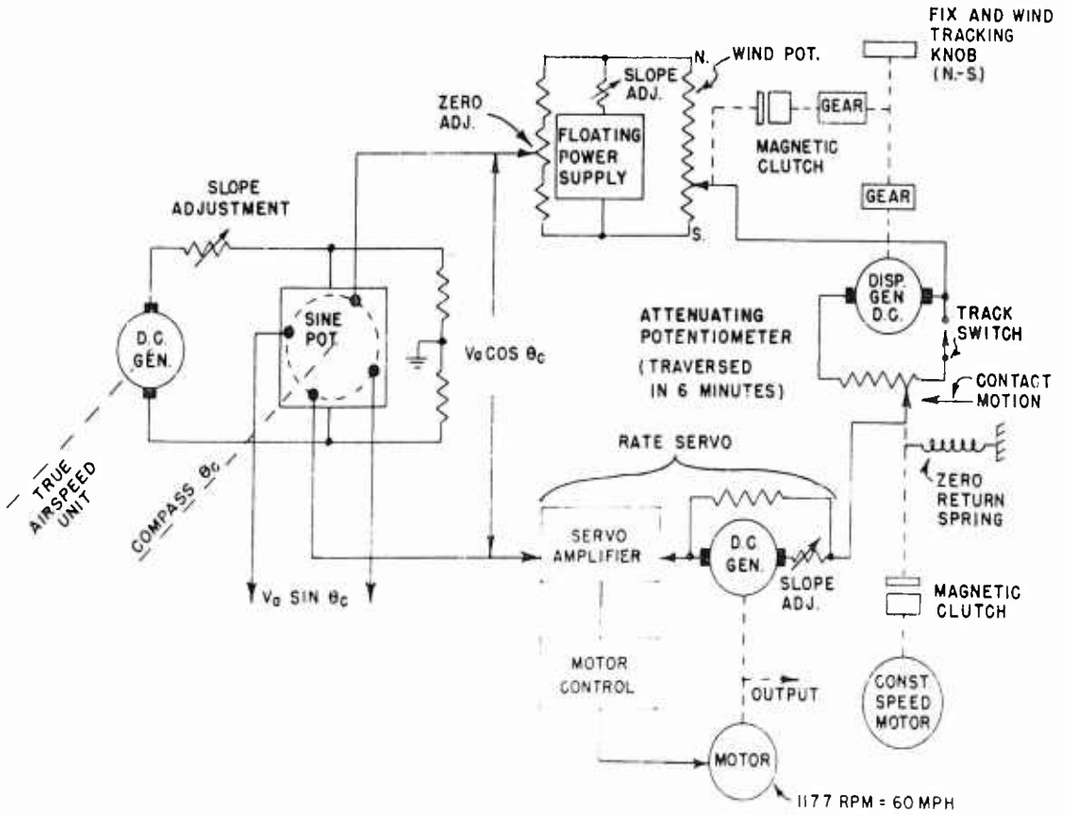


Fig. 29-03 One component circuit of the GPI

rate-servo amplifier for the motor control circuits. The rate-servo motor drives the rate-servo generator at such a speed that its output voltage is just equal and opposite to the sum of the sine potentiometer, wind potentiometer, and displacement generator output voltages, to within a few millivolts. This small residual voltage appearing at the input of the servo-amplifier serves to control the speed of the motor-generator combination. If at any time the voltage across the input terminals of the servo-amplifier exceeds a few millivolts, the motor rapidly accelerates or decelerates (depending on polarity) until the generator voltage is again almost equal to the sum of the other voltages in the loop. Thus the speed of the motor-generator combination is very nearly proportional to the sum of these voltages. Omitting, for the moment, consideration of any correction due to the "displacement generator", the motor-generator speed is therefore proportional to the east-west (or north-south) component of the aircraft's ground velocity, and mechanical counters run by the motor-generator combination integrate the ground velocity to indicate the ground mileage from the reference point.

At the beginning of a flight the operator may know the approximate wind data. However, the components of wind velocity are seldom known with sufficient accuracy to enable the apparatus to correctly compute the aircraft's ground position to the desired degree of precision. Therefore, some means must be provided for checking and correcting if necessary the setting of the wind dials and simultaneously correcting the integrated reading of the ground-position indicator dials. This is accomplished by tracking a reference radar echo with electronic slant-range and azimuth markers which are controlled by circuits in the ground position indicator. If the electronic index drifts off the reference echo due to incorrect wind data, the amount of drift in a given time interval is indicative of the error in wind velocity and may

be utilized to correct the error.

"Memory-point tracking" is used to facilitate the correction of wind error so that the electronic index can be made to properly track a chosen reference radar echo. A manually-rotated DC generator (referred to as a "displacement generator" in Figures 29-02 and 29-03) is in each of the two component circuits. While being rotated, its output voltage adds algebraically to the ground-velocity component voltage, thus momentarily changing the rate-servo speed, resulting in a small correction of the electronic-index displacement and a corresponding change in the readings of the GPI dials.

For convenience in the following discussion it is assumed that the setting of only one of the two component wind potentiometers is in error. When correcting for wind error, the amount of correction-shift introduced in a position component is proportional to the number of volt-seconds obtained from the displacement generator during its rotation, and is therefore proportional to the amount of rotation.

Across the terminals of the DC displacement generator is connected a linear potentiometer. the moving contact of which may be driven slowly away from its position of zero output by means of a constant speed motor. A given amount of generator rotation occuring at some time after the moving contact has left its zero position, produces an output in volt-seconds which increases linearly with the time elapsed since the potentiometer motion was initiated. Since the electronic index is drifting away from the reference echo at a rate proportional to the error of setting of the wind potentiometer, the total drift during a time interval is proportional to the interval. The amount of ground position shift (amount of rotation of the rate-servo) required for correction of the GPI mileage dials and the position of the electronic index, is proportional to the time elapsed since the moving contact left its point of zero output. This volt-second output, proportional to the elapsed time, is available at the output terminals of the attenuating potentiometer shown in Figure 29-03. A fixed amount of rotation of the displacement generator is required to produce the above mentioned output. Therefore, if the wind potentiometer is turned along with the displacement generator, at an appropriate ratio, the wind error may be eliminated by this rotation of the displacement generator. Therefore, further drift of the electronic index away from the reference radar echo will not occur unless there is a change in the wind velocity. Six minutes are required for the constant speed motor to drive the potentiometer contact over its entire range, so that a wind correction may be made at any time up to six minutes after making a setting upon a reference radar echo.

When the "memory-point tracking" function is not being utilized, the circuit remains in its normal condition with the constant speed motor turned off and the potentiometers at their points of zero output. The track switches, however, are open (see Figure 29-03), so that the displacement generators offer maximum voltage, when required, for quickly setting the electronic index to a new radar reference-echo, a procedure which is carried out about every 15 to 20 miles during step-by-step navigation.

Although the dials of the GPI read to $\pm$ 1000 miles from a chosen reference point, the electronic index on the PPI has a range limited to $\pm$ 20 miles.

The electrical connection from the GPI to the PPI index is controlled by 10-turn helipots (helical potentiometers) which are turned through reduction gears by the rate-servos. The rectangular-coordinate outputs of the GPI must be converted to polar form in order to control the range circle and azimuth marker comprising the electronic index which appears on the PPI. The rectangular to polar coordinate re-

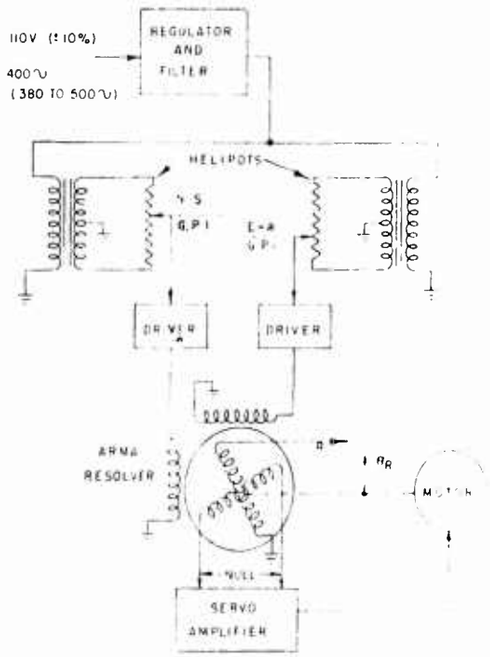


Fig. 29-04 Rectangular to polar coordinate resolver circuit

solver circuit is illustrated in Figure 29-04. It receives two AC voltages proportional to the rectangular coordinates, and delivers the polar coordinate information both in electrical and mechanical form, the radius or range information appearing as an AC voltage and the angle or azimuth data being given by the angular position of a rotor shaft. The GPI helipots are supplied with constant-magnitude 400 cps AC voltage of very low harmonic content. Transformers with grounded center taps are used so that the central or zero position of each helipot gives zero output voltage with respect to ground. North and south (or east and west) distances are differentiated from one another by signals of opposite phase. Voltages proportional to the north-south and east-west position coordinates are applied to the stator windings of an Arma resolver which is a synchro having two windings in space quadrature on both rotor and stator. The stator voltages produce in this machine an alternating magnetic field of strength proportional to the radial component and direction equivalent to the angle component of the desired polar coordinates. The voltage induced in one of the rotor windings is amplified and fed to a motor which turns the rotor until the coil is at right angles to the magnetic field and the voltage picked up by it is zero. The other rotor coil is then aligned with the magnetic field and the magnitude of the voltage induced in it is indicative of the desired radius coordinate. The angle is accurate to within $\pm 0.6^{\circ}$ and the radius or range voltage is accurate to within ± 40 yards in range measurement.

The azimuth marker system illustrated schematically in Figure 29-05 combines information from the compass system, from the radar antenna spinner, and from the GPI resolver in such a way as to provide an azimuth mark with each rotation of the spinner. The following information is provided mechanically on shafts: (a) from the compass system: the true heading of the aircraft, (b) from the radar antenna spinner: the relative bearing of the spinner, (c) from the GPI resolver: the true bearing of the electronic index. These three shafts are located in different parts of the aircraft, and electrical interconnection is accomplished by a differential-synchro system as illustrated in Figure 29-05 in which the dotted lines indicate mechanical couplings and the solid lines indicate electrical connections. Information from the compass and spinner is electrically combined to give the instantaneous true bearing of the antenna spinner. This information is compared with electrical information from a synchro on the GPI resolver giving the true bearing of the desired electronic index. When the above two directions coincide (i.e., whenever $\theta_R = \theta_C - \theta_S$), a radial azimuth marker is placed on the PPI screen. This occurs whenever the voltage from one of the terminals of the resolver synchro becomes zero as at points A and C in Figure 29-05. This null is used in the azimuth marker circuit to produce an intensification of the oscilloscope beam. Another null in the voltage occurs at point B when the antenna spinner is pointing opposite to the desired direction. The different phase properties of the voltage output from another terminal of this autosyn are utilized in an appropriate circuit to suppress undesired ambiguous azimuth marks corresponding to point B (see lower wave form of Figure 29-05.

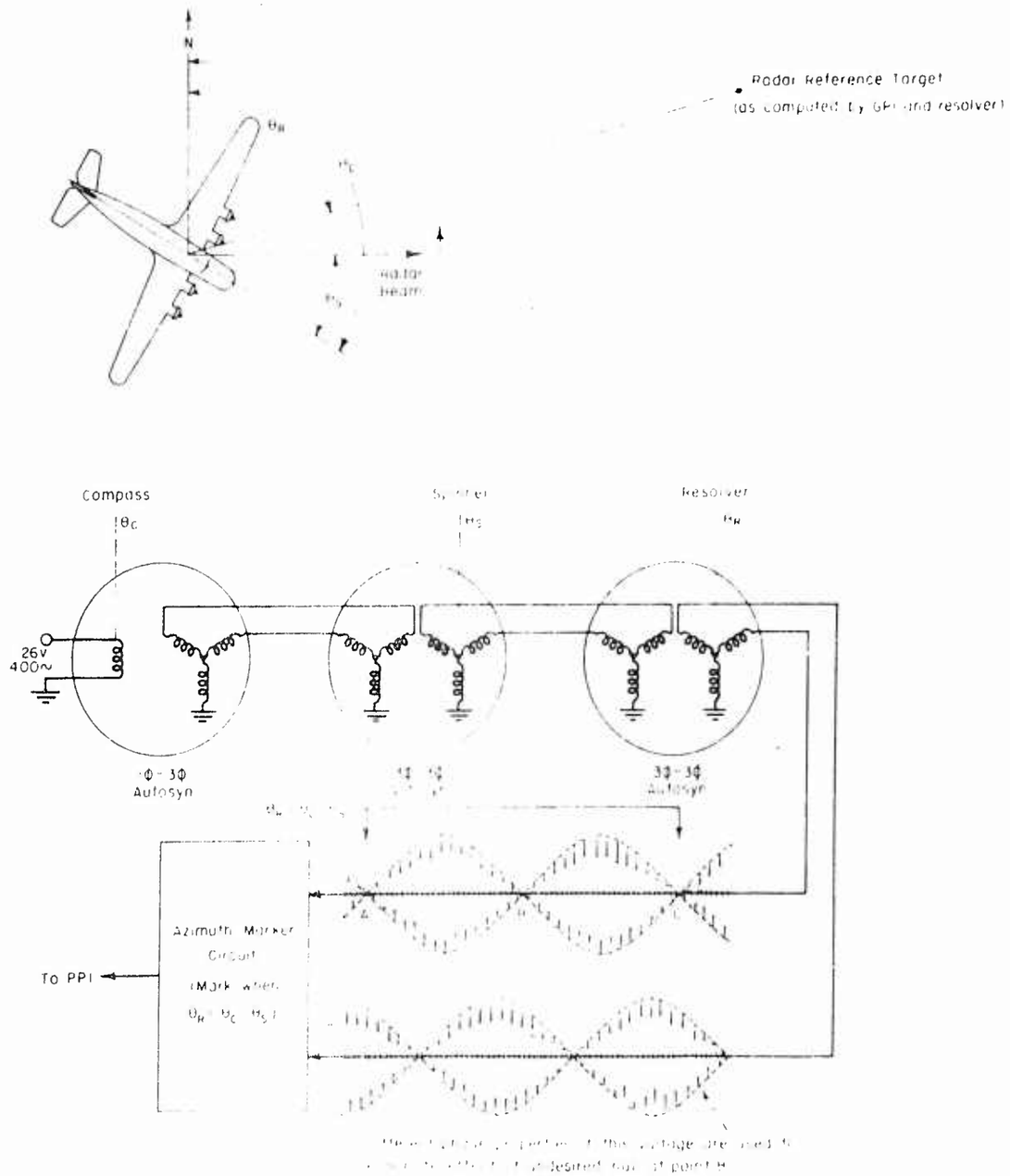


Fig. 29-05 Synchro system for coordination of azimuth data

The range marker consists of a momentary oscilloscope intensification for all spinner azimuths and occurs simultaneously with the radar returns from objects on the ground at the same ground range as the reference point upon which the electronic index is set. The range marker is controlled by a triangle solver containing circuits similar to those used in the GPI resolver to convert rectangular coordinates to polar coordinates. Two AC voltages differing in phase by 90^{0}, and proportional to altitude and ground range respectively are combined to yield a resultant, the amplitude of which is proportional to the slant range. This AC voltage is rectified, and the resulting DC voltage is used to control the delay introduced by the range marker circuit.

Bibliography

Identification	Classification	Title	Issued By
S-19	Confidential	Ground Position Indicator for Radar Navigation and Bombing	MIT Rad. Lab.
Section 4 Navigational Radar	Secret	U.S. Radar Survey (pages 4-1 to 4-4)	Div. 14 NDRC

This section contains brief descriptions of some of the lesser known German navigational systems. Much of the information has been obtained from prisoners of war, and hence is of questionable accuracy.

Electra is a German navigational system of the azimuth type employing radio beacon stations each of which maintains a fixed multi-lobe pattern of adjacent dot and dash sectors. The transmission consists of unmodulated CW dots and dashes at a frequency between 290 and 480 kcps. The azimuth indication is of the aural dot-dash variety with a steady tone for the on-beam indication. The navigating craft carries DF equipment in order to resolve sector ambiguities in the beam pattern. The on-course beam width is about 0.3° giving a theoretical bearing accuracy of $\pm 0.15^{\circ}$. The maximum usable range is claimed to be of the order of 1500 miles. The Electra system is also mentioned in the discussion of the German Sonne system in Section 17. The Electra field pattern is given in Figure 17-03.

The German Benito system may be used to control both the range and azimuth of an aircraft from a ground installation. The range to an aircraft is determined at the ground station by a phase-shift method and the range information is relayed to the aircraft over the radio communications channel. The ground-station carrier is amplitude modulated with a 3000 cps tone which is received by the aircraft and retransmitted on a different carrier-frequency. The range to the aircraft is obtained at the ground station by comparison of the phase of the modulation envelope of the received aircraft transmission with that of the original tone modulation of the carrier transmitted from the ground station. The fine range measurement contains a range ambiguity of some integral number of 50 kilometers. This ambiguity is eliminated by a course range measurement using a tone modulation frequency of 300 cps. When used for the control of bombers, the azimuth information is obtained at a ground station by direction-finding on the reply signal of the range measuring channel. The azimuth information is then transmitted to the aircraft by coded keying of the same transmission which is used for range measurement.

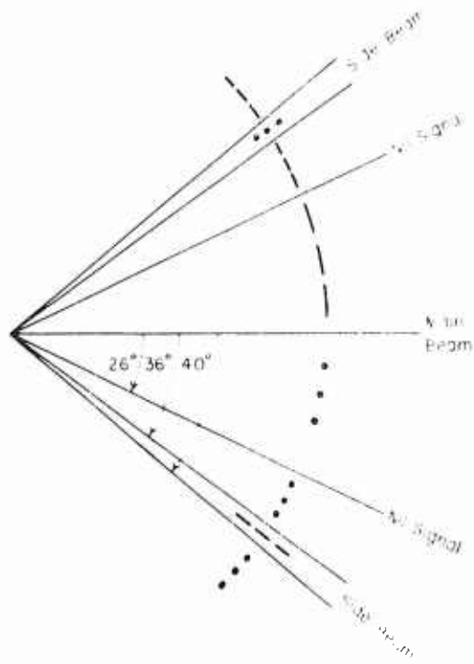


Fig. 30-01 The Knickebein beam

Benito transmitters and receivers operate at frequencies in the 40-50 mcps band, with an average carrier power of about 0.8 kw. The maximum useful range is between 100 and 200 miles depending to a great extent upon the altitude of the aircraft. The accuracy of range measurement is reported to be about ± 50 yards with a skilled operator.

Knickebein is a German navigational system used primarily for blind bombing. It is an azimuth type of system employing fixed radio-beams with a rather complex arrangement of the dot and dash areas as shown in Figure 30-01. Details concerning the unused back portion of the beam pattern are not known. Either meter-indication or aural dot-and-dash signals are used for the on-beam indication, and no range information is provided. Two beams may be crossed over a desired target. The angular spread of the equisignal Knickebein beam is about 0.3 degree which is suitable

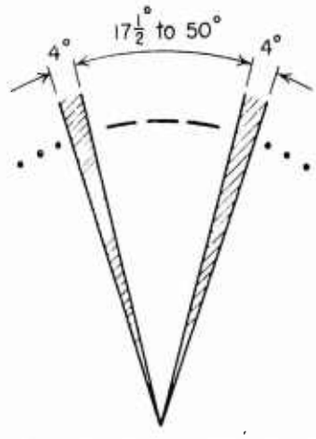


Fig. 30-02 Coarse Ruffian beam

for bombing a target the size of a town. Knickebein stations operate at a radio frequency between 30 and 33.4 mcps with an average power of about 1 kw. The maximum usable range is claimed to be of the order of 250 miles, and the claimed bearing accuracy is about $\pm$ 0.15°.

Ruffian is a blind bombing system using a complex arrangement of radio beams each beam operating on a slightly different frequency in the region of 80 mcps with an average power of about .8 kw. The system utilizes both coarse and fine beams, the characteristics of which are illustrated in Figures 30-02 and 30-03 respectively. The equisignal zone between dot and dash areas is 4° wide in the coarse beam, and 0.1° wide in the fine beam. The fundamentals of the Ruffian system are illustrated in Figure 30-04. The bombing aircraft flies with constant speed toward A along a beam emanating from the beacon transmitter at T_1. Beams from stations at T_2 and T_3 intersect the aircraft course at points P and Q which are spaced 15 kilometers apart. The height of the aircraft and the ratio $\frac{PQ}{PX}$ are set into an automatic clock mechanism. Keys are pressed when the aircraft passes points P and Q, and the clock mechanism automatically releases the bombs at the correct point R, the location of which depends upon the time required for the aircraft to pass from P to Q. As actually used station T_1 transmits a coarse beam in addition to a fine beam so that the pilot can fly the coarse beam during the early part of the flight in order to avoid fatigue. Station T_3 also transmits a coarse warning beam which the aircraft passes through shortly before reaching point P. Two extra emergency transmitters are also available one near T_1 and the other near T_2 and T_3 in case the regular transmitting stations should be either jammed or otherwise not functioning properly. Under ideal conditions the bombing accuracy is reported to be of the order of $\pm$ 80 meters at the maximum range of about 200 miles.

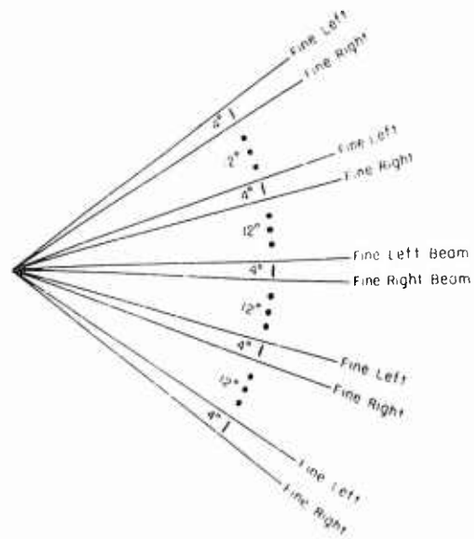


Fig. 30-03 Fine Ruffian beams

Hermine is a VHF German navigational system in which no special electronic equipment other than an ordinary communications receiver is required aboard the navigating craft. It operates on a frequency between 30 and 33.3 mcps. At the ground station the Hermine rotating beacon transmits a continuous tone upon which is superimposed a speaking clock which counts from 1 to 35, each figure representing tens of degrees in azimuth angle. A beacon-identification code-name is spoken in place of the figure 0, and the entire cycle of events takes place in one minute. The continuous tone partially masks the voice modulation except in a small sector of about 15° within which the masking tone gradually falls to zero and rises again so that the voice modulation momentarily becomes more audible. Pre-

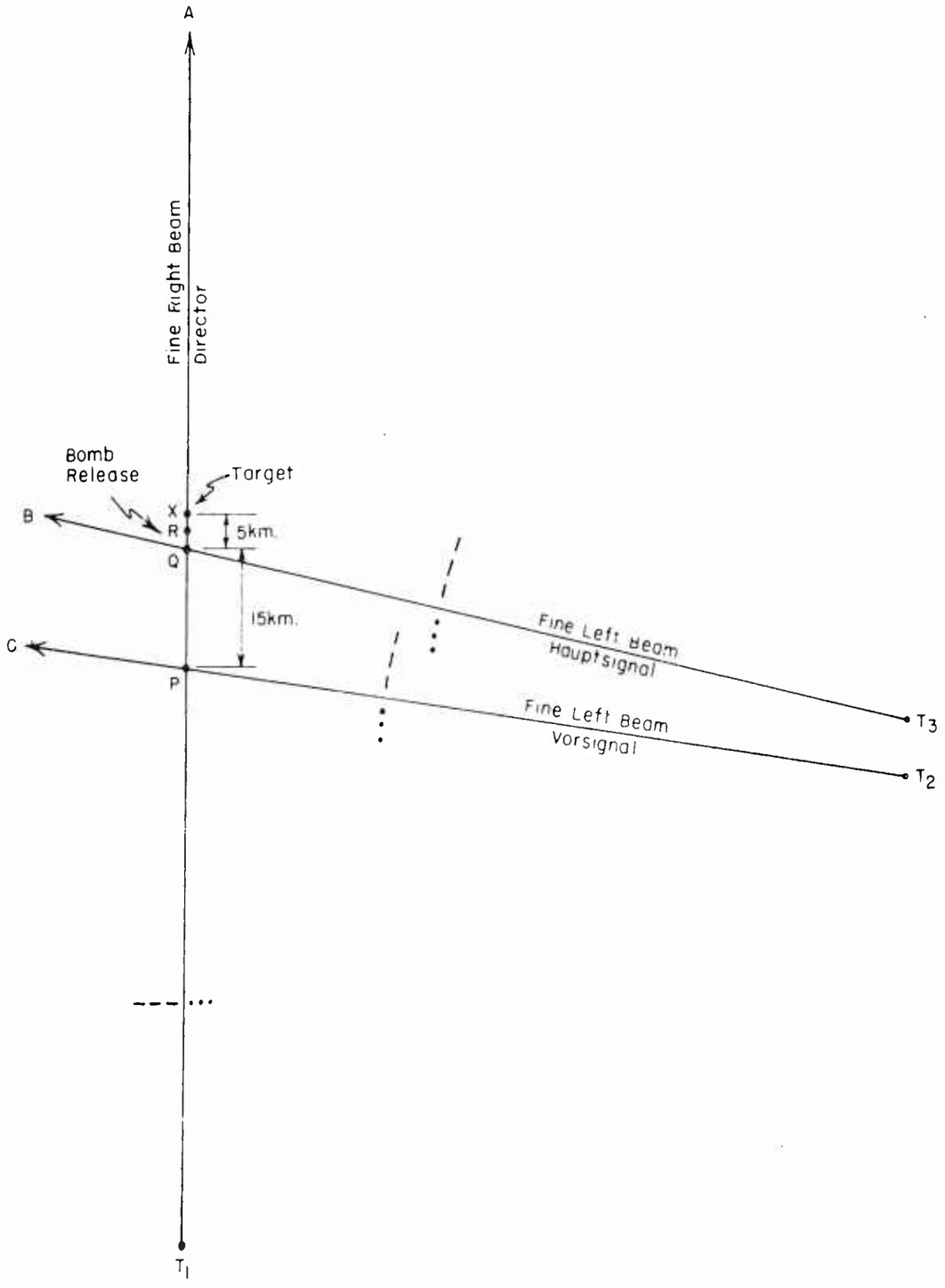


Fig. 30-04 Elements of the Ruffian system

sumably the field pattern of the masking signal is a rotating cardioid. The null in the masking tone moves uniformly through the 360^{O} of azimuth and an observer can estimate the position of the null to within 3^{O} to 5^{O}. A navigational fix is obtained by taking bearings on two Hermine stations. Although its accuracy is not very great, the Hermine system has the advantage of great simplicity.

Ruebezahl (or Egon) is a German bomber-control navigational system in

which one aircraft is controlled by two Freya radars. The position of the aircraft is continuously plotted from Freya data, and course corrections are transmitted to the aircraft by either code or voice signals on a radio communication channel. Either aural or visual indications may be used. One Freya plots the course of the aircraft until it is quite near the target and then a more accurate Freya takes over for the bomb release instructions. In the Ruebezahl or Egon system, IFF responses from equipment in the aircraft greatly increase the range of the Freyas. The airborne equipment operates on a frequency of 116 to 146 mcps with pulses of 2 to 3 microseconds duration, and with a peak power of from 15 to 20 kw. The aircraft may be controlled in range to within ± 100 yards and in bearing to better than ± 1°.

Bernhard-Bernhardine is a German navigational system used by night fighters for the interception of an enemy bomber force. Bernhard is the ground station and Bernhardine is the aircraft installation used with Bernhard. The ground station (Bernhard) is a very large rotating antenna array 34 meters in diameter and making two revolutions per minute. It operates on a wavelength of between 7 and 9 meters with a power output of the order of 1 kw., and is essentially a ranging and direction-finding set. In the night-fighter aircraft the Bernhardine equipment gives a continuous indication of the bearing of the Bernhard station, and also gives the location, course, altitude, and approximate strength of the enemy bomber force which the nightfighter is trying to intercept. All of this information is printed on a tape once per minute, the printing requiring 10 seconds. The printing on the tape appears as shown in Figure 30-05. In the case of Figure 30-05, the azimuth or bearing of the Bernhard ground station from the night fighter aircraft is 90° as indicated on the scale directly below the V-shaped notch in the printed lines. The bearing is accurate

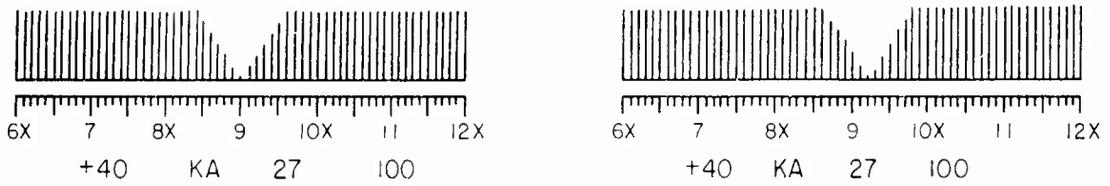


Fig. 30-05 Typical Bernhardine printed tape presentation

to within 0.5°. The figures appearing below the horizontal azimuth scale form a coded message. The + sign indicates the start of the message. The figure 40 indicates the height in hundreds of meters of the leading enemy bombers in the formation being attacked. The letters KA indicate a coordinate grid position of the night-fighter at the head of the attacking stream. The figure 27 indicates in tens of degrees the azimuth of the enemy bomber formation under attack, and the final figure 100 is an estimate of the number of bombers.

Hyperbol (or Hyperbel) is the German copy of the British GEE system which is discussed in Section 11.

Truhe is a German navigational system very similar to Hyperbel.

Zyklop (or Cyclop) is a German navigation beacon similar to Knickebein. The radio transmission is in the 30-33.3 mcps band, and consists of intermittent CW with sine-wave modulation. The indication is of the dot-dash variety, either aural or visual, on a kicking-type meter. Zyklop is believed to be mobile Knickebein.

Dora is a German rotating radio-beacon with a figure-eight field pattern. A bearing on one beacon is obtained by measuring the time interval between a minimum signal and a fixed marker signal. Dora beacons operate in the 30-100 meter band with a power output of about 1.5 kw. The maximum usable range is of the order of

1000 kilometers.

Erika (and New Erika) are beacons giving a beam pattern which makes detection of an intended target extremely difficult. It is similar to Knickebein but there is no single beam upon which a bomber aircraft attacks a target, and hence, night fighters cannot attack by flying on the beam. It is based on the principle of a VHF (30-33 mcps) beam oscillating rapidly over a segment of about 60^{o} - 90^{o}. The beam has a different phase in different sections of the segment and the phase of the received signal is compared with that of a standard phase producer in the aircraft. Six dials automatically indicate zones, and fine zones do not have to be flown until just before dropping the bombs. Its main disadvantage is its vulnerability to jamming.

Diskus is a German radar navigational and bombing system in which an aircraft flies a circular course at constant range from one ground station A and releases its bombs upon reaching the proper range from a second ground station B. A pulse transmitter is located in the aircraft, and responder beacons are located at the ground stations. It is similar to the Micro-H system as used to fly a cat-mouse course (See Section 5).

Schwanboje beacons are German floating target beacons operating on frequencies between 42.1 and 47.9 mcps. A navigating craft may home on the target beacon by direction-finding on its radiated signal.

The German Nachtfee system is a method for transmitting fighter direction commands over the beam of the controlling radar by space (phase) modulation of the Freya pulses within a repetition cycle. In order that a number of fighters may be controlled from a single Freya ground station, the airborne equipment is built in 10 different models with crystal controlled repetition rate oscillators operating at frequencies grouped around 15 kcps. Fighter direction commands are indicated by the angular position of pips appearing on a circular sweep CRO trace.

Bibliography

Identification	Classification	Title	Issued by
	Secret	Notes for Pilots, Observers, and special W/T operators on enemy radio aids to navigation and accurate bombing under blind conditions.	Headquarters of North 80 Wing, RADLETT
WA-2266-12 Loga Z 34?	Secret	German bombing and Navigational aids.	ETOUSA, OC Sig O, RCM division
No. 357/1945 Loga L-2641 JEIA 10784	Secret	Radio and radar equipment in the Luftwaffe-II	A.D.I.(K)
Loga L-2520 JEIA 10555	Secret	BHF Rundschreiben Nos. 3, 4, 5; 9 July 1945	OC Sig O Headquarters U. S. Forces European Theatre
Loga F 1583	Secret	German "Nachtfee" system of control of night fighters	U.S. Naval Technical Mission in Europe
Loga L-873 JEIA 7887	Secret	Extract from USSAFE Air Intelligence Summary 66	U.S.S.A.F.E.
Report No. 33 20.4.45	Secret	Air Scientific Intelligence	Air Ministry, A.D.I. (Science)

Comparison of Navigational Systems

Any universal comparison of the various electronic navigation systems here described must necessarily be inadequate because of their widely differing objectives. Thus a short-range high-precision system such as Shoran may not properly be compared with a long-range system such as Sonne. The following comments are however of a general nature, and are sufficiently fundamental to warrant the attention of anyone interested in electronic navigation.

1. Pulse systems, in which the received signals are displayed on a CRO, are not nearly so susceptible to meaconing, or to hidden errors produced by varying propagation conditions, as are continuous-wave systems. The reason for this is two-fold. Firstly, any irregularity in received pulse signals (such as spurious pulses, distortion of pulse shape due to plural-path transmission) is visible to the operator on the CRO trace. (Cathode-ray indicators have produced misgivings among uninitiated personnel, due to a natural distrust of glassware and hidden wires, but they have an enormous versatility compared with meters, audible indicators or automatic-control systems.) Secondly, a pulse system offers the possibility of separating ground-wave and sky-wave returns. As pointed out in connection with SS Loran, the minimum delay between sky-wave and ground-wave signals is of the order of 65 microseconds at 2 mcps (possibly lower at LF Loran frequencies), so that if the rise-time of the pulses (as seen by the navigator) is short enough, the leading edge of the pulse represents ground-wave transmission only and is therefore dependable. In continuous-wave systems however, the transmission is not broken up into discrete pulses so that ground-wave and sky-wave returns cannot be separated.

2. Pulse systems require a larger band-width than CW systems and are therefore more easily accomodated at high than at low frequencies. However, the use of high frequencies would impose a limitation on ground-wave range, and the tendency with long-range systems of any kind is therefore towards the use of lower frequencies. With pulse transmission, this leads to two difficulties; wide-band transmission produces considerable adjacent-channel interference, and the attainment of the required band-width in the radiating system is difficult even with very high antennas. The total spectrum allotment required for a pulse system may be kept down to a reasonable figure by "stacking" a number of transmitters (using different pulse repetition rates) on the same frequency as is done in the case of Loran.

3. Provided that sufficient ingenuity is exercised and that there are no restrictions on weight and space, any given system can be made to present its final indication in any desired form. Automatic piloting, applied to either aircraft or guided missiles, could presumably be realized with Loran transmissions. At the other end of the scale, the Sonne system probably requires less additional equipment on the craft than any other.

4. The comparative value of radar as a navigational aid

(a) Airborne Radar. Any general navigational system must make use of a chart. In the case of non-radar systems, the chart usually exhibits a number of lines of position, each corresponding to a particular indication given by the craft equipment. These lines of position may be of a special nature, as in the case of Loran hyperbolae, or they may be merely spherical coordinates of latitude and longitude. In either case, the navigator determines his position by identifying lines of position on the chart.

A Radar system giving a PPI presentation is different in that the navigator now has two charts, one of which is his PPI presentation. Superposition of the two (either actually, as in NALOC, or mentally as in ordinary use of a PPI pic-

ture for navigation) gives the navigator's position.

The Radar method has the advantages of displaying the positions of other craft (and even of storm centers), and of requiring no ground station transmission over areas where natural Radar landmarks exist: it can be used in areas where Loran coverage is not provided or is unreliable. Radar, being a versatile technique, presents opportunities for other specialized uses: for example, collision prevention, Radar mapping, communication by pulse-time modulation, retransmission of an airborne PPI display to a ground or shipborne information center. Disadvantages are that oversea navigation is not possible at distances from Radar landmarks greater than the Radar range, that over land a number of landmarks having a particular disposition is necessary for certain identification of position, that there is distortion in the PPI picture at close range due to slant range data being presented instead of ground range data (unless a hyperbolic sweep is used), and the additional weight, complexity and cost of the equipment as compared with (say) a Loran receiver and indicator.

The use of beacons or corner reflectors with airborne radar provides a system of identification of a particular course, airport or natural hazard. These are problems of restricted or special navigation and as such are very elegantly handled by radar means.

Unless beacons are used, the accuracy of a Radar fix may not be equal to that of a good Loran fix, but it would appear to be more constant over a large area if available at all, and is probably adequate for purposes of general navigation.

(b) Ground Radar. In situations where the emphasis is on ground control of air traffic rather than on the presentation of individual fixes to pilots of aircraft, ground radar may well become the accepted solution to the control problem. Any complete control system must include some communications link so that coordinated information and specific instructions can be transmitted to the pilot of the craft. Such a system is expensive to install and maintain, and would only be justified at airports, control points, and possibly at major hazards. Several closely coordinated schemes have been proposed, such as the RCA system and the Federal traffic-control system. A disadvantage is that such systems must be used by all of the traffic if true ground control and collision prevention are to be obtained with zero visibility, requiring certain equipment to be compulsory on all craft. Such a coordinated system requires careful design if the problem of identification is to be fully solved. Unless identification is provided for, the function of control cannot be exercised fully on individual craft. Such systems may be designed so that the craft equipment may also be used for blind approach and possibly blind landing techniques. Such extensions are essential if all-weather commercial air traffic is to become a reality.

5. Regarding accuracy and precision of position-line determination, the following general statements may be made:
   (a) Range-measuring systems have the same position-line precision at all ranges, since the separation of the circular position lines in miles per microsecond is constant. This statement neglects errors in crystal control, which are usually very small. Hyperbolic and azimuthal systems give a precision in line of position which varies inversely as the range, at distances greater than about five times the base line.
   (b) Azimuthal precision is uniform at all azimuths with systems using rotatable antennas, such as radar systems. It is not uniform with hyperbolic systems, being greatest along the perpendicular bisector of the base-line.
   (c) Continuous-wave systems such as Decca offer great accuracy at short ranges if the ambiguity involved can be tolerated. This great accuracy arises from

the precision resulting from phase measurement at radio frequency. Proportionately good accuracy at great ranges is claimed if a long base-line is used. However, a long base-line means that the system can be of only limited range for reliable results, because the use of signals containing any appreciable amount of sky-wave return, or consisting solely of sky waves, is ruled out. Consider for example a base-line of 300 miles. Using sky waves for phase comparison, the distance between the points where ionospheric reflection takes place for master and slave transmissions to the craft will be of the order of 150 miles. Since there is no reason to expect that ionospheric conditions at these two widely-separated points will vary in a sufficiently similar way over a period of time, the phase difference measured at the craft will show wide variations with corresponding uncertainty in the line of position obtained.

A similar argument applies to signals composed of a mixture of ground- and sky-wave returns. Variations in the phase and amplitude of the sky-wave component will produce variations in the phase of the resultant. Assuming for the purpose of illustration a Decca system working on a frequency of about 200 kcps, a complete reversal in phase of the sky-wave signal (180° phase change) represents only 2.5 microseconds change in time of travel. Studies of the variations in sky-wave delay which have been made in connection with Loran pulse transmissions show that short-period variations of several times this amount may easily occur and are not at present predictable. In the case of mixed sky- and ground-wave returns, the maximum difference in phase (in degrees) between the resultant signal and the ground-wave signal is the angle whose sine is the ratio of sky-wave amplitude to ground wave amplitude. This maximum difference will be encountered when the phase of the sky-wave is approximately in quadrature with that of the ground-wave (if the sky-wave amplitude is not too large a fraction of the ground-wave amplitude). Thus, if the amplitude of the sky wave is as much as one-sixth of that of the ground wave, a maximum phase shift of about $\pm 10^{\circ}$ in the resultant signal will be encountered as the phase of the sky-wave component fluctuates about its average value, and changes in amplitude will also occur. Since the accuracy of the Decca system depends on phasemeters which are sensitive to a 2° phase change, it will be seen that the amount of sky-wave return which can be tolerated is very small. Thus a continuous-wave system depending on phase comparison is essentially limited to the area within which pure ground-wave reception is obtainable.

The extent to which the above considerations may be modified by using a lower frequency cannot be accurately foreseen, since data on propagation at such frequencies is lacking at the present time.

(d) Where extreme range and good precision are both desired, LF Loran (with cycle matching) appears to be an attractive possibility.

6. Sky-Wave errors. In addition to the fluctuations in position-line reading mentioned above in 5(c), which will be evident to the operator and therefore not dangerous (even though they limit the useful range of a system), large and relatively consistent errors in line of position may result from sky-wave propagation in systems depending on radiation patterns (radio "ranges", Sonne, Federal long-range system). Consider as an example the Federal system, in which a sequence of two pairs of directional patterns is radiated by changing the relative phasing of the currents in two antennas spaced one-half wavelength apart. At the receiver, the stronger signal from each of the two pairs is attenuated to give output signal ratios of unity, and a line of position is then obtained from the attenuator settings. (It may be remarked in passing that transmitter and receiver band-widths must be considerably greater than the values quoted to reproduce adequately the modulation envelope shown.) Now if sky waves are used, the difference between the

transmission paths from the two antennas to the receiving point at some given azimuth will no longer be the same as it would have been for ground-wave propagation at the same azimuth, being a function of the angle at which the radiation leaves the ground station to reach the point of ionospheric reflection. Thus the position-lines will be skewed by an amount which depends on the transmitter-receiver distance and also on the azimuth of the receiver with respect to the transmitter. If this were all, the necessary sky-wave corrections would be calculable and could be applied by means of appropriate markings on the charts used. Variations in effective point of reflection, and in the relative magnitudes of returns from different ionospheric layers, will still produce a range of uncertainty in the readings. However, a much more serious consideration is that ground waves and sky waves are not separated, so that the percentage of sky-wave return present and the magnitude of the correction to be applied are unknown and inconstant factors. This is the fundamental argument which rules out the long-range use of such systems and will continue to do so until a great deal more is known about ionospheric propagation in general.

7. Range-measuring systems usually require transmission from the craft (an exception would be in the case of a ground-radar display which is communicated to the craft by audio or video signals). Range-measuring systems are saturable: hyperbolic and azimuthal systems are not.

8. It may be said that the subject of frequency and band-width allocations is very intimately connected with the development of long-range navigation, and such allocations will be a deciding factor in the effectiveness of any systems which may be developed. In this connection, what is important is the bandwidth required for a complete navigation system. With most systems, received signals are below the local noise level beyond a radius of about 3000 miles from the transmitter, so that channels assigned for (say) North Atlantic coverage may be used again in the Pacific or over Asia. Thus a pulse system, such as Loran, may cover the North Atlantic with a 50-70 kcps bandwidth allotment since the use of different pulse repetition rates allows the stacking of as many as 16 stations at the same frequency. A continuous-wave system such as Sonne, requiring about the same number of stations to give the same coverage, will need about the same bandwidth allotment for the complete system. The apparent advantage claimed for narrow-band systems is thus largely illusory. In addition, a Decca system to give the same coverage has the further complication of requiring a number of frequencies so spaced that the necessary numerical relations exist between them.

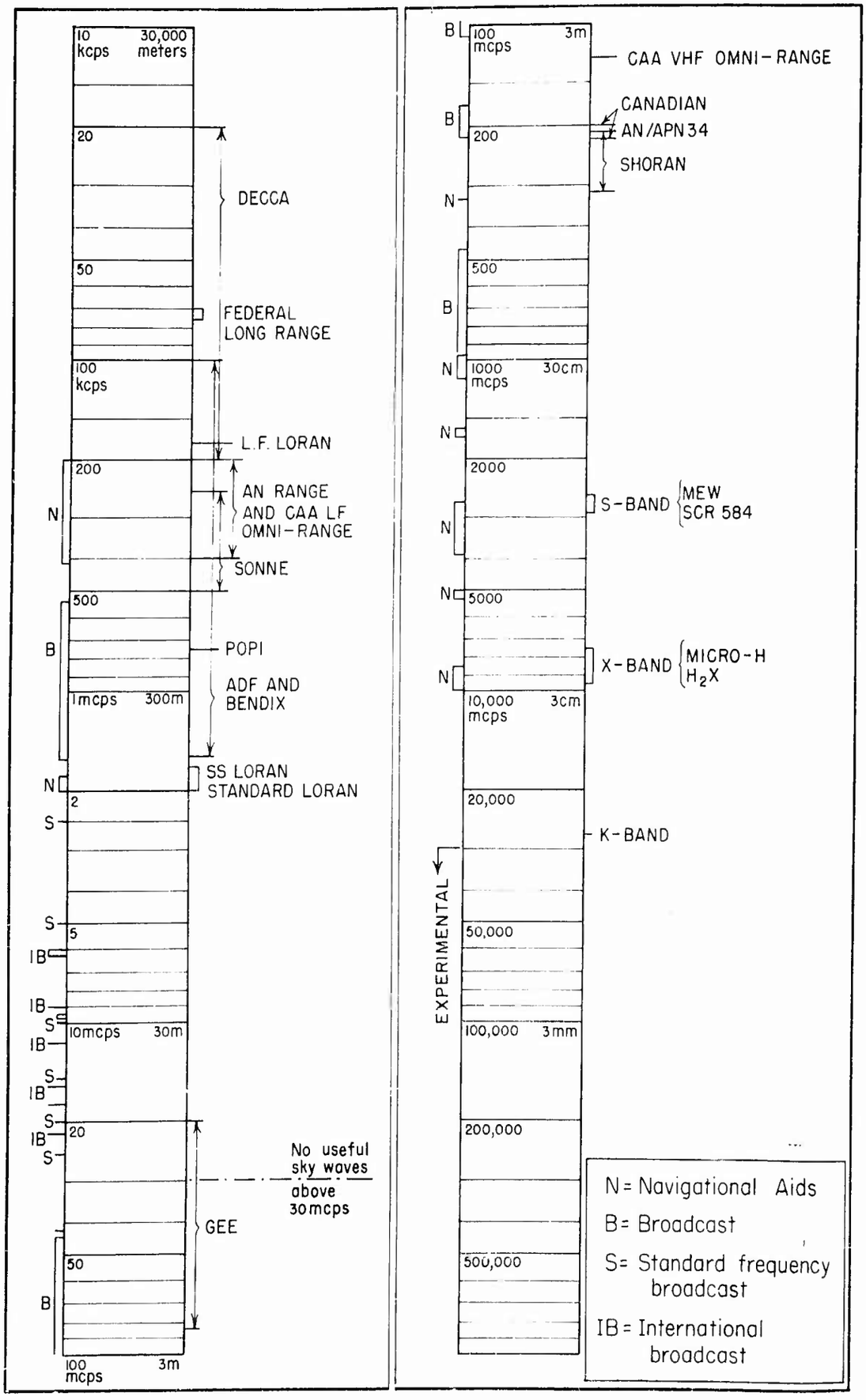
A chart showing the frequency-distribution of the various systems is given on page 31.05, and a table summarizing their principal characteristics appears on pages 31.06 and 31.07. Tabulation is useful only in so far as it presents unambiguous data, and for this reason the table of principal characteristics does not attempt to summarize the facts concerning such matters as siting requirements for transmitters. Four aspects of siting may be mentioned:

(a) The degree of accuracy required in the triangulation of proposed sites varies with the accuracy of the system. For Shoran, the triangulation must be extremely refined if the full capabilities of the system are to be realized.

(b) The size and expense of the ground system required is greater at low frequencies.

(c) The elevation of the transmitter site above the local horizon affects primarily the range attainable with ground waves.

(d) The flatness of the site, and the absence of non-uniformities, are factors of prime concern in systems such as radio ranges, Sonne and the Federal long-range system which depend on radiation patterns. Non-uniformities in the ground may attenuate the radiation in some directions, thereby modifying the theoretical radiation pattern.


10 kcps
30,000 meters
20
50
100 kcps
200
500
1mcps
300m
2
5
10mcps
30m
20
50
100 mcps
3m
DECCA
FEDERAL LONG RANGE
L.F. LORAN
AN RANGE AND CAA LF OMNI-RANGE
SONNE
POPI
ADF AND BENDIX
SS LORAN
STANDARD LORAN
No useful sky waves above 30mcps
GEE
B
N
S
IB
100 mcps
3m
1000 mcps
30cm
2000
5000
10,000 mcps
3cm
20,000
50,000
100,000
3mm
200,000
500,000
CAA VHF OMNI-RANGE
CANADIAN AN/APN34
SHORAN
S-BAND
MEW
SCR 584
X-BAND
MICRO-H
H_2X
K-BAND
EXPERIMENTAL
N = Navigational Aids
B = Broadcast
S = Standard frequency broadcast
IB = International broadcast

	Type of System	Maximum useful range (statute miles)*	Uncertainty in line of position: Min. Theoretical	Uncertainty in line of position: Ambiguities	Presentation to navigator	Special skills (craft)	Craft Equipment
Oboe	Range	Radar line-of-sight†	± 25 yards	none	Aural	some training	300 lbs. specialized
Shoran	Range	180 (at 12,000 ft.)	± 50 ft.	no less than 100 mi. apart	CRO	Trained Operator	232 lbs. specialized
Micro-H	Range	Radar line-of-sight†	± 50 yards	none	PPI	Trained Operator	15 lbs. plus H_2X equipment
ARL Intermittent Phase-Comparison	Range	36	not known	36-mile intervals	Meter	very little	specialized
ARL One-Shot	Range	100	not known	none	Veeder Counter	very little	specialized
Canadian	Range	100	± 1 mile	none	Meter	very little	specialized
GE Random Interrogation	Range	100	not known	none	Veeder Counter	very little	specialized
GE Time-Rationing	Range	100	not known	none	Meter	very little	specialized
Gee	Hyperbolic	400 (at 30,000 ft.) (see page 11.01)	± 0.062 mi. = 327 feet	none	CRO	Trained Operator	92 lbs. specialized
Loran (standard)	Hyperbolic	Day: 850(G) Night: { 600(G) 1600(S)	± 0.093 mi. = 492 feet	none	CRO	Trained Operator	specialized equipment 70 lbs. with small frequency converter if used for LF Loran
Loran (SS)	Hyperbolic	1600 (S) (night only no day-time trans-mission)	± 0.093 mi. = 492 feet	none	CRO	Trained Operator	
Loran (LF)	Hyperbolic	1500 to 2000 (?)	†2000 ft. (2) †50 ft. (3)	none	CRO	Trained Operator	
Decca	Hyperbolic	1500 (?) (Limited to ground wave)	140 feet (?)	multiple	Meters	very little	specialized
POPI	Hyperbolic	(Limited to ground wave if gross errors avoided)	0.636° azimuth	none	Meters	very little	standard rec. with POPI ind.
AN "Range"	Azimuth	200	± 5°	two or four	Aural	very little	low-freq. receiver
Automatic Direction Finding	Azimuth	200 to 400	± 3°	none	Pointer and scale	none	specialized
Sonne	Azimuth	Day: 1000 Night: 2000(S)	± 1/6°	multiple (solve by DR or DF)	Aural	very little	low-freq. receiver with BFO
Bendix	Azimuth	200 to 400	± 3°	none	Automatic plotting on chart	very little	2 ADF's, compass, computer
CAA VHF Omni-"Range"	Azimuth	100	± 3°	none	Meter and Dial	very little	specialized
CAA LF Omni-"Range"	Azimuth	(serious sky-wave errors probable)	?	none	Meter and Dial	very little	specialized
Federal Long-Range	Azimuth	1500 (?) (serious sky-wave errors probable)	± 0.2 to 1.5°	two: solved by DF	Meter and Dials	very little	specialized
Airborne Radar (H_2X)	Range and Azimuth	250 (beacon) 90 (search)	± 1-3° azimuth ± 50 yds. range	none	PPI	Trained Operator	370 lbs. specialized
Ground Radar SCR 584	Range and Azimuth	40	± 0.034°, ± 15 yds.	none	via communi-cation channel from ground	none	Communica-tion, beacon
Ground Radar MEW		250	± 1 mile	none			
AN/APN 34	Range, Azimuth, Track	50 to 100	± 2°, ± 1/2 mi.	none	Meters	very little	specialized
Federal Traffic-Control	Range and Azimuth	50 to 100	?	none	CRO	very little	specialized
Map-PPI Naloc	Range and Azimuth	10 to 100	± 1-3°, ± 200 yards approx.	none	PPI	Skilled Operator	Radar set, projection equipment
RCA	Range and Azimuth	200 (line-of-sight)	equal to that of ground Radar used	identi-fication (?)	Television image	Interpretation of PPI	television rec., beacon transponder
Sperry	Range and Azimuth	100 azimuth 24 range	± 3° azimuth ± 400 ft. range	Range over 24 mi.	Meters	very little	specialized
AN/APA 44 GPI	Range and Azimuth	1000 mi. from last reference point	± 3 % of range from reference point	reference Radar echo recognition	PPI and dials	Skilled Operator	175 lbs. plus Radar

* figures assume average noise level

(G) = ground wave
(S) = sky wave

(2) envelope matching
(3) cycle matching

† tentative figures

‡ approximately 250 miles at 30,000 ft. altitude

Frequency	Band-width	Type of transmission	Ground wave and sky wave separated	Meaconing Recognizable	Status	Saturable	Transmission required from Craft	Instantaneous fix with single equipment
S-band	8 mcps	Pulse (1-3 μs)	(No sky wave)	-	Opera-tional	Yes; one craft at a time	Yes	Release point indicated
210 - 320 mcps	4 - 5 mcps	Pulse (0.5 μs)	(No sky wave)	Yes	Opera-tional	Yes (20 craft)	Yes	Yes
X-band	2.5 mcps	Pulse (2 μs and 0.5 μs)	(No sky wave)	Yes	Opera-tional	Yes (50-100 craft)	Yes	Yes
VHF or above	6 kcps	Intermittent Continuous Wave	(No sky wave)	No	Develop-ment	Yes	Yes	No
VHF or above	not known	Pulse	(No sky wave)	No	Develop-ment	Yes	Yes	No
202 - 220 mcps	3 - 4 mcps	Pulse	(No sky wave)	No	Develop-ment	Yes	Yes	No
VHF or above	not known	Pulse	(No sky wave)	No	Proposed	Yes	Yes	No
VHF or above	not known	Pulse	(No sky wave)	No	Proposed	Yes	Yes	No
20 - 85 mcps	1 mcps	Pulse (2 - 10 μs)	(No sky wave)	Yes	Opera-tional	No	No	Yes
1700-2000 kcps	50-70 kcps	Pulse (40 μs)	Yes	Yes	Opera-tional	No	No	No
1700-2000 kcps	50-70 kcps	Pulse (40 μs)	Yes	Yes	Opera-tional	No	No	No
180 kcps	10 (?) kcps	Pulse (300 μs)	Yes, if front edge of pulse used	Yes	Trials	No	No	No
20 - 200 kcps	three single freq.	Continuous Wave	No	No	Trials	No	No	Yes
750 kcps (trials)	1 kcps or less	Continuous Wave, slow keying	No	No	Small-scale trials	No	No	No
200 - 400 kcps	3 kcps	Continuous Wave, slow keying	No	No	Opera-tional	No	No	No
100-1600 kcps	single freq.	Continuous Wave, no modulation necessary	No	No	Opera-tional	No	No	No
250-500 kcps	1 kcps or less	Continuous Wave, slow keying	No	No	Opera-tional	No	No	No
100-1600 kcps	two single freqs.	Continuous Wave, no modulation necessary	No	No	Proposed	No	No	Yes
127 mcps	24 kcps	double modulation	(No sky wave)	No	Trials	No	No	No
200 - 400 kcps	3 kcps	double modulation	No	No	Develop-ment	No	No	No
70 - 76 kcps	70 cps (?)	Continuous Wave, switched radiation patterns	No	No	Proposed	No	No	No
X-band	2.5 mcps	Pulse (0.5 μs and 2 μs)	(No sky wave)	Yes	Opera-tional	Yes	Yes	Yes
S-band	3 - 4 mcps	Pulse (1 μs)	(No sky wave)	-	Opera-tional	Yes	No (unless beacons are used)	Yes
210 mcps approx.	3 - 4 mcps	Pulse	(No sky wave)	No	Experi-mental	Yes	Yes	Yes
?	?	Pulse	(No sky wave)	Yes	Proposed	Yes	Yes	Yes
S-, X- or K-band	that of Radar	Pulse	(No sky wave)	Yes	Opera-tional	No	Yes	Yes
S- or X-band	that of Radar	Pulse, television signal	(No sky wave)	-	Proposed	Yes	Yes	Yes
C-band	250 kcps	Modulated and keyed	(No sky wave)	-	Proposed	Yes	Yes	Yes
X- or K-band	2.5 mcps (X-band)	Pulse	(No sky wave)	-	Opera-tional	No	Yes	Yes

Note: Transmission over sea-water is assumed where the ranges quoted involve ground-wave transmission

Transmitter siting requirements: see separate note in Section 31.

Coordination of navigation requirements

In view of the number of electronic navigation systems which are or have been proposed, developed or operational, and considering the increasing importance of such systems in both military and civilian applications, it is evidently desirable to evolve a standard system which will meet the largest number of requirements with the maximum of reliability and the minimum of cost and complexity. It is therefore of interest to examine the requirements of a navigation system, and to attempt to indicate the extent to which a single airborne equipment might meet them.

A general navigation system must provide indication of position while allowing the pilot free choice of course. Restricted navigation systems, which define a number of definite courses, have been successfully used in commercial point-to-point scheduled flying; but both military and civil interests require the fullest development of truly general systems. Any such system may of course be used in the more limited way: homing along a Loran hyperbola is a well accepted technique.

Since the ability to navigate under poor visibility conditions is one of the prime features of electronic systems, and since the lack of adequate blind approach and blind landing systems constitutes the chief obstacle to fully reliable air travel, it is assumed for purposes of this discussion that no land objects are optically visible to the navigator.

The ideal airborne electronic system must perform the following functions:
(a) long-range general navigation
(b) traffic control in the vicinity of airports
(c) blind approach
(d) blind landing
The distances or time intervals to be measured for each function are not the same: they decrease in the order given. Position determination within two or three miles is normally sufficient for long-range navigation: for blind landing the accuracy required is of the order of feet, corresponding to time intervals of the order of 0.001 microsecond.

For long-range navigation, ground-wave attenuation indicates the use of a low frequency, and the uncertainties inherent in the use of skywaves call for a pulse technique. Since the accuracy required is not of the highest order, long pulses with relatively long rise-times may be permitted.

As the range of operation becomes shorter and the required accuracy higher, the use of higher frequencies becomes desirable since advantage may then be taken of directional transmission and since the shorter pulses required for the increased accuracy are more readily usable at high radio frequency.

At very short ranges and where very high accuracy is required, the continuous-wave phase-matching technique might be considered. However, even if time intervals as short as 0.01 microsecond were to be measured by such means, the accuracy of distance measurement would still be barely sufficient for the blind-landing function. The limiting factor here being the high speed of propagation of a radio wave, it is natural to consider the use of sonic or supersonic methods for localizing a craft within such narrow limits. Since a discussion of blind-landing techniques is specifically excluded from this report, this subject will not be pursued.

Radar techniques are the obvious solution to the control and blind approach problem: LF Loran is attractive as the primary long-range system. The design of a suitable ground-based short-range system using radar is largely a matter of deciding upon standardized control locations, identification methods and the principle of communication to be used. Two such coordinated systems have been des-

cribed: RCA proposes to televise the information from ground to craft while Federal would retransmit the video PPI signal directly.

A general long-range navigation system over sea is entirely feasible, using Loran or Sonne. Over land, however, the number of ground stations required appears to be impractical owing to the reduced ground-wave range. The use of airborne radar with a combination of natural landmarks, beacons and corner reflectors is an alternative possibility although not too attractive. If any extended use of sky-wave transmission is to be made, further investigation into the properties of the ionosphere is very necessary.

From what has been said, it is evident that a single equipment to meet all four requirements is not practical. It appears that the problems of long and short range navigation require fundamentally different techniques for their solution.

The fact that a general over-land navigation system using LF Loran would require a very large number of ground stations may be seen by considering the problem of an all-weather New York-Chungking air route by a great-circle path. Such a path passes close to the North Pole (see Fig. 31-01), and this route is not necessarily advocated as an economically workable proposition: it is chosen merely as an illustration for navigational discussion.

The problem of providing polar Loran coverage is not easily solved if stations are to be located in even semi-accessible areas. The distances are too great for a quadrilateral of the SS Loran type. The only solution appears to be a ring type of network, with a master station A controlling slaves B_1 and B_2, which in turn control "sub-slaves" C_1, C_2, etc. Such a chain lends itself to extended coverage and to the provision of multiple-line fixes, but the number of sub-stages of control would be limited by the accuracy of synchronization attainable. Double-pulsing of certain slave stations would be possible, but since a number of stations would have to use the same repetition rate, pulse identification (by means of double pulses or pulse-blinking) would have to be provided.

Assuming for purposes of discussion that in polar regions synchronization would be obtainable at 1000 miles, and reception sufficiently reliable for position-line determination out to 2000 miles from any one station, it can be seen from Fig. 31-01 that polar coverage may be provided by such a chain if suitable locations can be arranged and if difficulties of supply and maintenance can be overcome. Such a polar chain constitutes a separate unit, giving navigational facilities for all polar routes. The advantages of combining meteorological stations with navigational radio stations are apparent. Considerable data on ground-wave and sky-wave transmission in polar regions would be needed if such a scheme were to reach the stage of practical planning.

Considering now the problems of navigation over the large land-masses adjacent to the polar regions, one must of course assume that the location, control and maintenance of Loran stations on any desirable territory by an international authority is realizable. Further, since any particular station must clearly be so situated as to be part of a coordinated system giving coverage for a number of regions or proposed air-routes, the locations shown in Fig. 31-01 probably do not represent a desirable solution to the general problem. Supposing the locations of the stations E, F, G, H, I and J (southern Greenland, Belle Isle, Nantucket, Charleston, Milwaukee, Port Nelson) to be so selected that coverage is given not only over the New York-Chungking polar route but also over the western Atlantic on one side, and the central United States on the other, it is seen that no less than six stations are required for this coverage alone, if the figures previously given for base-line

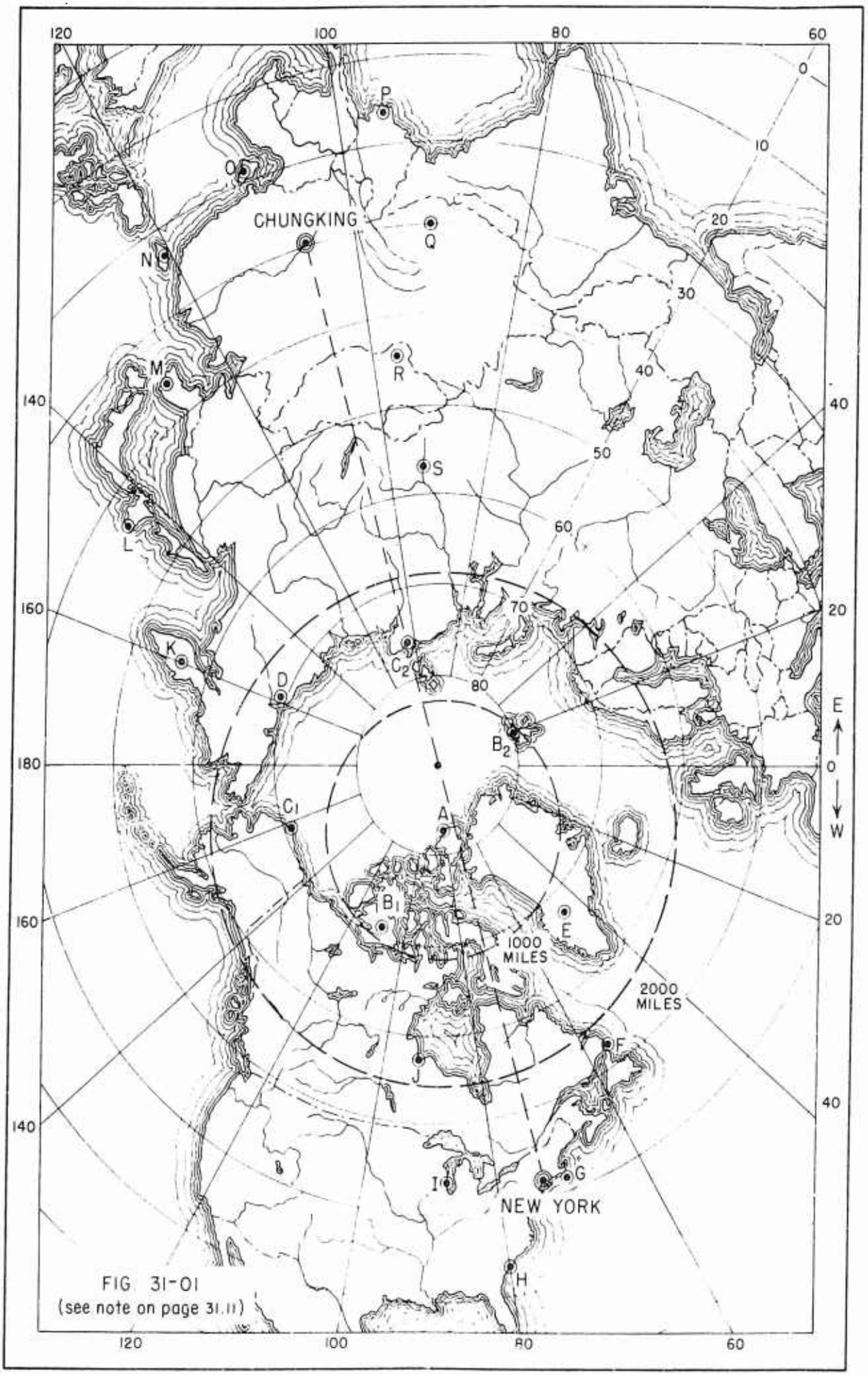


FIG 31-01
(see note on page 31.11)

and for range are retained. If sky waves are to be used, these figures might be realized over land, but difficulties would then be encountered with the cycle-matching technique. If ground waves only are to be relied upon, the number of stations required for this coverage might be more than doubled.

Turning now to the problem of navigation over north-eastern and eastern Asia, the difficulties are similar but greater. To the east, there is a temptation to follow the coastline (stations K, L, M, N, O and P)*, but if this is done coverage over the Chungking route would probably depend on sky waves. Stations Q, R and S do not appear to fit in very well with other possible Asiatic air-routes, and the present state of development of this territory is certainly not such as to justify the outlay on a general navigational system to cover this region.

The above discussion is only too inadequate, but perhaps enough has been said to illustrate the difficulties to be encountered in planning any general navigational coverage over land masses. If Standard Loran techniques and frequencies are considered, any such scheme is highly impractical if not impossible. Further research on propagation at LF Loran frequencies is required to determine whether or not such service could be realized using LF Loran.

Recommendations for further research

1. Basic research is required to determine all relevant information regarding the properties of the ionosphere, with particular attention to the lower fringe of the E-layer. For example, data on reflection coefficients and on the size, density and motion of ionic clouds would be of fundamental interest. Present ionospheric observations should be expanded to meet such needs.

2. The research indicated above should be accompanied by a basic study of actual propagation paths, including studies of the plane of arrival of reflected signals, the nature of their polarization, variability in time of arrival and in signal strength, and modification of pulse shapes due to ionospheric transmission. A comparison should also be made of signals received simultaneously at receivers spaced a few hundred yards apart. Basic research is also required on ground-wave transmission over sea and over land, and also on at least one sky-wave transmission path such that detailed ionospheric data are obtainable at the mid-point of the single-hop path.

3. A basic study should be made of the ideal specifications for pulse modulation, and of the practical means for approximating this ideal, with special attention to the low-frequency end of the spectrum.

4. Concurrently with the basic studies outlined above, it would be desirable to continue operational tests on LF Loran and on Sonne, while employing standard Loran (for the present) for the relatively long-distance overseas navigation.

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* A - Grant Land
B_1 - Victoria Island
B_2 - Spitzbergen
C_1 - Pt. Barrow
C_2 - Taimir Peninsula
D_1 - Pokhodsk
E - Greenland
F - Belle Isle
G - Nantucket
H - Charleston
I - Milwaukee
J - Port Nelson
K - Kamchatka
L - Hokkaido
M - Korea
N - Formosa
O - Hainan
P - Rangoon
Q - Lhasa
R - Barkol
S - Krasnoyarsk

The dashed circles indicate approximately areas within 1000 miles and 2000 miles of station A. Such areas are not accurately represented by circles, since the projection used distorts east-west distances. The distortion is however not serious in polar regions.

A short glossary of terms used in this report*

Accuracy refers to the degree of concordance between a given measurement and the true value (which is assumed known).

Azimuth angle or "Azimuth" is an angle measured in the horizontal plane. True bearing is an azimuth angle measured east (clockwise as seen from above) from true north.

Craft is here used to designate surface vessels, aircraft, land vehicles, and guided missiles.

A fix is defined as the point determined by the intersection of two or more lines of position.

An interrogater is a pulse transmitter used to emit a signal which elicits an automatic response from a transponder.

An inversion layer is an atmospheric layer in which the vertical temperature gradient, normally negative, becomes positive.

A line of position is a line such that some point on it is the instantaneous position of the navigated craft. This line may or may not lie on the surface of the earth.

Meaconing is the act of falsifying by radio means, the indications given by enemy radio navigation systems. The object of meaconing is to mislead enemy navigators by causing a false indication of position to be obtained without the knowledge of the navigator.

Navigation is the science of guiding a craft from one position to another by any chosen path. It includes the determination at any time of position, course bearing, etc. Various special navigational operations such as homing, flying fixed courses and vectoring is considered as limited or restricted navigation.

A navigation aid is a device which provides the navigator with some or all of the following information:

(a) present position
(b) course heading
(c) speed (ground or relative)
(d) location of geographical surroundings
(e) location of other craft in the vicinity
(f) right-left steering directions or automatic steering control †
(g) altitude (not covered in this report)

The phase aspect of two or more antennas refers to the relative phase relations existing, at a given point in space, between the electromagnetic fields produced at that point by radiation from the individual antennas. The reference point chosen is at a distance from the antenna array which is large compared to the dimensions of the array itself. The phase aspect will depend on the relative phases of the currents in the various antennas, the spacing between antennas, and the azimuth and elevation of the reference point with respect to the array.

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* This appears to be necessary on account of the diversity of meaning of many new navigational and radar words.

† The "navigator" may in this case be a robot.

As an example, consider two antennas driven in phase and separated by a distance equivalent to b electrical degrees at the frequency of operation. The phase aspect referred to a distant point, whose elevation angle is ϕ degrees and whose azimuth angle is θ (measured from the perpendicular bisector of the base line of the array), will then be $b \cos \phi \sin \theta$ electrical degrees.

The precision of a measurement is the numerical measure of its reliability, making allowance for all known errors and uncertainties. (The true value is not actually known.)

A racon (RAdar beaCON) is a radio beacon employing radio pulse signals.

The word radar is used in this report to describe equipment with which a distance is measured by recording the time taken by an electromagnetic disturbance to travel from one point to another and return. The returning disturbance may be a simple echo or a beacon response. Radar measurements are not necessarily restricted to pulse transmissions.

A radio beacon is a radio signal station. Radio beacons are used for determination of azimuth and range, or for identification.

Range means distance. This is common usage among ordnance, gunnery and radar personnel. The word range has also been used to designate a line defined by two fixed landmarks such as lighthouses or other easily visible markers. The word is used with this connotation in the expression radio-"range" to mean a line defined by radio signals from an antenna array. Whenever the word is used in this latter sense in the present report, attention is called to the usage.

Relative bearing is an azimuth angle measured clockwise from above from any arbitrary reference direction, as for instance the craft heading.

A responder beacon is a pulse-type receiver-transmitter used to receive an interrogating signal and to transmit automatically an identifiable reply signal. Responder beacons used for IFF purposes are commonly referred to as transponders.

A responser is a receiver used to accept the reply from responder beacons.

The word synchro is used here as a generic name for all such devices, including those having other names such as selsyn, autosyn, magnesyn, etc.

Probable values of some physical and geodesic constants

Velocity of electromagnetic waves in vacuum $v_0 = 2.99778 \times 10^8$ meters per second.

Refractive index of air at standard temperature and pressure n = 1.000294

Velocity of electromagnetic waves in air (S.T.P.) $v = 2.99690 \times 10^8$ meters per second
= 186,218 statute miles per second
= 161,711 nautical miles per second

1 nautical mile = 1.15155 statute miles

Microseconds per statute mile	$= \frac{10^6}{186,218} = 5.3700$
Microseconds per loop statute mile	= 10.7401
Microseconds per nautical mile	$= \frac{10^6}{161,711} = 6.1839$
Microseconds per loop nautical mile	= 12.3678
Frequency for λ = 2 statute miles	= 93,109 cps
Frequency for λ = 2 nautical miles	= 80,850 cps
One microsecond is equivalent to	299.7 meters or 0.1862 statute miles or 328 yards or 984 feet or 0.1617 nautical miles

1^o azimuth at 100 miles	= 1.75 miles
at 1000 miles	= 17.5 miles
1 mile at 100 miles	= 0.573^o azimuth
1 minute of azimuth at 100 miles	= 158.5 feet
Equatorial radius of earth	= 3963.34 statute miles
Polar radius of earth	= 3949.99 statute miles
Radius of a sphere having the same volume as the earth	= 3958.89 statute miles
1^o latitude along a meridian	= about 69.1 miles = 1^o longitude at the equator
1000 statute miles along a meridian	= about 14.5^o latitude

Distance d along a parallel of latitude for 1^o change of longitude:

Latitude	d (statute miles)	Latitude	d (statute miles)
0^o	69.1	50^o	44.4
10^o	68.0	60^o	34.6
20^o	64.9	70^o	23.6
30^o	59.8	80^o	12.0
40^o	52.9	90^o	0

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1441	Central Communications Research, Cruft Laboratory, Harvard University, Cambridge, Mass.	Analysis of Available Methods of Navigation

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, National Defense Research Committee [NDRC], from the War and Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

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ABSTRACT

A descriptivs and critical survey is presented of a numbsr of electronic navigation syetems dsveloped during the war, both in ths U. S. and in Europe. Some of the systems considered are or were operational during the war, while others are merely proposed. The principles underlying the three besic types of navigation systems are analyzed, and several eystems ere compared regerding their operational chsracteristics. Conclusions are drawn from this comparison. Recommendations ere made for further research.