A SURVEY OF CONTINUOUS-WAVE SHORT-DISTANCE NAVIGATION AND LANDING AIDS FOR AIRCRAFT*

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SUMMARY

The paper presents a survey of radio systems which provide short-distance navigation and landing aids for aircraft by continuous-wave transmission. Navigation requirements are discussed in relation to the needs of small and large aircraft. "Self-help aids" are considered to be preferable to "ground-supported aids," which are subject to saturation in areas of high traffic density. C.W. systems are very suitable for the operation of meter indicator instruments.

Short-distance navigation aids are classified into (a) fixed-track guides, (b) omni-directional radial-track guides, (c) rotating beacons, (d) hyperbolic systems, and (e) radio compass. The principal features of each system are stated. Distance measurement by continuous waves is considered.

Radio navigation problems of radio aids to approach and landing are discussed. The provision of a track in descent (glide path) and the presentation of track data on instruments are considered to be essential to the realization of a fully satisfactory landing system.

Radio altimeters have a particular contribution to make to navigation; their principles and applications are mentioned. The paper concludes with a statement of the need to provide navigation aids and landing aids as part of a comprehensive traffic-control plan, giving the maximum degree of safety by providing flexibility of operation of the traffic-control system.

INTRODUCTION

In the early days of radio devices for the navigation of aircraft, there was a tendency to consider each radio system as a device providing a single navigational service. The increase of air traffic density, both present and expected in the future, has demanded that each device shall be a part of a comprehensive navigation plan in which long-range navigation, short-range navigation, airfield control and landing are component parts which together provide a continuous source of information to the pilot or navigator of the aircraft and to the flying control organization; so that whatever the conditions of the weather, the continued safety of the aircraft can be ensured. Planning of the navigational services is also particularly important in aircraft, where the maximum economy of weight and size of component equipments is of paramount importance. It is therefore not surprising that equipment installed in aircraft is often expected to carry out more than a single service, as for example that provided by the V.H.F. communication receiver which can have facilities for receiving and interpreting the signals on the landing beam. It will not be possible within the scope of this survey to deal with the particular requirements of the Royal Air Force, the Fleet Air Arm or the civil air lines, since in many cases the techniques and the operational procedure adopted are designed to meet particular requirements. It is the object here to examine the progress in technical development of aircraft radio aids in their more general applications to short-range navigation and landing service for aircraft by using c.w. technique.

Other systems providing a similar service using pulse technique have been described in papers published for the Radiolocation Convention held in London in 1946.1

In the fulfilment of a comprehensive navigation plan, it is apparent that both types of technique can provide complementary services. For example, the display in plan position of the movement of large numbers of aircraft in the approach zone to an airfield cannot be achieved by other means than the use of pulse systems. In the navigational application, it seems that positional information in terms of the polar co-ordinates—bearing and range—is more convenient than the use of hyperbolic co-ordinates, since the mental interpretation of position by the pilot is instantaneous and the navigator is able to plot-track on standard air plotting charts without the need for charts overprinted with the special lattices.

In general, a short-range navigation system is required only where there is an airfield or a concentration of airfields. The primary service of these navigation aids is to ensure that a flight-plan procedure can be carried out and that the aircraft can be flown accurately to a point where the descent and landing can be made, without the risk of collision with airborne or terrestrial objects. The landing system should provide the means for a safe and accurate descent through cloud to a point on or near the runway, when final control can be realized by visual contact.

Since the short-distance navigation services are required to operate over only a limited area, and to give a reliable and accurate service within this area and not cause interference with other radio services outside it, radio frequencies can be used which would not be suitable for long-distance navigation. In practice, the frequencies used are usually between 30 and 130 Mc/s, and thus the service provided does not extend appreciably beyond the optical horizon between transmitter and receiver. Radio-frequency channels are more easily obtainable in this part of the spectrum compared with lower frequencies, the band is relatively free from static interference, and signals are not reflected by the ionosphere. On the other hand, the signals are susceptible to reflection by ground objects such as trees and large buildings, with the result that accuracy is impaired unless the ground stations are suitably sited. In some applications, horizontal polarization has been used because it has been shown that errors due to reflection are very much less than with vertical polarization.

NAVIGATIONAL REQUIREMENTS

The development of radio aids to navigation and landing has progressed in two directions, this being influenced by the particular requirements of small and large aircraft. For small aircraft, the primary requirement is a reliable radio-telephone communication system. The restrictions imposed on the weight and bulk of ancillary technical equipment have made it essential to obtain the best possible navigational and landing service using the communication equipment. To meet this requirement, such services as ground-based direction-finders, multi-course track guides, rotating beacons and landing beams have been developed, which give aural indications to the pilot of position or of departure from a known track. These devices are well tried and provide a useful navigational service, but in

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general they are not sufficiently accurate and flexible to meet the requirements created by large concentrations of aircraft flying an uninterrupted service in all weather conditions.

In large aircraft it has now become the practice to carry radio equipment supplementary to the communication equipment, to provide navigation and landing facilities. This has become necessary because precise navigation can be achieved only on instrument presentation, and furthermore, the navigational service must be supplementary to the communication service, which must now of necessity be continuously available and remain uninterrupted by the navigational requirements. For example, an instrument approach using an azimuth beam and a beam in the vertical plane to make a descent to the ground (glide path), using the cross-pointer-type indicator, can be achieved only by the use of supplementary radio equipment. The incorporation of these navigational services is now becoming too complex to be part of the service provided by the communication equipment.

To ensure against non-interruption of air traffic services, the large aircraft operating over great distances must be immune from the normal hazards created by the weather or the type of terrain. Accordingly, it is necessary to have available on the air route and in the aircraft not only the best possible aids, but also a standby service which can be used in the event of failure of one or more of the primary aids. It will be apparent that the ground systems which provide the navigational service to the small aircraft using the communication equipment, will be able to provide a secondary or standby service to the large aircraft. Some of the navigational aids such as ground-based direction-finders depend upon a ground organization to provide their service. These devices have been called "ground-supported aids." With low aircraft concentrations, they have in general the advantage that no special radio equipment is required in the aircraft other than communication equipment. With large concentrations of aircraft, there is a serious risk of saturation of the ground organization, so that a bearing or a fix may not always be available to an aircraft at a time when it is most urgently required. The limitations of these systems become all the more apparent with the increase of air traffic density and of aircraft speed, when the provision of an instantaneous bearing and fixing service becomes of paramount importance. Consequently, the trend of development is toward the provision of continuously available radio navigation aids which do not depend upon a ground organization to provide the directional or fixing service, and are not impaired in performance or accuracy by providing the service to a relatively large number of users at the same time. In this category are the aircraft radio compass, the ground-operating rotating beacons, radio track guides, lattice navigation systems and approach and landing systems. In general, these devices call for more complex equipment in the aircraft. Systems which are continuously available to the user when required have been called "self-help aids."

Within the classification of systems contained in the previous paragraph, there is a further sub-division of the facilities available to the user. Some navigation systems, for example the radio compass, provide the user with bearing of the ground beacon relative to the aircraft head and not with reference to a fixed point on the ground. Since the aircraft is in an air mass which is continuously moving relative to the ground, it is not possible to fly an accurate straight-line track to a ground objective, for example an airfield, without a precise knowledge of the wind vector and the application of a correction for drift. In these circumstances, it is improbable that the aircraft will be able to follow precisely the straight-line ground track, and corrections must be made to the aircraft heading to reach the ground objective. It will be apparent that these systems which provide a navigation service influenced by the moving air mass are a more precise aid to accurate navigation than those which provide a directional service relative to the aircraft head.

Along air transport routes where the traffic density is low, it is often quite sufficient to provide a homing service only, since position can be defined to an adequate degree of accuracy by dead reckoning. In general a radio beacon is acceptable for these special requirements and the accuracy called for need not be very high. Homing beacons, such as would be provided for the aircraft radio compass, are inexpensive and easy to site and maintain in remote areas where more complex systems would be uneconomic and too costly in this respect.

(3) INDICATORS AND INSTRUMENTATION

The method employed for the display of information is perhaps the most important aspect of any system. Whether bearing or deviation from track or any other type of information has to be presented, it is of the utmost importance that the information shall be capable of instantaneous interpretation. Aural indication, for example the reception of dot-and-dash signals, has been extensively used in the past on track-flying and landing systems. There appear to exist two schools of thought on the relative merits of aural interpretation and instrument presentation. For example, a pilot making a deck-landing approach is required to watch out for visual signals from the carrier while he is breaking cloud, and his ability to fly a beam giving aural signals is not seriously impaired by this requirement. On the other hand, a pilot working under conditions of mental stress during an approach to an airfield in bad visibility finds considerable difficulty in the interpretation of aural signals simultaneously with the reading of his flying instruments and with the operation of his flying controls. A departure is therefore being made from systems which present aural signals for indication, and it is likely to be more general practice in future to provide visual indicating instruments for this purpose.

C.W. systems have the merit that the signals available at the output of the receiver are particularly suited to the operation of meter instruments, i.e. instruments which usually indicate by means of a scale and pointer. Such instruments as the cross-pointer meter used for blind descent, or the Desyn used as a remote indicator for the aircraft radio compass, exemplify this practice. Typical indicators used on some present systems are shown in Fig. 1.

(4) SHORT-DISTANCE NAVIGATION AIDS

(4.1) Fixed-Track Guides

For the purpose of flying defined tracks, radio track beacons have been in use for many years. Most of the development of radio track beacons and their practical realization on a very large operational scale in civil aviation was achieved in the U.S.A. before the war. These beacons operated in the medium-frequency band by providing four intersecting field patterns radiating the morse characters "A" and "N" which were audible as a continuous tone along the tracks where the characters were of equal amplitude. The width of the beam was approximately 3 degrees.

The beacons in present use are of two types, both radiating the same basic field pattern consisting of two figure-of-eight diagrams mutually at right angles and keyed alternately by interlocked "A" and "N" morse characters. Under the normal condition of operation, the tracks defined by the steady-signal region are mutually at right angles, but some degree of flexibility of location of these tracks is achieved by manipulation of the phase and amplitude of the voltages applied to the elements of the ground aerials (see Fig. 2). The two beacons work on
similar basic principles, the main difference being in respect of
the aerial system. A mobile version uses two triangular crossed
loops erected mutually at right angles and supported by a single
central mast. The use of crossed loops makes the system
susceptible to error and split courses at night owing to the simul-
taneous reception of ground-wave and sky-wave signals, thus

resulting in the restriction of its reliable range to 25–75 miles
overland, with greater ranges over water.

The second type uses vertical mast radiators similar to an
Adcock pair, the radiators being fed by coaxial transmission
lines. A fifth radiator is centrally located with respect to the
other four. The reliable service is much improved by this aerial
arrangement, and ranges of 150–300 miles are obtainable overland,
with greater ranges over water. The central mast radiates the
carrier, which can be modulated with broadcast transmission
when required, and the outer masts radiate keyed sideband
transmissions of interlocked “A” and “N” morse characters.

In this country, the practice has been to use two-course radio
track beacons, usually operating in the band 30–40 Mc/s or
100–124 Mc/s. In general these track beacons are identical with
the standard beam approach and the v.h.f. beam approach
respectively, with the difference that greater power is usually
radiated. The signals transmitted are “E” and “T” or some-
times “A” and “N” interlocked morse characters. The technical
features of this system are dealt with more fully in Section 6 and
in the supporting papers. The greater mobility of equipment
working in this band, and the relative immunity from ionosphere
reflection, have much to commend the system, although it must
be conceded that the sites for high-frequency and very-high-
frequency beacons must be more carefully chosen if “course
bends” due to reflections from trees and buildings are to be
avoided. Further, the maximum range of operation of the
beacons is a function of flying height, and in general it is unlikely
that signals will be received at distances greater than 50% beyond
the limit of the optical path for the 30–40 Mc/s band and 25%
above the optical path for the 100–124 Mc/s band.

(4.2) Omni-directional Radial-Track Guide

Both the 2- and 4-course track guides have been and still are a
valuable aid to the air navigator, but their lack of flexibility and
the restriction of flying to two or four tracks in a flying area of
high traffic density, where aircraft should be able to use the whole
of the space around them in the greater interest of flying safety, is
now a serious limitation of these systems. Furthermore, the
advantages to be derived from pure instrument flying are fairly
generally agreed. For this reason, efforts are being made to
produce systems which will enable aircraft to fly any track and
which will give instantaneous indication of the degree of departure from the track.

To meet these requirements, developments have been proceeding in the U.S.A. and in this country on a system called the v.h.f. omni-directional radial-track guide. With this, the pilot can fly any track he may choose radial to the beacon by means of a left-right track indicator. The system has been satisfactorily demonstrated in the U.S.A., and in this country it has reached an advanced stage of development. The ground beacon operates at a fixed frequency in the band 112–118 Mc/s. Thus the working range attainable will be a little beyond line-of-sight distance, e.g. about 130 miles at 12 000-ft flying altitude.

The v.h.f. omni-directional radial-track guide uses a system of phase comparison of two low-frequency modulations to determine a bearing relative to the beacon. The two modulations are associated with the same carrier, and therefore only one r.f. channel is required for the operation of the system. One of the modulations is the reference signal, and its phase is unchanged by change of bearing of the receiver relative to the beacon. The other modulation has a phase delay, compared with the datum, which is equal to the change of bearing of the receiver relative to the beacon.

The beacon aerial system consists of five horizontal loops, four of these being located at the corner of a square, opposite elements being N/S apart, with the fifth loop at the centre (Fig. 3).

This loop radiates carrier which is 30% amplitude-modulated at 10 kc/s, which is itself frequency-modulated at 60 c/s. This 60-c/s signal is the reference component, since its phase will be unchanged with angular position of the receiver relative to the beacon. The opposite pairs of outer loops are fed by 60-c/s sidebands from balanced modulators, the phase of the modulation on the pair is displaced by 90 deg. By this means, a sideband field pattern is radiated by the four outer aerial elements which, combined with the carrier radiated by the centre element, produces a 60-c/s amplitude-modulated signal with a phase displacement of the modulation equal to the change of bearing angle of the receiver. It is arranged that the two modulation signals are in phase along the north line relative to the beacon; therefore, if a measurement of the phase-angle difference of the two modulations is made, for any position of the receiver, this measurement is the bearing angle.

The r.f. receiver unit follows conventional lines except that 10-kc/s and 60-c/s band-pass filters are contained in the receiver output circuits, for the purpose of separating the reference signal from the variable phase signal. The 60-c/s reference signal is derived from a frequency discriminator in the 10-kc/s channel. By incorporating a manually operated phase-shifter in one channel, it is possible to zero-balance one signal against the other. The phase shifter is calibrated 0–360°, and the scale indicates bearing when a zero balance is set on the track indicator, which is the vertical needle of the cross-pointer instrument. The accuracy of bearing measurement is of the order of ± 2 deg, and it is possible to hold a track about 1 deg wide.

The particular advantages of a bearing-and-distance system have been referred to earlier in the paper. If it were possible to incorporate with the omni-directional radial-track guide a service which would indicate the distance of the beacon from the observer, the result would be a complete self-contained fixing system. A system of this type has been proposed and is given the characteristic name "spider's web." The bearing lines are radial from the beacon, and lines of constant distance are concentric circles around it. Both lines are in effect position lines, and since the bearing lines cut the distance lines always at right angles, the fixing accuracy is uniform around the beacon and is inversely proportional to distance from it. The most convenient distance-measuring technique at present available is the pulse method, using an interrogator and receiver in the aircraft and a responder beacon on the ground. The measured time-interval between the transmitted pulses in the aircraft and the returned pulses from the ground, is displayed in terms of distance on a suitable distance meter. Thus both bearing and distance can be made available in the aircraft, and there now seems to be a need for co-ordinated meter presentation of this information in a simple form capable of instantaneous interpretation by the pilot. The measurement of distance is practicable by c.w. methods, and the technique will be discussed later in the paper.

The proposal discussed so far provides a track-flying and fixing service in an exceedingly useful and convenient form, all the information being related to the position of the ground beacon. It has been suggested that, if it were possible to use the track indicator to fly any track, not necessarily a radial track to the beacon, and to have a continuously-indicated distance to the destination of the aircraft, which is not the ground beacon, this would be the ideal solution for short-distance air navigation. A device called the "distance-bearing computer" has been proposed to provide precisely this ideal conception of a short-distance navigation service, and at the time of preparing this paper one experimental model has been made. The device is an electro-mechanical unit into which is fed the distance and bearing of the user relative to the ground beacon, and the distance and bearing co-ordinates of the point of arrival relative to the beacon. The computer solves the equation for distance and straight-line track from the aircraft to the arrival point, the distance to go being displayed on the distance indicator, and the track being shown on the left-right track indicator.
(4.3) Rotating Beacons

Rotating beacons have found their most useful application in providing a bearing service to the user, with normal types of communication receivers, i.e. with equipment operating from a few hundred kilocycles per second up to about 250 Mc/s. Almost all rotating beacons utilize the amplitude characteristic of a rotating-field pattern to provide bearing indications. The simplest form was provided by a loop radiating a figure-of-eight field pattern rotating at a uniform speed of one revolution per minute. A characteristic modulation reference signal was transmitted when the plane of the loop was normal to the north-south line, and the observer measured the time from the north-south signal to the instant when he was receiving a minimum signal, this being the instant when the plane of the loop was normal to the observer. Quite obviously if the loop is rotating at a uniform speed, the time interval is directly proportional to the bearing angle. By use of a stop-watch engraved on the dial with markings 0-360° it was possible to read off the bearing directly from the stop-watch. The accuracy of the system is dependent on the loop polar diagram and on the ability of the observer to discriminate the instant of minimum signal. An equipment of this type operating in the medium-frequency band was set up at Orfordness in 1929 and has provided a very useful service. The accuracy is 1-3 deg at a distance of 300 miles in daylight or 25 miles at night.

If it were possible to rotate a very narrow beam of radiation and to modulate this with code or r.f. signals to indicate bearings during the whole cycle of rotation, this beacon would provide a directional service to an observer provided with only a simple communication receiver. The accuracy would depend upon the beam width and the ability of the observer to discriminate the maximum amplitude of the received signal. Narrow beams require aerial systems of wide aperture. Beam widths of the order of 3-5 deg are attainable at centimetre wavelengths with aerials of moderate dimensions, but these aerials become more or less impracticable in the v.h.f. band owing to their prohibitive size. Further, the presence of sub-lobes in the radiation pattern will give false indications. Therefore it has been necessary in the design of v.h.f. rotating beacons to adopt very much wider beams than are highly desirable, and in general to accept systems of low accuracy compared with other more complex systems which require special receiving equipment.

Rotating beacons operating in the 200-Mc/s band are being used by the Royal Navy to enable aircraft to home on the carrier. As the beam sweeps through each true bearing, modulation is automatically transmitted which is characteristic for that bearing. The rotation of the aerial is stabilized in azimuth, corrections being applied to allow for alterations of the ship’s course. The radio equipment carried in the aircraft provides the homing service and the deck-landing service in the same r.f. band, using a beam similar to standard beam-approach.

During the war the Germans used a rotating voice-operated beacon for air navigation, called “Hermine,” which is of technical interest. This beacon, operating in the frequency band 30-33:5 Mc/s, used a single carrier and two modulation channels. An aerial system of four vertical radiators located on the corners of a parallelogram was excited in suitable amplitude and phase to produce a radiation diagram of cardiod shape and with a sharp minimum. The aerial was rotated at 1 r.p.m. and radiated a continuous tone-modulated signal. A fifth radiator symmetrically located with respect to the other four radiated an omnidirectional transmission on the same frequency which was modulated with r.f. bearing signals from 0 to 360° in 10° steps. The observer heard both modulations simultaneously and listened for the “fade out” of the tone modulation. The r.f. signal transmitted at this instant indicated the bearing sector in which he was flying. The accuracy stated for the system is ± 5 deg, with a range of 110 miles at 10,000 ft altitude.

A similar type of rotating beacon has been developed in this country to meet a military operational requirement for a lightweight ground beacon, suitable for transportation by aircraft to remote areas and providing a directional service to aircraft fitted with standard v.h.f. communication equipment operating in the band 100-156 Mc/s. This beacon, illustrated in Fig. 4, will provide r.f. bearing signals in the band 112-115 Mc/s. The complete aerial system, transmitters and modulators are mounted on a light framework, and the whole assembly rotates at 2 r.p.m. The two Yagi aerials provide a directive radiation pattern which is about 60 deg wide, and this array radiates a transmission which is modulated with r.f. bearing signals every 20 deg of rotation. After each bearing signal the code name of the beacon is transmitted. The two subsidiary aerials provide a cardioid-shaped pattern with its minimum in the direction of the main lobe. The signal supplied to this aerial is on the same carrier frequency and is tone-modulated at 600 c/s. The carrier of this secondary transmission holds the automatic gain control of the airborne receiver constant, and the modulation masks the

Fig. 4.—V.H.F. rotating beacon.
secondary lobes of the main pattern so that the observer does not hear false bearing indications. The observer hears the 600-c/s modulation note followed by a fade-out of this modulation and then a group of bearing announcements interleaved with the code name. The middle announcement of the group is the course he has to steer in order to home on the beacon. The accuracy of this type of beacon is \( \pm 5 \text{ deg} \) up to 110 miles at 10,000-ft altitude.

This Section of the paper would not be complete without reference to a rotating beacon called “Bernhard” used by the Germans for air navigation during the latter stages of the war. The aircraft component, called “Bernhardine,” comprised a

in the band 30–33.5 Mc/s and radiates two transmissions which are 10 kc/s apart and tone-modulated. The lower aerial consists of two groups of four vertical elements, fed in anti-phase to give a minimum signal along the line normal to the array. This aerial provides the azimuth bearing indication. The upper aerial consists of three vertical elements fed in phase and providing a directional pattern giving a maximum signal along the line normal to the array (Fig. 6). This aerial provides the signals which print bearing on the tape. Two 5-kW transmitters, contained in the building beneath the array, feed the two aerials.

The receiving equipment follows normal practice except that filters separate the modulation channels. The derived signals, after amplification, are used to operate the teleprinter, which works on the German Hellschreiber system.

The lower aerial radiates a continuous tone-modulated signal. During rotation of the beacon this signal is shown on the tape as a horizontal line about \( \frac{1}{4} \text{ in} \) wide. The signal amplitude falls to zero when the aerial is normal to the observer, thus marking a distinctive “V” notch on the tape. The upper aerial radiates an impulse-modulated signal which prints below the bearing-indication trace a complete scale with bearing readings and the code letter of the station. Alternatively, short messages may be sent on the upper aerial which are recorded in the same manner (see Fig. 7). The accuracy of the system is stated to be \( \frac{1}{4} \text{ deg} \) and the range depends upon flying altitude. Typical ranges provided by the equipment are 130 miles at 3,000 ft and over 300 miles at 25,000 ft.

![Fig. 5.—Bernhard station.](image)

A view of the ground beacon is shown in Fig. 5. This is a large rotating steel frame which carries the aerials and the transmitter equipment and turns at 2 r.p.m. The beacon operates a receiver and a teleprinter of small dimensions and provided the user with bearing indications printed on a tape.

A view of the ground beacon is shown in Fig. 5. This is a large rotating steel frame which carries the aerials and the transmitter equipment and turns at 2 r.p.m. The beacon operates

![Fig. 6.—Typical radiation diagram of Bernhard beacon.](image)

![Fig. 7.—Bernhardine indicating tape.](image)

(4.4) Hyperbolic Systems

Particulars of hyperbolic systems of navigation such as Gce and Loran, which depend upon the transmission of time-locked pulses from widely separated transmitting stations, have been published elsewhere. The c.w. counterpart of these systems is exemplified by the Decca Navigator and the Post Office position indicator. The former is a frequency-multiplex system and the latter is a time-multiplex system. Both systems are able to provide comparable service and differ only in the technique employed.

The Decca Navigator provides facilities for the navigation of aircraft and ships at short and medium distances, and depends for its operation upon the transmission of c.w. phase-locked
signals on geometrically related frequencies from a chain of four widely separated ground stations.

In the practical application, the master station of the chain radiates at 85 kc/s. This is received by the three slave stations, and, by a process of multiplication and division, new frequencies are derived which drive the slave transmitters, these being in the ratios 4 : 3, 3 : 2 and 5 : 6 of the master frequency.

The receiver unit comprises four separate phase-stable channels fed from a common aerial (Fig. 8). By frequency multiplication, the signals in each channel are converted to the least-common-multiple frequency, and the relative phase of the received signals is measured and displayed on suitable meter indicators.

Lines of constant phase-difference at the comparator frequency form a confocal family of hyperbolic position lines relative to each pair of stations, and the navigation lattices are formed by the intersection of the hyperbolae.

Since the indicators integrate the number of phase cycles through which the receiver has been moved, the operation of the system is dependent upon the correct setting of the integer phase-cycle co-ordinates on the meter at the starting point, after which the instrument pointers will follow the movements of the receiver, provided that there is no interruption of the received signals.

A system of "lane identification" which will enable the user to identify and set the correct integer co-ordinates on his meter has been demonstrated in an experimental form. This facility is essential when entering the coverage area or in the event of temporary interruption of the received signals.

The range for good fixing is about 200 miles, and the position-line accuracy is of the order of ± 0.06 deg. The accuracy is less reliable at night at distances beyond 200 miles, owing to the presence of appreciable sky-wave propagation.

In connection with this system, it will be of interest to refer to a development which is proceeding on a device called the track computer. This unit will enable the user of the Decca Navigator to fly any track by following the indications on a simple right-left track meter. Indication of ground speed, time to destination and minutes ahead of or behind schedule, are presented as direct numerical readings on the instrument. A number of tracks recorded on film can be set into the system, and the user is able to select the track he wishes to fly by operating a switch. If this development is successful it appears that some of the objections to hyperbolic-lattice systems will be overcome and navigation along pre-selected air routes will be greatly simplified.

(4.5) Radio Compass

It might be presumed that many of the navigation devices already mentioned will render the familiar aircraft radio compass obsolescent. This might well be so, if there did exist at the present time complete standardized systems of air navigation which covered the whole of the earth's surface with an internationally approved navigation lattice. Such is not the case, nor is this ideal state likely to be realized for many years. In the meanwhile, the aircraft radio compass can provide and will continue to provide a valuable navigation service utilizing the aircraft direction-finding loop to provide bearings from broadcast stations and from relatively simple ground beacons.

The relatively low order of accuracy attributed to the radio compass under certain conditions often causes it to be in disfavour compared with other self-help aids. The radio compass has the important advantage that a navigation service can be provided with a simple ground installation consisting of a 300-W m.f. beacon. It is common practice to set up these beacons at suitable intervals along our air transport routes. The low capital cost, simplicity of operation and ease of siting are strong reasons to commend the continued use of ground beacons and the aircraft radio compass to meet special requirements.

The equipment is primarily suited to the medium-size and large aircraft. The radio compass is best suited for short-distance and medium-distance operation, since a d.f. loop is susceptible to polarization error, so that when the sky-wave component of the transmission becomes appreciable compared with the ground wave, errors are likely to be present in the system. Obviously, the radio compass is far more reliable in daylight than at night, and is most satisfactory on the lower frequencies. For this reason, equipment is usually designed to operate between 100 and 2,000 kc/s, the band between 100 and 500 kc/s being most generally used.

The most important facility provided by the radio compass is homing. In areas of low traffic density, where small deviations from a great-circle track may be unimportant, the need for very accurate bearing indication can be partly disregarded. Being provided with a homing indicator, the pilot of the aircraft carries out unconsciously the mental process of averaging the information presented to him, and thus the track made good may not differ appreciably from the great-circle path.

The difficulty of locating an 11-in loop in a streamlined housing on a modern aircraft is likely to be an increasingly difficult problem with the greater drag due to increase of flying speed, and in this connection it is of interest to mention that, during the war, the Germans used iron-dust-covered loops of relatively small dimensions sunk into the aircraft skin. Tests conducted on these loops have indicated that a performance comparable with that of the 11-in circular loop as at present used in the Royal Air Force is attainable, and therefore there is little doubt that iron dust-covered loops suppressed beneath the aircraft skin will eventually be introduced.

Since the directional properties of the system are contained in the aircraft and not on the ground, it will be apparent that bearings are provided relative to the aircraft head and not relative to true north. This implies that the true bearing of the ground beacon must be computed by the navigator and also that, to make good a track, a correction for drift must be applied. This rather cumbersome procedure has been greatly simplified by the development of a system which provides indication of course, track and drift instantaneously in a very elegant presentation. This is achieved by combining into one indicator instrument: (a) a scale driven from the gyroscopic compass so that true bearing of the beacon is indicated directly; (b) a second fixed scale which indicates bearing relative to the aircraft head; (c) a scale which gives direct indication of drift angle; and (d) a visual indicator.
Fig. 9.—Marconator aircraft radio-compass indicator.
normally associated with the d.f. receiver for homing. By this means, the introduction of possible error due to the combination of a number of instrumental readings is avoided. A radio-compass indicator working on these principles is shown in Fig. 9.

A further development of the technique is embodied in a device called the automatic radio compass. In all respects it is the same as the radio compass, with the addition that when the receiver is tuned to a desired ground beacon, the receiver output signals are used to control the rotation of the loop by the embodiment of a loop-switching system and appropriate servo circuits, so that the plane of the loop always takes up a position normal to the arrival of the received signal. Thus the indicator will provide continuous reading of bearing of the ground beacon relative to the aircraft head, and, of course, true bearing is indicated in the same manner as described in the previous paragraph. Successful automatic radio compasses of U.S.A. origin are being extensively used, and development is proceeding into customary or similar systems.

The accuracy of the radio compass can be better than ± 2 deg under favourable reception conditions, and ranges as great as 600 miles in daylight are attainable. At night, range and accuracy are dependent upon frequency, transmitter power and ionospheric conditions, which are discussed in the paper entitled "Airborne Automatic Direction-Finders."\(^{16}\)

(5) DISTANCE MEASUREMENT

The application of phase measurement using continuous waves for the determination of distance was used by the Germans during the war in a system called "Ypsilon", the code name given to it here was "Benito." The system was used to guide aircraft to target objectives in this country. The aircraft flew on a beam, and distance measurement was made on the ground, using the phase characteristics of a 3-kec modulation frequency. The ground station transmitted the 3-kec modulated signals, which were received in the aircraft, and this modulation was retransmitted on the second carrier frequency and received on the ground. The phase difference between the transmitted and received modulation frequencies was displayed in terms of distance on a cathode-ray tube. For a change of one phase-cycle of 360 deg between the transmitted and received signals, the distance was 50 km. The Benito system was used successfully with relay aircraft up to distances of about 700 km. Resolution of ambiguity was achieved by one of two methods depending upon the system in use:

(a) A course measurement of distance was made by changing the modulation frequency to 300 cfs. This provided a service of lower accuracy without ambiguity up to 500 km.

(b) The modulation frequency was changed to 3-3 kec and a new value of distance indicated. If the new value represented an increase of 10%, the aircraft would be in the first phase-cycle, i.e. between 0 and 50 km. If the distance indicated increased by 20%, the aircraft would be in the second phase-cycle, i.e. between 50 km and 100 km, and so on.

The scheme had the disadvantage that distance measurement was made on the ground, and it was possible to control only one aircraft at a time.

It will be apparent that the application of distance measurement in conjunction with ground-based or ship direction-finding is likely to offer important advantages for special applications, for example on aircraft carriers or on forward airfields where it is not possible to set up a fixed d.f. network. If the position of an aircraft can be determined in terms of bearing and distance, the need for a network of d.f. stations to provide cross bearings is eliminated.

The Condar navigational system, now under development in this country, utilizes the principle of phase measurement for the determination of distance, in conjunction with a v.h.f. automatic direction-finder. An experimental Condar installation has been tested using standard aircraft v.h.f. communication equipment operating in the band 100-156 Mc/s. The equipment is modified to receive and transmit on two carrier channels simultaneously. The ground equipment shown diagrammatically in Fig. 10 is located on one site. The transmitter on the left of

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Fig. 10.—Block diagram illustrating Condar system.

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the diagram radiates signals at frequency \( f_1 \) amplitude-modulated at 809 cfs. These signals are received in the aircraft, and the 809-cfs signal is retransmitted from the aircraft as an amplitude modulation on a carrier frequency \( f_2 \). These signals are received on the ground by the automatic direction-finder, and the bearing of the aircraft is displayed as a radial trace on the cathode-ray-tube indicator. The modulation component is derived from the \( f_2 \) signal received by the direction-finder, and is compared in phase with the outgoing 809-cfs signal; the position of the aircraft is then displayed as a "blip" at the appropriate distance along the radial trace, indicating distance. There are no ambiguities in distance indication up to 100 nautical miles, and a typical working range for the system is 87 nautical miles for an aircraft flying at 10,000 ft. The expected distance-measuring accuracy is of the order of ± 1 mile at all distances.

Proposals have been made for distance measurement by continuous waves where the information is presented on an indicator in the aircraft and not on the ground. The possibility of the ground responder beacon being operated by several aircraft at the same time is overcome by a time-sharing scheme in which the beacon is available to only one aircraft at a time. The air-
craft obtains intermittent distance indication by selection of a short interval when the beacon is not being modulated by other aircraft transmissions. The proposal suggests that as many as a hundred aircraft may obtain distance information simultaneously by this means.

(6) RADIO AIDS TO APPROACH AND LANDING

(6.1) General

This Section is concerned with radio systems which will facilitate the landing of an aircraft in conditions of bad visibility. It is important to realize that from the pilot's aspect the radio landing system provides only a part of the relatively large amount of information which has to be instantaneously available to him in order to make a safe descent through cloud and to make a safe smooth landing on the runway. In addition he has to watch his gyro compass, airspeed indicator, altimeter and artificial horizon, and to manipulate his flying controls and engine throttles. The strain placed upon a pilot making a descent through cloud is so great that it has been necessary to make a very extensive study of this subject. The provision of a safe and reliable radio landing system has not yet been realized, although very great progress has been made in recent years toward its realization. Numerous types of landing systems have been developed and used operationally during the war. With few exceptions, these systems have provided lateral guidance only, and it has been necessary to use the barometric altimeter or sometimes the radio altimeter to control the descent. The need for a radio system to provide a track in descent to the runway has been fully recognized for some years, and although much technical effort has been expended both in this country and in the U.S.A., it is only in recent years that a reasonably satisfactory system has been realized. The radio system to provide this track is called the "glide path."

None of the systems so far realized can be considered as practicable for making a landing on an airfield in zero visibility; in fact the most that can be said of these systems is that they provide the means for a safe landing approach to the airfield through cloud or in poor visibility; the last stages of the approach and the landing of the aircraft can be achieved only by a visual-contact. Much progress in development has yet to be made before it will be possible for an aircraft to make a safe touchdown on an airfield and be brought to rest in zero visibility. Owing to these limitations, the systems about to be described are called "beam-approach beacons" and not "blind-landing systems."\(^8\)\(^9\)

By linking the radio systems to the automatic pilot, the pilot is relieved of the physical strain of flying the aircraft down the approach track, and is able to monitor the approach by his visual-approach indicator and to concentrate his attention on the other aspects of flight, such as undercarriage, flaps, airspeed and throttle controls. The final touchdown will be made by disconnecting the automatic controls and taking over manual control at the point where visual contact is established.\(^11\) Automatic approach has been proved to be technically possible, but the technical aspects of this problem are so great that considerable time will elapse before such a plan is likely to be in general use.

A typical radio landing system will consist of a number of component units on the ground and in the aircraft. The normal layout of a ground installation is shown in Fig. 11. The azimuth beam is located at the far end of the airfield runway remote from the aircraft touch-down point, and provides two field patterns intersecting in the vertical plane, which will give lateral guidance indications in the aircraft. The glide-path equipment is located near the approach end of the runway and is offset from the centre line of the runway so as not to present a flying obstruction. This equipment radiates two field patterns intersecting at the descent angle, and provides indications in the aircraft of track of descent to the airfield (Fig. 12). In addition, two or sometimes

![Diagram of radio landing system]

Fig. 12.—Radio landing system.
(a) Typical horizontal radiation for lateral guidance.
(b) Typical vertical radiation pattern for guidance in descent.

three marker beacons are located at suitable points along the approach track to indicate position during the descent. These beacons transmit characteristic signals which are only heard by the pilot while passing over them. The aircraft carries three receivers, one for the azimuth-beam signals, a second for the glide-path signals and a third, relatively simple, receiver for the marker signals. The aircraft aerials will be dependent on the particular system in use.

(6.2) Instrument Approach Systems

The standard beam-approach system S.B.A. is similar to the Lorenz radio approach system which was used in Europe before the war. This system was adopted for use by the Royal Air Force, and the equipment manufactured in this country differed from the Lorenz only in minor detail. The S.B.A. system operates in the band 35-40 Mc/s. S.B.A. is a system of amplitude-comparison of keyed signals and has the merit of simplicity in the technique employed. Course guidance signals are audible in the pilot's telephone, and consist of dot characters with a 1000-c/s note if the aircraft is to the left of the approach track, dash characters of the same tone if it is to the right of the track, and a steady note when it is on the track. A visual
display is readily obtained in the aircraft by a "kicking-pointer" instrument, which kicks to the right in the dot sector and to the left in the dash sector. This type of presentation, although relatively simple to realize, is not good and has been discarded on later systems. Another pointer on the instrument indicates the amplitude of the received signal, and by making an aircraft descent from the outer marker beacon in such a manner as to keep the received signal of constant amplitude, i.e. by flying to constant deflection of the needle on this instrument, it is possible to follow a glide-path track. This feature has the disadvantage that the descent track is not straight, and low approach angles are experienced in the proximity of the airfield boundary.

Two marker beacons are provided, operating at 38 Mc/s. One is located at 2 miles from the airfield boundary and the other at the airfield boundary. The beacons radiate characteristic signals which are heard by the pilot when the aircraft is over the beacons. The range of S.B.A. is about 25 miles, and its azimuth-beam width ± 1 deg.

Concurrent with the development in this country, a parallel development was proceeding in the U.S.A. on a system called SCS 51. This system provides an azimuth beam, a glide path and three marker beacons. Indication of track is presented to the pilot on a cross-pointer meter. Although in many respects these systems are very similar, there is a notable difference in the techniques employed. Whereas in this country keyed-carrier radiation patterns are used with characteristic interlocked signals for indication of the track, the SCS 51 uses two continuously radiated modulation-frequencies, the tracks being defined by modulation components of equal amplitude. The azimuth beam operates at about 110 Mc/s, and the glide path at about 335 Mc/s with horizontal polarization, and both units use modulation frequencies of 90 and 150 c/s. This type of technique proved to have important advantages, notably that no keying unit is required in the transmitter and the circuits are more suitable for the operation of a steady-reading pilot's indicator. The system provides a range of 20 miles at 2,000-ft altitude, with a typical beam width of ± ¾ deg. It has now been agreed among the Governments operating the main air lines that the SCS 51 type of system is the most satisfactory for future application, and developments using this technique are proceeding in this country.

(6.3) Instrument-Approach Site Characteristics

One of the most difficult problems in the realization of any good landing system is the effect of the local site features, such as trees, buildings and terrain, upon the linearity of the landing track. It has always been necessary to select good sites relatively free from such obstructions, to obtain a good landing beam free from course bends. At the higher frequencies the effect of obstructions becomes more serious, unless a high degree of directivity of the radiation pattern is possible. The type of directive pattern required is probably only realizable by using aerials of wide aperture on centimetre wavelengths, and this may well be the ultimate solution to a fully satisfactory landing system. It has been shown, during investigations on its effects, that horizontal polarization is more satisfactory than vertical polarization as regards errors in the track due to site obstructions. An experimental centimetric landing system has been designed in the U.S.A., but very little information is available in this country concerning its characteristics, and whether it has advantages which would merit its ultimate adoption is not yet known. However, it is most certainly true that systems which radiate narrow field patterns and which do not depend upon ground reflections to form these patterns are likely to offer a very considerable improvement of the present siting restrictions.

(7) RADIO ALTIMETERS

A device which made a useful contribution to aircraft navigation is the radio altimeter. This instrument is in reality a terrain-clearance indicator, since it indicates the altitude of the aircraft relative to the terrain immediately beneath it (Fig. 13).

![Fig. 13.—Principle of f.m. radio altimeter.](image)

The beat frequency between the direct signal from T to R and the ground-reflected signal is proportional to altitude.

At least three techniques are employed in the design of radio altimeters: change of capacitance, frequency modulation and pulse time-difference.

The capacitance altimeter depends for its operation upon the change of capacitance between two electrodes mounted on the wing tips of an aircraft, when the aircraft is flying in proximity to the ground. As would be expected, such an instrument is effective at low-flying altitudes only, and its range of service is from ground level to about three times the wing span of the aircraft, which on a large aircraft may give altitude indications up to 200 ft. An instrument of this type, although useful for certain special applications, has very limited utility and is therefore not used very extensively.

Frequency modulation is a technique which has found an exceedingly useful application up to nominal flying heights of about 5,000 ft, and also provides quite good performance down to about 10 ft. In this system a frequency-modulated transmitter feeds a dipole aerial mounted beneath the wing of the aircraft. Signals which reach the ground at normal incidence are reflected along the same path as the incident radiation and are picked up on a second aerial on the aircraft, usually located under the other wing. This signal is amplified in the receiver and is then mixed with the signal from the transmitter. It can be shown that the frequency of the beat signal is directly proportional to flying height. A meter-type indicator is provided whose deflection is proportional to the frequency of the input signal and is therefore proportional to altitude. The accuracy attainable up to 4,000 ft is ± 6 ft ± 5% of height.

The third type of radio altimeter uses pulse transmission and depends for its operation upon the measurement of time difference between the transmitted and ground-reflected pulses. Pulse altimeters are not suitable for the measurement of low altitude, owing to the inability to measure very small time differences between
pulses, and in practice they are able to provide a service from about 800 to 50,000 ft. The accuracy in this region is of the order of ±(50 ft + 1% of height).

Present types of radio altimeters operate at about 450 Mc/s. Developments are now proceeding on radio altimeters which will operate in the 1,600-Mc/s band. The aerial systems used with the present altimeters are simple dipoles mounted below the metal skin of the wing, and therefore are not very directive. However, since only those signals which reach the ground by normal incidence are reflected back in the direction of the aircraft, the system responds mainly to the signals which are reflected from immediately below the aircraft. Radio altimeters are not very useful over rugged country and find their main application over water or relatively flat terrain.

It is notable that radio altimeters provide a good service under conditions where accuracy of the barometric altimeter is least, i.e., at low-flying altitudes and when a zero correction for barometric pressure along the flight route is unobtainable. In this field they have found a useful application in the Fleet Air Arm and in Coastal Command. A safe descent can be made through cloud to sea level, and in this respect the radio altimeter, with the provision of an azimuth beam such as S.B.A., can be used by flying boats landing on the water. The radio altimeter cannot be successfully used to provide the descent track to an airfield in bad visibility, except in emergency, because the descent track would follow the contours of the ground and would therefore be difficult and hazardous to follow. For this application, the barometric altimeter, although inaccurate, is more satisfactory, since after zero-correcting the instrument for pressure at the airfield surface, it is possible to follow a straight descent to the ground.

(8) CONCLUSIONS

It has been stated that the ready availability of a variety of navigation aids is not in itself sufficient to ensure the safety of aircraft in flight in areas of high traffic density. These aids must fit into the comprehensive traffic-control plan. Systems are preferred which do not restrict the passage of aircraft to narrow lanes, and thus dangerous concentration of air traffic near landing fields can be avoided.

The arrival of aircraft at the landing approach must be most carefully controlled, and it may sometimes be necessary to apply a delaying action on aircraft before arrival at the airfield to ensure the smooth working of the air-traffic control plan. The air-traffic control zones extend 100 miles or more from the landing fields, and within this area reliable r.t. communication to and from the aircraft is a vital requirement. The aircraft in this zone may be flying to different destinations on a variety of time schedules. Diversions may be necessary owing to the weather, normal flight plans may have to be altered at short notice, and it is essential that the aircraft be provided with navigation devices of considerable flexibility to enable the instructions of the air-traffic control organization to be fulfilled. Communications, airfield-control radar, radio navigation and instrument approach systems are all required in the satisfactory fulfilment of the plan.

(9) REFERENCES


(12) SHARPE, B. A.: “Low-Reading Absolute Altimeters.”

* Supporting paper, to be published in a later issue of Part IIIA of the Journal.

† Supporting paper, being considered for publication in a later issue of Part IIIA of the Journal.