C.W. RADIO AIDS TO APPROACH AND LANDING*

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SUMMARY

The problems involved in the design of landing approach systems are complicated by psychological and aerodynamic considerations. The display of intelligence from the system is of great importance, and the form that it should take has influenced system design.

The first attempt to provide guidance in azimuth made use of the magnetic field surrounding a cable on the ground, but this was superseded by radio systems. Keyed signals produced by overlapping field patterns were favoured in this country until fairly recently, but these have been replaced by modulation separation systems as being more suitable for operation of the preferred indicator.

Guidance in elevation is provided by a "glide-path" system, which is preferably of the overlapping pattern type and provides a straight line of descent.

Distortion of the course characteristics by re-radiation from objects near the transmitter is a problem which can only be solved by restricting the energy radiated towards the interfering object. This is achieved in present systems by the use of arrays, but the employment of equipment operating on centimetre wavelengths offers convenience in obtaining greater directivity.

It is considered desirable to control the automatic pilot from the landing approach system, and experiments to this end are in progress, the results of which will probably affect the design of landing systems.

(1) INTRODUCTION

There are two main aspects of the problem of landing-aid development: (*a*) the purely technical, which is concerned with providing a system enabling the pilot of an aircraft to follow a predetermined course, and (*b*) the manner in which the information from the system is conveyed to the pilot, i.e. presentation.

The latter is so important, and the factors involved are so complex, that the effect on development is considerable. Interference with the system characteristics by re-radiation from objects around a transmitter site is another major factor in the trend of development.

The fundamental problem is that an aircraft must be guided both in azimuth and elevation so that an approach to the airfield will be made in the required direction (e.g. into wind) and that contact with the ground will be made at a point which will leave enough room for the subsequent landing run. The conditions to satisfy these requirements become more stringent as aircraft become faster and larger and hence must be guided on to prepared runways.

(2) ORDER OF DEVELOPMENT

Practically all systems which have been developed up to the present time operate by comparing the relative amplitudes of two radiated signals, and probably the earliest attempt was by the use of the magnetic field surrounding a buried cable. This method was first used for marine navigation more than 30 years ago.

The normal radio systems fall broadly into two categories, namely (*a*) those which produce overlapping r.f. field patterns, and (*b*) those which produce differences in modulation depth about the desired course line. There have been attempts to use radio compasses for azimuth guidance, but the method is unsatisfactory since it entails considerable difficulty in finding and maintaining the correct approach line, especially in the presence of a cross wind. The use of radio compasses will therefore not be discussed in this paper.

The first system to be used in this country comes under category (*a*) and was known as Standard Beam Approach (S.B.A.) It was developed from the Lorenz system and the presentation was by audible signals and a meter. The principles were later applied in the 100 Mc/s frequency band for the use of fighter aircraft.

Experiments were then made with the use of a separate glide-path system, and attention was thus directed to the problem of presentation or display. The outcome of these experiments led to the use of modulation separation systems which provide a convenient form of meter display, and audible presentation is not now considered satisfactory.

Site interference has become of increasing importance, and present designs aim at securing the maximum possible relief in this respect. In this connection, systems which operate in the u.h.f. frequency bands (centimetre waves) are claiming attention, since they offer convenient methods of directing radiation away from sources of site interference.

In view of the problems associated with effective presentation, the application of the systems to the control of the aircraft automatic pilot is becoming of increasing interest, and the design of systems is bound to be governed by such application.

(3) DESCRIPTION OF SYSTEMS

(3.1) Leader Cable

A brief description of this method is not out of place in this paper because interest in it has frequently been revived, and it may have future applications. At least one installation has been made; the system has been described in the technical Press by E. N. Dingley of the U.S. Navy Department.*

In its simplest form the leader cable consists of a single cable laid on or in the ground along the desired approach line. The cable is grounded at one end and is energized by an alternator.

If two crossed loops are then so arranged that their planes are mutually perpendicular and at 45° to the vertical, then at a point directly above the cable the induced voltages across the loops will be equal, but with displacement to either side of this point the voltage across either loop will vary as the sine or cosine of the angle of displacement. By suitable combination of the loop voltages it is then possible to show on which side of the leader cable the loops lie.

In the installation referred to above the cable is arranged as a triangular loop with its longitudinal axis along the approach line. The aircraft receiving-loops are mounted as described above, each being connected through amplifiers to the appropriate pointer of a dual crossed-pointer indicator.

The current in the ground loops is so arranged that, at a predetermined height and provided the receiver is midway between the sides of the ground loop, the pointers of the indicator will cross in the centre of the dial.

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* Radio Section paper.

† Royal Aircraft Establishment.

* DINGLEY, E. N.: "An Instrument Landing System," *Communications*, June 1938 p. 7.

The current in the ground loop is then graded along its length, being a maximum at the end distant from the airfield and a minimum at the landing point. Thus if the aircraft is controlled during the approach so that the pointers of the indicator remain crossed in the centre, the descent path will be defined as the locus of a point of constant field strength, and the angle will be controlled by the current grading of the ground loop.

The sensitivity of the system is so arranged that the indicator pointers cross in the centre of the dial when the aircraft is located midway between the ground loop cables and at a height equal to half their separation. The angle of elevation of the aircraft is then 45° subtended at either cable, which ensures that as the aircraft deviates laterally from this location the pointer intersection will be to one side of the centre, but approximately on the horizontal line through the centre. This is because the voltage across each loop varies as the sine of the angle of elevation subtended at the ground cable to which the appropriate loop is coupled.

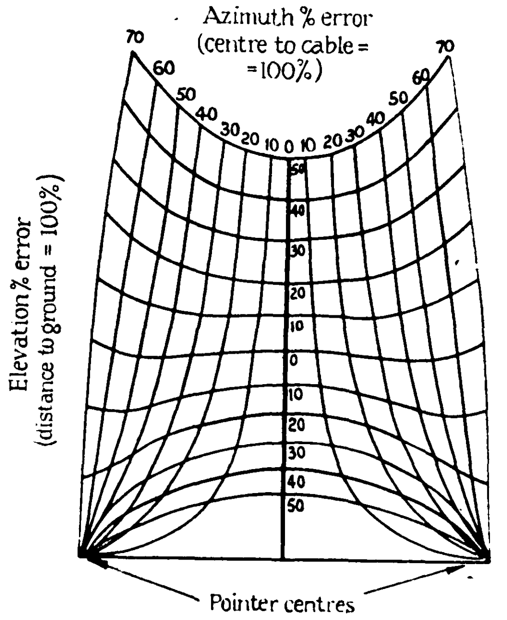

Fig. 1.—Graph of crossed-pointer indicator intersections (leader cable).

This can be seen from Fig. 1, which shows a typical graph of pointer intersections in terms of percentage course error. The pointers lie horizontally when at rest.

The advantages of such a system are that it is relatively simple and reliable and is not subject to siting errors; even if site errors did appear, they would probably be of such a nature that correction could be made by local adjustment of the cable current. A further advantage which may become of increasing value is that the receiving loops can be accommodated inside the aircraft, thus avoiding the problem of external fittings on high-speed aircraft.

The disadvantages are:—

(*a*) For satisfactory operation the aircraft must be laterally within the limits of the ground loop, the latter being defined by the operating height. This implies that the aircraft must first be located near to the approach line by other means.

(*b*) The problem of laying cables on a straight line for some distance outside the airfield, although this might be overcome to a small extent by local current adjustment.

(*c*) From the military point of view the cable may be considered vulnerable to air attack.

(3.2) Keyed-Pattern Systems

It is clear that the highest possible degree of reliability is a primary requirement of any approach or landing system, and consequently simplicity of design, by tending to inherent reliability, is to be commended. For this reason the Lorenz system was adopted in this country in 1935 and later came into general use in the R.A.F., being known as S.B.A.

Fig. 2 shows a typical pair of keyed r.f. field patterns and the manner in which course signals are derived from them. S.B.A. produces such patterns by three vertical half-wave dipoles, arranged in line so that the plane of the array is normal to the approach line. As the centre element is the only one which is energized by the transmitter, there is no question of the phase stability of transmission lines or amplifier circuits affecting the field pattern.

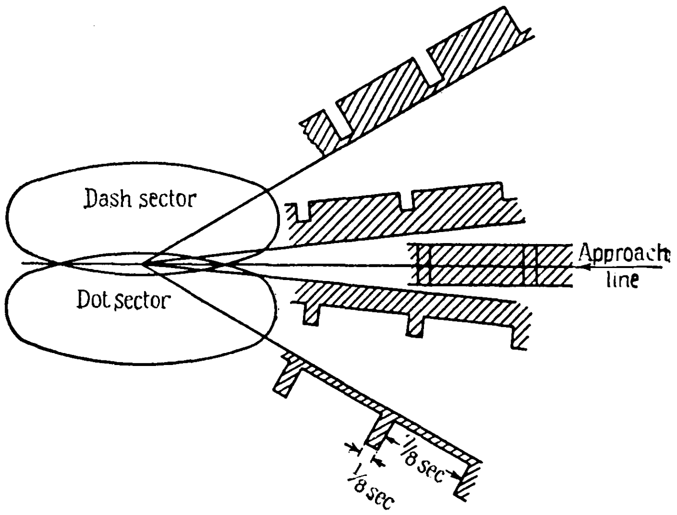

Fig. 2.—Typical keyed-field patterns.

The elements on each side of the radiator are tuned to operate as reflectors, and either can be rendered inoperative by breaking it at the centre by a relay-operated switch. Consequently, by symmetrical tuning and disposition of the reflectors and suitable operation of the switches, the pattern can be made to lie on either side of the approach line, thus producing rhythmic changes of field strength as shown in Fig. 2; by modulating the carrier with an audible frequency the field-strength changes can be presented to the pilot as morse characters, by means of headphones. The Lorenz and S.B.A. systems produce dots to the left and dashes to the right of the course, the signals interlocking to a steady tone on the course line, as is evident from the diagram. The modulation frequency employed is 1 150 c/s.

No comment need be made on the transmitter since standard technique is employed throughout, resulting in an equipment with a power output of 500 watts operating at 30–40 Mc/s.

It is necessary to provide the pilot with some indication of his distance from the airfield, and the minimum requirement, in the absence of radio guidance in elevation, is that a marker signal should be available at a point from which it is convenient to commence a steady rate of descent in order to arrive at the airfield boundary at a suitable height. For a cruising height of 1 000 ft this marker is usually about two miles from the airfield, another being placed at the airfield boundary. A typical layout of such a system is shown at Fig. 3.

The marker consists of a normal transmitter, distinctively modulated and keyed, with a power output of about 5 watts on a frequency of 38 Mc/s. This feeds an array of two horizontal dipoles mounted at a height $\frac{1}{4}\lambda$ above ground, λ being the wavelength.

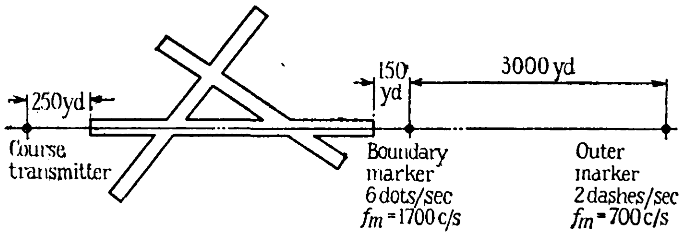

Fig. 3.—Layout of landing system as used for S.B.A.

The dipoles are arranged to restrict the radiation in line of flight for the outer marker, while the boundary array is arranged to restrict the radiation across the line of flight. This is necessary in order to minimize the spread of the marker signals at the greater height of reception at the outer point, while at the boundary it is desirable to restrict the marker more closely to the tolerable deviation of the aircraft from the course line.

The receiving equipment for S.B.A. consists of a superheterodyne for reception of the course signals and a straight receiver with two stages for the marker signals. The course receiver differs from the conventional type in the l.f. and a.g.c. circuits, the essential portions of which are shown in Fig. 4.

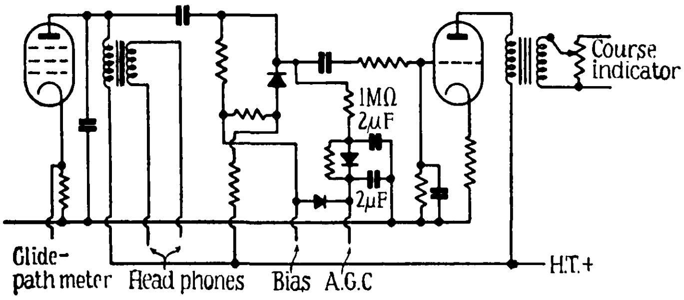

Fig. 4.—S.B.A. audio circuits.

The a.g.c. circuit has a large time-constant (of the order of 2 sec) and the a.g.c. rectifier is connected to the audio side of the detector. The large time-constant is necessary to ensure that discrimination between the keyed signals will be affected as little as possible by the smoothing action of the receiver circuits.

An indicator (Fig. 5) is provided which consists essentially of a centre-zero microammeter for the course signals, a microammeter with a vertical scale for descent guidance, and two neon lamps which flash individually in accordance with the appropriate marker signals.

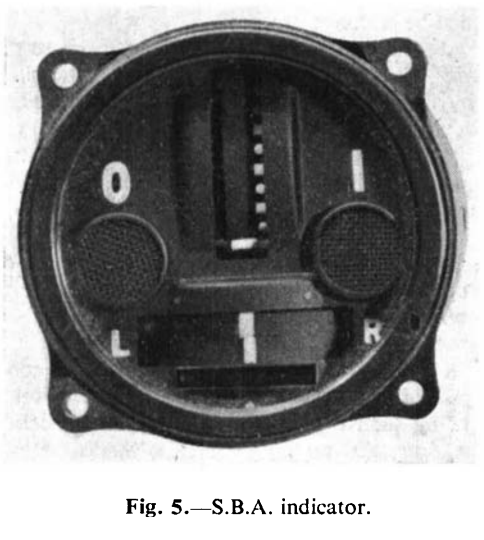

Fig. 5.—S.B.A. indicator.

The audio course signals are rectified and then applied through an amplifier and transformer to the course indicator. The dot and dash signals are thus differentiated as shown in Fig. 6, which is a typical waveform of the signal appearing at the input to the indicator. For small values of input the indicator will move to the right or left according to the sense of the signal, and the back kick will be small enough to pass unnoticed (due to meter damping); for larger values of input the meter field is made non-linear by cutting away the magnet pole-faces, the movement reaching the area of weak field by the velocity imparted by the initial impulse, so that the reversal of current at the end of the signal is ineffective. This indicator is of doubtful value, since it is possible to see the back kick on small signals and misinterpretation has been known to occur.

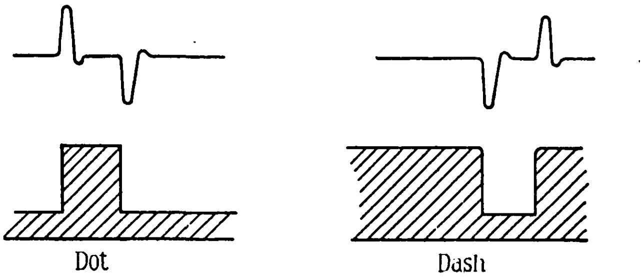

Fig. 6.—Differentiation of signal (S.B.A.).

One of the disadvantages of an audible system, in the absence of some form of contrast expansion, is that the accuracy is inherent in the field patterns. In the first place, the aural detection of differences in sound level is not a precise method of discrimination, although errors are reduced to a minimum by the comparison of levels in a continuous tone and the frequency chosen (1 000 c/s) is the best for the purpose. Under these conditions the threshold of sensibility to such changes is of the order of 0·5 db, so that this must be the limiting factor in considering the accuracy of the system.

The S.B.A. system, with a reflector-aerial spacing of $0 \cdot 45\lambda$, produced field patterns with a difference, near the course line, of about 0·5 db/degree deviation, and there was a small contrast expansion from the square law of the receiver detector.

An aerial system was developed which permitted more control over field pattern shape by driving the outer elements of the three-element array. The amplitude and phase of the currents in the elements could thus be controlled, and satisfactory patterns were produced with a slope at the intersection of about 1 db/degree deviation. Further improvements could obviously be made by increasing the number of elements, but these improvements were not introduced because, as will be shown, this type of system no longer satisfies requirements.

The S.B.A. principles were later applied to a system (developed for the use of fighter aircraft) operating in the 100 Mc/s communication frequency band. Thus, by modification of the a.g.c. time-constant on the appropriate channel, the standard communication receiver could be used for the approach system, thereby effecting an economy in weight.

The ground equipment for this system consisted of a standard communication transmitter, continuously modulated at 1 000 c/s and feeding a three-element driven array of vertical dipoles, the intersecting field patterns being produced by switching the end of a line of length $\frac{1}{8}\lambda$ connected across the centre radiator. The effect was to shift the phase of the centre radiator by ± 45° at the keying frequency of one per second, depending on whether the reactance at the centre was capacitive or inductive.

The marker transmitters for this system were line oscillators operated on 360 Mc/s, the power output being about 30 watts.

(3.3) Glide Path

It was proposed to provide guidance in elevation with the S.B.A. system by making use of the field pattern produced by a vertical half-wave dipole situated with its centre at a height $\frac{1}{2}\lambda$ above ground. The procedure was to fly the aircraft along a line of constant field strength by means of the vertical-scale meter in the indicator. A disadvantage of this method became apparent, since the shape of the glide path depends on the conductivity and dielectric constants of the earth, and therefore the descent-path characteristics vary with site conditions.

An attempt to overcome this difficulty was made by the use of horizontal polarization, but it was soon realized that a descent path of the shape defined by a line of constant field strength is undesirable because the rate of descent of the aircraft is changing continuously, and it is therefore difficult for the pilot to hold the aircraft to the chosen path. In addition, the method resulted in extremely low approaches over the airfield boundary.

A straight descent path was then produced by creating overlapping patterns whose intersection defined the track, as in the azimuth system. Horizontal polarization was used, the frequency being of the order of 300–500 Mc/s.

A system developed in this country employed an aerial system consisting of two elements arranged one above the other. The upper aerial, situated at a height of about 6λ above ground, produced a multi-lobe field pattern in elevation, the lowest lobe making an angle of about 2° with the ground; it intersected the underside of the pattern due to the other aerial at about 3°. This upper aerial consisted of a horizontal dipole placed at a distance $\frac{1}{4}\lambda$ in front of a wire-mesh reflector screen.

The lower aerial was a similar dipole placed at the focus of a parabolic reflector at a height of about λ above ground. The aperture of this reflector could not be greater than about 2λ because it was necessary that the field pattern should enclose the sub-lobes of the other pattern at least up to an angle where ambiguity was not likely to be seen by an approaching aircraft. This angle was of the order of 15°–20°.

Consequently the ground was a major factor in the formation of the field pattern, and the tilt of the parabola did not afford a satisfactory method of controlling the course angle.

In use, this type of equipment was situated near the runway at a sufficient distance for safety, and on a line perpendicular to the runway from the proposed landing point.

A feature of this system was that frequency modulation was employed, the excursion being $\pm$ 2 Mc/s about 480 Mc/s at a frequency of 250 c/s. This should relieve site interference by avoiding a static interference pattern and, in addition, the stability of the mean transmitter frequency need be no better than $\pm$ 0·5%.

The field patterns were keyed (by switching between aerials) in a dot-dash rhythm at the rate of 10 characters/second. The resulting audio signals were applied to a discriminating circuit as shown in Fig. 7, so that the direction of the direct current in the rectificer load depended on the predominance of either the dot or dash signals. A centre-zero meter connected in the load therefore indicated the sense and magnitude of departure from the field-pattern intersection.

A disadvantage of the use of dot-dash signals in this manner is that noise which might be present in an aircraft installation is liable to be rectified by the integrating circuit, thus causing the indicator deflection to be unstable.

The meter used as an indicator was embodied in the S.B.A. indicator, so that this now took the form shown in Fig. 8.

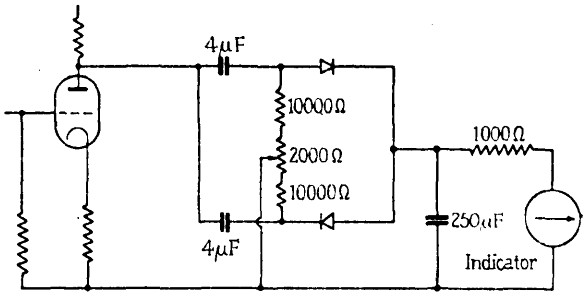

Fig. 7.—Glide-path indicator circuit.

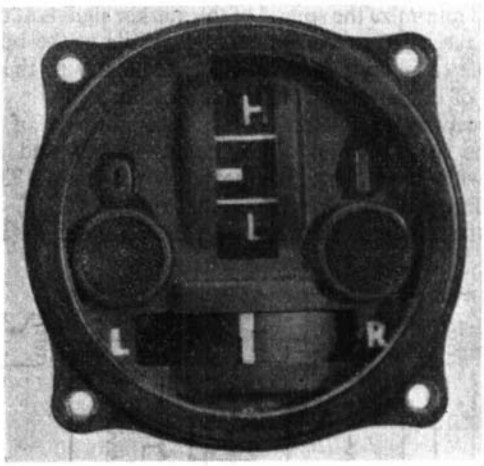

Fig. 8.—S.B.A. indicator with glide path.

(3.4) Display

During experiments on the glide path it became clear that it was not satisfactory to rely on audible signals for azimuth guidance while presenting the glide path on an indicator.

It was also shown that it is not sufficient to put the azimuth signals on to a meter and combine the latter with the glide-path indicator in a common case so that the two displays are very close together. The reason is that the control of the aircraft, in a landing approach by instruments, is such a complicated task that the pilot sees only those indications which he selects for inspection, and for quite long periods he will fail to see indications which are separated by only an inch or two from the one on which he is concentrating.

On the other hand, if all indications essential to the control of the aircraft are combined in one instrument, the pilot becomes confused by the complexity of the picture. A typical example of such a device is the "Flightray," which provided a cathode-ray tube indicator showing by traces the behaviour of the airspeed indicator, directional gyro, artificial horizon, azimuth approach beam, and glide path. A sketch of this display is shown at Fig. 9.

Various forms of indicator combining the display of azimuth and glide path were investigated, and a type was chosen which is now coming into wide use. A photograph of the instrument is shown in Fig. 10, and a sketch showing the effect of pointer deflection in Fig. 11. The horizontal pointer is controlled by the glide path and the vertical pointer by the azimuth system, the sense being such that the horizontal pointer deflects downwards if the aircraft is too high, while the vertical pointer deflects to the left if the aircraft is to the right of the approach line.

It will be noted in Fig. 10 that the ends of the pointers are

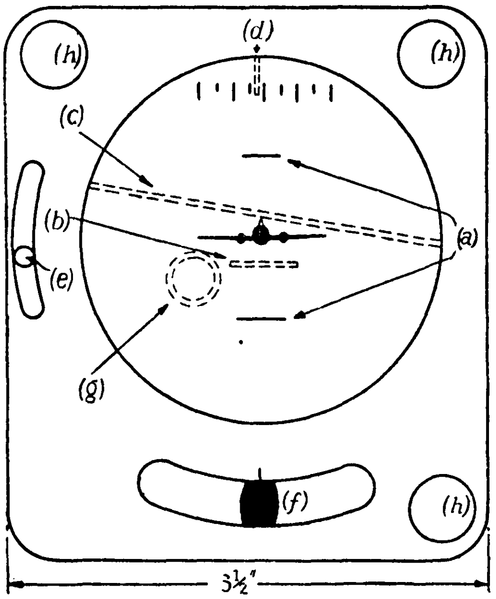

Fig. 9.—"Flightray" indicator (c.r.t. traces shown dotted).

(*a*) Airspeed limits.
(*b*) Airspeed.
(*c*) Artificial horizon.
(*d*) Directional gyro.
(*e*) Polarized brightness control.
(*f*) Level indicator.
(*g*) Azimuth and glide path.
(*h*) Marker lights.

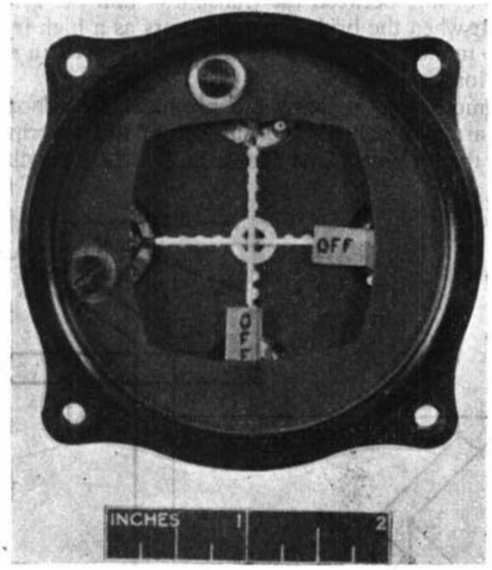

Fig. 10.—Crossed-pointer indicator.

obscured by small tabs—these act as serviceability monitors by moving out of sight when the system, including the receiver circuits, is operating correctly. This form of monitor was adopted because any other method which does not actually interfere with the display was found to be insufficiently arresting.

There has been a criticism of this indicator that, because the pointers are pivoted at the side of the instrument, the deflection of the horizontal pointer might be confused with the tilt of the artificial-horizon bar, and therefore an indicator has been produced in which the pointers are at all times mutually perpendicular. Such an instrument is more difficult to manufacture and it is not considered that the small advantage gained justifies the additional cost.

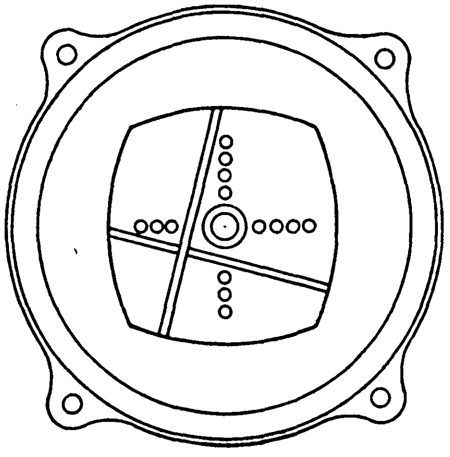

Fig. 11.—Indicator pointers deflected and monitor tabs operated.

(3.5) Modulation Separation Systems

The requirements for a steady-reading combined indicator having been established, and the rectification of dot-dash signals being regarded as unsatisfactory (Section 3.3), it is now necessary to convey the course intelligence in another manner.

Attention was directed to the use of tone separation in a system developed in the U.S.A. and adopted by the U.S.A.A.F. in a form known as the system type S.C.S. 51. Extensive tests of the system were made in this country and, since it has proved satisfactory in operational use, the principles have been adopted and will continue to serve in equipment now being developed and produced for civil aviation.

Intersecting field patterns are produced for both glide path and azimuth, but the boundaries of the patterns (Figs. 12 and 17) are now to be regarded as defining modulation depths, and it will be seen that the pattern on one side of the course line represents a modulation frequency of 90 c/s, while the other represents a frequency of 150 c/s. It will be clear that on the line of intersection the two tones are equal in magnitude, and that either one or the other will predominate with deviation from the line of intersection.

Therefore, if the receiver detector is followed by filters which will separate the two modulation frequencies, the voltages of the two channels thus created can be used to detect the sense and magnitude of departure from the course line.

The receiver used for such a system is of a conventional superheterodyne type, and the circuits following the detector for the operation of the course indicator are shown schematically in Fig. 13. It will be seen that there is a filter for each modulation frequency, each filter being followed by a bridge rectifier and the two rectified outputs being applied in opposition across a load resistor. The polarity of the voltage across the resistor will depend on the relative magnitudes of the currents in the two halves of the circuit, so that the course indicator connected across the load will read according to the magnitude and polarity of the unbalanced component.

The input to the valve which feeds these circuits is taken from a pre-set potentiometer so that the value of the unbalanced d.c. component can be varied, thus providing a control over the sensitivity of the system. These circuits are identical in the azimuth and the glide-path receiver.

The ground equipment transmitters are of conventional type, the azimuth transmitter operating in the 100 Mc/s band and the glide-path transmitter at about 330 Mc/s, but the method of producing the field patterns is of interest and will be described.

The glide-path transmitting aerial system is essentially similar

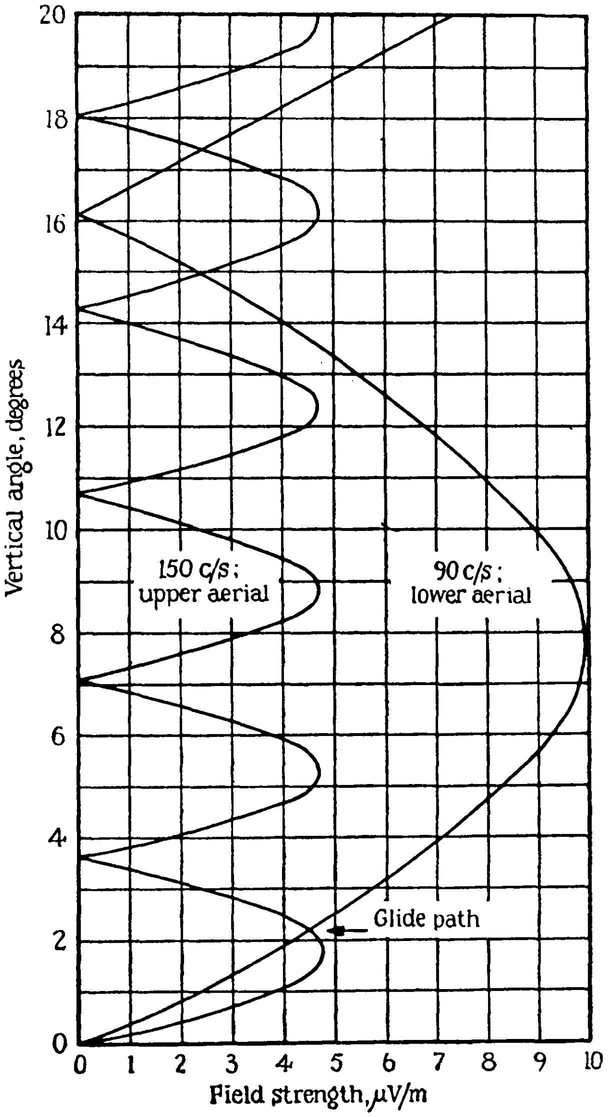

Fig. 12.—Glide-path field patterns.

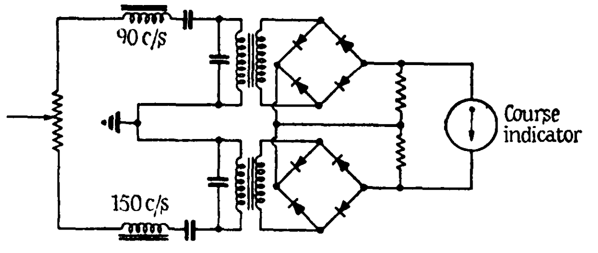

Fig. 13.—Modulation separation circuits.

to that described in Section 3.3 except that the lower aerial is placed in front of a flat reflector and the angle of intersection of the patterns is controlled by varying the height of both aerials. The transmitter feeds the aerials through a mechanical modulator circuit which is shown schematically in Fig. 14.

It will be seen that the circuit consists of two channels, one for each aerial, and there is a section of line, closed at one end, tightly coupled to each channel. This section is $\frac{1}{4}\lambda$ long, and when resonant it will cause the transmission line at that point to appear as a high impedance, so that no energy will be transmitted to the appropriate aerial. The tuning of the coupled section is varied sinusoidally by a moving vane which passes between the open ends at the rate of 90 c/s for the channel feeding the lower aerial and 150 c/s for the other. In practice the 90 c/s modulator consists of three radial vanes while the 150 c/s modulator carries five vanes, the two being driven at 1 800 r.p.m. by a common motor.

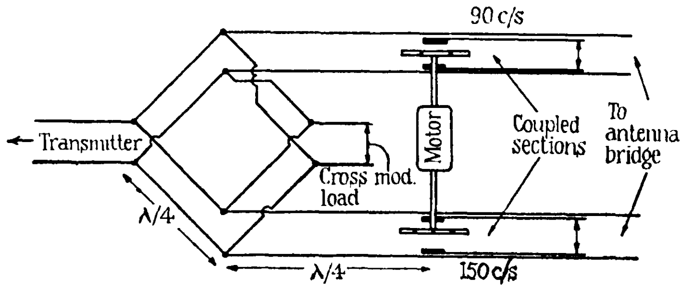

Fig. 14.—Cross-modulation bridge and mechanical modulator.

Since the method causes impedance changes between wide limits it is necessary to provide the bridge shown in the diagram in order to avoid cross-modulation. It will be clear from the diagram that any voltages appearing at either channel by reflection from the other will be cancelled by the bridge, provided that the impedance of the cross-modulation stub is equal to that of the transmitter as seen from the bridge input. In addition, the length of line between the transmitter and the bridge is so chosen that when the bridge input appears as a high impedance during the modulation cycle, the transmitter "sees" a minimum change of load impedance.

The azimuth field patterns are produced by a horizontally polarized array, which for the purpose of this description will consist of three elements, as shown in Fig. 15. It will be seen from the diagram that the array is fed from a bridge in such a way that the centre element will radiate the carrier and both modulation sidebands while the outer elements will carry the sidebands only, owing to the transposition of one leg of the bridge. The transposition will also effect a phase reversal of the 90 c/s sidebands at the outer feeder with respect to the centre feeder. It is to be noted that the bridge is supplied from a mechanical modulator circuit similar to that described for the glide path.

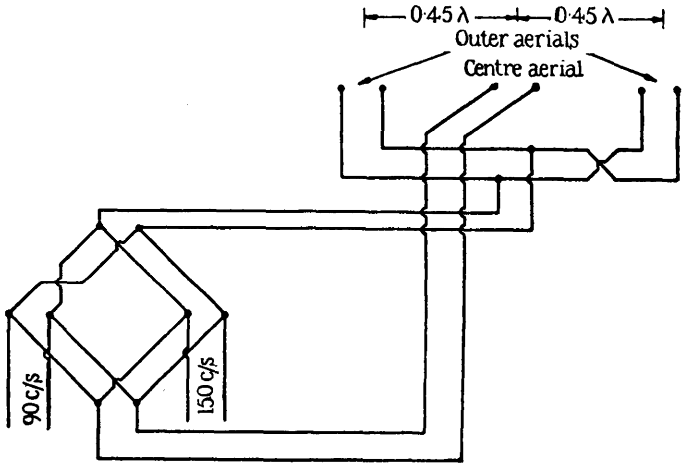

Fig. 15.—Antenna bridge and 3-element aerial system.

If the fields due to the centre element and the outer pair are

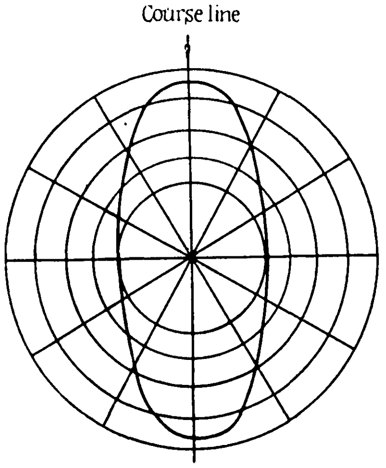

Fig. 16A.—Carrier and sideband pattern (centre aerial).

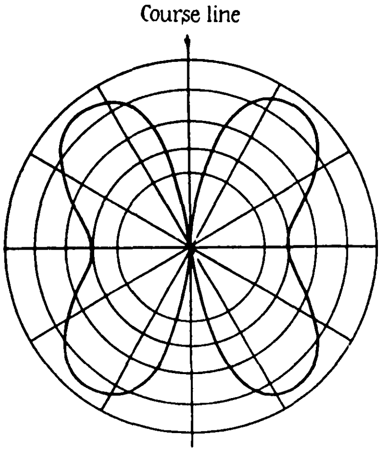

Fig. 16B.—Sideband pattern (outer aerials).

considered separately, Fig. 16A shows the type of pattern produced by the centre element, the shape being modified from the circular by the parasitic influence of the outer pair. Fig. 16B shows the pattern produced by the outer pair, and it is evident that the signal on the course line will be due to the centre aerial only, which will be modulated equally by 90 c/s and 150 c/s.

At all other points the signal will consist of the vectorial sum of the sidebands in the centre and outer elements. Therefore, since the two lobes of the outer aerial field pattern are in phase opposition, by combination in the receiver the sum of the 150 c/s sidebands radiated by the centre and outer aerials will appear on one side of the course line, and the difference will appear on the other side of the course line. There will be a similar combination of the 90 c/s sidebands, but the sum will occur on the opposite side of the course line owing to the phase reversal of the 90 c/s sidebands by transposition in the bridge mentioned above.

These resultant fields can, therefore, be shown as a pair of overlapping patterns which are symmetrical about the approach line and whose boundaries will define the character and variations in depth of modulation of the carrier in azimuth around the aerial system. Typical patterns are shown in Fig. 17.

Additional elements can be introduced to the basic array just described in order to sharpen the pattern intersection and increase the ratio of energy near the course line to that at the sides of the array; Fig. 18 shows a pattern which would be derived from an array of eight elements disposed and fed as shown in the diagram. This pattern is typical of the system which will generally be used.

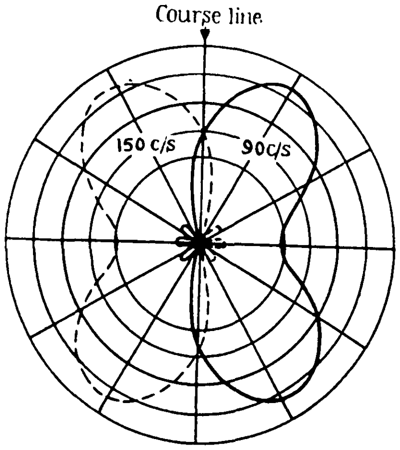

Fig. 17.—Azimuth modulation patterns.

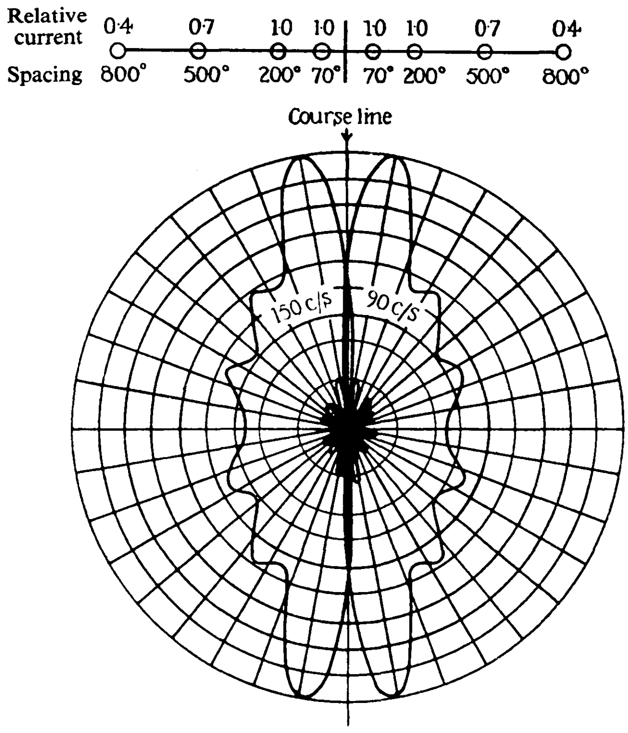

Fig. 18.—Azimuth pattern for 8-element array.

Alternative methods of producing modulation patterns exist, but these will not be described in detail. For example, the sidebands can be separated by the use of balanced modulators, or separate stages can be modulated by the audio frequencies, but the virtue of the mechanical modulator lies in its relative simplicity and, since a single transmitter output stage is used, its inherent reliability. Other methods which employ multiple output stages must carry a monitoring system which will feed back to the transmitter and correct any changes which cause the occurrence of relative differences in the field patterns.

(3.6) Site Interference

One of the major problems associated with the design of track guidance systems is the avoidance of course distortion arising from interference by re-radiation from objects in the vicinity of the transmitting equipment. Such objects are usually encountered in the form of trees, buildings and overhead lines, while metallic fences can also cause trouble under some conditions.

The problem is so complex that it will be treated only in general terms in this paper, but the information given will be sufficient to show the trend of effects and the steps which must therefore be taken to minimize them.

If a re-radiating object is situated at any point around the transmitter (other than on the course line) the re-radiated signal will have the same characteristics as an off-course signal normally presented to the receiver at the same angular deviation from the course line. Consequently, if such a signal is seen by the receiver while it is on the course line, an off-course indication will result, the sense and magnitude depending on the vectorial addition of the direct and re-radiated signals.

It is clear from the foregoing that, as the aircraft flies down the course line, the off-course indications will vary as a function of the difference in path length between the direct and re-radiated signals, and the course line will appear to contain recurrent bends, the frequency of which will increase until a point is reached on the course line opposite the source of interference.

In practice, the conditions are such that at distances greater than about two miles from the airfield the course bends are so slow that they either pass unnoticed or are interpreted as a course bearing error, but within this distance the bends eventually become too fast to follow and appear as a rhythmic deflection of the indicator about the zero.

When the interference is caused by a single object the source is not difficult to locate, but the problem becomes very difficult as the sources multiply. One of the chief points to be considered in the assessment of an interfering object is the predominant component of the structure with relation to the plane of polarization of the radiated energy, and since trees, which are predominantly vertical, are a common source of interference in this country, it is intended to use horizontal polarization in equipments now being manufactured.

Other factors governing the interference value of an object are as follows:—

(*a*) The electrical characteristics of the material of which the object is composed.

(*b*) The size of the object and its distance from the transmitter.

(*c*) The orientation of the object, especially if large plane surfaces are involved (e.g. aircraft hangars).

(*d*) Difference of the two field patterns in the direction of the object.

(*e*) The ratio of power in the direction of the object to that on the course line.

Of these factors (*b*) can be controlled to some extent by a general specification of clearance in the vicinity of the transmitter site, usually based on the assumption that the amplitude of radiation falling on the object will be approximately proportional to its height and to the inverse square of its distance from the transmitter.

This clearance area is also governed by factors (*d*) and (*e*), which are determined by the field pattern shapes. Consequently, the system is designed as far as possible to maintain the power on the course line while reducing the radiation at right angles, the direction of maximum radiated power being kept as close to the course line as possible. An additional gain is made by increasing the rise of signal difference about the course line, even though the relative powers referred to above remain the same. This is because the indicator sensitivity can then be reduced, leaving the same overall sensitivity but reducing the actual sensitivity to interference. This represents a further argument in favour of a steady indicator display as against an audible keyed-signal presentation.

In view of these considerations the value of the field patterns shown in Fig. 18 will be appreciated, since the course sharpness is of a high order and the maximum power is radiated at an angle of only ± 10° to the course line, while the radiation to the sides is kept low.

(3.7) Centimetre Systems

It has been shown that it is necessary to keep the radiated energy close to the course line and away from surrounding objects, and it is clear that this can be achieved only by aerial systems possessing a high degree of directivity.

As it is not practicable to attain the necessary directivity by arrays while simultaneously satisfying other requirements, the use of much higher frequencies becomes attractive since they will permit the employment of compact and highly directive radiators, usually in the form of an element at the focus of a parabolic reflector of wide aperture.

Frequencies of the order of 3 000 Mc/s are suitable for this work, and a system operating in this band has already been produced in the U.S.A. It operates as a modulation separation system with frequencies of 600 c/s and 900 c/s on both azimuth and glide path. Typical field patterns of such a system are shown in Figs. 19 and 20; it will be seen that the azimuth pattern is unidirectional, thus ensuring freedom from interference by objects near the transmitter site. In addition, the maximum radiation is contained within ± 4° of the approach line, so that the possibility of interference from airfield buildings is considerably reduced. The glide path also offers advantages over those systems already mentioned, in that the patterns are formed solely by the radiator and are therefore independent of ground conditions.

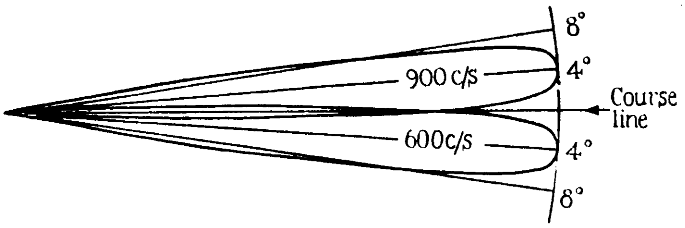

Fig. 19.—Azimuth field pattern—centimetre system.

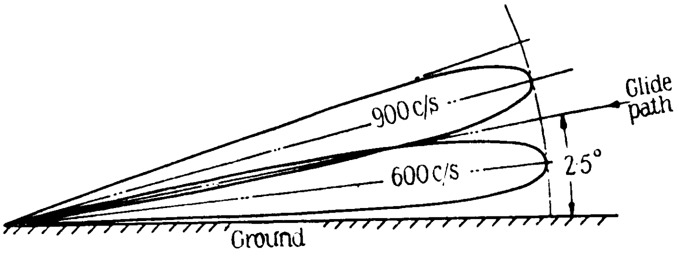

Fig. 20.—Glide-path field pattern—centimetre system.

In both azimuth and glide-path units the overlapping patterns are formed by switching the modulated transmitter output alternately between two waveguides, the terminations of each being slightly offset from the centre of the parabolic reflector so that the transmitted lobes are disposed symmetrically to either side of the axis of the reflector.

The switching frequency is of the order of 60 c/s and is carried out by a mechanical modulator which consists of two discs rotated by a common motor. Each disc enters a resonant cavity from which an aerial waveguide is fed and becomes part of the circuit. The edge of the disc is serrated over half its perimeter, the number and shape of the serrations being such as to create a sinusoidal modulation of the cavity tuning at the appropriate frequency of 600 c/s for one disc and 900 c/s for the other. The discs are then arranged on the common shaft so that one cavity is detuned by the plain half of its disc while the other is being modulated.

The transmitters for this system each employ a klystron oscillator with a.f.c. claimed to maintain the frequency to within ± 25 kc/s.

The receiver is a superheterodyne with two i.f. channels coupled to a crystal mixer which is fed with the local oscillator frequency and the signal frequencies of the azimuth and glide-path systems. The oscillator frequency is between the two system frequencies, which are chosen to provide the beat frequencies associated with their respective i.f. channels. The output circuits are essentially the same as those described in Section 3.5.

Another possible method of obtaining overlapping patterns would be similar to that used in certain radar equipments during the recent war. This would involve the rotation of an arm in a direction radial to the optical axis of the parabolic reflector. The radiating element would be carried on the end of the arm so that the locus of its travel would be a circle centred on the axis of the paraboloid, the plane of the circle being normal to this axis. Suitable modulation could then be introduced during the rotation to identify the position of the field pattern.

Another method has been proposed in which the lobe of the field pattern is made to oscillate symmetrically about the approach line, a voltage being derived in the receiver which is proportional to the mean time for which the radiation is received. This will clearly be a maximum on the course line and will decrease with deviation, the sense being determined by an identifying modulation applied at the limits of the lobe sweep.

Associated with the same proposal is a suggestion for avoiding the requirement of frequency stability in the transmitter oscillator. The oscillator would be modulated by a frequency which could conveniently be the i.f. frequency of a conventional receiver, and could therefore be of high stability. The incoming signal would then be passed to a crystal detector from which would be derived the modulation frequency.

Consequently, a common receiving aerial could be used for azimuth and glide path, and it is only necessary to space the two frequencies to avoid beats which would pass the i.f. amplifier. There would, of course, be separate i.f. channels for the two systems. Such a system should be inherently reliable because single amplifying and feeder channels are used throughout for each system.

No comment can be made at this stage on the performance of these systems, but they appear as promising lines of development if a requirement for such systems becomes confirmed.

(3.8) Control of Automatic Pilot

The difficulties of the pilot in controlling an aircraft during an instrument approach have been pointed out in Section 3.4, and it becomes increasingly apparent that, if the aircraft could be automatically controlled by the approach systems, the task of the pilot would be considerably relieved and a more precise approach would probably be made.

Modulation separation systems are particularly suited to the control of a modern automatic pilot (which is usually electrically operated), since by simple circuits they produce a d.c. output which is proportional to the angular deviation of the aircraft from the course line.

This information is not in itself sufficient, since the delay in effecting a change of attitude of the aircraft is such that hunting about the approach line is bound to occur to a degree which would make an approach impossible. Accordingly, it is necessary to provide additional information relating to the rate of change of angular deviation, $d\theta/dt$. This information can be extracted from the receiver by differentiation of the output. It is then fed back in opposition to the "θ" voltage when θ is decreasing. The relation between the two voltages can be so arranged that when $d\theta/dt$ is a maximum (i.e. the aircraft is flying a course normal to the approach line) the total d.c. output to the indicator will be reversed, so that the signal will appear to the automatic pilot as though the aircraft had passed through the approach path to the other side of the course line, thus causing a turn away from the course. For example, suppose that the approach path lies on a line passing between North and South and that the aircraft is at a point North-East of the transmitter, heading in a westerly direction: without a "rate" circuit in use, the indicator would show that the aircraft is to the left of the approach path and the aircraft heading would be maintained until the path was reached, when a turn to the left would be made until the heading agreed with the direction of the approach path. The aircraft should now be flying towards the airfield and located on the correct path, but, since the procedure can seldom be accomplished precisely, the aircraft passes through the approach path before the turn is completed, and the procedure required to regain the path results in "hunting" about the course line. With a "rate" circuit in use, the indicator may show the aircraft to be to the right of the path, even though it is actually to the left, owing to a high value of $d\theta/dt$. If this were the case a turn to the left would follow in obedience to the information given by the indicator, and the result would be a decrease in $d\theta/dt$ so that the indicator deflection would decrease by an amount roughly proportional to the rate of turn, thus making it appear that the aircraft was near to the approach path. By this process an aircraft heading can be established such that the voltage derived from $d\theta/dt$ is equal to the voltage derived from θ. The indicator will then show "on course," but since θ is decreasing continuously it will be necessary to modify the aircraft heading continuously if the indicator is to be maintained "on course," until the aircraft is on the approach path and heading towards the airfield. There will then be no voltage derived from either θ or $d\theta/dt$, and the indicator will show a true "on course" reading. The track of the aircraft into the course line will therefore be asymptotic, provided that the flight is controlled to satisfy the equation $\theta + K\,d\theta/dt = 0$, where K denotes the time-constant of the "rate" circuit. The value of K will be dictated by the response of the aircraft, since hunting will occur if the sensitivity of the indicator is too great, but a value can be chosen such that a smooth approach will be made. With a "rate" circuit in use it is important that the approach path of the radio system be straight, since, if the aircraft encounters an apparent bend in the path, a variation in $K\,d\theta/dt$ will appear to a value depending on the violence of the course distortion, and this may be of such a magnitude that the aircraft cannot follow the bend with the value of K chosen for a normal approach. Consequently the violence of the course bend would appear to be magnified.

This work is still the subject of experiment, and further discussion is not within the scope of this paper. It is mentioned, however, as an illustration of one of the factors affecting the design of approach systems.

(4) NOTES ON THE TREND OF DEVELOPMENT

In order to avoid site interference, attention is likely to be centred on the highly directive centimetre system, although there is a possibility that an entirely different approach to the problem may be made, arising out of the development of phase-comparison systems for navigation. The use of such systems for the purpose of both navigation and landing approach would probably result in an economy in aircraft equipment, but whether they could be disposed to satisfy both requirements is a matter for speculation.

None of the systems so far considered can be described as other than approach aids, because, although the glide path provides guidance practically to ground level, experience has shown that it is not practicable consistently to land aircraft with safety by attempting to follow the glide path to its termination. It is usual, therefore, to leave the radio system when the aircraft is sufficiently close to the ground to allow the runway lighting system to be seen; from that point a normal visual landing is made.

When satisfactory automatic control of the approach has been achieved it will then be necessary to solve the landing problem, and a different technique may have to be adopted for this stage. It is fundamental that the aircraft must make contact with the ground with a minimum vertical velocity, and this implies that the flight of the aircraft must be controlled by reference to the ground level rather than by reference to a path in space.

Consequently it would appear that to ensure a safe landing, information derived from some form of absolute altimeter is necessary. A requirement for such a device would be a high degree of accuracy near the ground, together with a continuous transmission of intelligence, and it is in this light that existing radio altimeters must be considered. Radio guidance in azimuth is likely to be required until the aircraft is brought to a standstill, so that this requirement will also have to be taken into account in any future design.

(5) CONCLUSIONS

(*a*) Of the systems available at the present time, those which offer a convenient means of driving a meter pointer are to be preferred. In general, such systems lend themselves readily to the control of an automatic pilot.

(*b*) Modulation separation systems most easily meet the conditions of (*a*) above.

(*c*) Site interference compels either a considerable reduction of operating frequency so that common objects become less effective as radiators, or recourse to highly directive field patterns. The latter method is to be preferred, and is achieved by the use of equipment operating on centimetre wavelengths.

(*d*) Any form of display requires interpretation by the pilot, and therefore the presentation must be simple and compact. A meter indicator of the crossed-pointer type is the most suitable at present available.

(*e*) A straight-line glide path offers advantages over a curved path in relation to the problems of controlling the aircraft during the approach.

(*f*) Any system now developed must be suitable for operation of the automatic pilot, since this is the method most likely to secure consistent performance.

(*g*) None of the systems at present available can be relied upon to control the actual landing, and a new technique for this aspect of the problem will have to be devised.

(6) ACKNOWLEDGMENTS

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