RP159

DEVELOPMENT OF THE VISUAL TYPE AIRWAY RADIO-BEACON SYSTEM

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ABSTRACT

Research work on a radiobeacon system for use on the airways of the United States has been under way at the National Bureau of Standards during 1926 to 1929. As a result of this work a system has been developed which fulfills the requirements for course navigation on the civil airways. A directive transmitter is employed on the ground, making possible the use of simple apparatus on board the airplane. A simple receiving set suffices to make use of all the radio aids provided. Visual indication is provided on the airplane instrument board by means of a tuned-reed instrument. The pilot observes the vibrations of two reeds. On the course the vibration amplitudes are equal. Off the course they are unequal, the reed vibrating with the greater amplitude being on the side to which the airplane has deviated.

Two types of beacon transmitters are described, the double modulation and the triple modulation. The former is capable of serving either 2 courses at 180° with each other or 4 courses at arbitrary angles. The latter serves 12 courses at any desired angles, and is adapted for use at any airport located at the junction of a large number of airways. Reed indicators for use with the double-modulation and triple-modulation beacons are described.

Descriptions are given of the receiving set and receiving antenna system developed. Airplane-engine ignition shielding is also discussed.

A marker beacon system has been developed whereby the pilot is given visual indication of his exact position at definite points along the route.

Special adaptations of the beacon system are being developed to facilitate landing in fog.

CONTENTS

I. INTRODUCTION

This paper gives a general description of the research on radiobeacon systems for the airways of the United States during 1926 to 1929. More specific descriptions of various features of the development are given in B. S. Research Papers Nos. 19, 28, 35, 77, 148, 154, and two now in press. The titles of these papers are given in references numbered, respectively, 15, 9, 22, 13, 12, 14, 10, and 21, in the bibliography (Sec. XI) at end of this paper.

The object of the research was to provide a system of navigational aids by which aircraft could be flown on a course in fog or any condition of visibility or no visibility. This system was to be specifically adapted to the requirements of navigation on the airways of the United States. The navigational aids developed have therefore had primarily in view the rendering of maximum service to fixed airways, the needs of aircraft on independent courses being secondary. Happily, as will be shown, the system evolved gives aid to the independent flyer as well as to the navigator of the regular airways.

The system furnishes a pilot the desired guidance without special maneuvers of the aircraft or more than ordinary attention on his part. All the complicated and expensive parts of the system are at ground stations maintained by the Government. The pilot is required to do nothing at all to obtain a reading but glance at an indicating instrument on his instrument board whenever he wishes.

1. THE NEED FOR THIS DEVELOPMENT

With the transportation of air mail, express, and passengers constituting its basic source of revenue, the success of air transportation in the United States depends in large measure upon the rigorous maintenance of scheduled flying by day and night. Present-day business requires the gathering of the mail at the close of a business day and its transportation to remote destinations for early delivery on the next or next following morning. The transportation of passengers by air can become a genuine service, and really popular, only when the traveler can count on a scheduled service as dependable as the railway trains and independent of weather or other contingencies.

The present limitation on this most essential feature of air-passenger service arises entirely from the hazards of the weather. Means are at hand to cope with every other limitation on flight. Multiple engines and improved controllability assure safety, landing fields are being provided in great numbers, aircraft of adequate strength and stability are available, and every comfort and convenience are offered the air traveler. And yet air traffic is still halted when meteorological conditions make the pilot uncertain that he can see landmarks, lights, or landing field.

It is impossible to exaggerate the difficulties of a pilot flying in dense fog. Deprived of all landmarks, under incessant strain at the controls to maintain equilibrium and direction, the aviator must

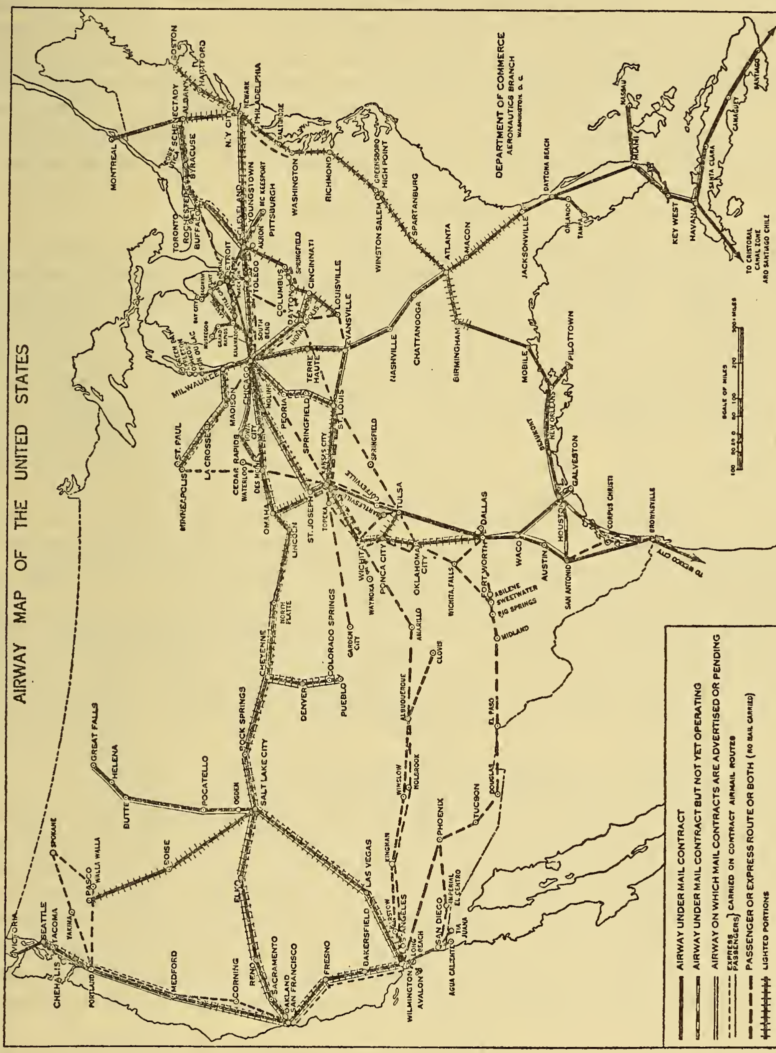

FIGURE 1.—*Map of civil airways of the United States*

frankly abandon dependence upon his senses and navigate according to the information conveyed by his instruments.

By means of the familiar instruments, such as the altimeter, bank and turn indicator, rate-of-climb indicator, and compass a pilot can continue flying in fog, but it is only by radio means that he can be certain to keep on a given course and find his landing field when the ground is invisible. Accurate as a compass may be, it can not tell the pilot how much he is drifting sidewise owing to cross winds, nor what actual progress he is making forward because of the unknown effects of head or tail winds. Unless radio aids are used fog always brings the hazard of getting off the desired course into unfamiliar or dangerous areas, and also makes even the possibility of a safe landing small.

By means of the radiobeacon system in its present form the pilot can keep accurately on his course, know the points he is flying over, and proceed unerringly to the landing field. Adaptations of the radiobeacon to the landing problem are now in progress which it is believed will also make possible landings in densest fog. With the system fully established a great obstacle to safe flight will have been conquered and additional dependability added to scheduled flying.

2. PREVIOUS WORK

The present development differs from much of the earlier work on radio navigational aids in its emphasis upon the requirements of fixed airways. The first work in this field was for military purposes in the World War. Military aircraft inherently require direction-determination service on independent courses. They do not generally fly fixed airways. The natural means chosen accordingly was the direction finder. The use of loop antennæ, with sensitive receiving sets, aboard (1)[1] airplanes, gave a homing device well adapted to military needs. This method has not been extensively used for nonmilitary aviation because of the great difficulties experienced with receiving apparatus of this type. It has the inherent limitation that it does not prevent wind drift from shifting the airplane off its course; the method does eventually bring the airplane to its destination, although by a circuitous route if there is a side wind.

The next chief development was also a direction-finder method, but with the direction finder located on the ground. This is the system (2) now used for aircraft navigation by radio throughout Europe. Every airplane in the commercial transport service carries a radiotelephone (or radiotelegraph) transmitter and receiver, used with a trailing-wire antenna. There are permanent direction-finding stations located at certain of the principal airports. When an airplane desires to learn its position, it transmits a telephonic request to the airport, whereupon two or more of the ground direction-finding stations each determine the direction by observations upon the radio waves transmitted by the airplane. Triangulation then gives the airplane's position, which information is transmitted to the airplane. The system requires the airplane to carry both transmitting and receiving apparatus. It is not effective when a large number of airplanes desire the position service simultaneously, as the ground station can serve only one airplane at a time.

A third method of furnishing navigational aid to the flyer is the rotating radiobeacon recently developed in England (3). This is a radio transmitting station, located at an airport, which has a directive antenna rotating at a constant speed of one revolution per minute. A figure-of-eight pattern is thus rotated in space. A special signal indicates when the figure-of-eight minimum passes through north

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[1] The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

and also when it passes through east. A pilot listening for the beacon signal with his receiving set can start a stop watch when the north signal is received and stop it when the figure-of-eight minimum reaches him. The number of seconds multiplied by 6 gives him his true direction in degrees from north. The stop watch may be calibrated directly in degrees, so that the position of the second hand when the minimum signal is received gives the bearing directly. This system thus serves any course within its range. It has, however, the disadvantages of slowness of operation and also of being difficult to use during conditions of severe atmospheric disturbances or interference from outside services.

The radiobeacon system described herein is an outgrowth of a development undertaken by the Bureau of Standards for the Army Air Service in 1920. The Air Service requested the bureau to devise a method whereby a directional transmission would serve as a guide to airplanes along a chosen course. Such a method was developed (4) having the advantages that direction service could be given simultaneously to any number of airplanes flying the course, and that each airplane only had to carry a receiving set, with no other special equipment whatever. A description of this method, the subsequent contributions of the Army engineers, and the more recent work by the Bureau of Standards, follow. A discussion of the relative merits and features of the various types of radio navigational systems is given in Section IX.

II. THE AURAL RADIOBEACON SYSTEM

The radiobeacon system employs two directive antennæ placed at an angle with each other. Along the line bisecting the angle between the two antennæ, the intensities of the radio waves from the two are equal. Elsewhere, one of the two waves is stronger than the other. An airplane could, therefore, follow a course along the bisector referred to if the two sets of radio waves could be distinguished from one another. A different signal is impressed on each set of waves for this purpose.

In the original apparatus transmission took place alternately from the two antennæ, a switch being used to throw the radio-frequency power from one antenna to the other. Tests made at Washington on the ground and on ships showed that a course was effectively marked out and could be followed. The apparatus was next set up by the Bureau of Standards with the cooperation of Army engineers, at Dayton, Ohio, and tests made in the air. The method was successful in airplane flights and had the advantage that no error was introduced by wind drift, which is an important limitation on the use of direction finders aboard aircraft. For a discussion of this see page 294 of reference (4).

In the following four years the Army engineers at Dayton, Ohio, developed this radio range [2] further (5); in particular, they devised a signal-switching arrangement such that the signals from the two antennæ merged into a steady dash when on the course, giving an added criterion besides that of equal signal intensity to enable the observer to tell whether he was on or off the course. They also introduced a goniometer, or mutual inductance device, to permit

[2] A name which is coming into use for any directive radiobeacon transmitter.

orienting the course in any desired direction without moving the antennæ. The idea of interlocking the two signals to be compared was founded on an early German patent (6). The theory underlying the operation of the goniometer was also known (7). The contribution made by the Army engineers was to combine the two in a practical operating system.

The subject received renewed study by the Bureau of Standards early in 1926. There was pending in Congress a proposal to create an Aeronautics Branch in the Department of Commerce with jurisdiction over commercial flying and with the duty of providing aids to air navigation. The department officers requested the Bureau of Standards to recommend ways in which radio could be used for aids to navigation on the airways. In the recommendations submitted the bureau proposed the providing of telephone broadcasts of weather information to aircraft from ground stations maintained by the Government and a radiobeacon service of the type here described. It was pointed out that this would put all the expensive and heavy radio equipment on the ground, to be maintained by the Government, requiring the airplanes to carry nothing but a very simple receiving set.

Accordingly, when the Aeronautics Branch was organized, in July, 1926, it assigned the necessary experimentation and development in this field to its research division, which was organized in the Bureau of Standards. In the work on the radiobeacon, which began immediately, several improvements over the existing form of the beacon were sought. These included some matters of design detail (involving the goniometer, interlocking switch, etc.), an automatic device for serving several courses simultaneously (for use at airports where several courses intersect), and especially means of replacing the telephone receivers by a visual indicator. The work, which still continues, has been done in the bureau laboratory at Washington and at two field stations, one at College Park, Md., a suburb of Washington, and the other at Bellefonte, Pa., chosen because of its location on the New York-Cleveland airway in particularly hazardous mountain terrain. These two stations were equipped with radiobeacon and also radiotelephone and radiotelegraph transmitting apparatus. The Bellefonte, Pa., station was transferred in 1928 to the Airways Division of the Department of Commerce, and is now used for giving regular radio service to the portion of the transcontinental air route on which it is situated. The College Park station continues to serve as a development laboratory and as a model and demonstration station, and is, in addition, available to give radio service to the air routes passing through Washington. A photograph of this station showing the directive antenna system is given in Figure 2.

Experiments with different transmitting arrangements led to the adoption of that shown in Figure 3. Numerous test flights over a period of more than a year proved this circuit arrangement to be satisfactory. A 250-watt master oscillator supplies power to two 1 kw. power amplifiers, which in turn feed the two loop antennæ crossed at 90° with each other. A 4-coil goniometer is interposed between the power amplifiers and the antennæ to permit orientation of the beacon courses in any desired direction. Each primary winding of the goniometer, acting in conjunction with the two crossed secondary coils and the two crossed-loop antennæ, sets up a system which

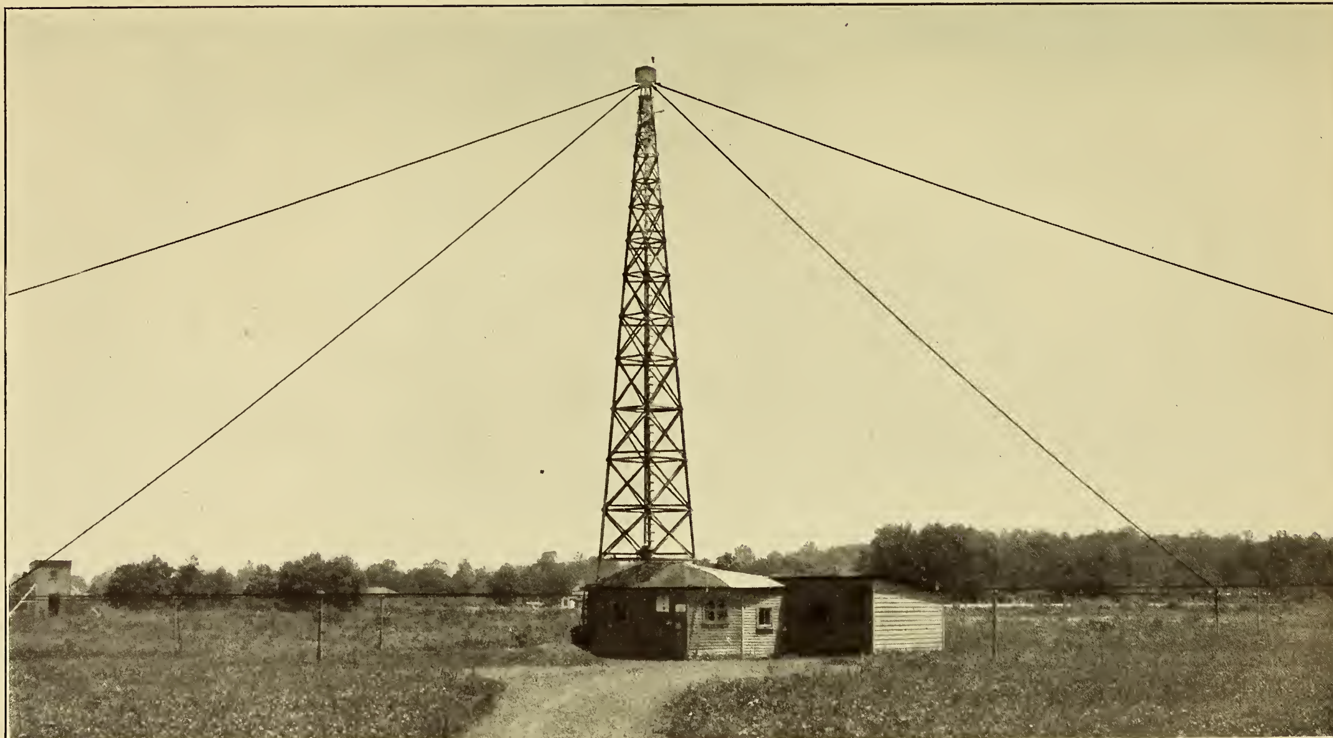

FIGURE 2.—*Experimental radiobeacon station at College Park, Md., showing directive antenna system*

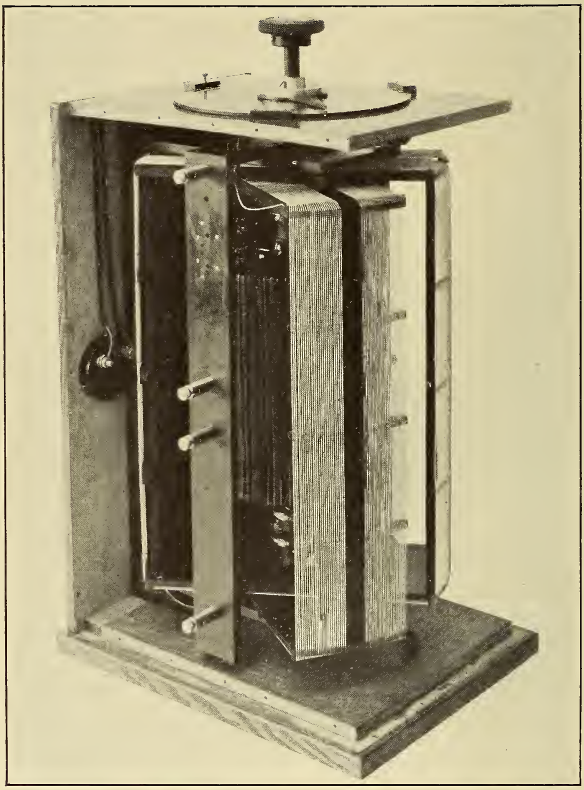

FIGURE 4.—*Simplified goniometer used in the circuit arrangement of Figure 3*

is electrically equivalent to a single-loop antenna. The plane of this phantom antenna is dependent upon the relative coupling of the secondary coils to the primary coil under consideration.

Since there are two primary windings, two such phantom antennæ exist, the angle between their planes being equal to the angle between the primary windings. The two phantom antennæ may be rotated in space (thus changing the position of the equisignal zones or courses formed by their space patterns) by changing the relative position of the primary windings with respect to the secondaries. This may be accomplished by rotating either the primary or the secondary coils. A photograph of the goniometer used in the transmitting circuit

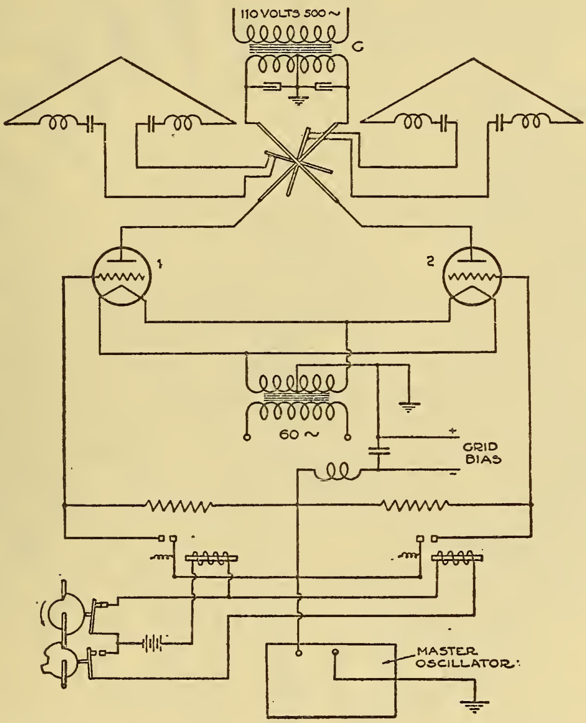

FIGURE 3.—*Improved circuit diagram of interlocking-signal type radio range*

arrangement of Figure 3 is shown in Figure 4. For convenience in mechanical construction the secondary coils are the ones capable of rotation. The primary coils are each of 32 turns of insulated wire and the secondary coils each of 8 turns of heavy litz wire.

The arrangement used for obtaining an interlocking signal is evident from Figure 3. As the cams rotate slowly, amplifier tube *1* is excited with the Morse letter *N* and amplifier tube *2* with the letter *A*. Phantom antennæ *1* and *2* are correspondingly excited. The two signals are so interlocked that an observer located on a line bisecting the angle between the two phantom antennæ (thus receiving signals of equal amplitude from both antennæ) obtains only long dashes. Were he not on this bisector line, he would receive a preponderance of either letter *A* or *N* depending upon his position with respect to the bisector. Figure 5 shows a diagrammatic representation of the interlocking signal for different angular positions around the beacon.

The goniometer shown in Figure 4 and the interlocking arrangement are both refinements over those used in the Army beacon. In the Army system the goniometer primary coils were usually of one or two turns and connected in a tuned circuit fed by the transmitter output, a cam-operated relay being provided to throw first one primary

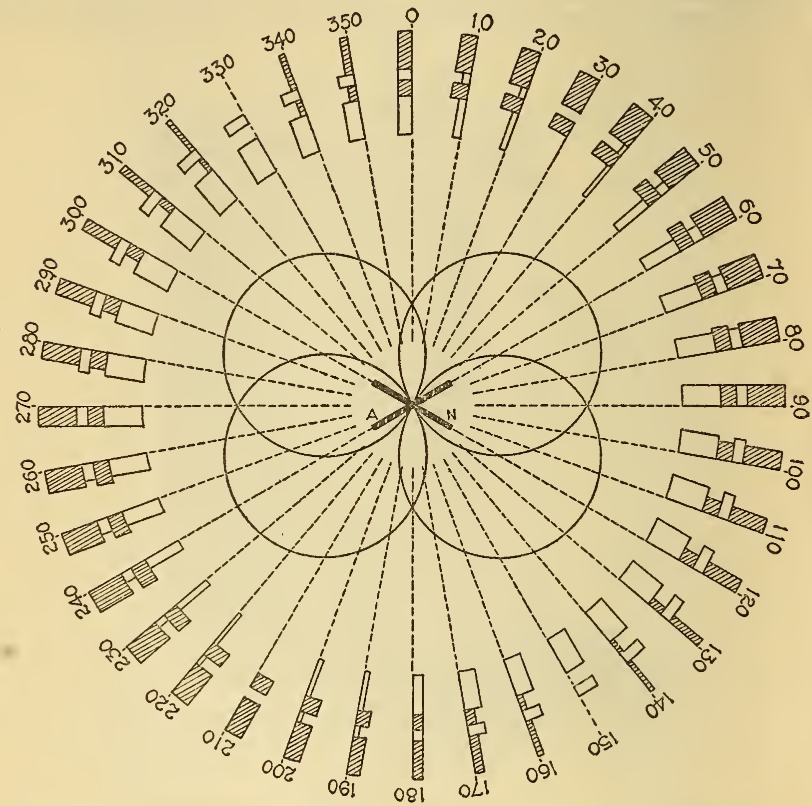

Figure 5.—*Interlocking characteristic of aural type radio range, showing change in relative intensity of the two signals received on an aircraft flying around the beacon*

and then the other in circuit in order to produce the desired interlocking signal. Interlocking, therefore, involved the breaking of heavy radio-frequency currents. In the circuit network of Figure 3 the interlocking is accomplished in the low-power side of the system, the relays controlling only the radio-frequency grid currents of the tubes.

It will be noted that tubes *1* and *2* never receive grid excitation simultaneously. This insures that the goniometer primaries are never excited simultaneously, and, in consequence, the angle between these primaries may be made of such value as to give the most useful beacon space pattern. The pattern shown in Figure 5 is for a 60° angle between primaries.

Tone modulation of the transmitted signals is obtained by exciting the plates of all the transmitting tubes from a 500-cycle source. The self-rectifying method of exciting the power-amplifier tube plates adds considerably to the stability of the circuit network.

III. THE DOUBLE-MODULATION BEACON SYSTEM

1. FIRST EXPERIMENTS

A number of disadvantages are inherent in the aural interlocking radio range. Of these, the constant strain on the part of the pilot in listening to the guiding signals and distinguishing between their

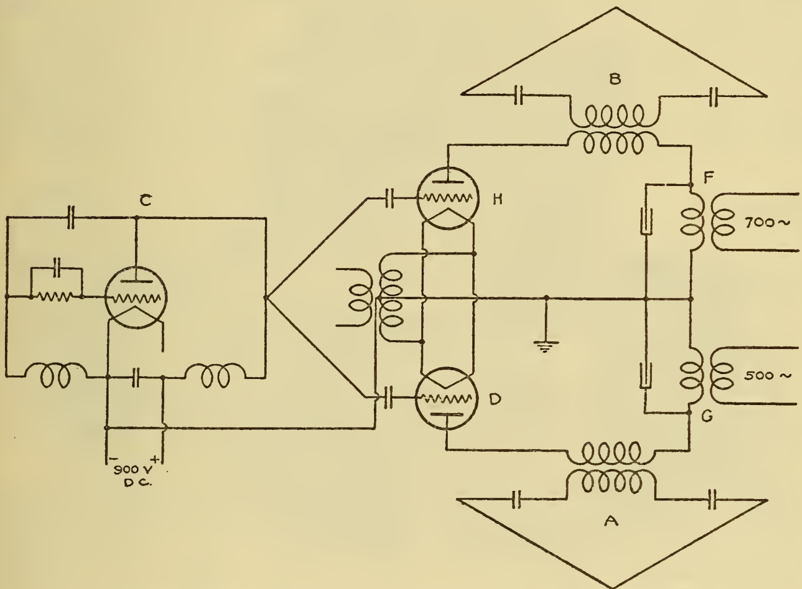

Figure 6.—*Circuit diagram of early type double-modulation beacon*

magnitudes is the most important. Another disadvantage is the masking of the guiding signals by atmospheric disturbances or interference from other services, with a consequent reduction in the effective distance of reception. A third is the skill required on the part of the pilot in interpreting the received signal.

The bureau, therefore, undertook the development of a visual means for receiving the guiding signals. A method devised in 1926 consisted of supplying both antennæ with radio-frequency power simultaneously, each supply being modulated by a different audio-frequency. The transmitting-circuit arrangement used is shown in Figure 6, and consists of a master oscillator supplying power to two amplifiers, which in turn feed the loop antennæ. A goniometer may be connected between the power amplifiers and the antennæ. The plate of one amplifier is excited from a 500-cycle source, and the plate of the second amplifier from a 700-cycle source. The receiving circuit shown in Figure 7 serves to separate the two modulation frequencies by means of rejector circuits *FH* tuned to 500 cycles and *GI* tuned to 700 cycles, and selector circuits *K* and *L* tuned to pass 500 and 700 cycles, respectively. Tubes *N* and *G* rectify the output currents of the two transformers, the zero-center microammeter *0* being so connected as to indicate the difference between the rectified currents. An equisignal zone or "course" is evidenced by zero reading of this instrument, a deviation to the left or right of a given course causing a deflection of the instrument pointer to the side of deviation.

In an attempt to simplify the transmitting apparatus a second visual system was tried in which the two sources of audio-frequency were reduced to one. The two transformers (*F* and *G*, fig. 6) were replaced by a single transformer with the secondary center tap grounded and 500-cycle supply impressed upon the primary winding.

With this self-rectifying method of supplying plate voltage, radio-frequency current flows in only one antenna at a given time. An observer, exploring the field around a beacon station so connected, will encounter four narrow zones of 1,000-cycle pitch (corresponding to the four equisignal zones). At points 45° on either side of these 1,000-cycle zones the signal from but one loop antenna is heard. In

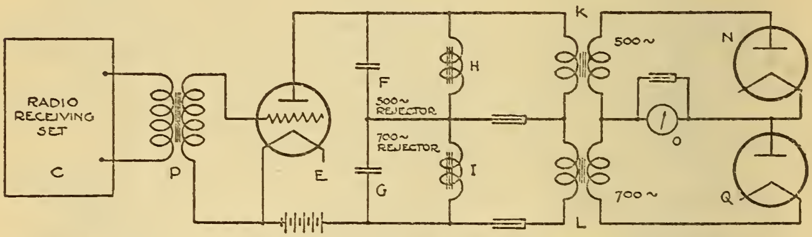

Figure 7.—*Circuit diagram for visual indicator using zero center micro-ammeter*

these positions a 500-cycle note is obtained. If the observer moves from any 1,000-cycle zone toward either of the neighboring 500-cycle zones, he finds a location where the amplitude of the received 500-cycle note equals that of the 1,000-cycle signal. Eight such positions exist and may be used as beacon courses, the same receiving system as shown in Figure 7 being employed for indicating these courses, except that the circuits are tuned to 500 and 1,000 cycles instead of 500 and 700 cycles. Further information on this method, including a diagram showing the beacon space pattern, is given on pages 900 to 902 of reference (8).

While the above two systems of visual indication had some promise, both had the inherent disadvantage of being susceptible to errors due to interfering signals. There were also other disadvantages, such as complexity of apparatus and lack of positive indication when on course (since the beacon could be inoperative and the indicating instrument still read zero).

2. USE OF TUNED-REED INDICATORS

A method was then worked out which overcame these difficulties. Two low-modulation frequencies were employed, 65 and 86.7 cycles per second. The visual indicating instrument (9) for use on the

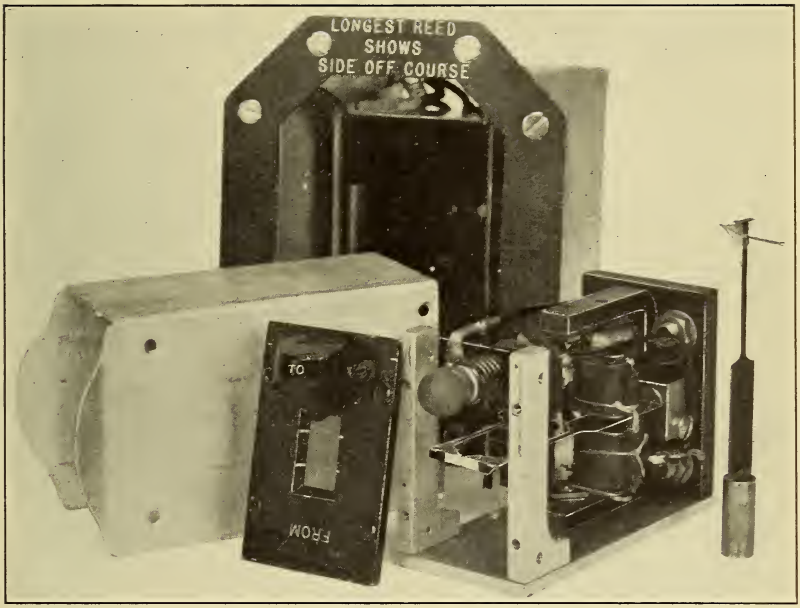

FIGURE 8.—*Visual beacon course indicator with shock proof mounting, 2-course type*

FIGURE 9.—*Airplane instrument board with course indicator mounted above the other instruments*

airplane consists of two vibrating reeds mechanically tuned to the two beacon modulation frequencies, actuated by small electromagnets connected to the output circuit of the receiving set. When the beacon signals are received, the two reeds vibrate, and, since they are tuned to the two modulation frequencies used at the beacon, serve as a device for indicating equality of received signals from the two antennæ. The tips of the reeds are white against a dark background, so that when vibrating they appear as vertical white lines. When the two lines are equal in length, the airplane is on its course. In the interest of simplicity, the adjustment is always such that a deviation from the course to the left serves to increase the relative deflection of the left reed, and the reverse is true if the airplane deviates to the right. To return to the course, the pilot turns in the direction of the shorter reed deflection. A photograph of the reed indicator with shock-proof mounting is given in Figure 8. Figure 9 shows this indicator installed on the instrument board of the bureau's experimental airplane.

Simplicity of operation has resulted from the use of this system. An ordinary receiving set with a small reed unit weighing less than an ordinary pair of headphones constitutes the airplane equipment. A signal is received whether on or off the course, a glance at the relative reed amplitudes being sufficient to tell the pilot whether or not he is on the course, and, if not, approximately how far off he is and to which side. Finally, the sharp mechanical tuning of the reeds adds the very desirable feature of freedom from interfering signals, the reeds operating effectively through interference sufficient to ruin aural reception.

A diagrammatic representation showing the relative deflections of the two reeds comprising the visual course indicator for different deviations in degrees from a given beacon course is shown in Figure 10. As may be observed, a deviation of $\pm 1°$ may be readily detected.

To make the use of the course indicator as simple as possible, a plug-in arrangement is provided so that the relative position of the two tuned reeds of the indicator may be reversed (by turning the indicator upside down). Reference to Figure 10 will indicate the purpose of this reversal. Suppose that a pilot is flying away from the beacon on either course *A* or *C*. If he deviates to the left of his course, the amplitude of the 65-cycle reed will increase and that of the 86.7-cycle reed will decrease. A deviation to the right of the course results in an opposite effect. It is desirable, therefore, to place the 65-cycle reed on the left of the 86.7-cycle reed in order that the pilot may observe the simple and instinctive rule (longest reed shows side off course—turn to the shorter reed). When flying to the beacon, however, this rule holds true only if the relative position of the reeds is reversed, the 65-cycle reed being now on the right of the 86.7-cycle reed. Consider, now, the two 90° courses, *B* and *D*. On these courses the relative position of the two reeds (in order to make the rule stated above apply) is exactly the reverse of that for courses *A* and *C*, whether flying from or to the beacon. To distinguish between the two sets of courses (*A*, *C* and *B*, *D*) a color system may be adopted on the airway maps, *A*, *C* being in one color and *B*, *D* in another. A shutter is mounted on the course indicator front which exposes either one color or the other. When set to the first color the words [TO / FROM] are exposed, while when the shutter is set to expose the second color, the words [FROM / TO] are exposed. The pilot then sets the shutter to the color of the course to be flown and plugs in the course indicator in order that the direction (with respect to the beacon) which he is to fly is right side up. The simple rule stated above then obtains. A complete description of the shutter arrangement is given in a separate paper (10).

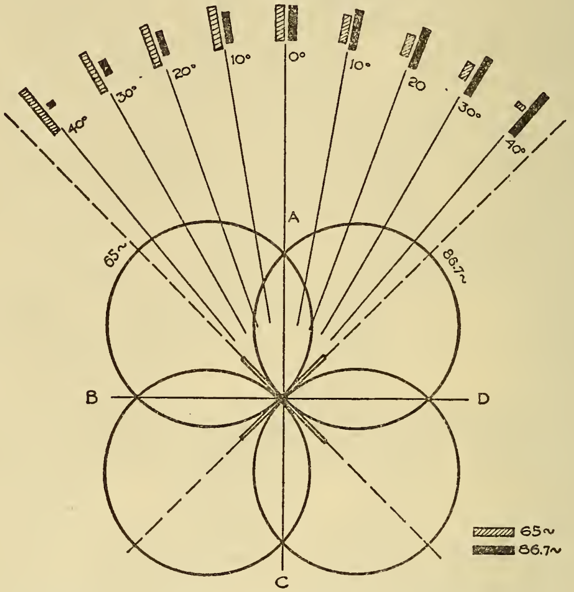

Figure 10.—*Space characteristic of double-modulation type radio range showing relative deflections of the two reeds comprising the course indicator for different deviations in degrees from the beacon course*

3. GENERAL DETAILS OF TRANSMITTING ARRANGEMENT

Since the vibrating reeds are sharply tuned to their particular frequencies, it is necessary that the modulation frequencies of the transmitter be kept constant within certain limits. In the earlier beacon transmitting arrangements (see fig. 11) this requirement was met by the use of electron-tube driven tuning forks mechanically tuned to the desired frequencies. The outputs from these tuning forks, after sufficient amplification, were made to modulate the 290-kc. carrier in the two amplifier branches of the beacon set. Heising plate modulation was employed. A photograph of the transmitting set using this method of modulation is shown in Figure 12.

The practical application of this modulation arrangement resulted in a beacon set somewhat more complex than was considered desirable.

Since the maintenance of a "beacon course" or "equisignal zone" in space depends upon a balance of the modulated output of one amplifier branch and its associated loop antenna with the modulated output of the second amplifier train and its loop antenna, it became necessary to insure a balance between (*a*) the r. m. s. values of current in the two antennæ, (*b*) the percentages of modulation in the two amplifier branches, and (*c*) the wave forms of the two modulation frequencies when applied through the Heising chokes. To accomplish this it was necessary to provide controls for varying the radio-frequency voltages supplied from the master oscillator to each amplifier branch, and also for varying the degree of modulation on each amplifier branch. The wave forms of the two modulation frequencies were kept as nearly sinusoidal as possible.

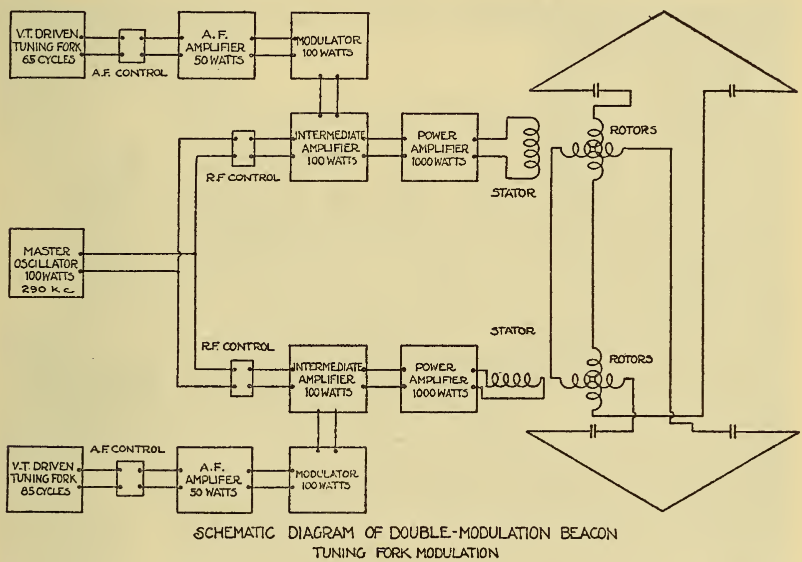

FIGURE 11.—*Schematic diagram of double-modulation beacon using electron-tube driven tuning forks as sources of the modulation frequencies*

It was also important that no coupling exist between the two amplifiers, either by direct induction or by virtue of an impedance common to the two amplifiers. This necessitated the use of a considerable number of expensive condensers and chokes or the adoption of separate generators for supplying the plate and grid voltages to each amplifier branch. The use of the commercial 60-cycle alternating current for heating the tube filaments was also found not possible. Owing to the amount of audio amplification involved, any stray 60-cycle voltages introduced in the early stages were amplified sufficiently to cause a 5-cycle beat on the 65-cycle reed. A further description of this method of modulation is given in (8).

Early in the development of the double-modulation beacon the use of low-frequency generators for supplying the modulation frequencies was attempted. The modulation arrangement was essentially that indicated in Figure 13, where the plates of the intermediate amplifier tubes are supplied through suitable transformers with high a. c. voltages of the proper frequencies. Synchronous motor drive of these alternators was employed. Owing to the variation of the commercial supply frequency, however, it was found impossible to obtain the desired constancy of speed for driving the low-frequency alternators. However, the considerable simplification of the beacon transmitting circuit network that could be effected by the use of this system of modulation, coupled with the fact that both amplifier branches would then be positively modulated to the same degree, thus eliminating the need for modulation controls, led to further efforts to make its application feasible.

An obvious method of attack was to broaden the resonance curve of the vibrating reeds comprising the course indicator to the point where small variations in the modulation frequencies became unimportant. This could not be carried too far, however, since the reed sensitivity materially decreases as the resonance curve is broadened.

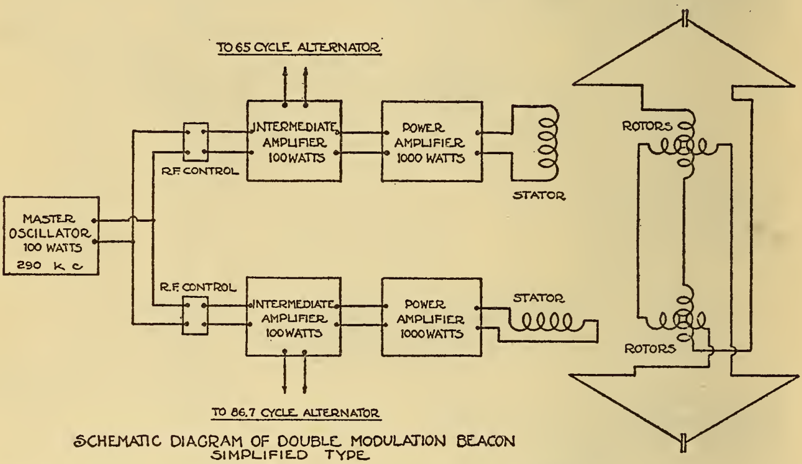

FIGURE 13.—*Schematic diagram of double-modulation beacon using simplified modulation*

A further change in the design of the vibrating reeds made possible a still further reduction in the requirements for speed constancy in the driving motor. The two alternators supplying the modulation frequencies, one having 6 poles and the other 8 poles, were rigidly coupled and driven at 1,300 r. p. m. by the same motor. Variations in the speed of the motor, therefore, resulted in the same percentage change in the two modulation frequencies. The two reeds could then be designed to have, as nearly as possible, equal reductions in deflection for equal percentage frequency change. See reference (10). In many installations this makes possible the use of a synchronous motor as the driving motor. Since the nearest synchronous speed is 1,800 r. p. m., a chain drive is necessary for driving the alternators at 1,300 r. p. m.

By the method described above, variations of the order of 0.3 per cent in the supply frequency can be permitted. Many of the larger power-supply companies maintain their line frequency to this accuracy. Where the frequency variations of the supply mains are greater than this value, a motor other than of the synchronous type

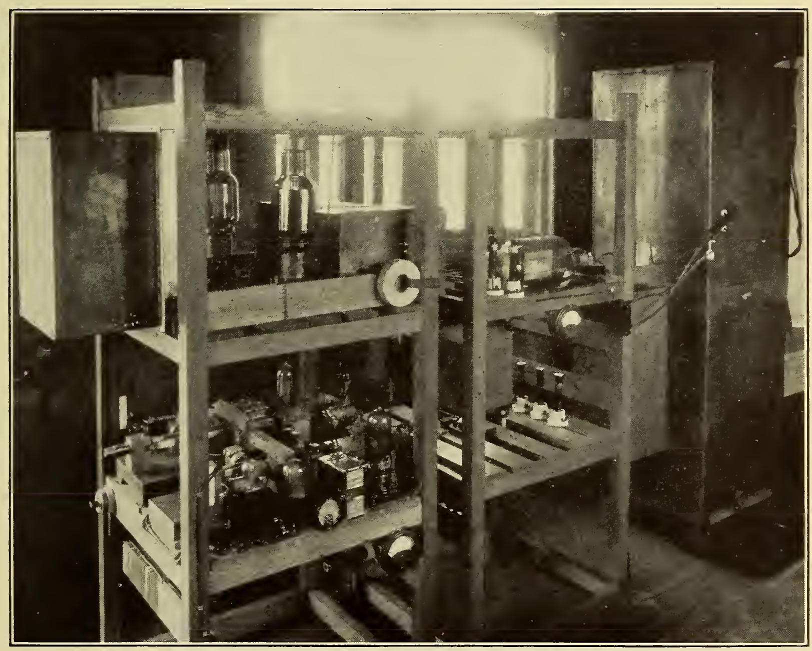

FIGURE 12.—*Transmitting set for double-modulation beacon using tuning fork modulation*

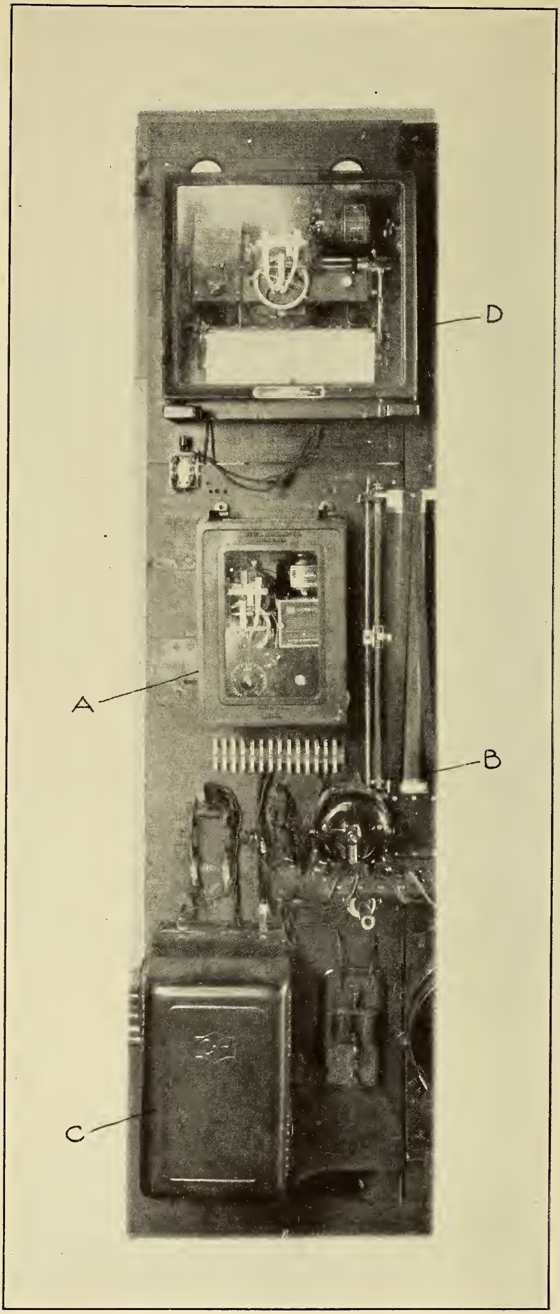

FIGURE 14.—*Control panel for constant frequency unit*

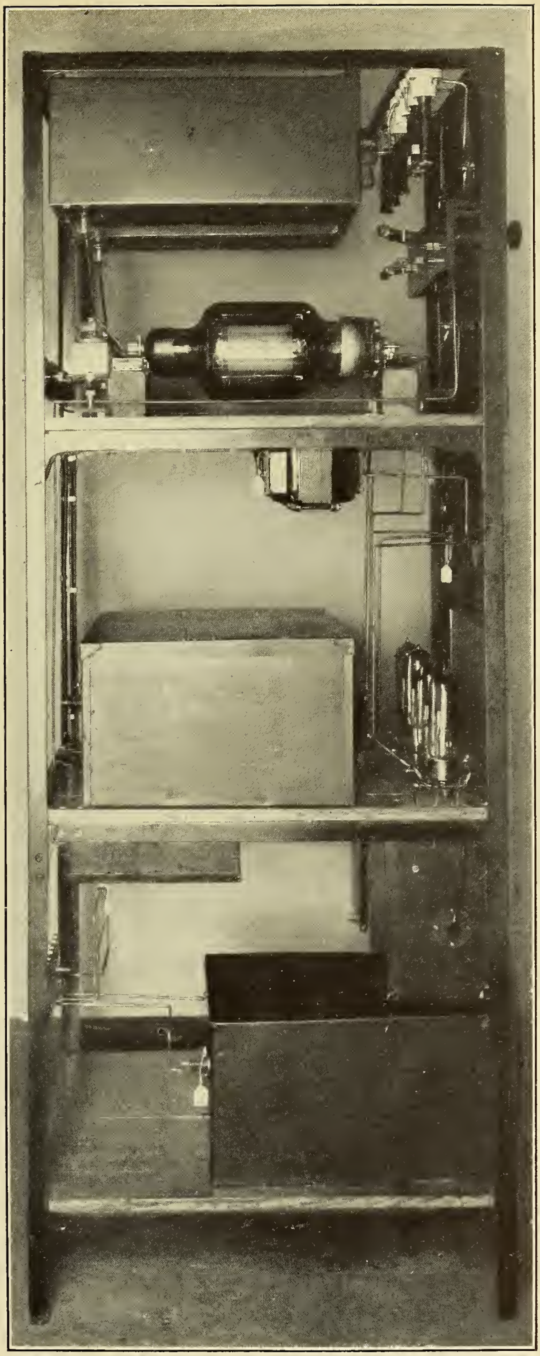

FIGURE 15.—*Transmitting set for double-modulation beacon using simplified modulation*

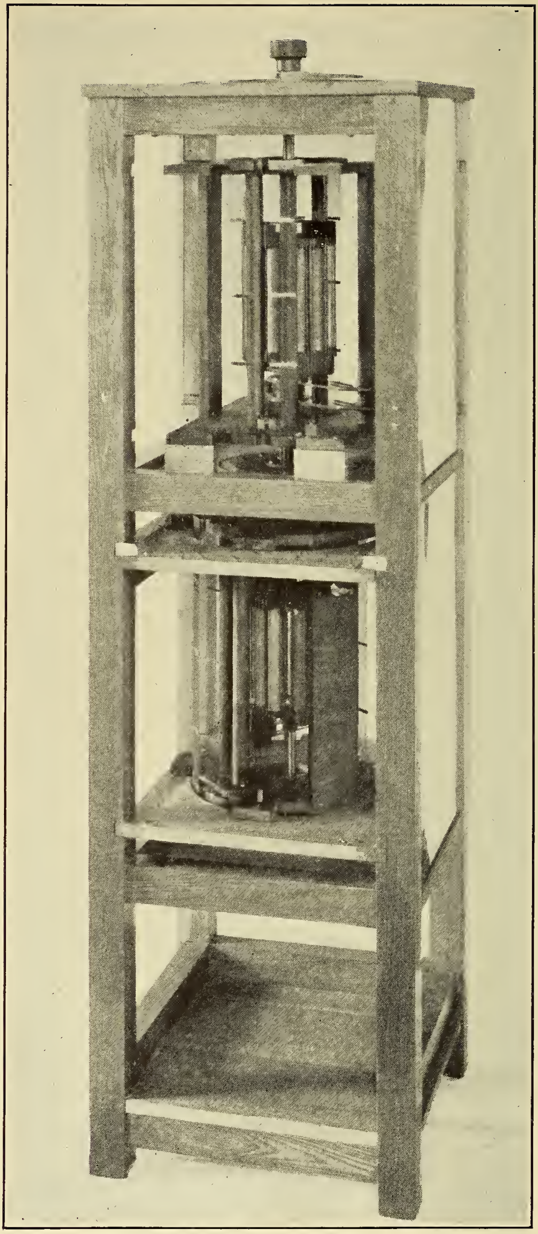

FIGURE 16.—*Double rotor type goniometer used with double-modulation beacon*

must be employed, with provisions for controlling its speed within the desired limit of accuracy. The securing of a suitable constant-speed motor has been difficult. While the advent of television has given considerable impetus to the development of constant-speed motors, most of these are not of sufficient power. A constant-speed unit having the desired characteristics was finally obtained through the cooperation of the Leeds & Northrup Co. and has been in satisfactory operation at College Park for several months. This motor is essentially a rotary converter operated inverted, a portion of the alternating current output being impressed upon a frequency bridge. This bridge operates a galvanometer which controls, through suitable relays, a motor-driven field rheostat connected in the shunt field circuit of the rotary converter. Any change in output frequency of the converter thus results in a change of the speed of the converter in such direction as to correct for the frequency change. A constancy of speed within 0.1 per cent is thus maintained. A photograph of the control panel showing the frequency controller, *A*, the motor-driven field rheostat, *B*, and the automatic starting box, *C*, is shown in Figure 14. A frequency recorder, *D*, used for checking the degree of speed constancy, is also shown. Figure 15 is a photograph of the beacon transmitter using the simplified modulation arrangement. The rotating machinery made necessary when using this modulation is more than compensated for by the great simplification in the transmitting circuit and the attendant improvement in performance and stability. The number of transmitting tubes employed is reduced from 18 to 8.

As noted above, intercoupling between amplifier branches was found to affect the usefulness of the beacon space pattern. To reduce this coupling to a minimum it was found necessary to redesign the goniometer, placing the stator windings in separate compartments in order to facilitate shielding between them. This is indicated in Figure 16. Duplicate rotors, one being placed in each compartment (see figs. 13 and 16), served to make this goniometer the electrical equivalent of the earlier type.

An improvement in the operation of the beacon was obtained by a change in the location of the loop-antenna tuning condensers. Previously the tuning condensers were inserted in the base of the triangular loop antennæ, as shown in Figure 11. The distribution of voltage along the antenna is then as indicated in Figure 17 (a), the portion of the antenna nearest the ground being at the highest potential. With this connection it was found that the tuning of the antennas changed considerably with the weather, often affecting the course settings. The effective capacity to ground constituted the variable factor. By placing the tuning condensers at the apices of the antennas (see fig. 13) the voltage distribution becomes that shown in Figure 17 (b), the portions of the loop antennas nearest the ground being at the lowest potentials. The effect of the weather on the tuning is then very much reduced. The weatherproof box used for housing the tuning condensers on top of the beacon tower may be seen in Figure 2.

4. ADAPTATION OF BEACON TO FOUR INDEPENDENT COURSES

In order to use the beacon practically at any airport, it is necessary to adjust the angles between the equisignal zones arbitrarily so as to make them coincide with the airways converging on the airport.

To understand how this may be done, it is necessary to study the polar pattern of the field radiated by the double-modulation beacon (11).

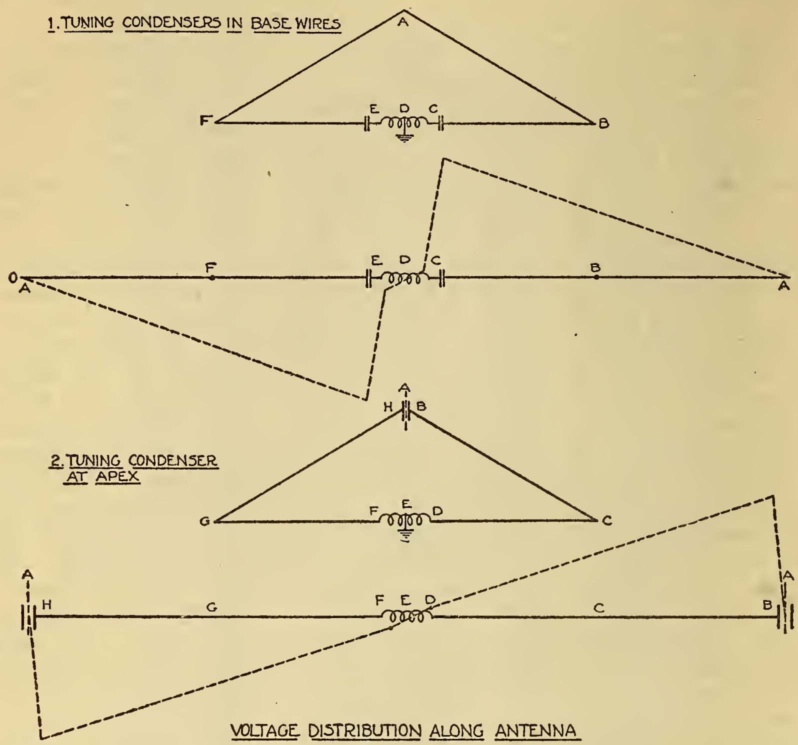

FIGURE 17.—*Voltage distribution along loop antennæ for two different locations of the tuning condensers*

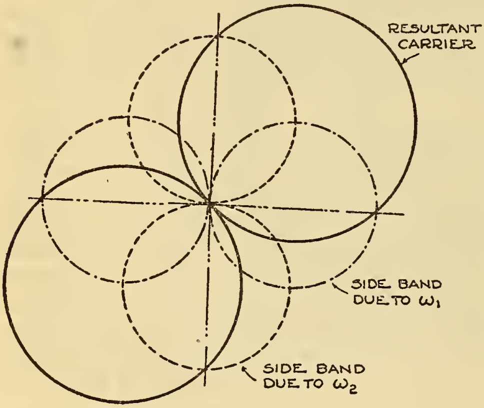

FIGURE 18.—*Space pattern radiated by double-modulation beacon when the carrier currents in the two antennæ are in time phase*

One loop antenna radiates a 290-kc. wave modulated to 65 cycles, while the other loop antenna radiates a 290-kc. wave modulated to 86.7 cycles. The wave due to each antenna may be resolved into a carrier and two side bands. The carriers in the two loop antennæ being of the same frequency and in time phase, combine into a carrier having its maximum intensity along a plane bisecting the angle between the two antennæ. The side bands of the two antennæ do not combine, since they are of different frequencies. The maximum intensity of each side band is therefore in the plane of the antenna radiating it. The space pattern indicating the field intensities of the combined carrier and the two sets of side bands is shown in Figure 18. Since the reeds operate as a result of the low frequencies in the receiving set output produced by the beating of the side-band frequencies with the carrier in the detector, they respond to a space pattern characteristic as indicated in Figure 19. This assumes a square-law detector. It will be noted that but two courses are produced, practically no signal being radiated in the directions at right angles to these courses.

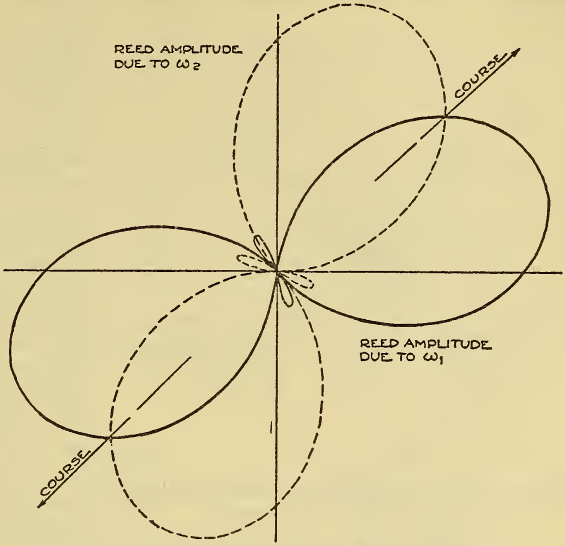

FIGURE 19.—*Received pattern corresponding to space pattern of Figure 18*

In many cases the elimination of the two 90° courses is desirable. In the application of the beacon to course navigation on the airways, however, airports requiring only two courses 180° from each other are the exception rather than the rule.

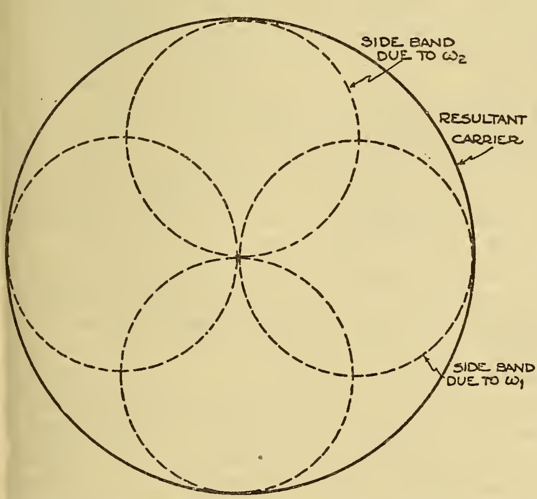

FIGURE 20.—*Space pattern when the carrier currents in the two antennæ are 90° out of time phase*

At those airports where two courses are sufficient, these are usually at an angle other than 180°. The beacon may be easily modified to permit the use of four courses at arbitrary angles. By a suitable coupling arrangement to the master oscillator, one of the carrier-frequency currents can be advanced in phase 90° ahead of the other. Since the two loop antennæ are in 90° space phase and their carrier currents in 90° time-phase relationship, a revolving field is set up in space, so that the carrier space pattern becomes circular. (See fig. 20.) The polar pattern as received by the reeds is that indicated in Figure 21, four courses being obtained.

These four courses may be shifted considerably from their 90° relationship in order to make them coincide with the airways converging on a given airport. Several methods are employed for effecting the course shifting. One consists of reducing the magnitude of current in one of the two loop antennæ. A second method utilizes the circular radiation from a vertical antenna extending along the beacon tower, in addition to the normal figure-of-eight radiation due to each loop antenna. The vertical antenna is coupled to the output circuit of either one or both of the two amplifier branches of the system, the space pattern due to either one or both loop antennæ being thus altered. Combinations of the two methods described are also useful. A detailed description of these methods and an analysis of their degrees of usefulness are given in a separate paper (12).

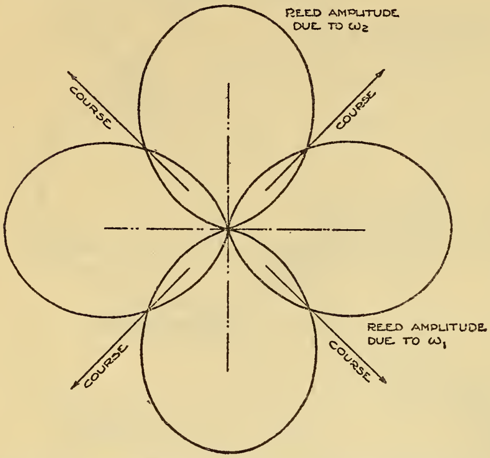

FIGURE 21.—*Received pattern corresponding to space pattern of Figure 20*

5. STATION COURSE-SHIFT INDICATOR

In the practical operation of a radiobeacon system it is necessary to make periodic checks of the correctness of the courses it marks out. For this purpose an indicating instrument was developed and put into operation at College Park, Md., which makes possible the checking of the courses of the 2 or 4 course beacon to within an accuracy of 0.1 of a degree (13). This device indicates at the station whether the courses as laid out in space remain unvarying from day to day. If such variation occurs this instrument shows it, and an adjustment of the transmitting set may then be made to correct this deviation, thus eliminating the necessity of recalibration at a distant point.

The circuit arrangement used in applying this instrument at the beacon station comprises a rotatable pick-up coil inductively coupled, preferably with equal coupling, to the two loop antennæ of the beacon, a detector-amplifier unit, a suitable filter unit, and a differential ratio instrument. The ratio instrument consists of two fixed field coils and an armature or rotor coil. A pointer attached to the rotor coil moves over a suitable scale. The force actions of the two field coils upon the rotor coil are in opposition, so that with equal currents in the field coils the pointer assumes a mid-scale position. The filter unit is so designed that with equal 65 and 86.7 cycle voltages impressed upon the instrument equal currents flow through the field coils. If the 65-cycle voltage becomes greater than the 86.7-cycle voltage, one field coil carries a greater current than the other and the net force acting upon the rotor coil becomes greater than zero, the pointer attached to the rotor coil moving to the left of its mid-scale position. The reverse is true if the 86.7-cycle voltage becomes greater than the

65-cycle. The differential action of the two field coils upon the rotor coil, therefore, serves directly as a means for comparing the relative amount of 65 and 86.7 cycle modulation in the radio-frequency voltages induced in the pick-up coil.

Recalling, now, that the pick-up coil is inductively coupled to the two antennæ of the beacon, rotating this coil about its axis changes the relative coupling to the two antennæ both in magnitude and in sign. Rotating this coil is therefore equivalent to circling the beacon with a nondirectional receiver. There are, then, as many positions of this coil at which the ratio instrument reads zero (that is, equal 65 and 86.7 cycle voltage are induced in the coil) as there are beacon courses. If these coil settings have been determined during the original calibration of the beacon, the correctness of the courses marked out by the beacon may be checked at any later time in very simple fashion. The ordinary course indicator may, of course, be used to replace the differential ratio instrument, together with its filter unit. The accuracy of the course settings will then not be as great (1° to 2° rather than 0.1°).

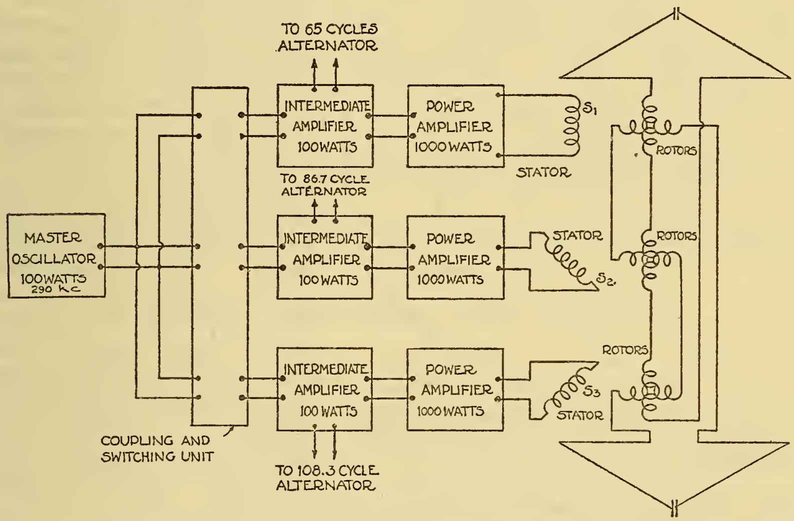

FIGURE 22.—*Schematic diagram of triple-modulation beacon*

IV. THE TRIPLE-MODULATION BEACON SYSTEM

1. TRANSMITTING ARRANGEMENT

To render the beacon system still more flexible and thus make it suitable for use at cities located at the junction of a large number of airways, a beacon transmitter was developed capable of serving 12 courses simultaneously. The increase in apparatus over the beacon described above is not great. The same crossed-coil antenna system and the same circuit arrangements are employed (see fig. 22), except that three amplifier branches, modulated to three different frequencies, are necessary. The modulation frequencies used are 65, 86.7, and 108.3 cycles, respectively. A special goniometer is also required. The rotor system of this goniometer is the same as before; three stator coils are, however, required, one stator coil being connected to each power-amplifier tube. The stator coils are disposed at 120° to each other, although these angles may be deviated from in order to obtain certain desired conditions.

Since the stator coils are not at right angles to each other, it is essential that but one stator be excited at any given time in order that coupling between stators be avoided. This is accomplished by radio-frequency switching provided in the grid circuits of the intermediate amplifier tubes. By means of a suitable coupling arrangement to the master oscillator the carrier voltages applied to the grid circuits of the three intermediate amplifiers of the transmitter are displaced by 120° in time phase from each other. The modulated voltages applied to the three stator coils are thus similarly displaced. Consequently neglecting the fractions of a cycle when any two of the three voltages are of like sign,[3] but one stator is excited at a time. Further information regarding this method of switching is given in a separate paper (14).

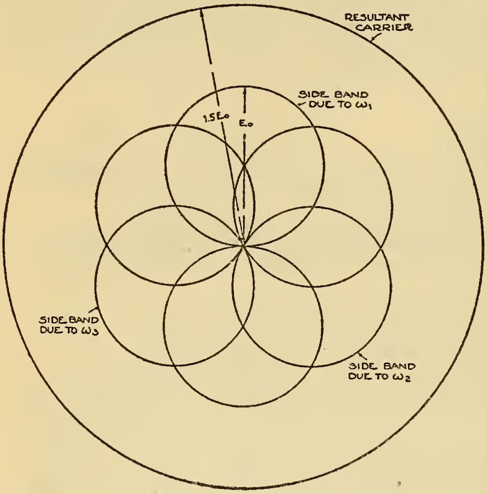

FIGURE 23.—*Space pattern radiated by triple-modulation beacon using radio-frequency switching*

Referring to Figure 22 it will be observed that one stator carries a 290-kilocycle current modulated to 65 cycles, the second stator a 290-kilocycle current modulated to 86.7 cycles, and the third stator a 290-kilocycle current modulated to 108.3 cycles. Each stator, acting in conjunction with the two crossed rotor coils and the two crossed loop antennæ, sets up a system which is electrically equivalent to a single loop antenna. For zero rotor setting the plane of this phantom antenna coincides with the plane of the stator coil considered. Since there are three stator windings, normally disposed at 120° to each other, three such phantom antennæ (also crossed at 120°) exist, each phantom antenna carrying current of the same radio-frequency, but modulated to a different low frequency. The space pattern radiated by the beacon is given in Figure 23. The carriers in the three phantom antennæ being 120° out of phase both in time and in space, a revolving field is set up, the resultant carrier space pattern being represented as a circle. The three sets of side bands are of different frequencies and do not combine. Assuming square-law detection, the polar pattern as received on the reeds is given in Figure 24. This pattern is obtained by the beating of each side band with the in-phase components of the three carriers making up the resultant revolving field. (See (14).)

[3] This assumption is permissible, since the power transmitted during these fractions of a cycle is small.

As will be observed from Figure 24, 12 useful courses exist, any two adjacent courses being separated by 30°. Of the 12 courses, 4 courses (*M*, *N*, *O*, *P*) can be received by a reed box tuned to 65 and 86.7 cycles, 4 courses (*Q*, *R*, *S*, and *T*) by a reed indicator tuned to 86.7 and 108.3 cycles, and 4 courses (*W*, *X*, *Y*, and *Z*) by an indicator tuned to 65 and 108.3 cycles. The equisignal zone of 2 of each set of 4 courses (for example, *M* and *N*) is from 1° to 1.5° wide, while the equisignal zone for the other two courses (viz, *O* and *P*) is from 2° to 3° wide.

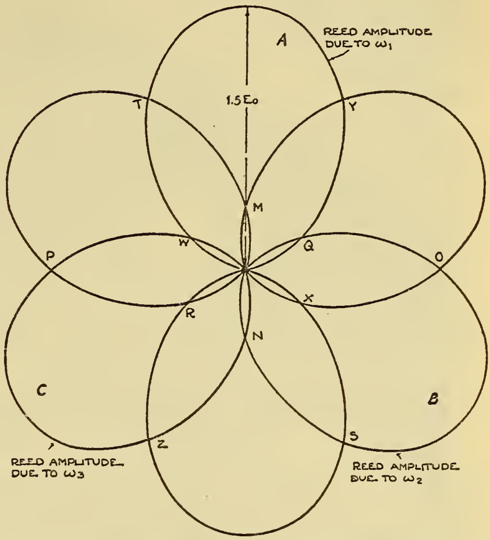

FIGURE 24.—*Received pattern corresponding to space pattern of Figure 23*

A 12-course radio range of the type described has been installed at College Park, Md., and is giving satisfactory results. On the basis of the results obtained, the Airways Division of the Department of Commerce is constructing seven sets of this type with a view to perfecting the design and employing these sets on suitable air-mail routes.

2. SPECIAL THREE-REED COURSE INDICATOR

To obviate the necessity for using three separate indicators in order to receive all 12 beacon courses, a special course indicator containing 3 reeds tuned to the 3 modulation frequencies of the beacon has been developed. Using this indicator, any 1 of the 12 beacon courses may be followed. Two shutters are employed on the indicator front. One shutter serves to expose any 1 of the 3 sets of reed combinations which go to make up the 12 course indications, each reed combination (for example, the two reeds tuned to 65 and 86.7 cycles, respectively) serving 2 sets of 2 courses (viz, *M*, *N*, and *O*, *P* of fig. 24). Two different colors are exposed corresponding to each setting of this shutter in order to facilitate the choice of the proper 2 reeds for a given course. Thus, if on the airways map, courses *M* and *N* are shown in black and courses *O* and *P* in red, the shutter setting which exposes the 2 reeds tuned to 65 and 86.7 cycles, respectively, also exposes the 2 colors black and red. The second shutter provided on the indicator front serves the same purpose as the shutter used with the 4-course indicator (see Sec. III, 2); that is, to simplify the choice of the proper relative position of the two reeds in use in order that the rule (longest reed shows side off course, turn to the shorter reed) may apply. This shutter has two settings, one exposing the words [TO FROM] and the three colors corresponding to the three sets of courses (M, N), (Q, R), and (W, X) (see fig. 24), while the other setting exposes the words [FROM OL] and the colors corresponding to the three sets of courses (O, P), (S, T), and (Y, Z). The pilot uses the 12-course indicator exactly as he would the 4-course indicator, except that he must set 2 shutters to expose the color (according to the airways map) of the course to be flown rather than one.

A photograph of this special 3-reed indicator mounted on the intrument board of an airplane is shown in Figure 25. The indicator is of cylindrical shape in order to conform with the other airplane instruments. The operating characteristics of this indicator are the same as for the 2-reed type, with the exception that since three pairs of actuating coils are employed, 50 per cent greater voltage is required for equivalent reed deflections. The sensitivity may be made equal to that of the 2-reed type by means of a suitable arrangement for switching out the pair of coils controlling the reed not in use. This special indicator is further described in (10).

3. ADJUSTING THE COURSES TO AIRWAYS AT ARBITRARY ANGLES

With the 12-course radio range, as with the 4-course type, the problem of adjusting the angles between the beacon courses arbitrarily so as to make them coincide with the airways converging on a given airport must be solved. The methods previously described (see Sec. III, 4) for effecting the arbitrary shifting of the courses of the 4-course beacon from their normal positions are all applicable to the 12-course system. The first method described is the simplest and may well be employed. The other methods, although entirely practicable, are not quite as simple and need not be used, particularly since an additional method, applicable only to the 12-course beacon and very simple, is available.

This method consists of displacing the stator windings from their 120° space relationship, thereby modifying the space pattern radiated by the beacon. It will be recalled that for zero rotor setting the plane of each phantom antenna coincides with the plane of the stator winding which produces it. A displacement of a given stator winding, therefore, results in a displacement of the space characteristic due to the phantom antenna associated with that stator winding. The space characteristics of the three phantom antennas may, therefore, be crossed at any angles found desirable. This does not mean, however, that in the received polar diagram (see fig. 24) the three component characteristics (A, B, and C) are necessarily crossed at the same angles. As stated previously, each set of side bands beats with the in-phase component of the carrier due to each phantom antenna, yielding the received polar pattern corresponding to that side band. When the three sets of side bands (and consequently the three carriers) are symmetrically disposed in space, there is reason to expect a symmetrical received pattern. With an unsymmetrical radiated space pattern, however, the received pattern is not necessarily similar to the radiated pattern. Nevertheless, the three component characteristics of the received pattern are displaced from their 120° relationship, the angles between adjacent beacon courses being, therefore, adjustable.

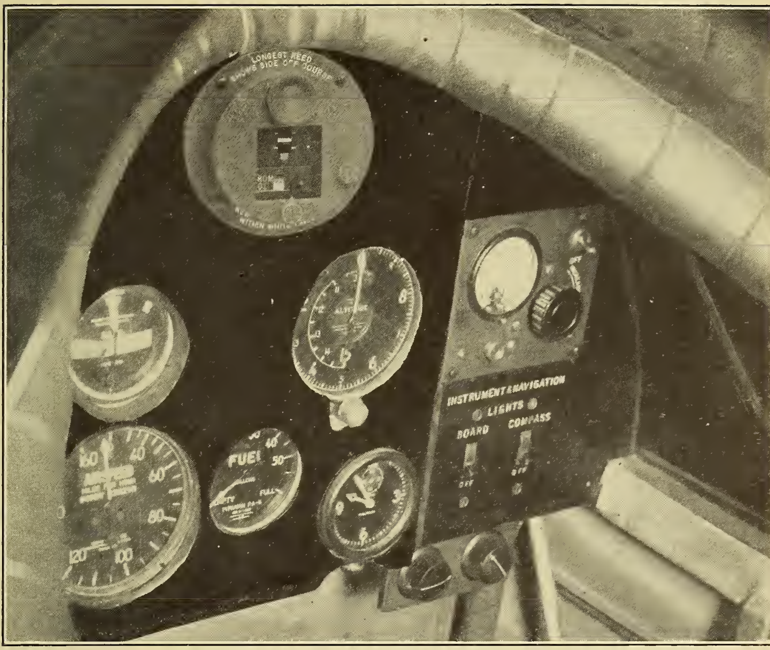

FIGURE 25.—*Special 3-reed course indicator mounted on airplane instrument board*

FIGURE 26.—*Airplane showing vertical pole antenna*

Using the two simple methods outlined it becomes possible to adjust the angles between the beacon courses over a wide range of values. (See (14).) Obviously, each installation will require a different adjustment, which may be more or less difficult. The statement that these methods will prove successful in all possible cases can not therefore be made.

4. INDICATION OF CORRECTNESS OF COURSES

The course-shift indicator described for use in checking the correctness of the courses marked out by the 4-course beacon is not applicable for use with the 12-course system. If the circuits of the filter unit could be made sufficiently sharp to exclude the third modulation frequency (108.3 cycles), this device could be used for checking 4 of the 12 courses. It is difficult to obtain the necessary sharpness of tuning. The special 12-course indicator is therefore used to replace the differential ratio instrument and filter unit, thus making possible the checking of all 12 courses to within 1° to 2°.

V. AIRPLANE RECEIVING EQUIPMENT

1. AIRPLANE RECEIVING SETS

The beacon system can be used with any receiving set which operates at the frequencies employed merely replacing the telephone receivers by the simple reed-indicator unit. There are, however, a number of special conditions involved in receiving on an airplane, and the bureau has developed special receiving sets (15) in order to use the beacon system under the most advantageous conditions.

The receiving set designed employs 6 tubes and weighs less than 15 pounds, the auxiliary batteries weighing an additional 10 pounds. The receiving set operates in the frequency range from 285 to 350 kc. and is used to receive either the beacon signals or radiotelephone weather messages at will. It is highly selective and sensitive. The audio-frequency amplifier is specially designed to be efficient at the low-modulation frequencies used in the beacon. The selectivity of the set is supplemented by the selectivity of the vibrating reeds, which helps greatly in reducing interference. Nevertheless, it is important that a good degree of selectivity be provided in order to make the most efficient use of the frequency channels provided for this service, and also to make the receiving set suitable for the reception of weather telephone messages. The set has remote-control arrangements for tuning and volume, so that it may be mounted in any location on the airplane.

The bureau interested several manufacturing companies in building receiving sets of suitable characteristics. Three companies are now ready to furnish receiving sets, all of which have proved satisfactory.

The result of more than two years of flying on the visual-type radio range has proved that a receiving set designed for beacon reception should have as high an undistorted power output as possible. Since the reeds are practically immune to interference, atmospheric and other disturbances will not affect their operation unless they are of sufficient strength to overload the receiving set. The greater the overload point of the receiving set the greater will be the range of the beacon during severe interference.

The incorporation of an automatic volume control is highly desirable, since such a device would still further reduce the effort expended by a pilot in making use of the radio navigational aids. The 2-course, the 4-course, and the 12-course visual radio ranges as now employed will each function properly with or without automatic volume control. Automatic volume control is, however, not possible with the aural radio range, since its effect would be to reduce to equal signal strength the two coded signals the relative magnitudes of which it is desired to compare. The chief value of automatic volume control with the visual radio range would be within 10 to 15 miles of the beacon in the region where the beacon signal strength changes most rapidly. At great distances from the beacon an auxiliary manual control would be essential, since the effect of large interfering signals (when using automatic control) would be to reduce the amplitude of vibration of both reeds. This may well prove troublesome, particularly since interference is normally intermittent in nature.

2. AIRPLANE ANTENNA

The development of receiving sets having the necessary sensitivity made possible the use of an antenna system on the airplane, consisting of a metal pole extending vertically from the fuselage, the total length of this pole being but 6 to 8 feet. (See fig. 26.)

The antenna system in common use on airplanes previous to this development was the weighted trailing wire. This system had numerous disadvantages. It was heavy, difficult to handle, and dangerous. It had marked directive properties, resulting in erroneous indications of the beacon course unless it lay in the vertical plane containing the transmitting station (16); in additional errors when near the beacon (where the angle between transmission path and ground is appreciable); and in marked apparent variations of the beacon courses at night.

The existence of errors at night in the apparent direction of radio stations has long been known (17, 18). Investigations as to the causes of direction shifts have been under way for some time (19), and experimental proof has been secured that these shifts are largely due to the horizontal component of the downcoming reflected or refracted wave. The existence of these apparent shifts in the directive radiobeacon courses was first observed in August, 1927 (20). The tests were made on the aural type beacon using a trailing-wire antenna for receiving on the airplane. The results of these tests are summarized below.

1. Within 25 miles of the beacon the shifting was not of a very serious nature.
2. At 50 miles the shifting became pronounced, but due to the zone appearing to be stationary in its proper position for possibly 75 per cent of the time, the beacon could still be depended upon when used with judgment.
3. At a distance of 100 miles the shifting became very pronounced and persisted for more than 50 per cent of the time, giving the beacon a questionable value.
4. At 125 miles the beacon was of no further use as a guide.

Later tests made on the ground, and also reported in reference (20), indicated that the use of a vertical antenna reduced to a considerable degree the amount of variation of the course. This was one of the contributing reasons which led to the adoption of the vertical pole antenna. Since this type of antenna is not affected by horizontal electric fields, the results obtained were in accordance with what was expected.

More recent tests carried on periodically during the past two years, using the visual type beacon, tend to corroborate these results. With tuned-reed indication it became possible to estimate more closely the variation of the courses in degrees. The tests were made in the air and on the ground, the results obtained in each case being very nearly the same. These results are summarized below.

1. Within 75 miles of the beacon the shifting was not serious.

2. At a distance of 125 miles the shifting was readily detectable, maximum variations ranging from 10° to 20° being observed. The period of the variations appeared regular, the reed indicator showing "off course" first to one side and then to the other. However, the true course could still be estimated with a fair degree of accuracy, visual indication having the psychological effect of averaging out the variations.

3. At a distance of 200 miles the course shifting appeared not very much worse than at 125 miles, an estimation of the true course being still possible. Not enough data was taken at this distance to permit of definite conclusions.

The improvement due to the use of the vertical antenna is evident. The normal range expected from the beacons is about 125 miles. For this range the apparent night variations of the course should not prove serious.

An added advantage for the use of the vertical pole antenna is that it becomes possible to guide an airplane directly over the beacon tower. With the trailing wire this was a difficult feat, becoming impossible when a side wind produced a side slant to the antenna. Furthermore, since the vertical antenna is affected only by vertical electric fields, a region of zero signal is met with directly above the beacon tower, where no vertical field exists. The beacon can thus be located to within 100 to 200 feet when the airplane is not over 1,000 feet above it, a most valuable aid in fog.

3. ENGINE IGNITION SHIELDING

The use of a sensitive receiving set, together with a short vertical antenna located near the airplane engine ignition system, makes necessary a considerably more rigorous shielding of the ignition system than was previously required to prevent ignition interference. The entire electrical system of the ignition must be encased in a high-conductivity metallic shield. This requires that the magnetos be provided with such metal covers as will completely inclose the distributing heads. The booster-magneto outlet must also be covered. All distributing wires must be inclosed in a metal tube or braid, the spark plugs must be completely shielded and the booster leads and leads to the ignition switch, including the ignition switch itself, similarly treated.

The bureau has been in active cooperation with airplane engine, magneto, spark plug, and cable manufacturers in an effort to develop a safe method for effecting this shielding and to make the necessary equipment available commercially. As a result of this cooperation, suitable shielding assemblies may now be purchased for use on all Wright and Pratt-Whitney airplane engines. A metallic ignition manifold is employed with high-tension cable drawn through it in the usual way. The leads from the manifold to the spark plugs and the groups of leads from the manifold to the magneto outlets are inclosed in liquid-proof flexible aluminum tubing with copper braid on the outside to insure effective shielding. Each flexible tube is suitably fitted to the ignition manifold and to the magnetos or spark plugs, as the case may be. The magnetos are provided with covers which completely inclose the distributor blocks. A single outlet permits the use of an elbow fitting for connection to the large flexible metal tubing. This elbow fitting differs for different types of engines. Outlets are provided in the elbows for the booster and ground leads. The spark plugs are of a type in which the shield is an integral part and are provided with elbows for connection to the smaller flexible metal tubing. The ignition switch is totally inclosed in a metal cover, the booster magneto is also covered, and the leads from the magnetos to the ignition switch and booster magneto are inclosed in flexible metal tubing. The complete assembly insures electrical safety, mechanical sturdiness, liquid proofing of magnetos, spark plugs, and ignition cable, and ease of installation and of servicing.

At a conference held at the Bureau of Standards on June 11, 1929, in response to a number of requests from representatives of the aircraft and radio industries, the present status of shielding was discussed. In addition, a beginning toward the standardization of shielding-assembly practice was made and a series of standard tests whereby the mechanical, electrical, and radio efficiency of a given shielding installation may be determined were adopted.

Further details regarding the bureau's work in this field are given in a separate paper (21).

VI. MARKER BEACONS

The directive radiobeacon will successfully guide a pilot along a given course, but does not directly indicate his exact location along that course. Where it is desirable that this indication be given (for example, at the intersection of two beacon courses or at a dangerous portion of the airway), it can be obtained by the installation of a small marker-beacon transmitter of very low power (a few watts). The marker beacons operate on the same radio-frequency as the main beacon. This signal operates a 40-cycle reed indicator mounted at a suitable location on the airplane instrument board and connected in series with the main course indicator, and is received for two or three minutes as the airplane passes over the marker. The pilot can thus locate his exact position on the airway.

The first experimental work with the marker beacon involved the use of a reed indicator tuned to 60 cycles. Modulation of the marker beacon was accomplished by supplying the oscillator with a plate voltage secured from the commercial 60-cycle supply. This resulted in an inexpensive marker-beacon transmitter. The use of 60 cycles was not practicable, however, since a 5-cycle flutter was observed on the 65-cycle reed of the main course indicator during the entire period that the receiver was within the range of the marker-beacon transmitter. This destroyed the usefulness of the main beacon course during that period. A self-rectifying circuit, still using the 60-cycle supply but giving a 120-cycle modulation frequency, was then tried, the marker-beacon reed being tuned to 120 cycles. The 5-cycle flutter on the 65-cycle reed still occurred. The frequency of 40 cycles was then chosen. The beat frequency (25 cycles) is then sufficiently high so that neither reed has opportunity to follow this beat frequency owing to mechanical inertia. A 4-pole alternator driven by a 6-pole synchronous motor operated from the commercial supply is used as the 40-cycle source.

In the earlier experiments it was decided to use an open antenna with the marker beacon and to code the transmitted signal with a characteristic corresponding to that used on the light beacon at the same location (if there is one there). The use of an open antenna is, however, not entirely satisfactory. A sharp indication of the exact marker-beacon location is obtained only when passing directly over the antenna, a region of zero signal being then observed. The use

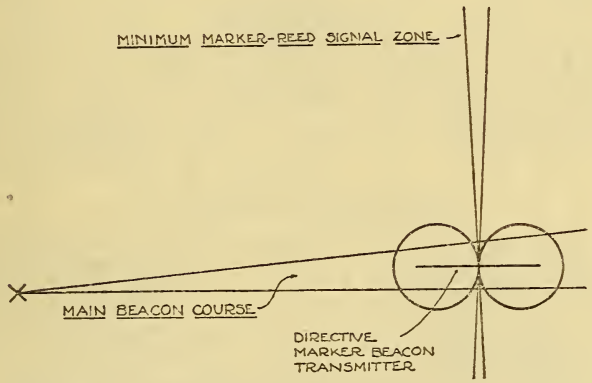

FIGURE 27.—*Diagram illustrating use of directive marker beacon on the airways*

of a loop antenna, oriented as shown in Figure 27, removes this objection. As will be observed from the loop characteristic, sharp indication of a line perpendicular to the airway route is obtained, a drop in the marker-beacon reed indicator deflection being observed when crossing this line. Coding of the transmitted signal is, however, not practicable when using this antenna arrangement. Actual use on the airways will determine which antenna system is the more desirable.

When located at the intersection of two main beacon courses, an arrangement must be provided on the marker beacon to permit the emission of its signal on each of the two radio-frequencies used by the main beacons. A satisfactory audio-frequency switching arrangement for accomplishing this purpose has been developed and is included in the circuit diagram of Figure 28. Either open or loop antennæ may be employed. The two antennæ shown are tuned to the two different beacon frequencies. These are excited alternately at a 40-cycle rate by means of transformer *G*.

VII. FOG LANDING

By the use of the radiobeacon system described, it will become entirely feasible to fly between any two points along a given airway and to arrive within a few thousand feet of the desired destination regardless of weather conditions. The problem of effecting a safe landing during fog and extremely low visibility is not yet, however, completely solved.

Recent tests indicate that fog-penetrating lights are not yet available. The dissipation of fog by mechanical means has been the subject of considerable laboratory experimentation, the general result being that it is not economically possible on a useful scale.

The most feasible method of attack at the present time appears to be in the application of radio. When attacked from this angle, the problem of fog landing resolves itself into two separate problems, namely, field localizing and the development of a suitable altimeter.

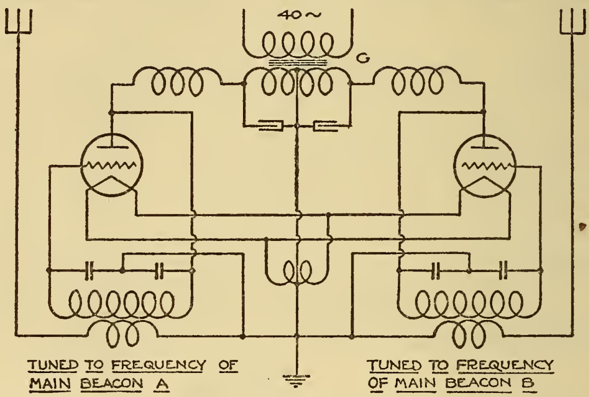

Figure 28.—*Circuit diagram of marker beacon located at the intersection of two main beacon courses*

1. FIELD LOCALIZERS

Practically all previous experimentation in this field has been in the use of "leader cables." The principal installations are those of the British Government at Farnborough and of the French Government at Chartres. The British installation uses a complete circuit around the landing field with a visual indicator on the airplane instrument board. The French installation uses straight cables. The Loth Co., of Paris, has also conducted experimental work using straight cables.

The ground equipment at Farnborough consists of an oval loop of cable about 5 by 2 miles buried 2 feet in the ground. One of the straight sides of this oval loop passes through the airdrome. Near this straight side and surrounding the portion of the airdrome free from obstructions is a second smaller oval loop. A pilot circles around the major loop coming lower and lower. Once each revolution he receives a signal from the smaller loop indicating that he is directly over the airdrome. When he is at a sufficiently low altitude and over the airdrome a safe landing may be effected. An obvious disadvantage of the leader cable method of field localizing is its great cost.

The success obtained with the radio range in its application to point-to-point flying suggests its possibilities as a field localizer. With the main beacon used for guiding an airplane to a given landing field, a low-power beacon with small loop antennæ may be employed for marking out the major, or most desirable axis or runway of the landing field. This can be done quite as effectively as with leader cables. For example, consider a class A field having the required dimensions of 2,500 by 2,500 feet with two perpendicular runways at least 300 feet wide. The equisignal zone of the two-course radiobeacon is at a maximum 5° wide. (The use of the 2-course beacon is here assumed because of the obvious advantages of eliminating the 90° courses.) If, then, a course is oriented along a particular runway, with the beacon at one end of the field, a pilot can locate the axis of this runway at the other end of the field within 100 feet. He is thus certain to land on the runway.

An installation has been made at College Park, Md., and a second installation for the Guggenheim Fund for the Promotion of Aeronautics at Mitchel Field, Long Island, with a view to obtaining a practical arrangement. Each installation includes a localizing beacon for guiding an airplane along the major runway of the field and suitably placed marker beacons for defining the beginning of the hazard-free approach to the field and the limits of the field. This arrangement, combined with a suitable landing altimeter, gives promise of making fog landing feasible.

3. LANDING ALTIMETERS

The method of fog landing demonstrated by Lieut. J. H. Doolittle, of the Guggenheim fund (33), consists of maneuvering the airplane into a glide from a position in space of fixed bearing and altitude with respect to the landing field. The barometric altimeter is adjusted to read altitude above the field based on data communicated from the ground. If the landing is entirely blind, the glide continues until a landing is made without the usual "flattening-out," owing to the lack of knowledge of the altitude to the accuracy required.

Experiments are being undertaken by a number of investigators looking toward the development by several means of altimeters indicating the absolute height above ground. One is the developments of a sonic altimeter. Another device is the capacity altimeter which measures the distance from the ground by detecting the change in the electrical capacity between two plates on an airplane, as the airplane approaches the ground. A third method is by the use of direct reflection with radio waves. It is doubtful at the present time whether any of these instruments will be sufficiently sensitive for use in "flattening-out" so as to make a normal landing. These instruments when available will, however, be exceedingly valuable in determining the altitude from which the glide shall be started in landing and also in maintaining a safe altitude during point-to-point blind flying.

The bureau is conducting experiments on making possible normal three-point landings in dense fog. A special radio beam at the landing field is so oriented in space as to define the proper gliding path which if followed will permit such landings. Experiments on the production of such a beam with a suitable visual indicating device on the airplane show some measure of success. High frequencies are employed (about 70 megacycles), making the necessary equipment on the ground and on the airplane rather simple. This arrangement, if found suitable, will, of course, merely obviate the need for an altimeter in landing; the localizing and marker beacons will still be necessary.

VIII. TESTS OF THE BEACON SYSTEM

The practicability of the visual radio range system described has been demonstrated by a considerable amount of test flying on the College Park station. The useful distance range of the beacon under summer and winter conditions is a function of the power used at the beacon station, the length of receiving antenna, sensitivity and overload point of receiving set, sensitivity of the reed indicator, and degree of airplane-engine ignition shielding.

Using 1 kw. tubes in each power-amplifier stage of the beacon transmitter, a current of 12 amperes may be obtained in each loop antenna. The antennæ are triangular in shape with a base 300 feet long and a net height of 70 feet. On the airplane a receiving antenna 6 to 8 feet long was employed. The receiving set with which 90 per cent of the tests were made has a sensitivity of about 120 decibels and begins to overload slightly at an output voltage of 12 volts. Serious overloading occurs when the output voltage is 20 volts. The 4-course reed indicator has an impedance of about 4,000 ohms and requires 4 volts across its terminals to give normal reed deflection; the 12-course reed indicator has an impedance of about 6,000 ohms and requires 6 volts. Perfect ignition shielding is assumed. Under these conditions, the average winter range of the 4-course beacon is 200 miles and the average summer range about 100 miles. With the 12-course beacon the useful distance depends upon the courses used. Referring to Figure 24, the range on courses *M*, *N*, *Q*, *R*, *W*, and *X* is 150 miles in the winter and 75 to 90 miles in the summer, respectively. The range on courses *O*, *P*, *S*, *T*, *Y*, and *Z* is as great as with the 4-course beacon. The reduction of indicator sensitivity as compared with the 4-course type is compensated for in part by the fact that in the 12-course beacon 3-power amplifier tubes rather than two feed power into the antennæ. In addition, the greater indicator impedance more nearly matches the plate impedance of the output tube of the receiving set.

Preliminary tests using a receiving set of approximately the same sensitivity as the receiving set mentioned above but having an overload voltage of about 30 volts show that the summer range may be somewhat increased over the figures given above. A typical test will be described. Using the first receiving set on a partially shielded airplane, a range of 40 miles was obtained before the ignition interference began to affect the operation of the reeds. With the second receiving set, having the greater overload point, mounted on a different airplane (but shielded to approximately the same degree), the College Park beacon signals were received at Hadley Field, N. J., a distance of about 185 miles, the reeds operating properly and with full-scale deflection. Although the conditions under which the tests were taken were not identical, the effect of greater load capacity in the receiving set is nevertheless positive.

The remarkable selectivity of the reed indicator has been demonstrated in numerous flights from College Park, Md., to Hadley Field, N. J., with the double-modulation radio range at College Park and the aural-type Hadley beacon both operating on the same radio-frequency and approximately the same power. Using the receiving set having the lower overload voltage rating, the interference due to the Hadley beacon began to affect the reeds at a point about 140 miles from College Park and only 45 miles from Hadley.

The ruggedness of the radio equipment on board the airplane was demonstrated when an airplane crashed in July, 1929. Several pilots remarked that this was the worst wreck that this particular type of airplane had ever experienced. All the instruments on the instrument board except the reed indicator were completely demolished. The shock mounting case for the reed indicator was seriously damaged. The indicator itself, however, was found to be in good condition and in accurate adjustment. The receiving set, which was shock-mounted in a compartment behind the pilot's cockpit, also escaped with minor injuries.

The simplicity of operation of this system and its adaptation to the needs of the pilot is evidenced by the following typical test: On a day of low visibility a pilot, unfamiliar with the route, took the air in Philadelphia for Washington with no maps or instructions as to landmarks; he was told to proceed to Washington (a distance of 120 miles) and land at College Park Field solely in accordance with the guidance given by the beacon indicator on his instrument board. He not only flew in a straight line to Washington, but when over College Park Field, the location of which he did not know, the sudden drop in the reed deflections told him he was at his journey's end, whereupon he landed.

IX. COMPARISON OF VARIOUS TYPES OF RADIO AIDS TO AIR NAVIGATION

It is of interest to compare the advantages of the radiobeacon system described in this paper with the other systems in use for guiding aircraft. A brief description of the various systems employed is given in the introduction to this paper under "Previous work." The discussion will be limited to the application of these systems to course navigation on fixed airways which is of primary importance in the United States.

1. REQUIREMENTS FOR COURSE NAVIGATION ON FIXED AIRWAYS

The fundamental requirement of a radio system for guiding airplanes traveling the fixed airways is that it shall give the pilot information to enable him to continue along a given airway when no landmarks or sky are visible. If he leaves the course, it should tell him how far off he is and to which side, should show him the way back to the course, and should inform him when he arrives at his destination. Guidance along the airway means guidance along the route regularly flown, with its emergency fields, lights, and other facilities. The guidance system must be entirely free from errors owing to wind drift. The system must provide service to all airplanes flying the course and must be adaptable to the complex conditions on the busiest airways.

In addition to these requirements, there are a number of additional desiderata which are not strict necessities. The identity of the portion of the airway traversed should be indicated by the radio signals utilized. The service should be continuous rather than intermittent. The pilot should receive the service by a mere glance at an instrument, being free from any necessity of using ear phones, or adjusting anything, or correlating with other instruments, or changing the course of the airplane. The radio-frequencies, power, type of emission, and location of transmitting stations should be so chosen as to serve the needs with maximum efficiency and conservation of the limited radio channels. The radio equipment on the airplane should be simple, rugged, and inexpensive. Finally, the transmitting equipment on the ground should be as simple as possible.

2. DIRECTION FINDER ON AIRPLANE

The use of a direction finder on aircraft makes possible a very simple transmitting station on the ground. Available radio stations may be utilized and guidance obtained in every desired direction. Simultaneous service to any number of airplanes is possible. Complicated equipment must, however, be carried aboard the airplane. This system does not fulfill the major requirements listed above. It does not take care of wind drift, resulting in circuitous courses to the airport. It therefore does not generally guide aircraft over the lighted or marked airway and does not give a pilot the advantage of the emergency landing fields and other aids along the airways.

3. DIRECTION FINDER ON THE GROUND

This system also has the advantage of giving guidance in every desired direction. The apparatus on the ground is more complicated than with the previous method, two or more radio stations with an intercommunication system being required in order to give the pilot a bearing. Simultaneous service to several airplanes in the air is not possible, individual service to each airplane from two stations being necessary. The apparatus on the airplane is bulky, comprising a transmitter and a receiver. Two-way communication must be maintained. Since but infrequent bearings are available, the pilot must rely on blind flying by means of his other flight instruments during the greater portion of his flight. Consequently, the route traveled is not generally over the regular airways.

4. ROTATING RADIOBEACON

This system has relatively simple apparatus both on the ground and aboard the airplane. The use of this system, however, burdens the pilot more than is desirable. It is capable of giving simultaneous service to any number of airplanes in any direction. This service is, however, intermittent and slow, requiring at least 30 seconds for each bearing. Drift may be checked by determining positions periodically and correction may be applied. Since the determination of a minimum signal must be made, this system is particularly subject to interference and atmospheric disturbances. The errors in course determination with this system are somewhat greater than with the directive-type radiobeacon.

5. FOUR-COURSE AURAL RADIO RANGE

The use of a directional transmitter places the complicated apparatus on the ground under skilled supervision and makes possible the use of a simple receiver on the airplane for taking advantage of all radio aids. The radio-marked channels coincide with the airways so that the pilot can utilize the other navigational aids provided on these airways. The system can furnish simultaneous service to any number of airplanes. Wind drift is readily detected. An observation is made without any necessity for maneuvering the airplane or correlation with maps or any flight instrument. The safest route is radio marked, and is over the route flown in good weather. This aids greatly in missing obstructions and safely takes the pilot through mountain passes and canyons. The system acts as a homing device, guiding the pilot to the airport and informing him when he has reached the airport. It has the disadvantages of requiring the pilot to wear head phones and to recognize coded signals. It is at present capable of serving but four courses and can not, therefore, furnish guidance in more than four directions.

6. FOUR-COURSE VISUAL RADIO RANGE

This system has all the advantages of the 4-course aural system. In addition, visual indication removes the necessity of wearing head phones. A glance at the reed indicator tells the pilot his exact position with respect to the course. No skill is required on the part of the pilot in the use of this system. Finally, the selectivity of the reed indicator renders the system almost immune to interference from other services or atmospheric disturbances. Course guidance is therefore available when no other radio service is possible. The chief disadvantage of this system is that only four channels are available, thereby making its use difficult at airports located at the junction of a large number of airways.

7. MULTICOURSE VISUAL RADIO RANGE

This system removes the only objection inherent in the one just described. Twelve radio channels (with the angle between adjacent channels controllable over a considerable range) are sufficient for the busiest airport. Directional guidance is obtained in any desired direction with all the advantages of the previous system.

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