Elements of
Electronic Navigation

Second Edition

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Preface to the Second Edition

A considerable time has elapsed since the book was written and in this period remarkable developments in navigational aids have taken place. All the aids dealt with in the previous edition are continuing in use with perhaps changes in the hardware with advances in the art of electronics. Since the basic principles remain the same and as the emphasis in the book is on these, it has not been found necessary to effect many changes.

One way in which the developments in field of electronics have made a difference is the advent of powerful, compact and relatively low cost computing devices. This has opened up possibilities of new techniques of navigation. An outstanding example of this is the Global Positioning System (GPS) developed by the American Department of Defence which can provide very accurate positional information all over the globe to the military, and with slightly reduced accuracy, to all others. Some space has been devoted to this topic because of its importance and its potential for worldwide use. As a consequence chapter nine has been changed to 'Satellite Navigation Systems'.

The Microwave Landing System (MLS) which is intended to replace the currently used Instrument Landing System (ILS), in due course of time, has also been dealt with briefly.

The treatment of the subject is directed to the students of engineering, in particular communication and electronics engineering, and the emphasis is on the technical rather than operational aspects of the subject, as in the earlier edition.

For information on the new material introduced, I must gratefully acknowledge the assistance given by Bharat Electronics Ltd., Bangalore and in particular their central Research Unit. I am indebted to the staff of the unit, particularly H Ramakrishna and G Raghava Rao with whom I have had many helpful discussions. I must also thank the Gujarat Communication and Electronics Ltd. (GCEL), who have supplied me with information on the Navigational Aids manufactured by them, which I have included in this edition.

NS NAGARAJA

Preface to the First Edition

As in many other fields, electronics has made a revolutionary impact in the field of navigation. This art which started with the use of a few instruments such as the sextant and the compass followed by the manual calculations has now developed to such an extent that the navigator has at his disposal a vast array of instruments and computers which automatically present his position and the distance he has to travel to his destination and other navigational information. All this has been made possible by the advent of electronics. There are now numerous radio aids to navigation and some aids which do not involve radio emissions of any type but are dependent on electronics for their functioning.

This book aims at giving an introductory treatment of this vast and expanding field. While navigation as such is the field of the professional navigator, the electronic engineer cannot afford to be ignorant of the variety of ways in which the technology of electronics has been applied to navigation. Appropriately then, the subject figures in the syllabus of the bachelor's degree in electronics in most universities. This book is addressed to such an audience.

The emphasis here is on systems and engineering principles rather than details of equipment. Only in a few places are circuits given. Treatment of the details of circuits, etc. are out of place in a book of this nature and size. An attempt has been made to cover most of the important navigational facilities that are in operation in this country and abroad.

A subject such as this where rapid developments are taking place and much of the latest developments are only available in classified literature, any book which deals with details, tends to get obsolete. But a treatment of the basic principles is likely to have a more lasting value.

The book is divided into nine chapters, the first being introductory and the next seven dealing with various common navigational aids including the self-contained systems of Doppler radar and inertial navigation. The last chapter deals briefly with some of the recent developments. Additional matter of relevance is given in the four appendices. A list of references including textbooks is given for further reading on the topics dealt with. As the book is intended for students in the final year of their bachelor's provided by commonly available tests like Terman's *Electronic and Radio Engineering* is assumed. A set of questions and exercises has been included in the end with a view to help the reader increase his appreciation of the subject and to encourage further reading. Metric units of distance have been used throughout the book. As much of the literature on the subject makes use of other units such as the statute mile, nautical mile, knots, etc., the conversion factors are given in a footnote for ready reference.

This book is the result of a suggestion made by Prof S V C Aiya, formerly Head of the Department of Electrical Communication Engineering at the Indian Institute of Science, and the encouragement he gave me.

It has been used in the class room for a number of years and owes its present form to the many helpful suggestions made by the students themselves, for which I thank them. I am also thankful to the Director, Indian Institute of Science, for permitting me to bring out this volume and to Prof B S Ramakrishna, Chairman of Electrical Sciences, for the encouragement he has given. The drawings were prepared by Mr Vijayendra and the manuscript was typed by Mr Govindaraju, and I am grateful to them for the care and trouble they took.

Bangalore,
26th March, 1975

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Introduction

1.1 INTRODUCTION

Navigation, the art of directing the movements of a craft from one point to another along a desired path, has an origin going back to pre-historic times. Many great voyages of migration appear to have been undertaken even in the pre-Christian era. In the early days, none of the aids of later navigators, such as the compass, the chronometer and the sextant, were available. These voyages were accomplished perhaps by the voyagers' knowledge of the movements of the sun and the stars and the winds.

As time progressed, various instruments came to the aid of the navigator. By the sixteenth century, the compass, the clock, the theodolite and, at least, crude charts of the known world were available to the navigator. The great navigator, Magellan, circumnavigated the Globe in the early sixteenth century with the aid of these instruments. By the eighteenth century, the chronometer, a very accurate clock, was produced. With the chronometer, the navigator was able to determine his longitude by noting the transit time of heavenly bodies. The other instruments were also improved and the charts became more extensive and accurate. Navigation, by then, had become a science as well as an art. In the twentieth century, electronics entered the field. Time signals were broadcast by which the chronometers could be corrected. Direction finders and other navigational aids which enabled the navigator to obtain a fix using entirely electronic aids were developed and came into extensive use.

Our principal concern in this book is with electronic navigational aids, i.e. navigational systems which employ electronics in some way. However, a brief account of other methods of navigation are included to present the main topic in the proper perspective.

1.2 FOUR METHODS OF NAVIGATION

Navigation requires the determination of the position of the craft and the

currently used methods of navigation may be divided into four classes:
(i) Navigation by pilotage (or visual contact),
(ii) Celestial or astronomical navigation,
(iii) Navigation by dead-reckoning, and
(iv) Radio navigation.

We will be concerned with only the last two of these, but, before we proceed, some general ideas regarding the other methods of navigation are desirable.

(i) *Navigation by pilotage* In this method, the navigator fixes his position on a map by observing known visible landmarks. In air navigation, for example, when the ground is visible, the navigator can see the principal features on the ground, such as rivers, coast-lines, estuaries, hills, etc. and thereby, fix his position. Even at night, light beacons, cities and towns provide information about the position of the craft. Pilotage in this sense is, of course, possible only under conditions of good visibility.

Pilotage is also possible with the aid of an air-borne radar and this is called 'Electronic-Pilotage'. The radar used for this purpose is generally a microwave search radar provided with a plan-position (PPI) display on which the terrain is mapped. The PPI picture has, of course, poor resolution compared with the human eye, because the angular resolution is typically 3° and the resolution radially, along the time-base scan is of the order of a few kilometers. This is, however, sufficient for indentifying the more prominent features of the terrain. Electronic pilotage has the advantage that its range is high, generally 50 to 100 km and that it can be used under conditions of poor visibility. In addition, the distance of the objects 'seen' can be determined far more accurately than by visual means. Because of these advantages, radar can be a valuable navigational aid under certain conditions. Both the methods of pilotage require recognizable features in the terrain and would, therefore, be useless over stretches of sea if there are no islands in the field of vision. Both methods of pilotage depend upon the availability of accurate maps of the terrain.

(ii) *Celestial navigation* Celestial navigation (also called astronomical navigation) is accomplished by measuring the angular position of celestial bodies. Almanacs giving the position of celestial bodies at various times (measured in terms of Greenwich Mean Time) are readily available. The navigator measures the elevation of the celestial body with a sextant and notes the precise time at which the measurement is made with a chronometer. These two measurements are enough to fix the position of the craft on a circle on the face of the globe. If two such observations are made, the position or 'fix' of the craft can be identified as one of the two points of intersections of the circles. If the position of the craft is known approximately, the ambiguity between the two possible positions may be eliminated. Sometimes, a third observation may have to be made to remove the ambiguity.

The basis of this method is as follows. Referring to Fig. 1.1, if P is the position of craft on the surface of the earth, and Q the point on the surface of the earth at which the celestial body is at the zenith at the time of observation (called the sub-stellar point), the celestial body makes an angle θ with the vertical at P. The arc joining sub-stellar point and the position of the craft also subtends an angle θ at the centre of the earth. The locus of all points subtending this angle is a circle with the sub-stellar point as the centre. The position of the latter can be obtained from the almanac if the exact time of observation is noted. One observation of θ (or the elevation angle $90° - \theta$) gives one position circle. Two observations, providing two intersecting circles, are generally sufficient to obtain a fix. In practice, the two observations are not made at the same instant and consequently the craft will have moved between the instants of observations. But this can be allowed for in the reckoning.

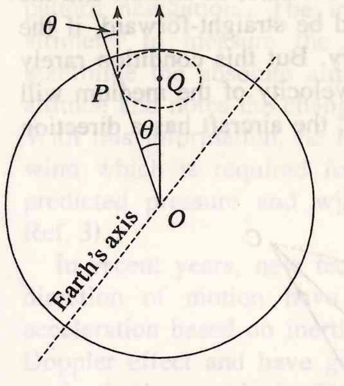

Fig. 1.1 Principle of celestial navigation

The advantage of celestial navigation is its relative independence of external aids. It has the disadvantage that the visibility should be good enough to take elevation angles of heavenly bodies. This may not be always possible at sea, but in air navigation, with modern aircraft flying at altitudes above 5000 m, visibility is always good.

The accuracy of fixes obtained in this method of navigation depends mainly on the accuracy with which the elevation of the heavenly body is taken. This, in turn, depends on the accuracy with which the horizon can be located. Under favourable conditions, these angles can be measured correct to 1 min of arc, which implies the position line accuracy of one nautical mile.

(iii) *Navigation by dead-reckoning* In this method of navigation, the position of the craft at any instant of time is calculated from the previously determined position, the speed of its motion with respect to earth along with the direction of its motion (i.e. its velocity vector) and the time elapsed. The term 'dead-reckoning' abbreviated 'DR' stands for 'deduced calculation*'. This is the most common and widely used method of navigation.

Navigation by dead-reckoning, requires some means of finding the direction of motion of the craft (called the "track angle") and a speed

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* The origin of the term is attributed by some to the use of a log attached to the line used in taking measurement of ship's speed at sea. The log is 'dead', i.e. stationary in water while the ship is in motion.

indicator. The first requirement may be met by a magnetic compass and the second by an instrument such as the air-speed indicator in aircraft and the mechanical log in ships. DR navigation would be straight-forward, if the medium in which the craft travels is stationary. But this condition rarely prevails. The complication introduced by the velocity of the medium will be appreciated by referring to Fig. 1.2. In this, the aircraft has a direction of apparent motion, *OA*, which is called the 'heading' of the aircraft. The wind has a velocity in a different direction, *OB*. The velocity of the aircraft with respect to ground is given by the vector combination of these two, i.e. by *OC*. The angle which the vector *OC* makes with the North is called the 'track angle.' It is clear that the heading and track angle are not, in general, the same, the exception being when the wind is in the direction of *OA* or its reciprocal. Further, the air speed and ground speed are not the same when there is a wind. The true ground speed and direction can, however, be determined by constructing the velocity triangle and *DR* navigation is, thus possible, if the wind velocity is known. Similar considerations apply to navigation of ships as tidal currents require to be taken into account. But these are known to much better accuracy than wind velocities which keep changing in magnitude and direction constantly. Navigation by dead-reckoning over long distances is subject to appreciable errors unless intermediate checks are possible.

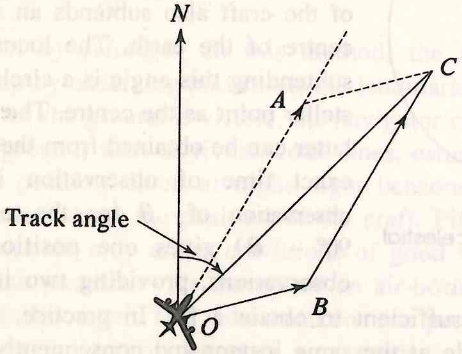

Fig. 1.2 The velocity triangle

In air navigation, the wind velocity is generally obtained in the course of the flight from weather broadcasts or by communication with ground stations. In long flights over water, modern air operations resort to 'minimal flight paths', i.e. paths which require minimum flying time. If there were no winds, this would be the path of minimum geographical distance, which is the great-circle path between the starting point and the destination. But the presence of winds, particularly high velocity air currents at high altitudes completely alters the situation. The path taking the shortest time uses favourable wind directions and may be longer geographically. If the pattern of isobars ('the pressure pattern') over the

region of flight is known, the experienced navigator can take a route which is long geographically but requires shorter time. This is called 'pressure pattern navigation'. The instruments required for this are a barometric altimeter to measure the 'pressure altitude' and a radio altimeter to determine the absolute altitude. The navigator flies at constant pressure altitude and notes the change in absolute altitude over an interval of time. With this information, he is able to compute the cross-component of the wind which is required for dead-reckoning, and serves as a check on predicted pressure and wind. (For further details of this method, see Ref. 3).

In recent years, new techniques of determining the true velocity and direction of motion have been developed. These employ sensors of acceleration based on inertial principles and sensors of velocity based on Doppler effect and have given rise to 'Inertial navigation' and 'Doppler navigation' respectively. The principles of these methods are the subject of Chapters 7 and 8.

(iv) *Radio navigation* This method is based on the use of electromagnetic waves to find the position of the craft. The various techniques employed form the subject matter of the greater part of the following chapters where a number of common systems are described. All these systems depend upon transmitters and/or receivers at known locations on the earth's surface and transmitters and /or receivers working in cojunction with them in the vehicle. These systems involve a dependence of the craft on installations on land and are, therefore, not self-contained systems of navigation like the DR system. In the last analysis, all these systems depend on the properties of rectilinear propagation and constant velocity of electromagnetic waves and the navigational parameters (direction, distance, etc.) are obtained by direct or indirect measurement of delay (or delays) occuring in the transmission. The positional information is related principally to (i) the measurement of direction, (ii) the measurement of distance, or (iii) the difference in distance of two transmitters. These give the locus of the craft on (i) a line, (ii) a circle, and (iii) a hyperbola, respectively. The intersection of two or more such loci gives the fix or position of the craft.

Satellite navigation systems, dealt with in chapter 9, also depend on the establishing of loci on which the craft is located. The Transit system, the operation of which depends upon the measurement of Doppler shift in the frequency it radiates, defines a hyperboloid of revolution, the intersection of which with the surface of the earth gives the locus of the possible positions of the receiver, and the intersection of two or more loci establishes the position of the receiver. The Navstar system depends on the measurement of the exact distance of the receiver from the satellite and so the locus is the intersection of a spherical surface with the earth (or a concentric sphere in the case of aircraft flying over the earth), and again the intersection of two or more loci establishes the position of the receiver.

In the following chapters the principles underlying the operation of

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Radio Direction-finding

The earliest method of electronic navigation was by direction-finding, i.e. the determination of the direction of arrival of electromagnetic waves at the receiving station. As electromagnetic waves travel along the great-circle path, direction-finding helps to locate the transmitter along a great circle. Though the oldest form of electronic navigation, this method is still in wide use both on ships and aircraft.

The direction-finder may be located either on the craft or on ground. In the former case, the determination of the bearing of two or more fixed stations will give a 'fix'. In the latter case, the ground station finds the bearing of the craft and passes on the information to the craft by a radio communication channel. Both the methods are in vogue.

Direction-finding may be carried out in any region of the radio spectrum, though certain frequencies are specifically allotted for navigational purposes, in the LF/MF, HF and VHF bands. The technical features of direction finders operating at these frequencies naturally differ, but the fundamental principles involved are the same. These will be considered next, with the loop antenna (which is used mainly at low and medium frequencies) as the basis.

2.1 THE LOOP ANTENNA

Consider a rectangular loop antenna of length a and width b (Fig. 2.1) with its plane vertical, mounted so that it can be rotated about the vertical axis. Let there be a vertically polarized electromagnetic wave incident on it, coming from a direction making an angle θ with the plane of the loop*. The source will be assumed to be so far away, that incident wave is a plane wave. Voltages are induced in the vertical members of the loop, but not in its horizontal members as the wave is vertically polarized. The magnitude of the voltage induced in the two vertical members is $a \cdot \varepsilon$, where ε is the magnitude (say rms) of the electric field. The voltages in the two members will not be in phase, as can be seen in the phasor diagram, Fig. 2.1 (c). Taking the electric field at the centre of the loop as the reference, the voltage induced in AB [represented by phasor OX in Fig. 2.1 (c)] lags by an angle ϕ and that induced in CD leads by an equal angle. The difference in path lengths being $\frac{1}{2}b \cos \theta$, the phase difference ϕ is given by

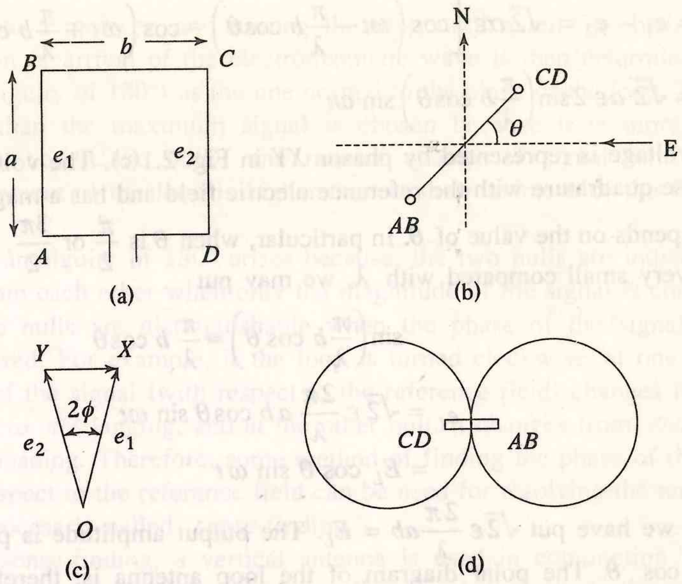

Fig. 2.1 (a) Loop antenna, (b) its setting, (c) phasor diagram and (d) polar diagram

$$\phi = \frac{2\pi}{\lambda}\,\frac{1}{2}\,b\cos\theta$$

$$= \frac{\pi}{\lambda}\,b\cos\theta \qquad (2.1)$$

If the electric field at the centre of the loop is

$$\varepsilon\,(t) = \sqrt{2}\,\varepsilon\cos\,(\omega t)$$

the voltages induced in AB and CD are then

$$\left.\begin{aligned} e_1 &= \sqrt{2}\,a\varepsilon\cos\left(\omega t - \frac{\pi}{\lambda}\,b\cos\theta\right) \\ \text{and}\qquad e_2 &= \sqrt{2}\,a\varepsilon\cos\left(\omega t + \frac{\pi}{\lambda}\,b\cos\theta\right) \end{aligned}\right\} \qquad (2.2)$$

The resultant voltage around the loop is thus

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* In all the following discussions, it will be assumed that the direction of the incoming wave is fixed, i.e. from the east. The polar diagram is therefore, interpreted as the polar plot of the loop output when the loop is rotated about its

$$e_L = e_1 - e_2 = \sqrt{2}\,\alpha\varepsilon\left[\cos\left(\omega t - \frac{\pi}{\lambda}b\cos\theta\right) - \cos\left(\omega t + \frac{\pi}{\lambda}b\cos\theta\right)\right]$$

$$= \sqrt{2}\,a\varepsilon\,2\sin\left(\frac{\pi}{\lambda}b\cos\theta\right)\sin\omega t \qquad (2.3)$$

This voltage is represented by phasor XY in Fig. 2.1(c). The voltage e_L is in phase quadrature with the reference electric field and has a magnitude which depends on the value of θ. In particular, when θ is $\frac{\pi}{2}$ or $\frac{3\pi}{2}$, $e_L = 0$. If b is very small compared with λ, we may put

$$\sin\left(\frac{\pi}{\lambda}b\cos\theta\right) \approx \frac{\pi}{\lambda}b\cos\theta$$

and

$$e_L = \sqrt{2}\,\varepsilon\,\frac{2\pi}{\lambda}ab\cos\theta\sin\omega t$$

$$= E_L\cos\theta\sin\omega t \qquad (2.4)$$

where we have put $\sqrt{2}\,\varepsilon\frac{2\pi}{\lambda}ab = E_L$. The output amplitude is proportional to cos θ. The polar diagram of the loop antenna is, therefore, a 'figure-of-eight' as shown in Fig. 2.1(d). Note that the 'zero's or nulls occur when the plane of the loop is perpendicular to the direction of arrival of the electromagnetic wave, i.e. parallel to the wave front. The other points that emerge on examination of expression (2.4) are:

(a) The output voltage is proportional to the area of the loop, ab.

(b) The phase of the output voltage reverses when loop passes through a null, i.e. if in one lobe of the figure-of-eight it is leading the reference field by $\pi/2$, then in the other lobe it lags the reference field by $\pi/2$.

If the loop has $\mathcal{N}$ turns instead of one, the output voltages of the turns add up and the resulting output is $\mathcal{N}$ times that of a single turn loop. In the above discussion, we have considered a rectangular loop, but the conclusions are applicable to loops of other shapes (e.g. triangular or circular ones) because these may be considered as made up of an infinite number of elementary rectangular loops, for each of which the output voltage is proportional to the area. As a consequence, the loop voltage is proportional to the loop area, irrespective of the shape of the loop.

In the above analysis, we have obtained the voltage output of the loop from the electric field of the incoming wave. Precisely the same results are obtained if we calculate the voltage on the basis of the magnetic field. The output in this case, will depend on the rate of change of magnetic flux linked with the loop. When the loop is East-West, the linkage is maximum and the output is, likewise, maximum. When the loop is North-South, its plane is parallel to the wave front and there is no flux linkage. The output is, therefore, zero.

The markedly directional property of the loop antenna can be used for

output to a receiver, and turning the loop until a null is obtained. The direction of arrival of the electromagnetic wave is then determined (with an ambiguity of 180°) as the one normal to the plane of the loop. The null, rather than the maximum signal is chosen because it is more sharply defined, i.e. at the null, the rate of change of signal with angular displacement of the loop is higher than at the maximum of the figure-of-eight.

The ambiguity of 180° arises because, the two nulls are indistinguishable from each other when only the magnitude of the signal is considered. But the nulls are distinguishable when the phase of the signal is also considered. For example, if the loop is turned clockwise, at one null the phase of the signal (with respect to the reference field) changes from $\pi/2$ leading to $\pi/2$ lagging, and at the other null, it changes from $\pi/2$ lagging to $\pi/2$ leading. Therefore, some method of finding the phase of the signal with respect to the reference field can be used for resolving the ambiguity. This process is called 'sense-finding.'

For sense-finding, a vertical antenna is used in conjunction with the loop. The vertical antenna is non-directional (i.e. its horizontal polar diagram is circular) and it is kept close to the loop antenna so that the voltage induced in it is in phase with the reference field. The output voltages of the vertical antenna and the loop antenna are then respectively

$$\left.\begin{aligned} e_v &= \mathcal{K}\cos\omega t \\ e_L &= \cos\theta\sin\omega t \end{aligned}\right\} \qquad (2.5)$$

omitting some constants of proportionality. The factor $\mathcal{K}$ is the ratio of the vertical antenna output amplitude to the maximum loop antenna output amplitude. These two voltages are in phase quadrature, as is also evident from the phasor diagram in Fig. 2.1(c). If the phase of one of them is changed by 90° and the two voltages are then added, sense-finding is possible because the voltage from the loop will add to or subtract from that of the sense aerial depending on the direction of arrival of the electromagnetic wave. Let us assume that the phase of the loop output is changed by $\pi/2$ making it

$$e'_L = \cos\theta\cos\omega t$$

The sum of the two voltages, which is the input to the receiver E is given by

$$E_i = \mathcal{K}\cos\omega t + \cos\theta\cos\omega t$$

$$= (\mathcal{K} + \cos\theta)\cos\omega t \qquad (2.6)$$

Thus when $\theta = 0$, the amplitude of the input is $(\mathcal{K} + 1)$ and when $\theta = \pi$, it is $(\mathcal{K} - 1)$. If E_i is plotted as a function of θ, we get the polar diagram of the combined antenna. These plots are shown in Fig. 2.2 for several values of $\mathcal{K}$. Ideally, $\mathcal{K}$ should be unity, giving the cardioid pattern [Fig. 2.2(c)] in which the correct direction of the wave and its reciprocal

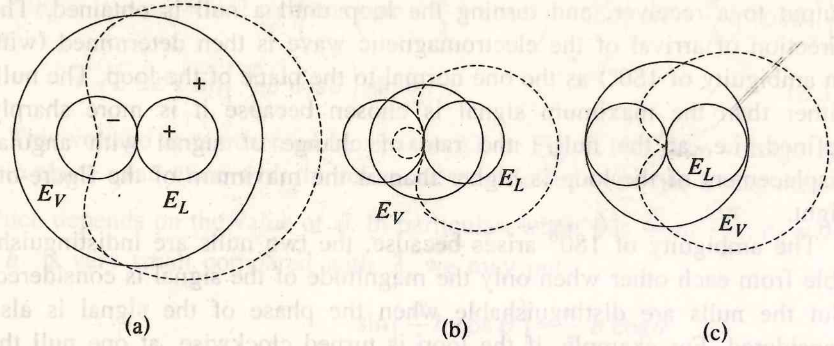


Fig. 2.2 Polar diagrams of combined vertical antenna and loop antenna (a) $\mathcal{K} > 1$, (b) $\mathcal{K} < 1$, and (c) $\mathcal{K} = 1$

are distinguished by a large difference in the combined output. It should be noted, however, that while for direction-finding the loop is turned to give zero or minimum signal, for sense-finding, it should be turned to give the maximum loop signal. The procedure for direction-finding consists, then, of the following steps: (a) with the sense antenna disconnected, the loop is turned to give the minimum signal and its angular position is noted; (b) then the loop is turned clockwise (say) by 90°. The signal increases to its maximum; (c) the sense antenna is now connected. If the orientation of the loop indicates the correct direction, the signal increases and if it indicates the reciprocal, the signal decreases. (Note that two conventions have been introduced in this procedure—firstly that the loop is turned *clockwise* after obtaining the null and secondly that the signal *increases* when the correct direction is indicated. In order that this may be true, appropriate connections of the loop terminals have to be made).

In loop antennas, an undesirable effect known as the 'antenna effect' arises due to the pick-up of a small voltage (either in the receiver or elsewhere) which is independent of the orientation of the loop. The loop antenna is used to find the zero signal position, and, therefore, even a very small extraneous voltage adversely affects the operation. If the pick-up voltage is in phase quadrature to the voltage around the loop, it merely changes the null to a minimum and broadens it ('*quadrature antenna effect*'). If it is in phase with the loop output voltage, it makes the two lobes of the figure-of-eight pattern unequal, as in Fig. 2.2(b) ($\mathcal{K} < 1$). The most important change brought about in this case is the non-opposite nature of the two minima, which can be readily checked in practice.

2.2 LOOP INPUT CIRCUITS

The loop antenna is by itself inductive and the loop output is not generally used directly as an input to the receiver. A variety of circuits is used at the

the loop voltage and to establish the desired phrase relation between the output of the loop circuit and the output of the vertical antenna for sense-finding. A description of some of these circuits is given in Ref. 2 and 3. The basic elements of a few of these circuits are shown in Fig. 2.3. In the circuit shown in Fig. 2.3(a), the inductance of the loop is tuned out by a capacitor, the two together making a series tuned circuit, and the voltage across the capacitor or half of it is used as the input to the receiver. The series tuned circuit provides a certain amount of circuit magnification of the loop voltage e_L. As the current in a series tuned circuit is in phase with the applied voltage, the voltage across the capacitance lags by $\pi/2$ with respect to the input voltage. Figure 2.3(b) and 2.3(c) show developments of the same circuit to achieve a better balance than is possible with the first circuit.

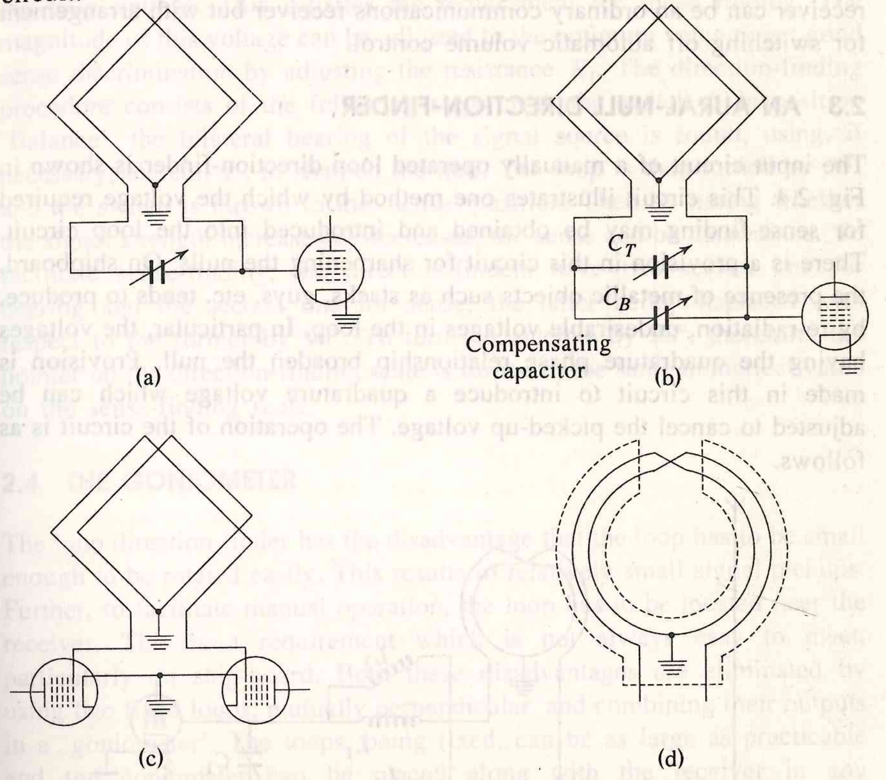


Fig. 2.3 Loop input circuits: (a) series tuned; (b) and (c) balanced circuits; (d) a screened loop

One of the important sources of antenna effect is the asymmetry of the loop antenna with respect to the ground. To minimize antenna effect, the centre of the loop is earthed and its output is, thereby, balanced. If the input stage of the receiver is single-ended, half the voltage across the tuning capacitor is applied to the grid of the first stage and some unbalance either a compensating capacitor C_B may be used as in Fig. 2.3(b) or a balanced input stage may be employed as in Fig. 2.3(c). Any residual antenna effect can be compensated by introducing a controllable voltage in phase with antenna voltage. In all adjustments aimed at eliminating antenna effect, a check is made to see whether the minima correspond to opposite bearings by tuning in a station and turning the loop. Ideally, the two bearings obtained must differ by 180° and any departure from this figure is minimized by adjustment of the compensating circuits.

Balancing of the loop is made more effective and accurate by enclosing it in an electrostatic shield which is broken at one point near the Top. A completely shielded loop will, of course, not pick up any signal but if a break is introduced, the performance of the loop is scarcely affected, while any unbalance introduced by surrounding objects is minimized. The receiver can be an ordinary communications receiver but with arrangement for switching off automatic volume control.

2.3 AN AURAL-NULL DIRECTION-FINDER

The input circuit of a manually operated loop direction-finder is shown in Fig. 2.4. This circuit illustrates one method by which the voltage required for sense-finding may be obtained and introduced into the loop circuit. There is a provision in this circuit for sharpening the nulls. On shipboard, the presence of metallic objects such as stacks, guys, etc. tends to produce, by re-radiation, undesirable voltages in the loop. In particular, the voltages having the quadrature phase relationship broaden the null. Provision is made in this circuit to introduce a quadrature voltage which can be adjusted to cancel the picked-up voltage. The operation of the circuit is as follows.

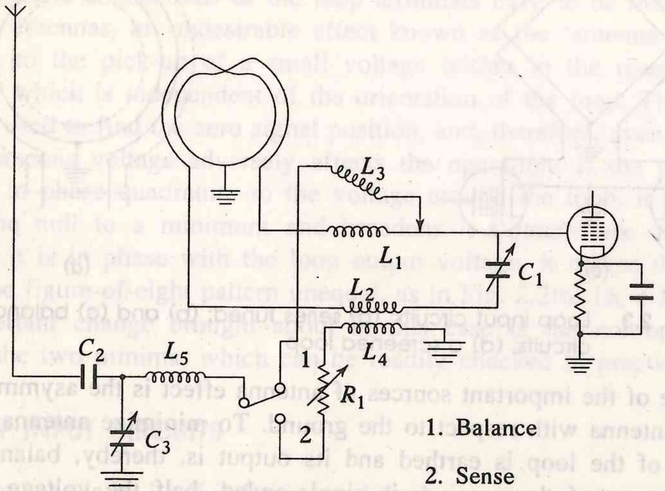


Fig. 2.4 Input circuit of an aural-null direction finder

The loop circuit consisting of the loop antenna, L_1, C_1 and L_2 is a series tuned circuit for the loop voltage. In the 'Balance' position of switch S, an additional voltage is introduced through the variable inductive coupling between L_3 and L_1. This voltage is obtained from the vertical antenna and the components C_2, L_5 and C_3 are so adjusted that this voltage is in phase quadrature to the loop voltage. With the variation in magnitude and sign permitted by the variable coupling between L_1 and L_3, the quadrature component arising from 'antenna effect' can be cancelled out. For sense finding, the switch S is thrown to position 2. The vertical antenna circuit has now a large series resistance R_1. The current in L_4 is, therefore, in phase with the vertical antenna voltage and the voltage induced in L_2 is in phase quadrature to this, i.e. it is either in phase or in phase opposition to the loop voltage. This satisfies the requirement for sense finding. The magnitude of this voltage can be adjusted to the optimum value to get good sense discrimination by adjusting the resistance R_1. The direction-finding procedure consists of the following steps: with the switch S in position 'Balance', the bilateral bearing of the signal source is found, using, if necessary, the coil L_3 to sharpen the null. The loop is then turned by 90° and the switch is thrown to the 'sense' position. Then by noting whether the signal strength increases or decreases, the sense can be determined. To facilitate sense-finding, the direction-finders have two scales, one for bearing and the second one for sense, the latter being displaced with respect to the former by 90°. To turn the antenna by 90°, therefore, the pointer on the direction-finding scale is turned to the same numerical value on the sense-finding scale.

2.4 THE GONIOMETER

The loop direction-finder has the disadvantage that the loop has to be small enough to be rotated easily. This results in relatively small signal pickups. Further, to facilitate manual operation, the loop has to be located near the receiver. This is a requirement which is not always easy to meet, particularly on ship-board. Both these disadvantages are eliminated by using two fixed loops, mutually perpendicular, and combining their outputs in a 'goniometer'. The loops, being fixed, can be as large as practicable and the goniometer can be placed along with the receiver in any convenient location. The antenna and goniometer arrangement is shown in Fig. 2.5.

The goniometer consists of two windings, mutually perpendicular (called the 'stators'), and a winding at the centre of these, called the 'rotor', which can be rotated about the axis of symmetry. The two fixed loops are connected to the two stator windings and the voltage induced in the rotor is taken to the receiver. It will be shown in the following paragraph that the voltage induced in the rotor is equivalent to the voltage in a rotating loop antenna.

Referring to Fig. 2.6(a), let the two loops be oriented *N-S* and *E-W* and let the incident electromagnetic wave (vertically polarized) make an angle θ with the North. The currents flowing in the two loops are then proportional to cos θ (*N-S* loop) and cos $(90 - \theta) = \sin\theta$ (*E-W* loop). For convenience, let the corresponding stator coils be called *N-S* coil and *E-W* coil. The magnetic flux in these coils, produced by the loop currents are proportional to cos θ and sin θ respectively [Fig. 2.6(b)], and the resultant magnetic flux has the same direction with respect to the *N-S* stator that the electromagnetic wave has with respect to the normal to the *N-S* loop. The voltage induced in the rotor is maximum when the flux is perpendicular to the plane of the rotor and zero when it is parallel to the plane of the rotor. The bearing can be found by turning the rotor to a null, and taking the direction of the plane of the rotor to the normal to the *N-S* stator coil as the direction of the incoming wave with respect to North. The signal from the rotor can be combined with the signal from a vertical antenna for sense finding.

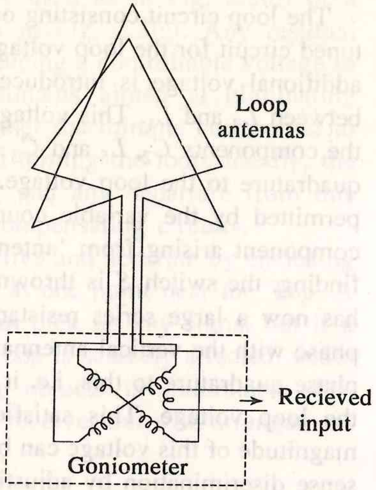
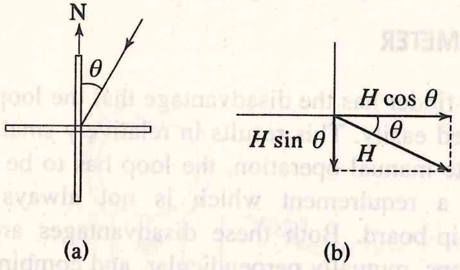


Fig. 2.5 Sketch of the goniometer



(a) (b)

Fig. 2.6 (a) Plan of the loop antennas, and (b) the magnetic field within the goniometer

2.5 ERRORS IN DIRECTION-FINDING

In the analysis of the loop direction-finder given in Sec. 2.1, we have assumed that a vertically polarized wave is arriving at the antenna from the direction of the transmitter. This condition will hold good only for ground-wave propagation over a perfectly conducting earth. In practice such conditions do not prevail; the wave may not be normaly polarized, it may

not be the same as that of the transmitter. Errors will arise in direction-finders on this account. These may be divided into four broad classes as given below.

(a) Errors due to abnormal polarization of the incoming wave (night effect and aeroplane effect).
(b) Errors due to abnormal propagation.
(c) Site errors, arising from re-radiation of energy from neighbouring objects.
(d) Instrumental errors, arising from imperfection of the receiving apparatus.

These will be considered in turn.

(a) Polarization Errors

In the early days of direction-finding, a type of error was observed, mainly at night time, which was characterized by displaced minima, rapid changes in their position, a poor null, etc. The cause of this proved to be the abnormal polarization associated with ionospheric propagation. As sky-waves were more prominent at night in the low frequency band, the name 'night effect' was given to this phenomenon. However, at high frequencies, it may occur at all times of the day. Abnormal polarization also occurs in radiation from aircraft transmitters and the so-called 'aeroplane effect' has, therefore, the same basic origin as night-effect.

Consider a loop antenna set to receive an electromagnetic wave incident at an angle β measured from the vertical (Fig. 2.7). Let the polarization be vertical, i.e. let the electric vector be in the vertical plane in the direction of propagation. The emf induced in the loop may be regarded as the sum of those due to two components of the electric vector E, a vertical component $E \sin\beta$ and a horizontal component $E \cos\beta$ in the plane of propagation of the incoming wave. If the loop is positioned with its plane at right angles to the plane of propagation, the net voltage developed in the loop due to the vertical component is zero, and the horizontal component does not induce a voltage in any part of the loop at all. Therefore, a null is obtained in the correct direction and no error will result. An electromagnetic wave polarized in this way is said to be 'normally polarized'.

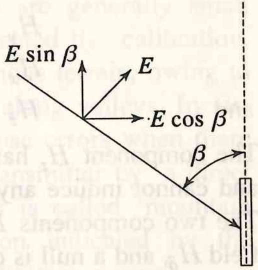
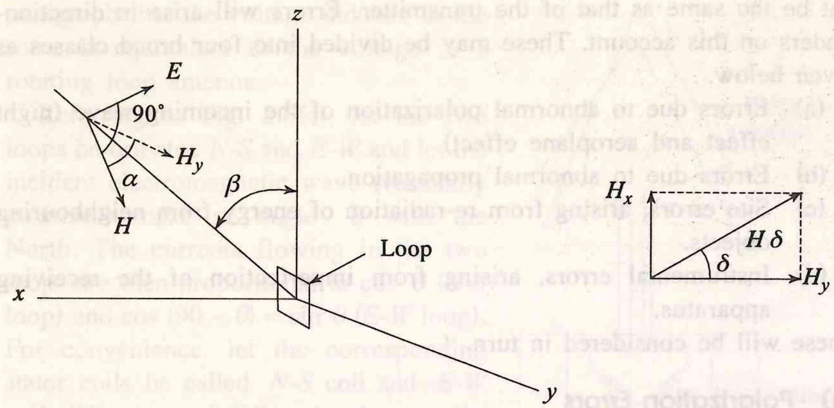


Fig. 2.7 Sketch of normally polarized wave incident on loop antenna

Consider now a plane polarized wave incident at an angle β but with the electric vector making an angle α with the vertical. This situation is represented in Fig. 2.8(a), where cartesian coordinate axes have been drawn. The direction of propagation is in the



(a) (b)

Fig. 2.8 (a) Sketch of abnormally polarized wave incident on loop antenna and (b) components of the magnetic field inducing the loop voltage

XZ plane and the loop can be rotated about the *Z*-axis. If the loop is positioned in the *YZ* plane, a null is not obtained as with normally polarized wave because there is a *y*-component of the electric field which will induce voltages in the horizontal members of the loop. A null is obtained away from this position. It is easier in this case to analyze the behaviour of the loop with reference to the magnetic vector *H*, noting that the voltage induced in the loop is proportional to the magnetic vector normal to the loop and that no voltage is induced if the magnetic vector is parallel to the loop. The *H*-vector of the plane-polarized wave can be resolved into three components

$$\left.\begin{aligned} H_y &= H\cos\alpha \text{ along the } y\text{-axis} \\ H_x &= H\sin\alpha\cos\beta \text{ along the } x\text{-axis} \\ \text{and} \quad H_z &= H\sin\alpha\sin\beta \text{ along the } z\text{-axis} \end{aligned}\right\} \qquad (2.7)$$

The component H_z has no effect as it is parallel to the plane of the loop and cannot induce any voltage in it, whatever the orientation of the loop. The two components H_y and H_x, being in time phase, produce a resultant field H_δ, and a null is obtained if the loop is turned by an angle δ such that its plane is parallel to H_δ instead of H_x as with a normally polarized wave. By simple trigonometry [Fig. 2.8 (b)],

$$\tan\delta = \tan\alpha \cdot \cos\beta \qquad (2.8)$$

The bearing obtained is in error by the angle δ, which is a function of both the angle of incidence (β) and the polarization angle α. For purposes of comparison of different direction-finders, a 'standard wave' is specified, having $\alpha = \beta = \pi/4$. The error δ obtained with this wave is called the 'standard wave error'. For the loop aerial which has been studied, this is,

In the above simple analysis, only the effect of the incident wave is considered and the wave reflected by the ground has been ignored. This will not lead to a serious error as the effect of the reflected wave is generally small.

Sometimes the down-coming wave is not plane-polarized and the various voltages induced in the loop by the components are not in time phase. In such a case, the null is poorly defined or it may even be impossible to obtain any null at all. Methods of eliminating polarization errors are discussed in Sec. 2.6.

(b) Errors due to Abnormal Propagation

It was earlier assumed that the electro-magnetic wave travelled along the great circle path from the transmitter to the direction-finder. This is generally true but sometimes the path deviates from the great circle plane. When the propagation is via the ionosphere, such deviations can occur owing to scattered reflections and tilt of the reflecting regions. As both these phenomena are associated with propagation via the ionosphere, they are more evident at high frequencies. Errors arising from these causes are random and can be specified only in terms of the rms value, which appears to be about 1° (Ref. 4).

Abnormal propagation can also occur at low and medium frequencies under certain conditions. When the direction-finder is near a coast and the direction of arrival of the wave makes a small angle with the coast-line, there is a bending of the wave towards the land owing to the differences in the conductivity of the sea and land. The transmitter, therefore, appears to be more towards the sea than it actually is. This phenomenon is sometimes called 'coastal refraction.' These errors are generally small (about 1°) and generally constant and could be corrected by calibration. A similar phenomenon may be observed in mountainous terrain, owing to the tendency of the electromagnetic wave to travel along valleys. In airborne direction-finders, mountainous terrain may cause errors when there is a simultaneous reception of the signal from the transmitter by a direct path and by reflection from a mountain side. This is called 'mountain effect'. When it is present, the apparent direction indicated by the direction-finder shows irregular fluctuations about the true course.

(c) Site Errors

An ideal site for a direction-finder must be flat (i.e. without any obstacles) and must have a high conductivity. In actual sites, these conditions are not fulfilled and errors arise either on account of reflections from large surfaces or on account of re-radiation from various objects nearby. Even objects underground, such as buried cables, pipes, etc. can produce errors because the soil conductivity is low and the electromagnetic wave penetrates the soil to some depth. It is difficult to assess the effect of nearby objects with any certainty but as a broad generalization it may be said that larger the object and nearer it is to the direction-finder, the greater is its potentiality for introducing site errors. A full discussion of the problems of siting direction-finders may be found in Ref. 5.

In a mobile installation, as on a shipboard, the choice of site is very restricted and the direction-finder is invariably surrounded by objects which absorb some of the energy from the wave and re-radiate it. These cases merit separate study both in view of their special features and of their importance.

On shipboard, metallic objects such as stacks, poles, guys and rigs act as 're-radiators'. This last term is used in a broad sense as the fields produced by these objects at the direction-finder antenna are not necessarily radiation fields, but include induction fields, both magnetic and electrostatic. If the antenna is on the centre-line of the ship, the errors tend to be zero in four directions, namely forward, astern, and to either side. The plot of error versus the bearing of the transmitter appears as shown in Fig. 2.9, and the error is called 'quadrantal error' as it is maximum in each of the four quadrants. The sign of the quadrantal error is such that the apparent bearings tend to be shifted towards the forward or stern part of the ship. The reason for the quandrantal nature of the error is that the large errors are introduced by the loop structures on the ship, made up of mast and hull or stack, which are aligned roughly fore and aft. The loop antenna has maximum coupling with these when its plane is also fore and aft., and minimum coupling when its plane is turned by 90°. When a transmitter is along the centre-line of the ship, the loop structure of the ship has maximum induced currents, but these do not induce any voltage in the loop antenna when the latter is turned to obtain a null, for it will then be at right angles to the centre-line and will have minimum coupling to the loop structure. The error is, therefore, zero or minimum. When the transmitter is at right angles to the centre-line of the ship, the loop structure has net zero voltage induced in it and will, therefore, not affect the loop antenna minimum. The error is thus again zero or minimum. Between these four positions, the error is maximum and the nulls may also be poor, requiring balancer adjustments. In addition to the loop structure, some vertical members may re-radiate and give rise to 'semi-circular errors', i.e. errors which are maximum at two points on the circle. These errors, which are of the nature of 'antenna effect' can generally be compensated by balancer adjustments.

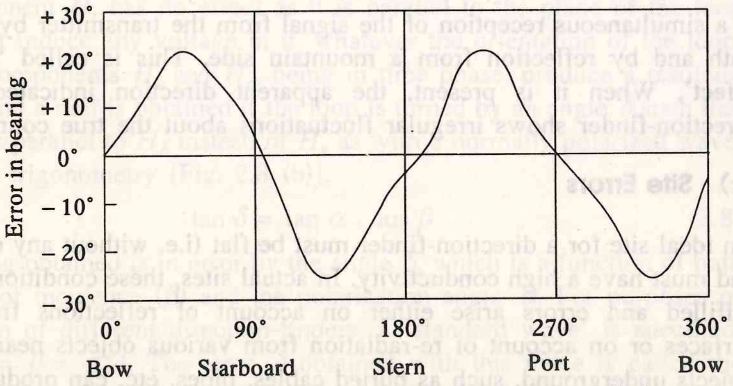


Fig. 2.9 Quadrantal error curve of a ship-board direction-finder

The loop structure of the greatest importance is the mast-stack combination making up an open loop. The errors arising from this can be compensated largely by closing the loop by a "compensator"[6] which consists of one or more conductors stretched between the mast and the stack. Shielding the loop, as stated earlier, also helps to reduce the errors arising from open radiators. In spite of all these precautions and compensations, the residual errors in ship-borne direction-finders are appreciable and calibration is essential. In some installations, mechanical means of automatically applying the correction are incorporated.

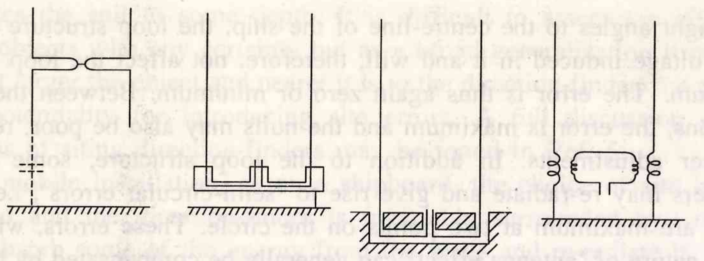
Quadrantal error occurs in aircraft direction-finders also, owing to the distortion in the field pattern produced by the wings, engines, propellers and other parts of the aircraft. Airborne direction-finders are almost always provided with cam mechanisms, by which corrections are automatically applied.

(d) Instrumental Errors

Errors also arise owing to imperfections of the components used in direction-finders. In manually operated ones, the most important is the octantal error introduced by the goniometer. In automatic direction-finders, other components such as synchros, resolvers, etc. may also introduce errors. All these errors are generally small and if required could be compensated by calibration.

2.6 ADCOCK DIRECTION-FINDERS

It was shown in the last section that polarization errors arise owing to the voltage picked up by the horizontal members of the loop. The Adcock antenna is designed to eliminate polarization errors by dispensing with the horizontal members. It consists of a pair or more of vertical antennas, the signals from these being taken to the receiver either by underground conductors or by shielded balanced pair of wires. In the first case, no voltage will be induced in the horizontal member, if the conductivity of the earth is good, and in the second case, whatever voltages are induced in the two horizontal members tend to cancel out. Several forms of the Adcock



(a) 2° – 6° (b) 6° – 10° (c) < 5° (d) 1°

Fig. 2.10 Adcock direction finders (the standard-wave error is indicated in each case)

H-type Adcock antennas, depending on the position of the horizontal members, relative to the vertical members.

Electrically, the Adcock antenna is equivalent to a single-turn loop, and, therefore, for equal sized ones, the output of the former is very low. To compensate for this, the vertical antennas are made large and consequently, a fixed antenna system in conjunction with a goniometer is employed at the low, medium and high frequencies. The need for large antennas also makes the Adcock direction-finder unsuitable for mobile installations. Another disadvantage of this type of antenna is that it has a high internal impedance which is largely capacitive and presents some difficulties in connecting it to the input circuits of a receiver^6. Sense-finding in the Adcock antenna system is carried out in the same manner as in the loop systems by using a vertical antenna.

The Adcock direction-finder is not completely free from polarization errors, because some voltage is induced in the horizontal members even when buried underground. The errors are, however, reduced. Typical values are also indicated in Fig. 2.10. In antennas of the type shown in Fig. 2.10(a) which are used commonly in the VHF band, errors can arise due to unequal capacitance between the antenna and the earth, but they become less as the height of the antenna system above the earth is increased.

2.7 DIRECTION-FINDING AT VERY HIGH FREQUENCIES

Direction-finding in the frequency band 100–150 MHz is widely employed for aeronautical navigation purposes. This is done by ground-based installations, which obtain the aircraft bearing and pass it to the aircraft by radio telephony. Adcock direction-finders are invariably used for this purpose. In the VHF band, the size of the vertical antenna and its spacing are such that the complete antenna system can be easily rotated. A typical manually operated installation consists of a rotatable aerial system mounted on a mast above the direction-finder (DF) hut with the receiver in the hut. Modern direction-finders are commonly of the automatic type

principles of operation a "phase-comparison' direction-finder are given in Sec. 2.8. An alternative type, employing modulation techniques, is described in Ref. 4 and 7. Recently, a direction-finder employing a new technique has been developed. This is the Commutated Aerial Direction-Finder (CADF)) and is dealt with in Sec. 2.9.

As VHF propagation is confined essentially to line-of-sight ranges, direction-finders in this band mainly serve aircraft, though some use is made of them for harbour control. Errors at these frequencies generally originate from polarization and site irregularities. Radiation from aircraft is often abnormally polarized and inspite of using vertical H-Adcock antennas, some error will be present, particularly when the radiation is incident from a high angle. Site errors are more prominent when the radiation arrives at a low angle and in this case, the choice of a good site is important.

2.8 AUTOMATIC DIRECTION-FINDERS

Manually-operated direction-finders have the virtue of relative simplicity and the advantages associated with a human operator who can exercise the faculty of auditory discrimination in the presence of interfering signals. But in many situations, the need for an operator and the slowness inherent in manual operation are serious disadvantages. An obvious example is that of a direction-finder in an aircraft, where the air crew is fully occupied with other tasks and carrying an additional crew member is uneconomical. Another instance is where the ground direction-finder has to take the bearing of an aircraft and pass on the information to the control tower. An automatic direction-finder which can give a remote indication at the control tower has distinct advantages in this situation. Automatic direction-finders of many types have been developed to meet such requirements$^{2, 4, 7, 10}$. Here, only two such systems will be described, namely the radio compass, an air-borne direction-finder operating in the LF/MF band (200–3000 kc/s) and the ground-based automatic direction-finder operating in the VHF band.

(a) The Radio Compass

The radio compass uses a loop antenna in a servo feed-back system. The loop antenna is coupled to the servo-motor which is actuated by an error signal derived from the loop output and turns the loop until the error signal and, therefore, the loop output is zero. It thus automatically positions the loop to a null. For the proper operation of the system the error signal must change its sign as it passes through zero and to achieve this, an arrangement equivalent to a phase sensitive detector is used. As pointed out in (b) in the analysis of Eq. 2.4, the phase of the carrier undergoes a change its sign if a phase sensitive detector is used. This arrangement still permits two positions of equilibria corresponding to the two nulls but one of them is unstable. The loop, therefore, takes up only one position in these circumstances.

A block-diagram of the radio compass is shown in Fig. 2.11. The equipment is provided with a pair of fixed loops and a gonio which is mechanically coupled to a motor and a synchro-generator. The motor is a two-phase one, actuated by two inputs—one from the switching oscillator and the other from the receiver output. The former is a constant input and, therefore, provides a fixed reference and the latter, a signal in phase with this or exactly 180° out of phase, depending on the position of the loop with respect to the direction of arrival of the signal. The direction of the torque on the motor correspondingly changes its sign depending on the position of the loop and the motor tends to move the gonio to the position of the zero torque or the null.

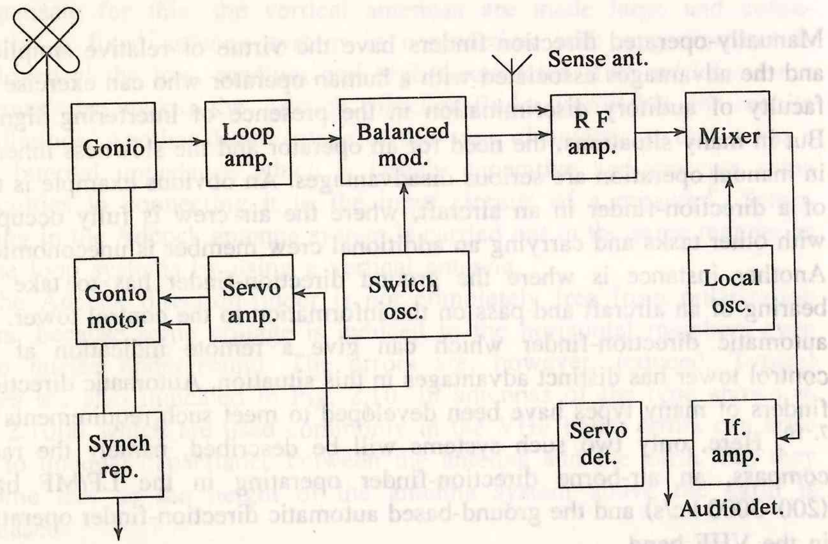


Fig. 2.11 Block diagram of a radio compass receiver

To obtain an output which is dependent on the phase of the gonio signal, the following method is employed. The output of the gonio is fed to a balanced modulator and modulated by a signal from the switching oscillator. The output of the balanced modulator, which consists only of the side band components, is combined with the sense aerial input, which is phase-shifted so as to be in phase with the suppressed carrier of the signal. The resultant is fed to a superheterodyne amplitude-modulated receiver. The demodulated output of this will have a switching frequency waveform, the phase of which, in relation to the input to the balanced modulator, will now be determined. For simplicity, it will be assumed that the output of the switching oscillator is sinusoidal. The balanced modulator gives the product of the gonio signal and the switching sinusoid, i.e.

$$e_0 = A \cos \omega_s t\, [\cos \theta \cdot \cos \omega_c t] \tag{2.9}$$

where ω_c is the incoming carrier frequency, ω_s is the switching frequency, generally a low audio frequency such as 135 Hz and θ is the orientation of the goniometer rotor coil with respect to the reference direction. The term within the square brackets is the gonio output. The output e_0 is combined with the vertical antenna signal, say $B \cos \omega_c t$ $(B > A)$. The input to the superheterodyne receiver is then

$$\begin{aligned} e_{in} &= \cos \omega_c t \cdot A \cos \omega_s t \cdot \cos \theta + B \cos \omega_c t \\ &= B \left[1 + \frac{A}{B} \cos\theta \cdot \cos\omega_s t \right] \cos \omega_c t \end{aligned} \tag{2.10}$$

This expression represents a carrier of frequency ω_c amplitude modulated by a sinusoid of frequency ω_s, the phase and amplitude of the modulating signal being dependent on the value of $\cos \theta$. If $\cos \theta$ is positive ($\pi/2 > \theta > -\pi/2$), the demodulated output is in phase and when $\cos \theta$ is negative ($\pi > \theta > \pi/2$) and ($-\pi < \theta < -\pi/2$), it is in anti-phase to the switching sinusoid $\cos \omega_s t$, as shown in Fig. 2.12. The demodulated output may be amplified and fed to the second winding of the two-phase gonio motor, but such an arrangement will have low power efficiency. Instead, a motor

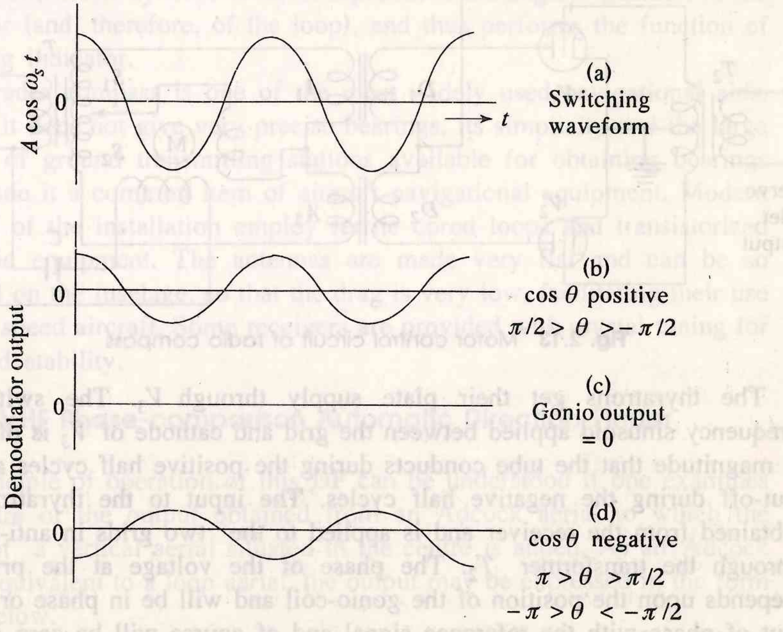


Fig. 2.12 Comparison of waveforms: (a) Switching sinusoid, and (b), (c) and (d) are Servo detector ouputs for various values of θ

control circuit employing thyratrons is generally used. A simplified circuit of one such is shown in Fig. 2.13. The operation is as follows. The gonio motor M has two windings, one of which is supplied directly from the ac input to the transformer T_1, through a capacitor C giving a phase change of about 90°. The other winding of the motor is fed from one half of the secondary of the transformer through saturable reactors which act as switches. The saturable reactors have two windings each, the dc windings (D_1, D_2) which are connected to the thyratrons, and the ac windings (A_1, A_2) which are in the motor circuit. The impedance measured across the ac winding depends upon the current in the dc winding. If the latter is zero or very small, the impedance is high. When the current increases above a certain value, the core saturates and the impedance of the ac windings becomes very low. The saturable reactors thus act as switches which are closed when there is a current in the thyratron and open when there is no current. The phases of the voltage applied to the second winding of the motor and, therefore, the direction in which it turns, thus depends on the reactor which is saturated.

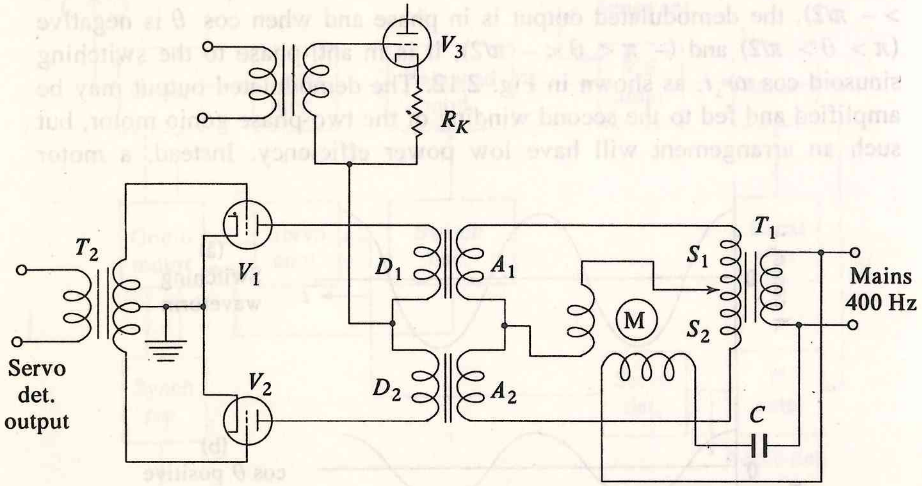


Fig. 2.13 Motor control circuit of radio compass

The thyratrons get their plate supply through V_3. The switching frequency sinusoid applied between the grid and cathode of V_3 is of such a magnitude that the tube conducts during the positive half cycles and is cut-off during the negative half cycles. The input to the thyratrons is obtained from the receiver and is applied to the two grids in anti-phase through the transformer T_2. The phase of the voltage at the primary depends upon the position of the gonio-coil and will be in phase or 180° out of phase with the reference signal and of course will be zero at the nulls. If it is in phase, one of the thyratrons (say V_1) will conduct and if

it is in anti-phase, the other (V_2) will conduct. The direction in which the motor turns depends upon the position of the gonio coil and it can be shown that the coil attains the equilibrium position in one of the nulls. The demonstration of this is left to the student.

The gonio, the receiver and the motor constitute a feed-back control system and the details of its behaviour such as its tendency to hunt about its equilibrium position and the closeness with which it follows a changing null may be studied by application of feed-back theory. These aspects will not be dealt with here. Mention is, however, made of two points relevant to this. The first is the use of the resistor R_k in the cathode of V_3 as shown in Fig. 2.13. This resistance provides the bias for V_3. When the error signal is small, (i.e. near the null), the average current tends to be low, and this is counteracted by a small voltage drop in R_k. When the error signal is large, the average current is large and increases the bias on V_3 and thus again counteracts the effect of the signal. As a result, the motor torque is kept more nearly constant. The second point of importance is that many versions of the equipment provide an 'anti-hunt' circuit, which is essentially a tachometer feed-back, the necessary input being obtained from a generator coupled to the same shaft as the one driving the gonio-coil. This eliminates oscillations or 'hunting' without adversely affecting the speed of response. The gonio motor is also coupled to a synchro generator, which is connected to synchro receivers (see appendix III) at remote points. The synchro receiver reproduces the angular position of the generator (and, therefore, of the loop), and thus performs the function of a bearing indicator.

The radio compass is one of the most widely used navigational aids. Though it does not give very precise bearings, its simplicity and the large number of ground transmitting stations available for obtaining bearings have made it a common item of aircraft navigational equipment. Modern versions of the installation employ ferrite cored loops and transistorized electronic equipment. The antennas are made very flat and can be so mounted on the fuselage, so that the drag is very low, facilitating their use on high speed aircraft. Some receivers are provided with crystal tuning for increased stability.

(b) A VHF Phase-comparison Automatic Direction-Finder

The principle of operation of this DF can be understood if one examines the nature of the output obtained from an Adcock aerial to which the output of a vertical aerial situated in the centre is added. As an Adcock pair is equivalent to a loop aerial, the output may be expressed in the form given below.

$$e_0 = (\mathcal{K} + \cos\theta)\cos\omega t \qquad (2.6)$$

where $\mathcal{K}$ is the ratio of the peak amplitudes of the vertical and Adcock antennas and θ the angle which the plane of the aerial makes with the direction of arrival of the signal. For convenience, let the angles be measured from North and let ϕ be the direction of arrival and ψ the angle which the plane of the antenna makes with the North. Then in Eq 2.6

$$\theta = \psi - \phi$$

Let the antenna be rotated with an angular velocity ω_s, so that

$$\psi = \omega_s t \text{ and}$$

$$e_0 = [\mathcal{K} + \cos(\omega_s t - \phi)] \cos \omega t \qquad (2.11)$$

This is an amplitude modulated signal. When it is demodulated in an envelope detector, the variable component of the output obtained is proportional to $\cos(\omega_s t - \phi)$.

Suppose a reference sinusoid of the same frequency (ω_s) is obtained by coupling an alternator to the rotating antenna. By suitably positioning the poles of the alternator, one can obtain from it the sinusoid $\cos \omega_s t$. The phase difference between the demodulated receiver output and the alternator voltage, i.e. the angle ϕ, gives the direction of arrival of the signal. The bearing may, therefore, be read off directly on a phase measuring device. This is the basic principle of some VHF DFs employing the phase-comparison technique. A block diagram of one such equipment[8] is shown in Fig. 2.14 and its operation is explained in what follows.

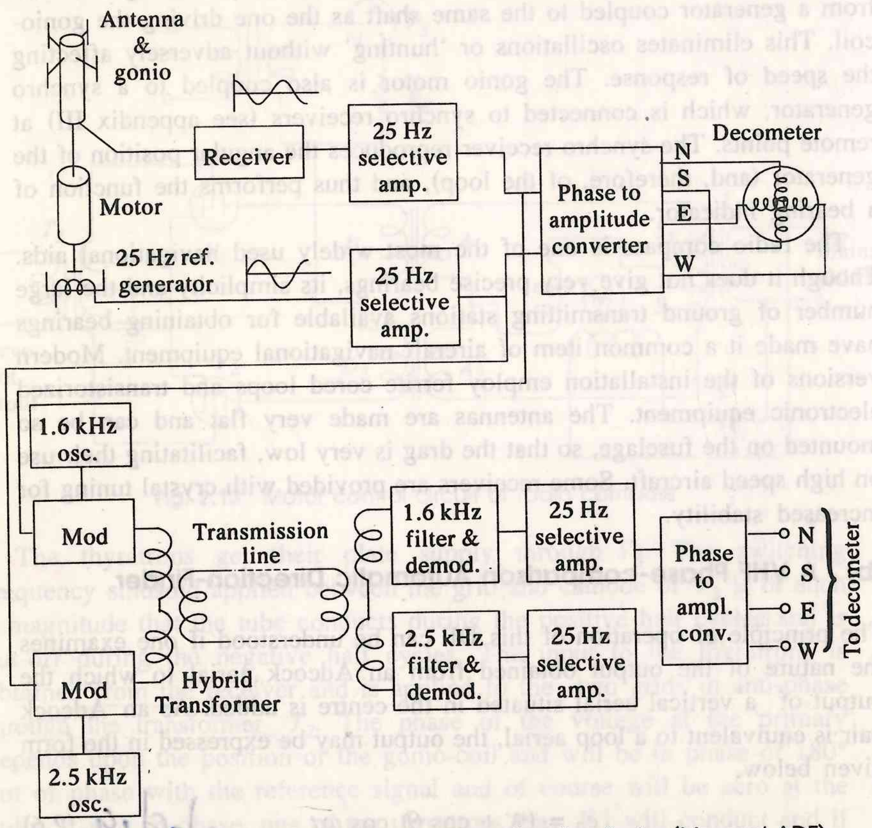


Fig. 2.14 Block diagram of VHF automatic direction-finder (Marconi ADF)

The DF employs a pair of fixed Adcock antennas with a capacitance goniometer to obtain the rotating figure-of-eight pattern. Instead of using a vertical antenna for obtaining a fixed phase signal, an unbalanced output is taken from the capacitance goniometer rotor. The vector sum of the voltages induced in the rotor, when combined with the figure-of-eight pattern gives the required cardioid as represented in Eq. 2.6. The gonio rotor is coupled to a motor and rotated at 25 rps. To the same shaft is attached an ac generator which gives a 25 Hz ac voltage of fixed reference phase. The signal from the goniometer, which is modulated at 25 Hz by the rotation of the rotor, is applied to the receiver and after demodulation and amplification is passed through a selective amplifier and is applied to a phase measuring device along with the signal from the reference generator. For remote indication, the two 25 Hz signals are made to amplitude modulate two audio frequency carriers which are then transmitted to the remote point where they are demodulated and the two modulating 25 Hz signals are recovered. These are then applied to a phase-meter.

The phase-meter and the associated circuits are shown in Fig. 2.15(a). The meter is provided with two coils whose axes are at right angles to each other and in the centre is a small permanent magnet mounted on a spindle to which the indicating pointer is attached. When two direct currents are passed in the coils, the magnet aligns itself with the resultant magnetic field. The angle to which it turns is such that the tangent of this angle is equal to the ratio of the currents in the two coils. If these two currents are made proportional to $\cos \phi$ and $\sin \phi$, the position of the pointer will directly indicate the direction of arrival of the electromagnetic wave. The circuit shown in Fig. 2.15(a) is the phase-to-amplitude discriminator which performs the function of giving output currents proportional to $\cos \phi$ and $\sin \phi$ when provided with two inputs $\cos \omega_s t$ and $\cos(\omega_s t - \phi)$. Its operation is as follows. The reference signal is split into two components by phase-splitting networks and amplified by push-pull amplifiers to obtain two equal voltages in phase quadrature in the secondaries of the transformers T_1 and T_2. These are represented by phasors OA and OB [Fig. 2.15(b)], which lead the original reference voltage in the primary by 45° and 135° respectively. The variable phase signal is applied to a similar phase-splitting network and amplified and two equal outputs are obtained from two centre-tapped secondaries of transformer T_3. These outputs lead the variable phase input by 135°. The secondaries of the transformers are

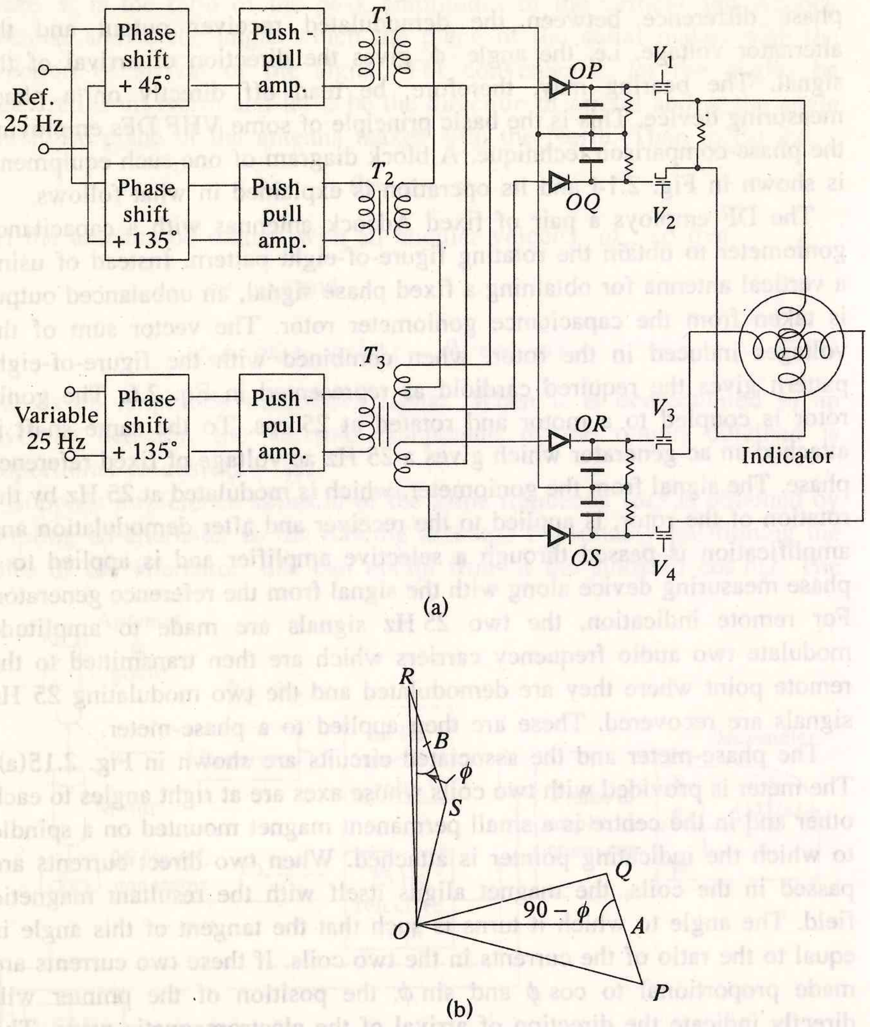


Fig. 2.15 (a) Circuit of the phase measuring part of the receiver and (b) phaser diagram of voltages in the circuit

secondaries of T_3 to the quadrature reference voltages, giving the four phasor quantities.

$$\vec{OP} = \vec{OA} + \vec{AP}; \quad \vec{OQ} = \vec{OA} + \vec{AQ}$$

$$\vec{OR} = \vec{OB} + \vec{BR}; \quad \vec{OS} = \vec{OB} + \vec{BS}$$

The variable phase signal is much smaller than the reference phase voltage. The above relations may then be approximated as follows

$$OP = OA + AP \cos (90 - \phi) = OA + AP \sin \phi$$

$$OQ = OA - AP \sin \phi$$

$$OR = OB + BR \cos \phi, \; OS = OB - BR \cos \phi$$

The voltages are rectified and the resultant direct voltages, which are nearly equal to the peak ac input are applied to the grids of the tubes V_1, V_2, V_3 and V_4. The currents which flow in the windings of the phase-meter are proportional to the difference between the corresponding grid voltages at the tubes. The differences are equal to $2\,AP \sin \phi$ and $2\,BR \cos \phi$, but as AP and BR are equal (as the secondaries of T_3 are identical), they are proportional to the sine and cosine of the phase angle ϕ, which is also the bearing angle.

To maintain the desired accuracy in this type of instrument, the various components must be accurately constructed and must maintain stable values. Some octantal error arises in the instrument as the variable phase signal is not very small compared with the reference phase one, but this is made to cancel the octantal error arising in the capacitance goniometer. The overall accuracy may be as high as about 1°.

The DF operates on a VHF radio telephony channel. The speech frequencies are modulated at 25 Hz by the goniometer and intelligibility is impaired. To overcome this drawback, the receiver output going to the speech channels is demodulated by applying a 25 Hz voltage to variable gain amplifiers.

2.9 THE COMMUTATED AERIAL DIRECTION-FINDER

We have so far considered DFs which employ antenna of dimensions small compared with the wavelength. If the width of the antenna (b in Eq. 1.1) is increased beyond several wavelengths, the antenna will have a multiple lobe polar diagram and cannot be used in the same manner as the smaller one for direction finding. Such an antenna, called a wide-aperture antenna would, however, have the advantage of reduced site errors. Site errors arise because objects in the site tend to produce local distortions in the wavefront. A small aperture antenna is affected by these but a large aperture antenna, of a width of many wavelengths, tends to even out the effect of these distortions and reduce site errors. But different techniques (rather than null location) have to be used to utilize the wide aperture antenna. A 'commutated aerial direction-finder' (CADF) for use in VHF/ UHF bands is made by GCEL in India. It operates in two bands, 100–156 MHz and 225–399 MHz. The commutation pulse rate is 216 Hz. The antenna consists of 16 dipole elements for VHF and UHF. The errors in normal sites are said to be within ± 2°. The system is fully solid state and employs microprocessor and VLSI technologies. The "commutated aerial direction-finder" employs the method described in what follows.

Consider an antenna system consisting of two antennas A and B (Fig. 2.16) separated by a distance of less than $\frac{\lambda}{2}$ and rotated around the circumference of a circle of radius $r (r \gg \lambda)$.

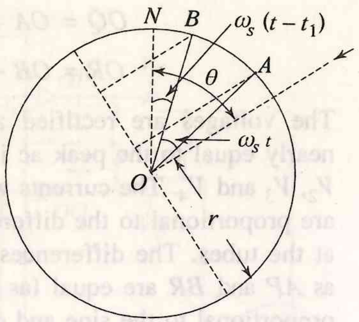


Fig. 2.16 Rotation of two antennas a circle in producing phase modulation

Let ω_s be the angular velocity of rotation of the antennas about the centre O and $\omega_s t_1$, the angle subtended by the two antennas at O. Consider an electromagnetic wave incident from a direction making an angle θ with the North. The phases of the voltage in the two antennas, (with respect to a reference phase at 0) are then:

$$\phi_1 = \frac{2\pi r}{\lambda} \cos(\omega_s t - \theta) \text{ in } B$$

$$\phi_2 = \frac{2\pi r}{\lambda} \cos(\omega_s \overline{t - t_1} - \theta) \text{ in } A \tag{2.12}$$

The phase difference ϕ between these two voltages is thus

$$\phi = \phi_1 - \phi_2 = \frac{2\pi r}{\lambda} [\cos(\omega_s t - \theta) - \cos(\omega_s \overline{t - t_1} - \theta)]$$

$$= \frac{2\pi r}{\lambda} \cdot 2 \sin \frac{\omega_s t_1}{2} \cdot \sin\left(\omega_s t - \theta - \frac{\omega_s t_1}{2}\right)$$

Since the chord length $AB = 2r \cdot \sin\left(\frac{\omega_s t_1}{2}\right)$,

$$\phi = \frac{2\pi}{\lambda} AB \cos(\omega_s \overline{t - t_1/2} - \theta) \tag{2.13}$$

If the signals from A and B are applied to a phase detector, the output voltage will be proportional to cos $(\omega_s t - \theta - \omega_s t_1/2)$. The bearing θ may be obtained by phase comparison with a reference signal cos $\omega_s t$, which can be obtained from the antenna rotation. This is the basic method employed for determining θ. In practical implementation, instead of rotating the antenna pair, a number of antennas are fixed at equal distances along the circumference of a circle and the signals from pairs of these antennas are sequentially sampled. For details of the implementation, see Ref. 9, 10. The term 'commutated aerial direction-finder' arises because of this technique.

The CADF gives improved performance over the Adcock system, not only in the presence of site imperfections but also when multipath

2.10 RANGE AND ACCURACY OF DIRECTION-FINDERS

Ground-based direction-finders are generally of the Adcock type and are relatively free from polarization errors. In day time, such installations when installed on a good site have the limiting accuracy of the instrumentation, generally of the goniometer, which may be under 1°, if calibrated. At night time, when sky-wave propagation is predominant, errors will arise which may range from 2° to 4° depending on the distance of the transmitter (150 to 600 km)*. Most ground-based Adcock stations operate between 2 and 3 MHz and serve ships. Such stations are not suitable for aircraft as aircraft transmissions are generally confined to much higher frequencies because of the difficulties associated with equipping the aircraft with efficient antennas operating in this range.

Ground-based VHF DFs are widely used, particularly in civil aviation. Their range is mainly limited by the line-of-sight propagation. The principal errors are due to the site. When such direction-finders are installed in an airport, these errors can be quite large. But with the provision of remote indication (as in ADF), the DF can be installed in a good site and the errors reduced. The commutated antenna DF enables a further reduction of site errors by a large factor.

Airborne DFs are generally of the loop type and operate in the MF/LF band. Reliable operation is possible with ground waves up to several hundred miles under favourable conditions. Accuracies up to 2° (after correcting for aircraft quadrantal errors) are possible. At night times, sky waves contaminate the signal and long range operation is not possible. Under these conditions, fairly reliable operation is possible only at the lower end of the frequency range and up to much shorter distances (less than 150 km). The calibration of these DFs holds only at one frequency and the condition of pitch and roll may also alter it. Taking all these factors into consideration, the bearings obtained from ground wave cannot be relied on to better than ± 5°.

In spite of the errors in the bearing determined, the aircraft (or ship) can always use the bearing for 'homing', i.e. going towards the transmitter. In the case of aircraft, when flying over the transmitter, a rapid reversal of bearing takes place. This gives an indication of the position of the aircraft. In the case of ships, it is inadvisable to home on to a beacon, because of the risk of collision. Transmitters transmitting continuous waves or modulated continuous waves are widely used in civil aviation for navigational assistance. These are called 'non-directional beacons'

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* In literature on Navigation, distance are often given in Nautical Miles and Statute Miles and speed in Knots. The following conversion factors may then be used.

1 Nautical Mile = 1.85 km
1 Statute Mile = 1.61 km
1 Knot = 1.85 km/hr

QUESTIONS AND PROBLEMS

1. Show that the voltage induced in the loop when it is derived on the basis of the rate of change of magnetic flux linking the loop is the same as given in Eq. 2.4.
2. A loop antenna consists of 10 turns of wire. The loop is tuned and the output voltage is 100 times the induced voltage. It is required that the loop output be at least 100 μV when the field strength of the electromagnetic wave is 10 μV/m at the frequency of 300 kHz. Suggest suitable dimensions of the loop.
3. Why is a balanced modulator stage used in the radio-compass receiver? It has been stated in the text that the operation of the receiver is equivalent of that of one using coherent demodulation. Justify this.
4. The automatic VHF direction finder described in Sec. 2.8(b) employs two selective amplifiers [or active filters]. Discuss the effect of a slight mistuning of one of the filters.
5. Draw the phasor diagram of 2.15 (b) when an aircraft is approaching the direction finder from 30° East of North.

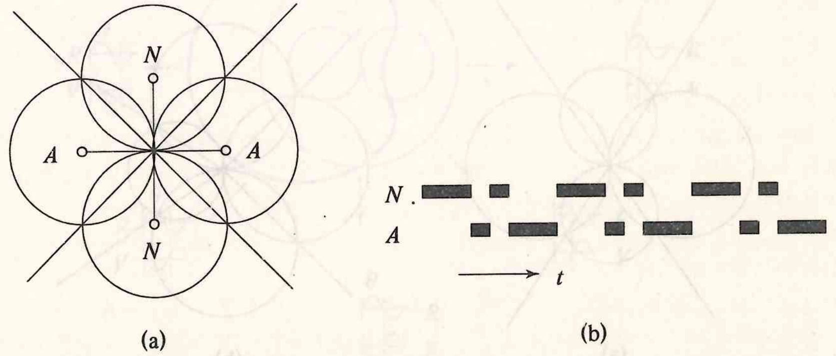
3

Radio Ranges

Radio ranges are navigational aids which are mainly used by aircraft. There are two types of radio ranges in use, the low frequency four-course radio range and the VHF omni-directional radio range. The former can be used by any aircraft equipped with a receiver which can tune to the frequency of the ground station, which is in the LF/MF range of 200–400 kHz, while the latter requires special equipment. The LF/MF radio range is obsolescent and so only a brief treatment of the principles of its operation is given. The VHF omni-range (generally abbreviated or VOR) is in use in most parts of the world.

3.1 THE LF/MF FOUR-COURSE RADIO RANGE

The LF/MF radio range employs two antenna systems each of which has a polar diagram of the figure-of-eight type, these two being at right angles to each other [Fig. 3.1(a)]. The points of intersection of these two figures-of-eight, when joined to the centre, give four directions in which the signals from the two sets of antennas have the same strength. These are



(a)

(b)

Fig. 3.1 (a) Polar diagram of the four-course radio range and called equi-signal courses. A transmitter is made to energize these antennas alternately by a relay called the link circuit relay. In order to distinguish the transmission from the two antennas, one of them is made to transmit the letter *N* (— ·) in morse and the other to transmit the letter *A* (· —) the two being inter-locked as shown in Fig. 3.1(b). Both these transmissions are modulated by an audio frequency note of 1020 Hz. When the aircraft is on course, the two signals being equal, a continuous note of 1020 Hz is heard. At points off the course, either the letter *N* or the letter *A* is predominant. Owing to the fact that the ear can distinguish only a finite change in the intensity of the signal, the equi-signal course appears spread over a small angle, generally about 3°. The radio range, thus provides four paths at right angles along which the aircraft can navigate. These paths are arranged to be along the most useful routes.

In a variation of this system, called the SRA (Simultaneous Range Adcock) five antenna towers are used, four at the corners of a square and the fifth at the centre. Power is fed to all the antennas. The transmission from the corner towers give rise to two figure-of-eight polar diagrams. The transmissions from the centre tower, which differs in frequency by 1020 Hz, combines with the others to give four equi-signal courses. In addition, by a combination of the power and phase of radio frequency energy fed to the four corner antennas, the figure-of-eight patterns can be reduced or increased in size and the two lobes of the pattern can be made unequal. This enables one to obtain courses which are not perpendicular to each other, as shown in Fig. 3.2. These are called course-bending and course-shifting. In addition, by feeding the power to the antennas through a goniometer, rotation of the courses is also made possible. In this system, it is possible to arrange the courses to serve routes which are not necessarily perpendicular to each other. The radiation from the central antenna can also be modulated to serve as radio telephony channel to broadcast weather news.

The radio range facility gives good service over a range of about 200 km. The transmission from the central tower can be used for radio compass operation also. The disadvantages of the range are (1) the limited number of courses (i.e. four) available, (2) poor signal/noise ratio, (3) fatigue caused by listening to the tones, and (4) difficulty of identifying the course. These factors, and the emergence of the VHF omni-range have contributed to the obsolescence of the LF/MF radio range.

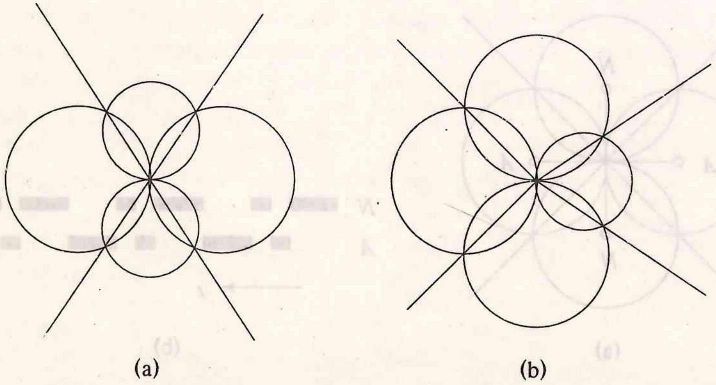


Fig. 3.2 (a) Course-shifting and (b) course-bending in LF/MF radio range

3.2 VHF OMNI-DIRECTIONAL RANGE (VOR)

This facility operates in the range 108–136 MHz in the VHF band. An aircraft provided with the appropriate receiving equipment can obtain its radial position with respect to the range by comparing the phases of two sinusoids obtained from the range radiation. Any fixed phase difference defines a radial course and so, in effect, the VOR may be regarded as providing an infinite number of courses, as against the four of the LF/MF radio range. The principle of operation is given in what follows.

The range transmitter radiates two patterns, distinguishable by different modulations, one of which is omni-directional and carries the modulation of a reference 30 Hz sinusoid, while the second pattern is a figure-of-eight rotating at 30 rps. The radio frequency phases of the two are locked. The omni-directional radiation has a much stronger field than the figure-of eight one, and therefore, the combination gives rise to a rotating cardioid. At the receiving point, the rotating cardioid, after demodulation, gives a 30 Hz signal of variable phase, while the omni-directional signal gives a 30 Hz signal of fixed reference phase. Figure 3.3 shows how the phase

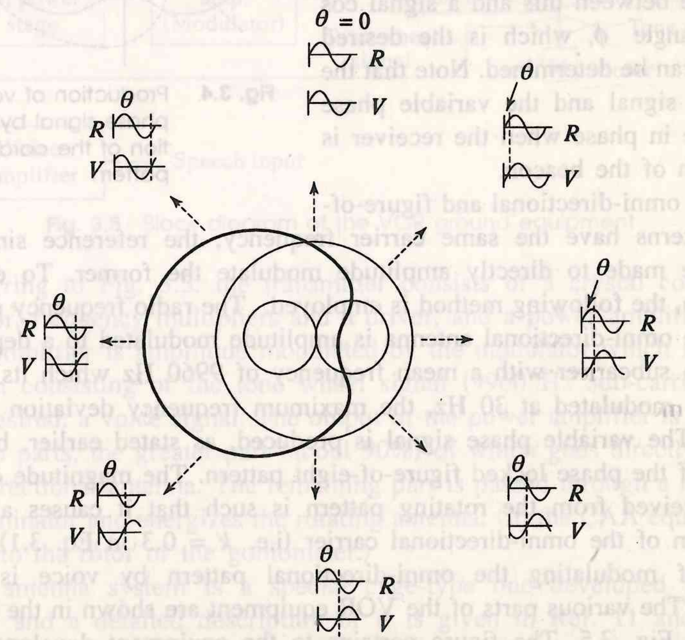


Fig. 3.3 Reference (R) and variable-phase (V) signals of VOR received

difference between these is equal to the bearing of the receiving point from the beacon transmitter. By suitable instrumentation in the aircraft, this phase angle may be directly displayed on a meter.

The dependence of the phase of the demodulated signal in the receiver on the bearing of the receiver is readily established in the following manner. Let the cardioid have its maximum in the direction of North at $t = 0$ and let it rotate clockwise with angular velocity ω_s. The equation of the cardioid (taken as representing the magnitude of the electric field) in polar coordinates is:

$$\varepsilon = 1 + k \cos \theta \ (k < 1) \qquad (3.1)$$

where θ is the angle measured from North. This is shown by the full line cardioid in Fig. 3.4, where the maximum of the cardioid ($\theta = 0$) is in the direction of North. At a time t, when the cardioid has turned by angle $\omega_s t$, the field magnitude in a direction ϕ is given by the same equation but with θ replaced by $\phi - \omega_s t$, as is clear from the cardioid shown by the broken line in Fig. 3.4. The signal received by a receiver in the direction θ is, therefore proportional to $1 + k \cos (\phi - \omega_s t)$, which has a sinusoidal component of angular frequency ω_s. By comparing the phase difference between this and a signal cos $\omega_s t$, the angle ϕ, which is the desired bearing, can be determined. Note that the reference signal and the variable phase signal are in phase when the receiver is due North of the beacon.

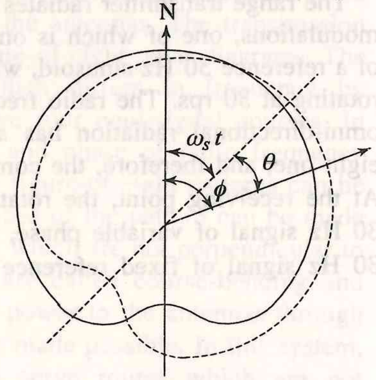


Fig. 3.4 Production of variable phase signal by rotation of the cardioid pattern

As the omni-directional and figure-of-eight patterns have the same carrier frequency, the reference sinusoid cannot be made to directly amplitude modulate the former. To enable separation, the following method is employed. The radio frequency power fed to the omni-directional antenna is amplitude modulated to a depth of 30% by a subcarrier with a mean frequency of 9960 Hz which its itself frequency modulated at 30 Hz, the maximum frequency deviation being 480 Hz. The variable phase signal is produced, as stated earlier, by the rotation of the phase locked figure-of-eight pattern. The magnitude of the signal received from the rotating pattern is such that it causes a 30% modulation of the omni-directional carrier (i.e. $k = 0.3$ in Eq. 3.1). The facility of modulating the omni-directional pattern by voice is also provided. The various parts of the VOR equipment are shown in the block schematic Fig. 3.5. The figure pertains to the equipment developed by Federal Telecom Laboratories[11]. This differs from the earlier equipment developed by the Civil Aeronautics Administration (CAA)[12], mainly in respect of the antenna system and the way in which a rotating figure-of-eight is obtained. In the CAA equipment, four Alford loop antennas, energized through a capacitor goniometer were used. Rotation of the stator of the goniometer produced a rotation of the polar diagram. In the FTL equipment, this pattern is produced by a dipole antenna which is itself rotated. In both these equipments the 9960 Hz sub-carrier which is frequency modulated at 30 Hz is obtained by a 'tone wheel' which is coupled to the rotating element. This part of the equipment will be described later.

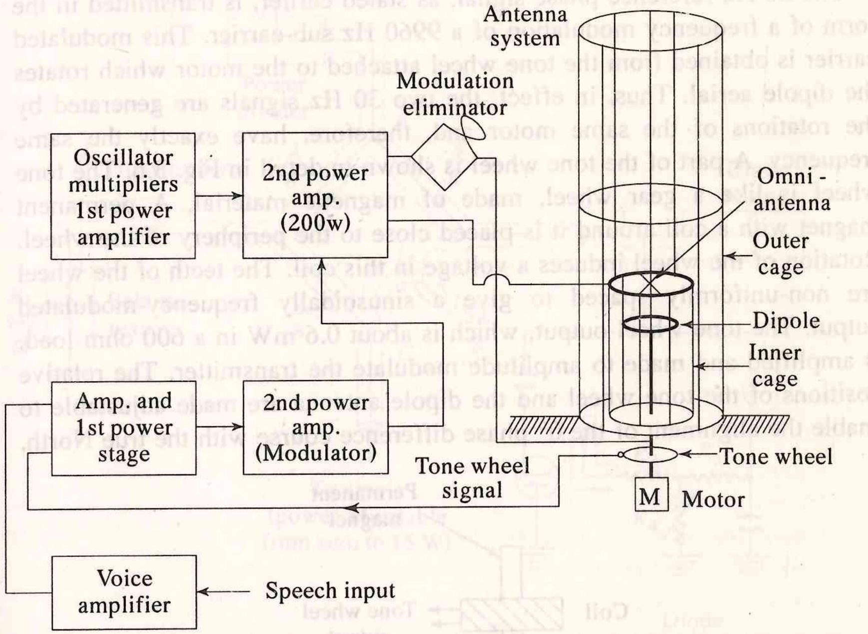


Fig. 3.5 Block diagram of the VOR ground equipment

Referring to Fig. 3.5, the transmitter consists of a crystal controlled oscillator, frequency multipliers and a driver, and a power amplifier. The power amplifier is amplitude modulated by the modulator which is given an input consisting of the tone wheel signal (9960 Hz sub-carrier) and when desired, a voice signal. The output of the power amplifier is divided into two parts, the greater part (about 90%) of which goes directly to the omni-directional antenna. The remaining part is passed through a modulation eliminator and energizes the rotating antenna. (In the CAA equipment, it goes to the rotor of the goniometer.)

The antenna system is a special cage-type one developed for this purpose and a detailed description of it is given in Ref. 11 and 13. It consists of a disc-type antenna with four slots which gives the omnipattern. The latter is enclosed in a double-cage made up of vertical rods and two end-plates which act as a radial waveguide coupled to free-space through vertical slots. The dipole is only a tenth of a wavelength long but because of its position within the waveguide, it presents a resistive impedance. The outer of the two cages enclosing the antennas is extended up by 12 feet. The net result of the antenna structure is to give a radiation made up of the two required patterns, the polarization of the radiation being horizontal. This antenna is also simple to adjust for correct operation, as the difficulty of properly phasing the four Alford loops in the older type of equipment is eliminated by the use of a rotating antenna.

The 30 Hz reference phase signal, as stated earlier, is transmitted in the form of a frequency modulation of a 9960 Hz sub-carrier. This modulated carrier is obtained from the tone wheel attached to the motor which rotates the dipole aerial. Thus, in effect, the two 30 Hz signals are generated by the rotations of the same motor and, therefore, have exactly the same frequency. A part of the tone wheel is shown in detail in Fig. 3.6. The tone wheel is like a gear wheel, made of magnetic material. A permanent magnet with a coil around it is placed close to the periphery of the wheel. Rotation of the wheel induces a voltage in this coil. The teeth of the wheel are non-uniformly spaced to give a sinusoidally frequency-modulated output. The tone wheel output, which is about 0.6 mW in a 600 ohm load, is amplified and made to amplitude modulate the transmitter. The relative positions of the tone wheel and the dipole antenna are made adjustable to enable the alignment of the 0° phase difference course with the true North.

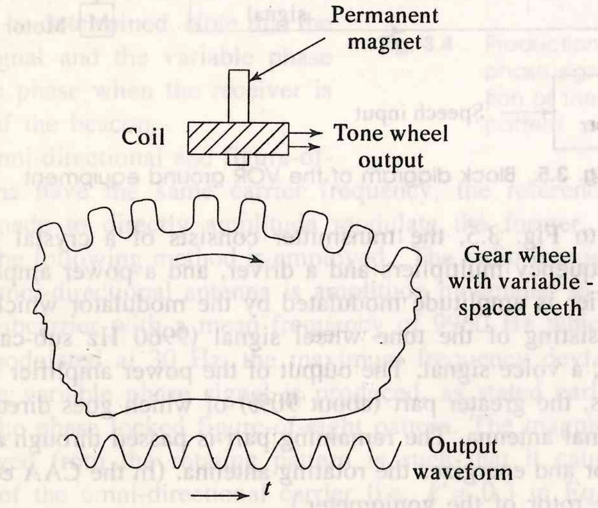


Fig. 3.6 Detail of the tone wheel

The importance of maintaining the phase relation between the carrier of the omni-directional radiation and the figure-of-eight radiation has already been mentioned. This requirement is met by first modulating the carrier, then separating a part of it and removing its modulation. If, one the other hand two separate power amplifiers were used for the modulated and unmodulated outputs, there is a possibility that the phase angle between the two carriers will change due to small changes of tuning. The method is, therefore, not employed and instead modulation eliminator, the circuit of which is shown in Fig. 3.7, is employed.

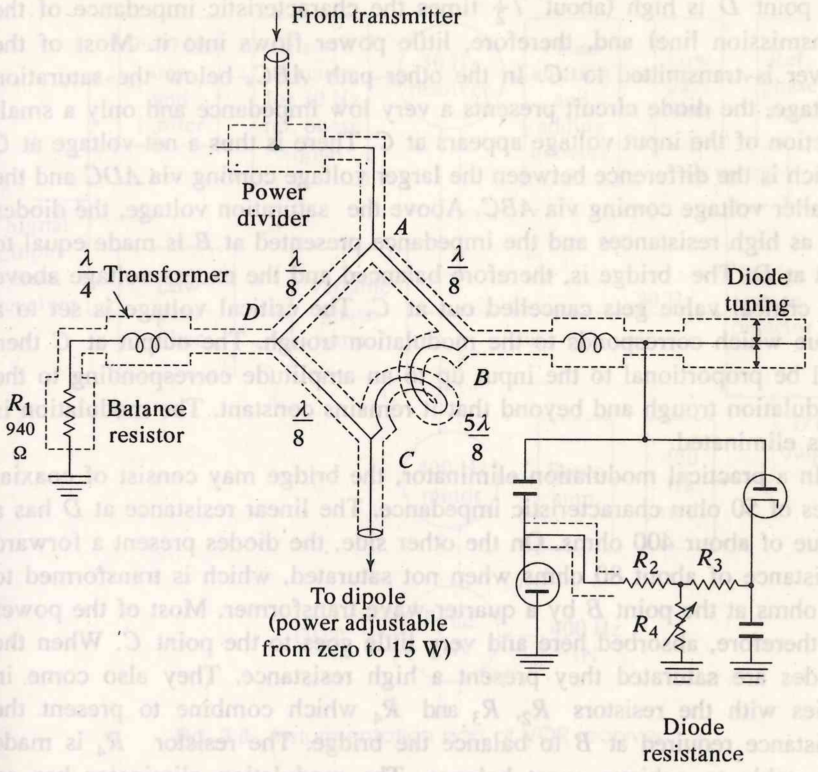


Fig. 3.7 Circuit of the modulation-eliminator

The operation of the modulation eliminator is as follows. The circuit consists of a bridge *ABCD* (Fig. 3.7) made up of coaxial lines, in which three arms, *AB*, *AD* and *DC* are $\lambda/8$ long and the fourth arm *BC* is $5/8\lambda$ long. At *D*, there is a resistance load and at *B*, a load consisting of two special VHF diodes which act as nonlinear resistors. The power arriving from *A* to *C* takes two paths, one via *D* and the other via *B*, and as these two are in anti-phase (because the arm *BC* is $\lambda/2$ longer than the others), the resultant voltage is the difference between the two. If the bridge is balanced, (i.e. if the impedances presented at *D* and *B* are equal), there will be no net output. The power arriving by the path *ADC* may be taken to be a constant fraction of the input power, as there is a linear resistance termination at D. The power arriving via ABC, however, depends upon the value of the terminating resistance presented by the diode circuit, which depends upon the actual voltage applied. The special diodes used have a characteristic such that for inputs below a certain value, they can be approximated by a linear resistance while for high inputs, saturation occurs and the slope resistance becomes high.

The value of the load resistance due to the balance resistor appearing at the point D is high (about $7\frac{1}{2}$ times the characteristic impedance of the transmission line) and, therefore, little power flows into it. Most of the power is transmitted to C. In the other path ABC, below the saturation voltage, the diode circuit presents a very low impedance and only a small fraction of the input voltage appears at C. There is thus a net voltage at C which is the difference between the larger voltage coming via ADC and the smaller voltage coming via ABC. Above the saturation voltage, the diodes act as high resistances and the impedance presented at B is made equal to that at D. The bridge is, therefore balanced and the excess voltage above the critical value gets cancelled out at C. The critical voltage is set to a value which corresponds to the modulation trough. The output at C then will be proportional to the input up to an amplitude corresponding to the modulation trough and beyond that it remains constant. The modulation is thus eliminated.

In a practical modulation eliminator, the bridge may consist of coaxial lines of 50 ohm characteristic impedance. The linear resistance at D has a value of abour 400 ohms. On the other side, the diodes present a forward resistance of about 80 ohms when not saturated, which is transformed to 16 ohms at the point B by a quarter-wave transformer. Most of the power is, therefore, absorbed here and very little goes to the point C. When the diodes are saturated they present a high resistance. They also come in series with the resistors R_2, R_3 and R_4 which combine to present the resistance required at B to balance the bridge. The resistor R_4 is made adjustable to achieve exact balance. The modulation eliminator has an efficiency of about 23% and delivers about 15 W to the rotating antenna.

3.3 VOR RECEIVING EQUIPMENT

The air-borne equipment which can utilize the VOR facility consists of a broad band omni-directional antenna, a multichannel amplitude modulated receiver which can be tuned over the required band, and an instrumentation unit which processes the receiver output to obtain the course indication. In most of the modern installations, a common receiver is used for the reception of VOR and ILS signals (see Chapter 6) and the demodulated output is switched to the required instrumentation and display circuits. The frequency band over which the receiver works in 108.0 to

ones by 50 kHz. Continuous tuning over this range is not desirable. Modern receivers are crystal controlled and tuned to spot frequencies. By a system of multiple heterodyning, the 560 channels are obtained with a limited number of crystals, as explained in Appendix II. Transistorized circuits are used in modern receivers.

The essential elements of the instrumentation part of the receiver are shown in the block diagram of Fig. 3.8. The demodulated output of the

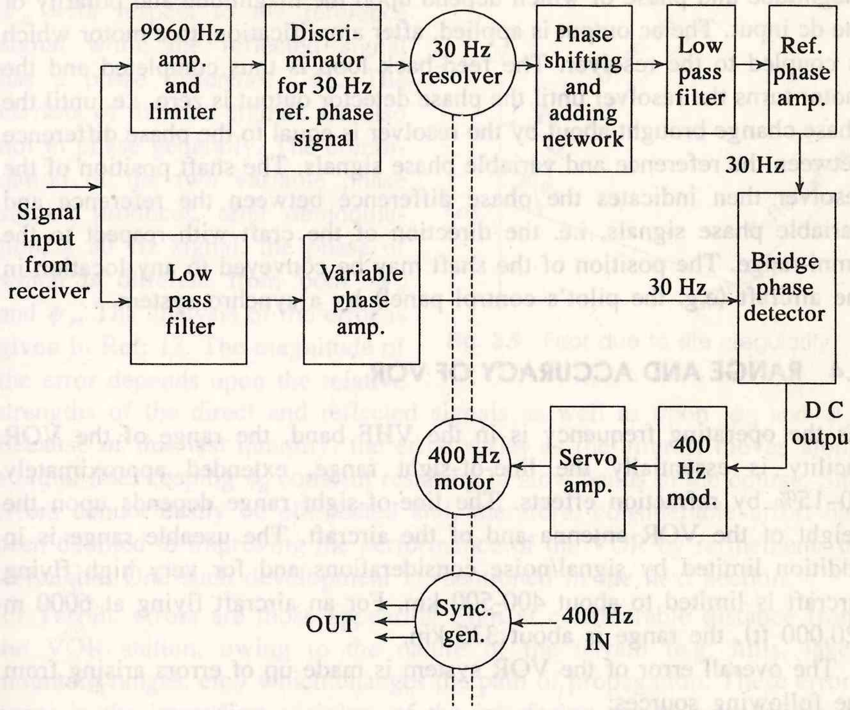


Fig. 3.8 Insturmentation part of VOR receiver

receiver, which is the input to the instrumentation unit contains the variable phase 30 Hz signal and the reference phase signal as frequency modulation on the 9960 Hz sub-carrier. These are separated by filters into two channels. The reference phase signal is passed through an amplitude limiter, a discriminator and a low pass amplifier to obtain the 30 Hz modulation. The variable phase signal is similarly amplified by a low pass amplifier. (It must be ensured that the phase changes introduced in these two branches are equal, as otherwise, the course will be in error by the difference between the two phase shifts.) The two 30 Hz signals thus become available and the phase difference between them is to be displayed. This is done by a feed-back arrangement utilizing a resolver, a phase-detector and a motor, as shown in Fig. 3.8. The resolver is a sine-cosine generator used to produce an angular phase-shift that is precisely equivalent to the angular position of its shaft (see Appendix-III). The reference phase signal is given to the resolver and its output filtered, amplified and applied to the phase detector. The variable phase signal is also applied to the phase detector. The output of this circuit is a dc voltage, the magnitude and polarity of which depends on the phase difference between the two inputs. The dc output goes to a balanced modulator which has a 400 Hz ac switching input, and its output is a 400 Hz voltage, the magnitude and phase of which depend upon the magnitude and polarity of the dc input. The ac output is applied, after amplification, to a motor which is coupled to the resolver. The feed-back loop is thus completed and the motor turns the resolver until the phase detector output is zero, i.e. until the phase change brought about by the resolver is equal to the phase difference between the reference and variable phase signals. The shaft position of the resolver then indicates the phase difference between the reference and variable phase signals, i.e. the direction of the craft with respect to the omni-range. The position of the shaft may be conveyed to any location in the aircraft (e.g. the pilot's control panel) by a synchro system.

3.4 RANGE AND ACCURACY OF VOR

As the operating frequency is in the VHF band, the range of the VOR facility is essentially the line-of-sight range, extended approximately 10–15% by refraction effects. The line-of-sight range depends upon the height of the VOR antenna and of the aircraft. The useable range is in addition limited by signal/noise considerations and for very high flying aircraft is limited to about 400-500 km. For an aircraft flying at 6000 m (20,000 ft), the range is about 335 km.

The overall error of the VOR system is made up of errors arising from the following sources:

(a) ground station and aircraft equipment,
(b) site irregularities,
(c) terrain features, and
(d) polarization.

(a) The ground station equipment error is mainly the octantal error in the installations using two antenna pairs and a rotating goniometer for obtaining the rotating figure-of-eight pattern. Octantal error can also arise owing to in homogeneity in the ground characteristics at the installation and could, therefore, occur even where rotating antennas are used. Equipment error in the receiver and indicator in the aircraft arise owing to imperfections of the circuits and components such as those contained in the feed-back control system. The magnitudes of the equipment errors are best specified in terms of the probability distribution. Analysis of a large number of ground station errors indicates[14] that the error distribution is

(b) Site errors arise when the signal arrives at the receiver by two paths, one directly from the range and the other after reflection from objects in the neighbourhood of the range. The reference phase signal is not appreciably affected by this, as the difference in the path delays is always small compared with the period of the modulation cycle. The variable phase components may, however, differ appreciably. Referring to Fig. 3.9, the signal arriving directly at the receiver has the variable phase component with a phase difference ϕ_d with respect to the reference signal while the reflected signal has a phase difference ϕ_r. The carriers of the two signals are also not in phase generally. The combination of the two variable phase signals produces, after demodulation, a 30 Hz signal, the phase of which is different from both ϕ_d and ϕ_r. The analysis of the error is given in Ref. 13. The magnitude of the error depends upon the relative strengths of the direct and reflected signals as well as upon ϕ_d and ϕ_r. Because of this last quantity, the error varies as the aircraft moves along a radial line, keeping ϕ_d constant resulting in slow bends in the course. Site errors cannot easily be eliminated and, therefore, considerable effort has been devoted to improving the performance of the VOR by refinements of technique. One such development is mentioned in the next section.

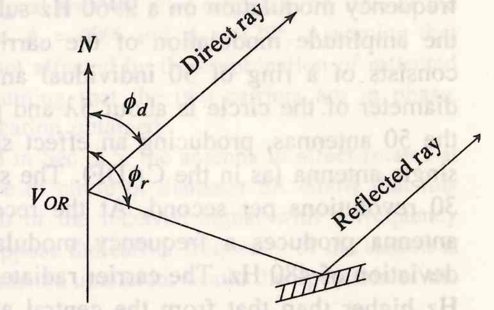


Fig. 3.9 Error due to site irregularity

(c) Terrain errors are those appearing even at considerable distance from the VOR station, owing to the nature of the terrain (e.g. hills, lakes mountain ranges, etc.) which changes the path of propagation. These errors occur in the immediate vicinity of the interfering objects and appear as rapid fluctuations ('Scalloping') in the course-deviation indicator.

(d) Polarization error arises because of the vertical component of the radiated electric field, which has a polar diagram different from that of the horizontal component. The error can be reduced by minimizing the vertically polarized component radiated by the ground antenna and by making the aircraft antenna insensitive to vertically polarized signals. The latter alone cannot provide a complete solution, because the aircraft has to bank in the course of maneuvers and, however good the antenna, it will then inevitably respond to the vertical field. Suppression of the vertical component from the transmitted radiation is, therefore important, particularly for radiation at higher angles.

3.5 RECENT DEVELOPMENTS

Though VOR is widely used, its performance falls short of the most stringent requirements demanded of navigational aids. The principal deficiency is its proneness to site errors, and their elimination has attracted considerable developmental effort. The Doppler VOR system has been developed by CAA in the United States and is claimed to give a reduction of site errors by a factor of 7 and has the merit that it is completely compatible with existing installations, i.e. it does not require any modification of the aircraft equipment.

In the Doppler VOR, the variable phase signal is transmitted as the frequency modulation on a 9960 Hz sub-carrier and the reference phase as the amplitude modulation of the carrier at 30 Hz. The antenna system consists of a ring of 50 individual antennas and a central antenna. The diameter of the circle is about 5λ and power is switched consecutively to the 50 antennas, producing an effect similar to that of the rotation of a single antenna (as in the CADF). The switching rate is such as to produce 30 revolutions per second. At the receiver, the effective rotation of the antenna produces a frequency modulation with a maximum frequency deviation of 480 Hz. The carrier radiated by the outer aerials is made 9960 Hz higher than that from the central aerial. Therefore, the resultant field appears to have an amplitude modulation at 9960 Hz which is frequency modulated at 30 Hz with a frequency deviation of 480 Hz. The phase of the modulation clearly depends upon the bearing of the receiver, as the frequency deviation is maximum when the antenna is moving in the direction of the receiver (either towards or away from it), and is zero when it is moving at right angles to this direction.

In one type of Doppler VOR (D–VOR) made by G.C.E.L. in India, the antenna system comprises the central antenna which radiates the amplitude modulated carrier, modulated by the 30 Hz reference phase signal, as also speech and station identification signals. The outer antenna system consists of a ring of 48 Alford loops, which are fed with the upper and lower sideband signals of a carrier modulated by 9960 Hz. These, combined with the carrier radiated from the central antenna, result in an amplitude modulation at a mean frequency of 9960 Hz which becomes frequency modulated at 30 Hz by the virtual rotation of the outer antenna.

Field studies of Doppler VOR have shown that site errors and bends under comparable site conditions are reduced by a factor of four to seven. The disadvantage of the Doppler VOR is the greater complexity of the ground equipment and the large area required for the installation. (A 50 m diameter counterpoise was used in the developmental models.)

The site errors having been reduced by the wide aperture antenna employed in Doppler VOR the remaining errors are principally instrumental ones. In a developmental system, these errors area sought to be reduced by the use of a multilobe technique similar to that in TACAN (see Chapter 5). This system requires[15] changes in the receiver equipment and has so far not been widely adopted.

QUESTIONS AND PROBLEMS

1. The VOR signal received by an aircraft consists of a carrier modulated by a 30 Hz sinusoid and also by a sinusoid of mean frequency of 9960 Hz. Taking the depth of modulation in each case as 30%, write down an expression for the received signal.
2. In the instrumentation part of the VOR receiver in Fig. 3.8, suggest suitable band-pass characteristics of the variable phase signal and reference phase signal filters.
3. Referring to Fig. 3.9, let the signal arriving after reflection be 10% of the signal arriving directly, and let $\phi_d = 60\%$ and $\phi_r = 120°$. Assuming that the reference phase signal is not affected by the combination of reflected and direct rays, and also assuming that the two carriers are in phase, calculate the error in the indication obtained.
4. In the Doppler VOR described in Sec. 3.5, the antenna in effect rotates at 30 revs/s on the circumference of circle of diameter 5λ. Show that this leads to frequency modulation of the received signal with a frequency deviation of about 480 Hz. Suppose the carrier frequency of the station is changed by 5%, keeping the antenna unaltered, would the operation of the receiver be affected?
5. In the CAA equipment of VOR, the rotating pattern is produced by feeding four Alford loops modulated in time quadrature at 30 Hz, by means of a goniometer. The four Alford loops in effect form two loop antennas at right angles to each other, producing a figure-of-eight pattern. Show that by feeding power varying sinusoidally at 30 Hz and in phase quadrature to the two antennas a rotating figure-of-eight pattern is produced.

4

Hyperbolic Systems of Navigation

Loran and Decca

Hyperbolic systems are based on the measurement of the difference in the time of arrival of electromagnetic waves from two transmitters to the receiver in the craft. The name arises from the fact that the locus of points which have a constant value of such a delay is a hyperbola on a plane surface.

Referring to Fig. 4.1, let us assume that station A and station B make synchronous transmissions and that some means is provided in the receiver at P to measure the interval between the time of arrival of the radiations from the two stations. This interval $t_d = \frac{AP}{c} - \frac{BP}{c}$, where c is the velocity of electromagnetic waves. Taking the coordinates of P as (x, y) with reference to the axes shown in the figure, we have

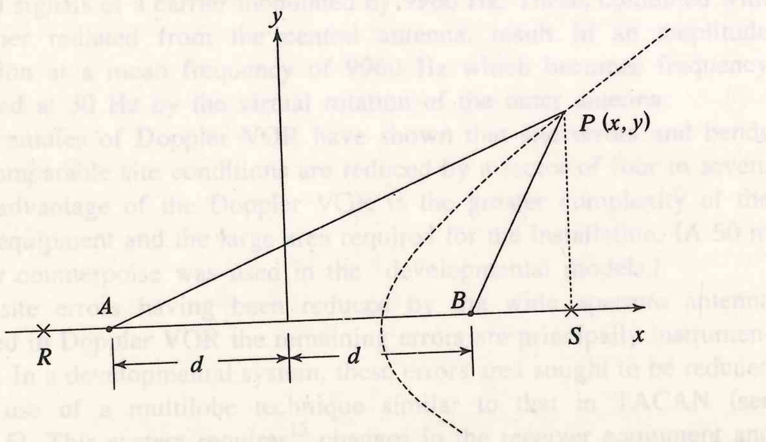


Fig. 4.1 Analysis of a hyperbolic system (A and B are transmitters

$$AP = \sqrt{(x+d)^2 + y^2}, \quad BP = \sqrt{(x-d)^2 + y^2}$$

and for a constant value of time delay

$$AP - BP = \sqrt{(x+d)^2 + y^2}, - \sqrt{(x-d)^2 + y^2} = \text{const.} = l \text{ (say)}$$

where l is the difference between path lengths AP and BP. Simplifying, this equation may be put in the form

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

where $$a^2 = \frac{l^2}{4} \text{ and } b^2 = d^2 - \frac{l^2}{4}$$

This is the equation of a hyperbola, with foci at A and B. All the possible values of the delay t_d give a family of confocal hyperbolae (Note, however, that the delay can be either positive or negative but its magnitude cannot exceed $2\,d/c$, which is the delay at all the points on the line joining A and B, to the left of A and to the right of B). The determination of the delay locates the craft on one of these hyperbolae. If there is a third sysnchro- nized station C, the determination of the delays between the reception of signals from A and B and also between those from B and C would locate the craft on two hyperbolae, and their intersection gives the fix, as shown in Fig. 4.2. This is the basic principle of hyperbolic navigational systems, in general. Different systems use different techniques for determining the delay.

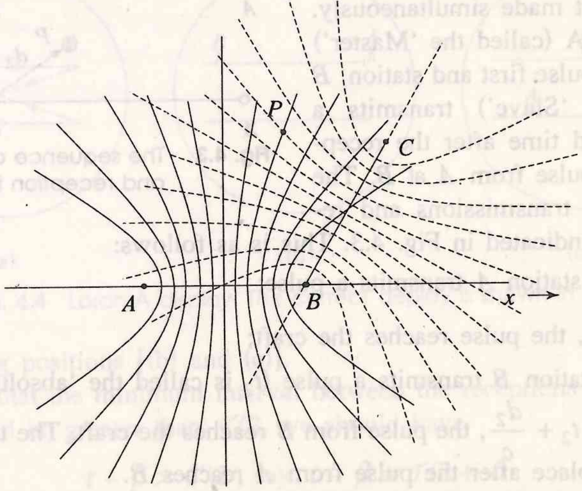


Fig. 4.2 Three stations producing two sets of hyperbolae

Three systems in current use are described below, namely LORAN, DECCA and OMEGA. Of these, LORAN (or LORAN–A) has been included for the purpose of explaining the principles. It is now obsolete and has been succeeded by LORAN–C, the basics of which are included. LORAN is a pulsed system while DECCA and OMEGA are C.W. systems.

4.1 LORAN-A

Loran stands for 'Long range navigational aid'. This system was developed during the last world war and found wide use. At present, certain regions of the world, principally the Pacific and Atlantic sea-boards of North America and the region around Japan are served by this facility. Loran-A or Standard Loran as it was previously called, is the earlier version and operates in the higher MF band around 2 MHz. A subsequent development, called Loran-C, operates in a band around 100 kHz. These facilities can be used both by ships and by aircraft because of the nature of propagation in these frequency bands.

Loran is a pulse system. The ground stations transmit a train of pulses with fixed time relation between them and at the receiver, these pulses are identified and the delay between them is measured on a cathode-ray tube. In the earlier paragraph, the example of two synchronized stations was given for simplicity. But if the transmitters at A and B transmit identical pulses simultaneously, there would be an ambiguity because it would not be possible to determine which pulse arrived first. To avoid this, the pulse transmissions are not made simultaneously. The station A (called the 'Master') transmits a pulse first and station B (called the 'Slave') transmits a pulse a fixed time after the reception of the pulse from A at B. The sequence of transmissions and receptions is indicated in Fig. 4.3. This is as follows:

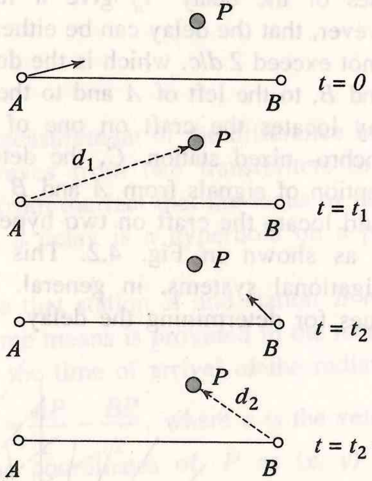


Fig. 4.3 The sequence of transmission and reception in Loran-A

$t = 0$ (say), station A transmits a pulse;

$t = t_1 = \dfrac{d_1}{c}$, the pulse reaches the craft;

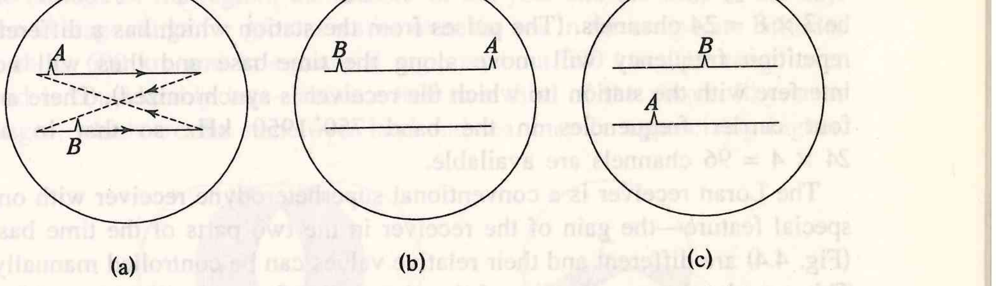
$t = t_2$, the station B transmits a pulse (t_2 is called the 'absolute delay').

$t = t_2 + t_3 = t_2 + \dfrac{d_2}{c}$, the pulse from B reaches the craft. The transmission of B takes place after the pulse from A reaches B.

The time interval between the two received pulses, i.e. $t_2 + t_3 - t_1$, is measured. The fixed delay in the transmission of B, namely t_2, is known and, therefore, $t_3 - t_1$ can be determined. This quantity may be either positive or negative, whereas $t_2 + t_3 - t_1$ is always positive. The line AB is called the base line and in the case of Loran-A is from 400 to 700 km.

The pulse repetition frequencies used in the Loran system are in the

by crystal clocks. The sequence of pulses for a master-slave pair is *ABAB....*, the interval between the A's and B's being one pulse repetition period ($\mathcal{T}$). The interval between one transmission of A and the next transmission of B is called 'absolute delay'. (The absolute delay must necessarily be greater than the time taken for the transmission to reach from A to B, i.e. $\frac{2d}{c} = \beta$). Let this be indicated by τ. Then the maximum interval between A and B pulses at the receiver is $\tau + \beta$, when the receiver is at a point on the line BA, beyond A (such as R in Fig. 4.1) and the minimum delay is $\tau - \beta$ when it is at a point on the line AB, (such as S in Fig. 4.1). In order to avoid ambiguity in the identification of A and B pulses and aid measurement, the absolute delay is made more than half the repetition period ($\mathcal{T}/2$). Therefore, the interval between an A and the next B pulse is always greater than $\mathcal{T}/2$, and the interval between a B pulse and the next A is always less than $\mathcal{T}/2$. At the receiver, the pulses are displayed on an oscilloscope which has a special type of time-base [Fig. 4.4 (a)], in which the period $\mathcal{T}$ is split into two parts, one half being displayed below the other. The spot moves from the left to top right, and flies back to bottom left in a period exactly equal to $\mathcal{T}/2$. The duration of each trace is nearly $\mathcal{T}/2$—actually $\mathcal{T}/2$ less the flyback time. A and B pulses can thus be identified by their positions on the two traces. Figure 4.4 illustrates the display when the pulses are in the correct position (a), and when they are in the wrong positions [(b) and (c)].



(a) (b) (c)

Fig. 4.4 Loran-A display. The correct display is shown in (a)

In order that the minimum interval between the receptions of A and B pulses should be greater than $\mathcal{T}/2$, we should have

$$\tau - \beta > \mathcal{T}/2\ , \text{ say } \ \tau - \beta = \mathcal{T}/2 + \delta$$

where δ is some small delay which is arbitrarily fixed. The obsolute delay τ is then

$$\tau = \frac{\mathcal{T}}{2} + \beta + \delta$$

The maximum and minimum interval between the pulses are:

$$t_{\max} = \left(\frac{\mathcal{T}}{2} + \beta + \delta\right) + \beta = \frac{\mathcal{T}}{2} + 2\beta + \delta$$

$$t_{\min} = \left(\frac{\mathcal{T}}{2} + \beta + \delta\right) - \beta = \frac{\mathcal{T}}{2} + \delta$$

When the path lengths from the craft to A and B are the same, as for the points on the y-axis in Fig. 4.1, the interval between the received pulses is τ, the absolute delay.

4.2 LORAN–A EQUIPMENT

Loran transmitters have a peak power of 100 kW which feed into a vertical quarter-wavelength antenna. The repetition rates of the pulses are accurately controlled by crystal clocks. The master station operates independently and transmits pulses of the required periodicity. The slave station is also provided with a crystal clock to maintain the repetition rate but the timing of these is controlled manually or semi-automatically to maintain the fixed delay.

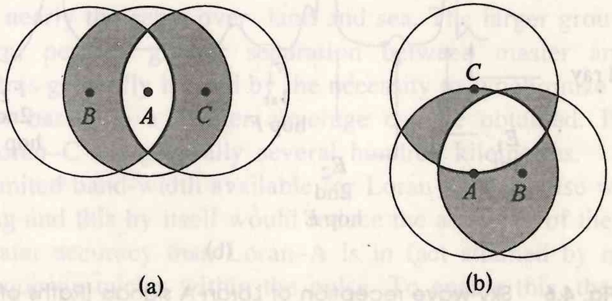
The Loran system employs three basic repetition rates of 20 Hz, 25 Hz and $33\frac{1}{3}$ Hz. Each basic rate is sub-divided into a group of eight frequencies which differ from the above by small but accurately controlled steps of $\frac{1}{25}, \frac{1}{16}$ and $\frac{1}{9}$ Hz. Thus, on any single carrier frequency, there can be $3 \times 8 = 24$ channels. (The pulses from the station which has a different repetition frequency will move along the time-base and thus will not interfere with the station to which the receiver is synchronized). There are four carrier frequencies in the band 750–1950 kHz so that in all $24 \times 4 = 96$ channels are available.

The Loran receiver is a conventional superheterodyne receiver with one special feature—the gain of the receiver in the two parts of the time base (Fig. 4.4) are different and their relative values can be controlled manually. This permits the equalization of the A and B pulse to facilitate matching. The bandwidth of the receiver is 40 kHz. Both this bandwidth and the shape of the transmitted pulses are carefully controlled so that the received pulses are of the same shape and in the process of finding the delay between the A and B pulses, the two can be brought into coincidence. Thus, though the pulse widths are nominally 40 μ sec, the error in the measurement of delay can be brought down to 1 μ sec.

The principal operation in the use of Loran is the measurement of the delay between A and B pulses. This is done in the Loran Indicator. In the earlier indicators, the time bases were controlled by crystals, which also gave calibration pulses. The measurement of the time interval followed a special procedure which involved the use of time bases of three speeds and a procedure for bringing the pulses into coincidence on the fastest time base. This took considerable time. In the modern receivers, the oscilloscope is still used to bring the pulses into coincidence by a delay control but the reading is obtained from an electronic counter which indicates the time difference in three decades.

4.3 RANGE AND PRECISION OF STANDARD LORAN

As Loran operates in the upper MF band, both ground-wave and sky-wave receptions are possible. Ground-wave reception is operative mainly in the day and is particularly good over the sea. At night, both ground- and sky-wave receptions are possible, the latter being more prominent at long distances. For navigation, signals from at least two stations, but generally three stations, are necessary and, therefore, the factor of importance is the area over which usable signals are received from the pair or triplet of stations, rather than the maximum range at which the signal from a transmitter can be received. This area is dependent both on the maximum range of the stations and on the distance between the stations, or their 'base-line' as well as on the relative positions of the stations. In Fig. 4.5 are shown two Loran triplets and their service area. The area within which a Loran fix can be obtained is shown heavily bounded and the areas where signals from only two stations can be obtained (providing only a hyperbolic line of position) is shown stippled. The service area depends on the latitude of the region, the season of the year and the time of the day. The average range for ground waves over the sea in the temperate latitudes is about 600 km and in equatorial regions about 500 km. The range over land is considerably less—about a half to a third of the above. Sky-wave ranges, which are the same over land and sea, may be appreciably higher.



(a) (b)

Fig. 4.5 Coverage of Loran-A chains

The accuracy attainable with the Loran system is dependent on several factors. The first of these is the accuracy with which time interval measurements can be made, which in turn depends upon the signal strength. The second factor is the accuracy with which ground stations are synchronized. The two factors taken together may lead to a probable error 1.5 to 2 μ sec in the measured time interval. Thirdly errors may be introduced by sky-wave propagation, because the path taken by the wave is not along the ground but a longer one via the ionospheric layer. Figure 4.6 shows the several possible paths which the wave can take via the ionosphere and the pulses these give rise to at the receiver. In addition to being delayed, the pulse appearing by the sky-wave path generally has a distorted shape which makes it difficult to match the waveforms of the pulses from two stations. However, with practice, an operator can identify and obtain the delay between two corresponding sky-waves (usually E_1 or E_2) and by averaging over a number of observations, reduce the measurement error to about 3 μ sec. Correction will still have to be applied for the additional delay introduced by the sky-wave path and curves and formulae based on average values of ionospheric heights, etc. are available for this purpose. However, they can be regarded as only approximate and so a further error is introduced into the computation of the delay.

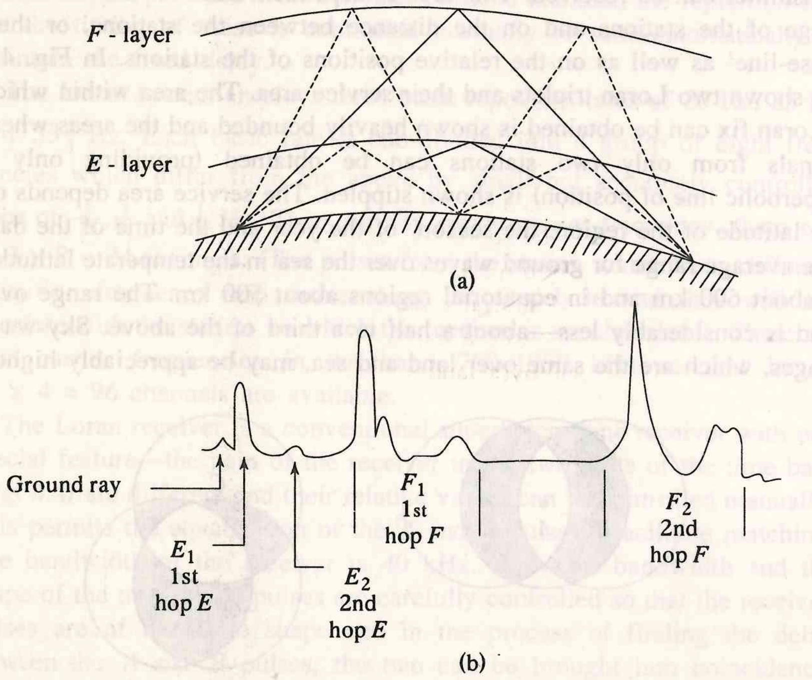


Fig. 4.6 Sky-wave reception of Loran-A signals [Paths of propagation are shown in (a) and the received signals in (b)]

The error in the determination of one time interval results in a corresponding uncertainty about the position of the hyperbola on which the craft is located. If t is the measured time interval and Δt is the probable error, the vehicle may be expected to be between the two hyperbolae corresponding to the delays at $t - \Delta t$ and $t + \Delta t$ as shown in Fig. 4.7 (a).

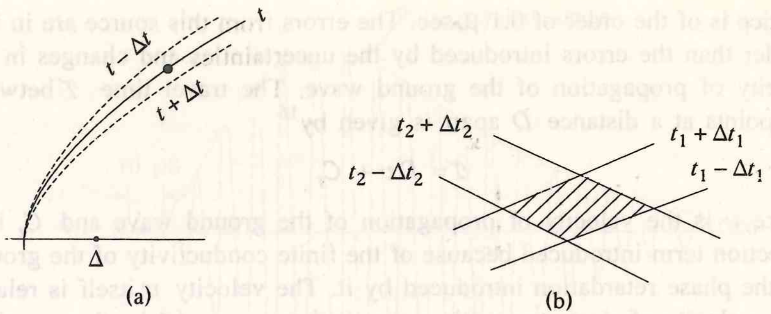


Fig. 4.7 Position errors in Loran-A navigation

chain gives a delay t_1 with an uncertainty Δt_1, and a delay t_2 with uncertainty Δt_2, the position of the craft will be within a quadrilateral area bounded by sections of four hyperbolic lines as in Fig. 4.7 (b). If Δt_1 and Δt_2 are very small, the two hyperbolae defining the limits of the error are nearly parallel at the point of intersection. The region representing the uncertainty in fix is, therefore, a parallelogram (shown shaded in Fig. 4.7), the area of which increases as the angle between the two intersecting hyperbolae decreases. There is thus introduced a further geometrical factor into the errors in Loran. These considerations are, of course, common to all hyperbolic systems.

4.4 LORAN-C

As stated earlier, Loran–C operates in the band 90–110 kHz. It is a development arising out of the wartime work on low frequency Loran operating on 180 kHz. The advantage of the low frequency is that the range of groundwave transmission is very much larger than at 2 MHz and attenuation is nearly the same over land and sea. The larger ground wave range, in turn, permits greater separation between master and slave stations, which is generally limited by the necessity to synchronize the two. With a longer base-line a greater coverage can be obtained. Base-line lengths for Loran–C are generally several hundred kilometres.

With the limited band-width available for Loran–C, the pulse width has to be very long and this by itself would reduce the accuracy of the system. However, greater accuracy than Loran–A is in fact attained by matching the carrier frequency cycles within the pulse. To enable this, the carriers of the transmitters are derived from cesium atomic clocks and the pulse envelope is standardised and accurately controlled. The master and slave station carriers are also accurately matched. At the receiver, a match between the envelopes is obtained (to eliminate ambiguity) and simultaneously, the *rf* cycles within the pulse are matched. The time measurement accuracy attainable thus becomes much greater than in Loran–A, and in practice is of the order of 0.1 μ sec. The errors from this source are in fact smaller than the errors introduced by the uncertainties and changes in the velocity of propagation of the ground wave. The travel time $\mathcal{T}$ between two points at a distance D apart is given by[16]

$$\mathcal{T} = Dv + C_t$$

where v is the velocity of propagation of the ground wave and C_t is a correction term introduced because of the finite conductivity of the ground and the phase retardation introduced by it. The velocity v itself is related to the velocity of electromagnetic waves in free speace (c) by the equation:

$$v = c/n$$

where n is the refractive index of the medium, in this case, the atmosphere. Corrections to take these into account are published by the authorities concerned with producing the Loran charts or are sometimes incorporated in the chart itself. Variations in these corrections put an ultimate limit on the accuracy of the system.

Though for higher precision, ground waves have to be used, over considerable areas, sky waves may have to be used. This would introduce errors because of the delay increase consequent on the increased path length. These can be corrected by the published estimated delays.

The Loran–C transmitters transmit pulses of long duration but of accurately controlled envelope, which is so designed that 99% of the energy is contained within the band 90–110 kHz. The pulse repetition frequency is locked to the carrier frequency of 100 kHz so that all the pulses are of exactly the same shape in envelope and carrier. One such pulse is shown in Fig. 4.8(a).

The peak power is 1 MW. The transmissions actually consist of a succession of pulses, eight in number for the slave stations and nine in the case of the master station, as shown in Fig. 4.8(b). These pulses are stored and combined in the receiver to improve the signal/noise ratio. The ninth pulse transmitted by the master station is used for coding to indicate malfunction in any station.

To measure the time delay, a special technique is used, whereby a null is obtained at the peak of the third pulse. Thereby, the initial pulses which may be corrupted by noise are avoided. For details, see Ref. 32.

Loran–C has a range of 3500 km over sea and 2200 km over land.

4.5 THE DECCA NAVIGATION SYSTEM

The Decca system operates in LF band (between 70 and 120 kHz) and employs unmodulated continuous waves. The measurement of the time difference in the reception of signals from two stations, which fixes the position on a hyperbola, is accomplished by measuring the phase

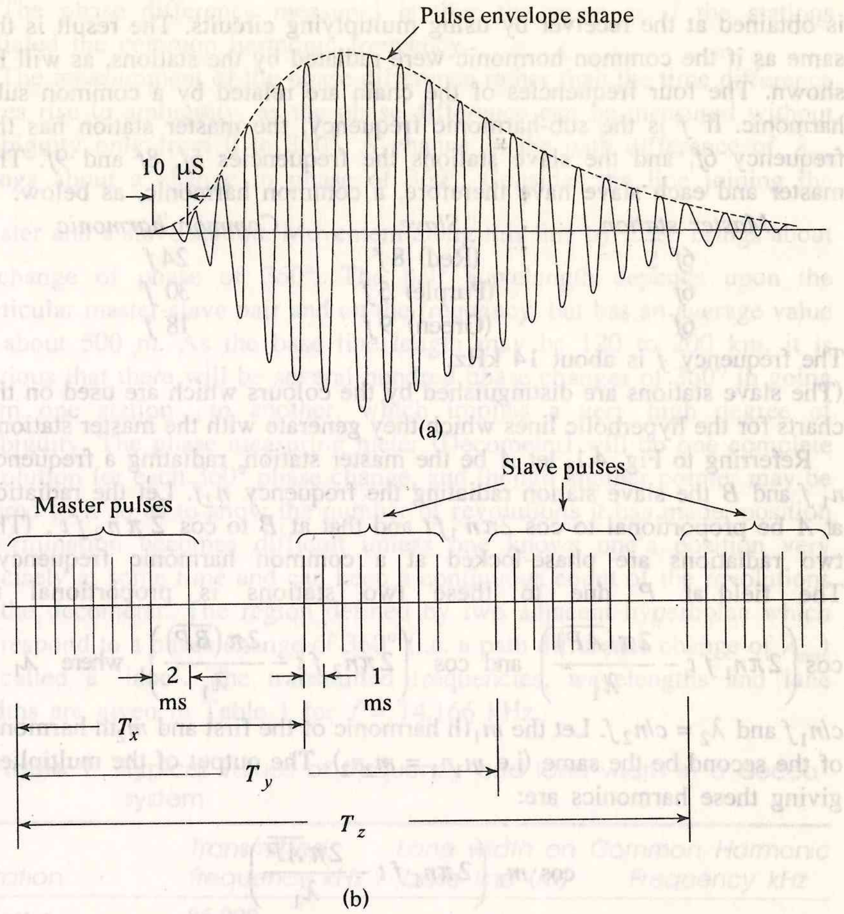


Fig. 4.8 Loran-C Pulses
(a) Shape of a single pulse
(b) Pulse groups transmitted. Each pulse is shown as a single line. T_x, T_y and T_z are the 'absolute delays' of the slave stations

difference between the signals of the two stations, the radiations of which are phase-locked, instead of the time interval between pulses, as in Loran. A decca chain consists of four stations, a master and three slaves, the latter being at the corners of a triangle and the former at the centre. These give three sets of hyperbolic position lines, one set corresponding to the master and each slave. Fix is obtained over a considerable area by the intersection of two hyperbolic lines.

If all the stations in a decca chain had the same frequency, their radiations will be indistinguishable at the receiver and the measurement of phase difference becomes impossible. This difficulty is avoided by radiating harmonically related frequencies from the four stations and making the phase measurements at a common harmonic frequency which is obtained at the receiver by using multiplying circuits. The result is the same as if the common hormonic were radiated by the stations, as will be shown. The four frequencies of the chain are related by a common sub-harmonic. If f is the sub-harmonic frequency, the master station has the frequency $6f$, and the slave stations the frequencies $5f$, $8f$ and $9f$. The master and each slave have therefore, a common harmonic, as below.

Master station	*Slave*	*Common harmonic*
$6f$	(Red) $8f$	$24f$
$6f$	(Purple) $5f$	$30f$
$6f$	(Green) $9f$	$18f$

The frequency f is about 14 kHz.

(The slave stations are distinguished by the colours which are used on the charts for the hyperbolic lines which they generate with the master station.)

Referring to Fig. 4.1, let A be the master station, radiating a frequency $n_1 f$ and B the slave station radiating the frequency $n_2 f$. Let the radiation at A be proportional to $\cos 2\pi n_1 f t$ and that at B to $\cos 2\pi n_2 f t$. (The two radiations are phase-locked at a common harmonic frequency.) The field at P due to these two stations is proportional to $\cos\left(2\pi n_1 f t - \frac{2\pi(\overline{AP})}{\lambda_1}\right)$ and $\cos\left(2\pi n_2 f t - \frac{2\pi(\overline{BP})}{\lambda_1}\right)$, where $\lambda_1 = c/n_1 f$ and $\lambda_2 = c/n_2 f$. Let the m_1th harmonic of the first and m_2th harmonic of the second be the same (i.e $m_1 n_1 = m_2 n_2$). The output of the multipliers giving these harmonics are:

$$\cos m_1\left(2\pi n_1 f t - \frac{2\pi\overline{AP}}{\lambda_1}\right)$$

and
$$\cos m_2\left(2\pi n_2 f t - \frac{2\pi\overline{BP}}{\lambda_2}\right)$$

The phase difference between these two outputs is:

$$\frac{2\pi m_1 \overline{AP}}{\lambda_1} - \frac{2\pi m_2 \overline{BP}}{\lambda_2}$$

$$= \frac{2\pi m_1 n_1 f \overline{AP}}{c} - \frac{2\pi m_2 n_2 f \overline{BP}}{c}$$

$$= \frac{2\pi \overline{AP}}{c/m_1 n_1 f} - \frac{2\pi Bp}{c/m_2 n_2 f} = \frac{2\pi}{\lambda_{mn}}(\overline{AP} - \overline{BP})$$

where $\lambda_{mn} = \frac{c}{m_1 n_1 f} = \frac{c}{m_2 n_2 f} =$ wavelength of the common harmonic frequency.

The phase difference measured is thus the same as if the stations radiated the common harmonic frequency.

The measurement of the phase difference rather than the time difference gives rise to ambiguity, as the phase difference can be measured without ambiguity only from 0 to 360°. A change in the path difference of λ_{mn} brings about a change in phase of 360°. Consider the line joining the master and a slave station. Movement along this line by $\frac{\lambda_{mn}}{2}$ brings about a change of phase of 360°. The half wavelength depends upon the particular master-slave pair and on the frequency, but has an average value of about 500 m. As the base line length may be 120 to 200 km, it is obvious that there will be several hundred phase changes of 360° in going from one station to another, which implies a very high degree of ambiguity. The phase measuring meter (Decometer) will do one complete revolution for each 360° phase change, and though another pointer may be geared to it so as to show the number of revolutions it has made, position determination becomes difficult unless one knows one's position very precisely at some time and can keep a continuous count of the revolutions of the decometer. The region defined by two adjacent hyperbolae which correspond to a phase change of 360° (i.e. a path difference change of λ_{mn}) is called a 'lane'. The transmitted frequencies, wavelengths and lane widths are given in Table 1 for f = 14.166 kHz.

Table 1 Typical values of frequency and lane width in a decca system

Station	*Transmitted frequency kHz*	*Lane width on base line (m)*	*Common Harmonic Frequency kHz*
Master	85.000 (λ = 3521 m)	—	—
Red slave	113.333 (λ = 2640 m)	440.074	340.00
Green slave	127.500 (λ = 2347 m)	586.765	255.00
Purple slave	70.833 (λ = 4275 m)	552.059	425.00

To reduce the ambiguity, the decca system employs a means of 'Lane identification'. This is done, in effect by measuring the phase difference between the signals from the stations and the frequency f ($\approx$ 14.0 kHz). The hyperbolae defined by this are more widely spaced and on a base line, the distance between adjacent hyperbolae (corresponding to a phase change of 360°) is a half wavelength at the frequency f, i.e. about 10.5 km. The region between two adjacent hyperbolae is called a 'zone'. Each zone comprises a number of lanes. The number of lanes per zone, clearly, is ratios are 24 (red), 18 (green) and 30 (purple). If the phase measurement is accurate to a hundredth of 360°, then the measurement of phase difference at *f* fixes the position within a fraction of the lane and so the particular lane within the zone can be determined with little probability of error. If one knows the position of the craft within about 5 km, then one can find the zone and the lane within the zone in which the craft is located. It must be realized, however, that even the zone may not be known with sufficient certainty, particularly in air navigation. A system of 'zone identification' has been introduced in the Mark *X* receiver and will be described later. Lane identification is called 'coarse fixing' and the determination of line of position within a lane is called 'fine fixing'.

The 14 kHz signal required for lane identification is provided by transmitting simultaneously from the master station the frequencies $6f$ and $5f$, and from each of the slaves in turn the frequencies $8f$ and $9f$. This is illustrated in Fig. 4.9. The lane identification signals are sent for short intervals thrice every minute, each time the master and one of the slaves making simultaneous transmissions. These transmissions are preceded by slight changes in the master carrier frequency which actuates certain circuits in the receiver and changes its configuration from that required for fine fixing to that required for lane identification. The sequence is as follows. At the beginning of each full minute, the normal transmissions are interrupted and the master station transmits $6f$–60 Hz, for 1/12 sec. This initiates the red lane identification cycle. Then the master station transmits $6f$ and $5f$ and the red slave transmits $8f$ and $9f$, for half a second. After this, normal transmission is resumed. At the beginning of the 16th sec. the green lane identification is similarly initiated, the master station in this case transmitting $6f$ + 60 Hz and the green slave transmitting $8f$ and $9f$ during this period. The normal transmission is then resumed and interrupted at the beginning of the 30th sec. for purple lane identification. The master station transmits $6f$ + 60 Hz and $6f$–60Hz for 1/2 sec. followed by $6f$ + 60 Hz for 1/25 sec. Then the purple lane identification follows for half a second. After this, for the rest of the complete minute, normal transmission is continued.

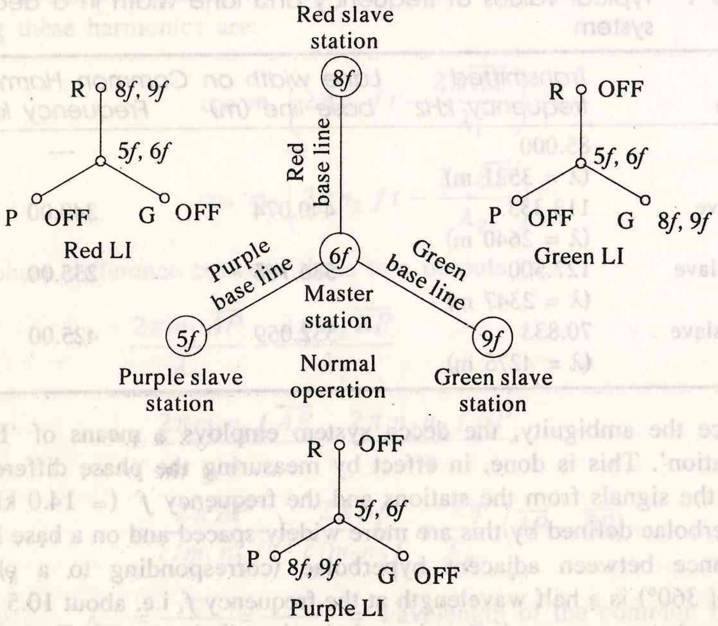


Fig. 4.9 A decca chain [normal transmission and lane-identification (LI) transmission are shown]

4.6 DECCA RECEIVERS

The block diagram of the decca receiver is shown in Figs 4.10(a) and (b). In Fig 4.10(a), the receiver is in the configuration required for fine fixing. The four frequencies received are separated by crystal filters, amplified, and applied to frequency multipliers. The appropriate outputs of the multipliers are given to the discriminators, the outputs of which are applied to the decometers. These meters indicate the phase difference between the two inputs to the discriminator and thus the position within the lane. Their rotors are geared to indicators which give lane and zone also, which, of course, have to be set initially to the correct figure. In Fig. 4.10(b), the receiver is shown in the configuration for lane identification. The master frequencies $5f$ and $6f$, and the slave frequencies $8f$ and $9f$ are amplified, and the two difference frequencies obtained from mixer are applied to a discriminator and the output of the discriminator is applied to a decometer called the 'sector pointer'. This meter by itself could indicate the lane if it is sufficiently accurate, but to increase the accuracy, a $6f$ signal is extracted and applied to a second decometer. If fed straight to a decometer movement, this would give 6 rotations per zone and, therefore, 6 fold ambiguity. To resolve this, the 'vernier' movement is geared down in the ratio 1 : 6 and drives a 6-arm pointer. The sector pointer is mounted concentrically with the vernier and indicates which of the six pointers gives the correct lane. The width of the sector is made less than $\pi/3$, so that only one arm of the 6-arm pointer can be within it.

The block diagrams given in Fig. 4.10 pertain to the Mark V receiver which is used mainly in marine navigation. The accuracy which can be obtained with it is very high. It is not very suitable for use in aircraft, however, as they move too fast to utilize the accuracy to the full, and there is also the risk that lane integration may be lost. So a different receiver (Mark VII) has been designed for aircraft use, which obtains a coarser grid by making phase comparison at the frequencies of the slave stations, viz. $5f$, $8f$ and $9f$. To achieve this, the master station frequency is first reduced to f and then multiplied by 5, 8 and 9 respectively for comparison

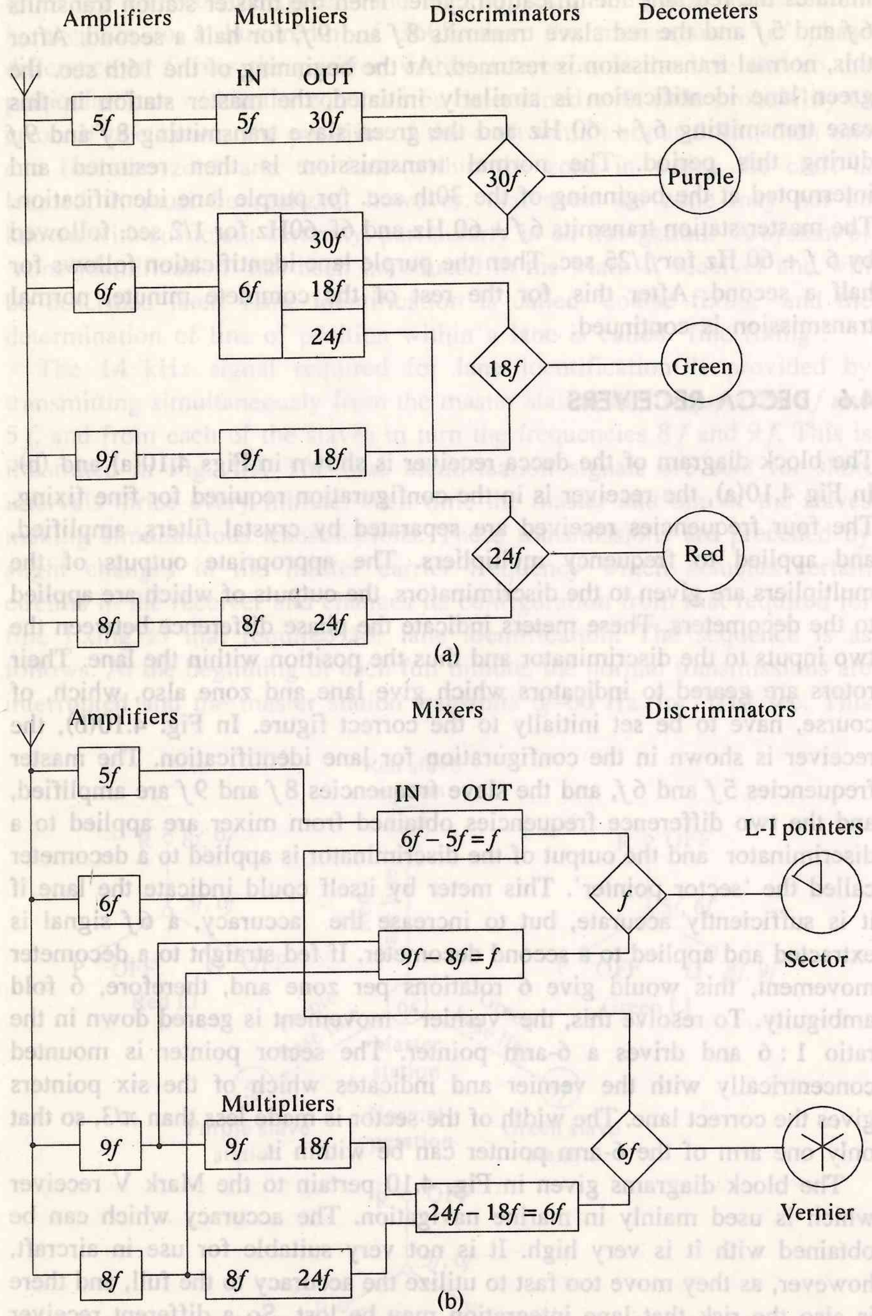


Fig. 4.10 Decca receiver configuration [(a) fine fixing, (b) lane identification]

with the transmission of purple, red and green slaves. Thereby, the corresponding lanes become wider by factors of 6, 3 and 2 respectively.

The Mark X receiver, to which reference has been made, was developed to overcome two of the drawbacks of the other types of receivers which are met with in air navigation applications. The first of these, as mentioned earlier is the zone ambiguity. The second one relates to the difficulties experienced in lane identification at night over fairly long ranges. Multipath reception tends to introduce random phase-shifts which bring about fluctuations in the phase-meter indications. The effect of this on lane identification can be such as to give wrong lane indications. Both these drawbacks are overcome in Mark X receiver by employing special types of lane identification and zone identification signals. During the lane identification period, all the four frequencies $5f$, $6f$, $8f$, $9f$, are momentarily radiated first by the master and then from the slaves. The received signals are brought to the same amplitude and added up in the receiver. This results in the formation of a train of pulses with recurrence frequency f (Fig. 4.11). The peak of this pulse, it has been shown[18], retains its correct

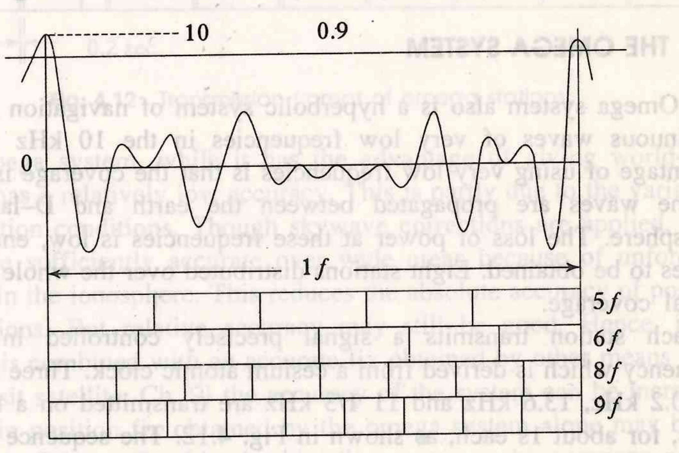


Fig. 4.11 Combined signals of 5 f, 6 f, 8 f and 9 f in Mark-X receiver

time relation even when there is a considerable phase shift of the components. This pulse train is, therefore, made the basis of the lane identification scheme. It is made to control phase-locked sinusoidal oscillators which 'remember' the phase information from each station in turn and facilitate comparison of the phases at the frequency f. To enable zone identification, a transmission on the frequency $8.2f$ is made along with the lane identification signal. This combines with the $8f$ signal in the receiver and the difference frequency $0.2f$ is used to synchronize an oscillator of that frequency. The two signals derived from the master and slave stations are applied to a phase-measuring circuit to obtain the particular zone. The ambiguity is reduced by a factor of five by this means.

Air navigation has also necessitated automatic pictorial presentation of the position of the aircraft on a chart. Several models of 'flight-logs' have been developed to meet this requirement. Flight logs are automatic plotting principles are described in literature,[19] and will not be dealt with here. In the flight log, the hyperbolic grid is transformed to a square one to simplify instrumentation of the recorder and, therefore, special distorted maps have to be used with them.

4.7 RANGE AND ACCURACY OF DECCA

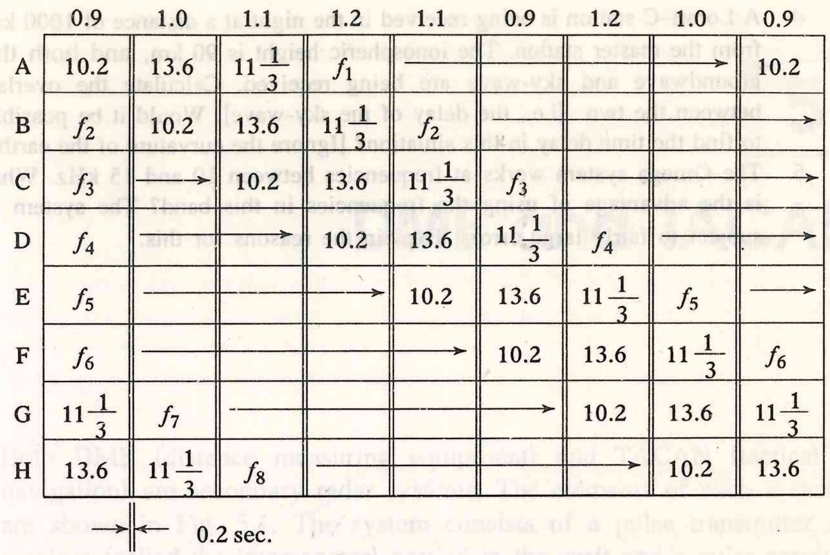
The range of a Decca chain can be stated only when the probable error of location (circle of uncertainty) is specified. It also depends upon the distance between the master and the slave, the ground conductivity, etc. Ref. 14 may be seen for details. To quote one figure, for a radial error of 100 m, the range is about 300 km when the distance between the master and slave is 200 km. The instrumental errors in Decca are very small but variations of effective base line length, phase deviations introduced by skywave, etc. contribute the greater part of the error at long distances.

4.8 THE OMEGA SYSTEM

The Omega system also is a hyperbolic system of navigation which uses continuous waves of very low frequencies in the 10 kHz range. The advantage of using very low frequencies is that the coverage is increased, as the waves are propagated between the earth and D–layer of the ionosphere. The loss of power at these frequencies is low, enabling long ranges to be obtained. Eight stations distributed over the whole world give global coverage.

Each station transmits a signal precisely controlled in time and frequency which is derived from a cesium atomic clock. Three frequencies of 10.2 kHz, 13.6 kHz and 11 1/3 kHz are transmitted on a time-shared basis, for about 1s each, as shown in Fig. 4.12. The sequence is repeated every ten seconds, and in the time not utilized for these transmissions, each station transmits a characteristic frequency of its own, indicated by f_1, f_2 etc. in the above figure. At any time, there is never more than one station transmitting at 10.2, 13.6 or 11 1/3 kHz. To determine the line of position, each Omega station can be paired with any other Omega station. There are no masters and slaves. All the stations constitute one chain.

The receivers are equipped with "flywheel oscillators" which lock on to the phase of the received signal and thus "remember" the phase of the signal till the next transmission at that frequency. Thus at any time, the phase of the received signal at these frequencies is available and the measurement of phase difference between the signals at any of these frequencies from two stations can be made though they are not transmitting at that time. This measurement gives the position of the receiver within a lane formed by the two stations. Lane identification is accomplished by phase comparison at the difference frequency of 3.4 kHz (13.6–10.2). This gives a coarse pattern like zones in the Decca system. Each zone has three



	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0	0.9
A	10.2	13.6	$11\frac{1}{3}$	f_1	→	→	→	→	10.2
B	f_2	10.2	13.6	$11\frac{1}{3}$	f_2	→	→	→	→
C	f_3	→	10.2	13.6	$11\frac{1}{3}$	f_3	→	→	→
D	f_4	→	→	10.2	13.6	$11\frac{1}{3}$	f_4	→	→
E	f_5	→	→	→	10.2	13.6	$11\frac{1}{3}$	f_5	→
F	f_6	→	→	→	→	10.2	13.6	$11\frac{1}{3}$	f_6
G	$11\frac{1}{3}$	f_7	→	→	→	→	10.2	13.6	$11\frac{1}{3}$
H	13.6	$11\frac{1}{3}$	f_8	→	→	→	→	10.2	13.6

Fig. 4.12 Transmission fromat of omega stations

The Omega system, while it has the advantage of giving world-wide coverage, has a relatively low accuracy. This is partly due to the variations in propagation conditions. Though skywave corrections are applied, these may not be sufficiently accurate over wide areas because of unforeseen variations in the ionosphere. This reduces the absolute accuracy of position determinations. But relative accuracy may still be good. Hence, if the omega fix is combined with an accurate fix obtained by other means (such as the transit satellite, Ch. 9) the accuracy of the system can be increased. The error in position fix obtained by the omega system alone may be as high as 6 to 7 kms. Combined with other systems, the accuracy can be much better.

QUESTIONS AND PROBLEMS

1. Two Loran-A stations, as shown in Fig. 4.1, are 200 km apart and an aircraft is 300 km from *A* [the master] and 200 km from *B* [the slave]. The prf is 20 pulses/s. The coding delay is 1333 μs. What is the interval that elapses between the reception of a pulse from *A* and the next pulse from *B*?
2. Discuss the merits of the frequency band or around 100 kHz for navigational aids with reference to (a) investment in antennas, (b) propagation characteristics, (c) ground wave and sky-wave signals, and (d) signal/noise ratio.
3. The Decca Mark VII receiver employs phase comparison at frequencies $5f$, $8f$ and $9f$. Draw a possible block diagram of the receiver on the lines of the receiver configuration for fine-fixing shown in Fig. 4.10(a).

4. A Loran–C station is being received in the night at a distance of 1000 km from the master station. The ionospheric height is 90 km, and both the groundwave and sky-wave are being received. Calculate the overlap between the two [i.e., the delay of the sky-wave]. Would it be possible to find the time delay in this situation? [Ignore the curvature of the earth].
5. The Omega system works at frequencies between 10 and 15 kHz. What is the advantage of using the frequencies in this band? The system is subject to fairly large errors. Explain the reasons for this.

5

DME and TACAN

Both DME (distance measuring equipment) and TACAN (tactical air navigation) are secondary radar systems. The elements of such a system are shown in Fig. 5.1. The system consists of a pulse transmitter and receiver (called the interrogator) carried in the craft and a pulse receiver-transmitter system (called the transponder) at a fixed position on the ground. The interrogator transmits *rf* pulses periodically at a frequency, say f_1. These are received by the receiver of the transponder, amplified, demodulated and made to trigger the transmitter, generally after a small fixed delay. The frequency of the transmitter, say f_2, is different from that of the receiver. In the craft, the receiver, which is tuned to f_2, receives these pulses and the delay between the transmitted and received pulses is measured to obtain the distance of the transponder from the craft. Both DME and TACAN work on this principle but a number of refinements are introduced to overcome some of the limitations of the basic system.

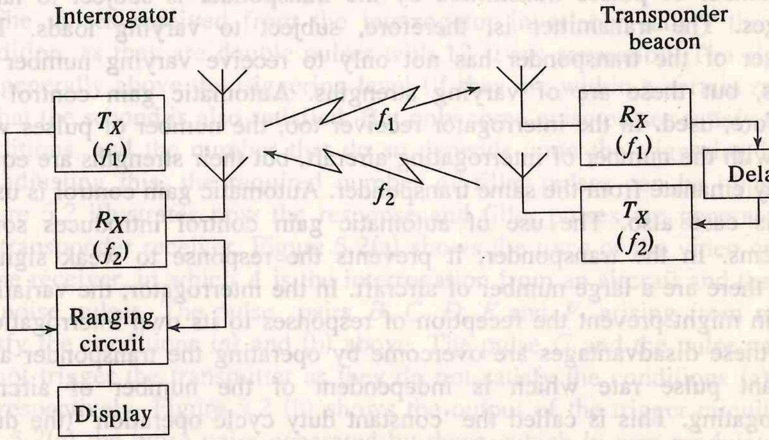


Fig. 5.1 Components of a secondary radar

The DME and TACAN were developed at about the same time. The aircraft. The latter was developed for the American Defence Services and was made public in 1955. While the DME provides only distance information, TACAN provides both distance and bearing (Rho-theta) with the same radiation. Civil aviation DME stations are usually supplemented by a VOR station at the same location, so that the two together provide rho-theta information for a suitably equipped aircraft. The frequencies of these two facilities are, however, in different frequency bands in contrast to the TACAN. The DME described here is identical in operation to the distance-measuring part of TACAN. (This is sometimes referred to as DME-T). Any aircraft equipped with DME equipment can make use of the range facility of TACAN and vice versa. We will first describe the DME and later show how the equipment is modified to provide bearing as in TACAN.

5.1 DISTANCE MEASURING EQUIPMENT

Before going into the details of the refinements in the DME, some of the problems of the simple secondary radar (Fig. 5.1) must be appreciated. One of the features of the pulsed secondary radar is that a number of aircraft can interrogate the transponder in the same channel (i.e. at frequency f_1). This is possible because the pulse repetition frequencies of the aircraft are not exactly equal, and each aircraft can isolate the responses to its own interrogation by using a timebase triggered by its own transmitted pulse. The responses of the transponder to other aircraft interrogations then appear as pulses rapidly moving on its time base and can be easily discriminated both by a human observer and by an automatic tracking system. However, this simultaneous interrogation creates some problems. As the number of aircraft interrogating is subject to variation, the number of pulses transmitted by the transponder is subject to large changes. The transmitter is, therefore, subject to varying loads. The receiver of the transponder has not only to receive varying number of pulses, but these are of varying strengths. Automatic gain control is, therefore, used. In the interrogator receiver too, the number of pulses will vary with the number of interrogating aircraft, but their strengths are equal as they emanate from the same transponder. Automatic gain control is used in this case also. The use of automatic gain control introduces some problems. In the transponder, it prevents the response to weak signals when there are a large number of aircraft. In the interrogator, the variation of gain might prevent the reception of responses to its own interrogation. Both these disadvantages are overcome by operating the transponder at a constant pulse rate which is independent of the number of aircraft interrogating. This is called the 'constant duty cycle operation' (the duty cycle is the fraction of the time that the transmitter is on) .

Another drawback in the simple system is that when very few aircraft are interrogating, the gain of the receiver in the transponder goes up and

In the DME, constant duty cycle operation is achieved by making the noise pulses trigger the transponder transmitter at a constant rate. When interrogations are received, these replace the noise pulses and keep the duty ratio constant. With the maximum number of aircraft interrogating, the gain of the receiver is reduced slightly so that the only pulses transmitted are the responses to interrogation. It requires only a small change of receiver gain to bring this about.

5.2 OPERATION OF DME

5.2.1 DME Transmissions

The DME interrogator operates in the band 1025–1150 MHz with 126 channels spaced 1 MHz apart. The transponder operates in the band 962–1213 MHz. For each channel, a pair of frequencies (f_1 and f_2) which differ by 63 MHz are allotted. The frequency of 63 MHz is used as the intermediate frequency in the receivers.

Both the interrogator and transponder operate with pulse pairs consisting of two pulses 12 μ sec apart. The reason for using pulse pairs instead of single pulses is that thereby, the probability of the transponder triggering to spurious noise pulses is reduced. The gain of the receiver may, therefore, be maintained at a high level. The pulse rate in the transponder is about 3000 pulse pairs per second. This rate is kept constant, as explained above, so that noise pulse-pairs trigger the transmitter in the absence of interrogation pulses. These additional noise-actuated pulses are called 'filler pulses'. In order that pulses trigger the transponder transmitter, they should satisfy two conditions, viz. (a) two pulses must be received 12 μ sec apart, and (b) both pulses must have amplitude exceed- ing the triggering level.

The pulses received from the interrogator invariably satisfy the first condition, as they are double pulses with 12 μ sec separation. The signals are generally above the triggering level (if they are within a certain range) so that the second is also satisfied. But only some noise pulses satisfy these conditions, and the number that do so depends upon the triggering level. By adjusting this, the required number of filler pulses can be obtained. Figure 5.2 illustrates how the response and filler pulses are generated in the transponder receiver. Figure 5.2(a) shows the trace of the video output of the receiver, in which *A* is the interrogation from an aircraft and the rest are noise pulses. The pulse pairs *B*, *C*, *D*, *E* and *F*, arising from noise, satisfy the conditions (a) and (b) above. The pulse *G* and the pulse pair *H* do not trigger the transmitter as they do not satisfy the conditions (a) and (b) respectively. Figure 5.2 (b) shows the output of the trigger circuit and Fig. 5.2(c) the pulse pairs generated by these, which in turn modulate the transmitter. These pulse pairs have the required 12 μ sec separation and each pulse is of 3.5 μ sec duration. The noise-generated pulses are

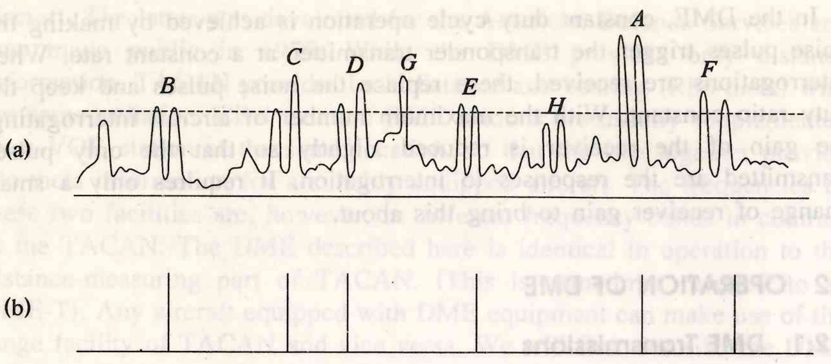


Fig. 5.2 Generation of response and filler pulses in the transponder receiver [(a) receiver ouput, (b) single pulses generated by pulse-pairs), (c) pulse-pairs generated by these]

5.2.2 Air-borne DME Interrogator

The block diagram of the interrogator is shown in Fig. 5.3. The transmitter rf chain consists of a crystal oscillator giving one of 126 frequencies around 45 MHz, a frequency multiplier and a power amplifier. The output power ranges from 50 W to 1 kW depending on the type of equipment. The power amplifier is modulated by a pulse modulator which is timed by wave-forms obtained from the ranging circuit. A common antenna is used for the receiver and transmitter. The transmitted energy is prevented from getting into the receiver by selective elements in the transmission line which act as wave-traps for the transmitter frequency. A part of the oscillator output is mixed with the incoming signal and because of the 63 MHz separation between the transmitted and received frequencies, an intermediate frequency of 63 MHz is generated. This is amplified, demodulated and applied to the ranging circuit. This circuit tracks the received signal and converts the delay into a distance display.

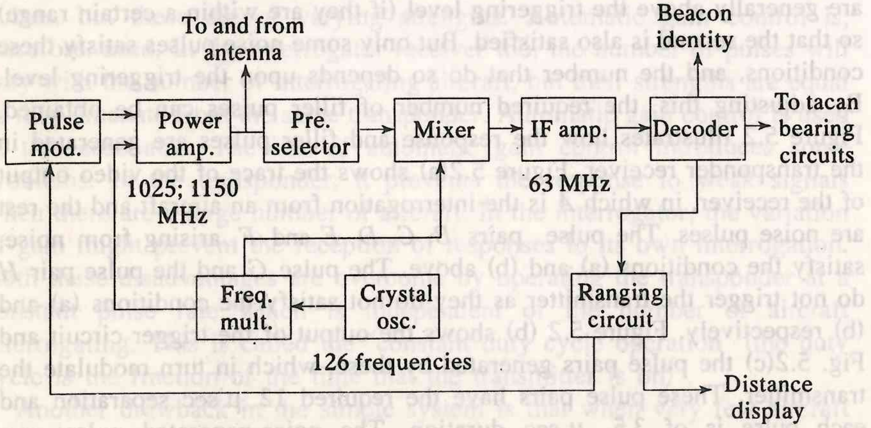


Fig. 5.3 Block diagram of airborn DME interrogator

The receiver has two modes of operation, the search mode and the tracking mode. Initially in the search mode, the transmitter operates at a pulse repetition frequency of 150 pulses/sec. The waveforms of the tracking circuit are shown in Fig. 5.4 which shows the transmitter pulse (a), the variable delay (b), and the gate wave-form (c). The output of the demodulator (video pulse pairs) is shown in (d) and the single pulse generated from them in (e). The operation of the tracking circuit is as follows. The transmitter pulses trigger a delay circuit which in turn triggers the short duration (20 μsec) gate pulse generator. The delay is variable and is increased gradually from zero to a maximum of about 2400 μsec by a motor driven potentiometer, thereby moving the gating pulse from left to right. This search may take about 20 sec. The output pulse pairs of the receiver are converted to single pulses and applied to a circuit which is gated by the wave-form shown in Fig. 5.4(c). As the gating pulse moves to the right, it allows the pulses which coincide with it in time to pass into a counter circuit. As long as these pulses are unsynchronized squitter pulses, the number of them passing the gate in a given time is small. This number can be calculated as follows. As there are 150 gate periods per second, each of 20 μsec duration, the gate is open for

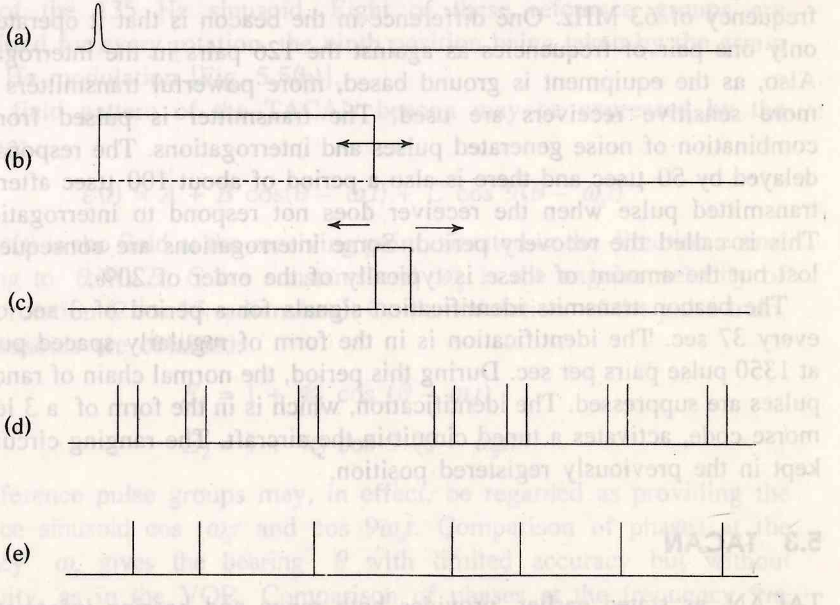


Fig. 5.4 Waveforms of the tracking circuit

a total period of 3000 µsec/sec. On the average there are 3000 pulses/sec received from the beacon and so in 3000 µsec about 9 pulses are received. On the other hand, as the gate pulse passes the relatively stationary response pulses, the rate increases suddenly. To calculate this, we have to assume a search rate. Taking this as 100 µsec/sec (i.e. approximately 10 miles per sec in range), the gate pulse takes 20/100 or 1/5 second to pass a distance equal to its width. In this time, 30 pulses of the response appear in the gate. This sudden increase in the number of pulses (from 9 to 30) actuates circuits which terminate the search mode and put the receiver in the track mode. The pulse repetition frequency of the interrogator is then reduced to about 25 pulses/sec and the 20 µsec gate follows the desired response. If the reply falls in the early part of the gate, it advances. If it falls in the later part, the gate is delayed. A low interrogation rate is possible in the track mode since the possible change in the position of the aircraft is quite small in one interpulse period.

The position of the aircraft, indicated by the delay of the gating pulse is displayed either in analog or digital form. Accuracies of 150 m are commonly achieved. The air-borne equipment is nowadays transistorized except for the transmitter-amplifier chain. Radiation is from vertical quarter-wave stubs (about 8 cm long) projecting from the belly of the aircraft.

5.2.3 DME Beacon

The beacon equipment has the same principal components as the interrogator and has a transmitter and a receiver with an intermediate frequency of 63 MHz. One difference in the beacon is that it operates at only one pair of frequencies as against the 126 pairs in the interrogator. Also, as the equipment is ground based, more powerful transmitters and more sensitive receivers are used. The transmitter is pulsed from a combination of noise generated pulses and interrogations. The response is delayed by 50 µsec and there is also a period of about 100 µsec after the transmitted pulse when the receiver does not respond to interrogations. This is called the recovery period. Some interrogations are consequently lost but the amount of these is typically of the order of 20%.

The beacon transmits identification signals for a period of 3 sec once every 37 sec. The identification is in the form of regularly spaced pulses at 1350 pulse pairs per sec. During this period, the normal chain of random pulses are suppressed. The identification, which is in the form of a 3 letter morse code, activates a tuned circuit in the aircraft. The ranging circuit is kept in the previously registered position.

5.3 TACAN

TACAN, as stated earlier, provides both range and bearing information with the same radiation. The operation is conveniently divided into the

range facility and the bearing facility. The operation of the range facility is precisely the same as in DME. The bearing information is provided by a method which is similar in principle to that used in the VOR. The antenna radiation has a cardioid polar diagram which is made to rotate at 15 rev/sec and provides a variable phase signal in the form of amplitude modulation of the pulse train. In the place of the reference sinusoid employed in the VOR, a distinctive group of pulses is radiated every time the maximum of the cardioid passes East (90°). This pulse group is a precisely regulated one, consisting of 12 pulses, each a 12 µsec twin, spaced exactly 30 µsec apart. A special pulse group decoder separates this in the air-borne equipment. The delay between a chosen datum point (say, the zero-crossing) of the variable phase signal and the marker pulse is computed and displayed in a bearing indicator.

The accuracy obtainable by this method is insufficient for the precision aimed at in TACAN, and a special technique is used to increase the accuracy. A nine-lobe pattern is superposed on the cardioid, making the combined radiation pattern appear as in Fig. 5.5 (a). This pattern has a fixed phase relation to the cardioid, one maximum of the nine lobe pattern coinciding with the maximum of the cardioid. The rotation of this antenna pattern at 15 rev/sec gives a signal which has a modulation of 15 Hz and 135 Hz. Phase comparison is made at both the frequencies, and as will be shown below, phase comparison at 135 Hz increases the accuracy ninefold. As a reference for phase comparison at 135 Hz, a group of pulses consisting of six 12 µsec twins with a spacing of 24 µsec is radiated at the zeros of the 135 Hz sinusoid. Eight of these reference groups are transmitted for every rotation, the ninth position being taken by the group for 15 Hz modulation [Fig. 5.5(b)].

The field pattern of the TACAN beacon may be expressed by the equation:

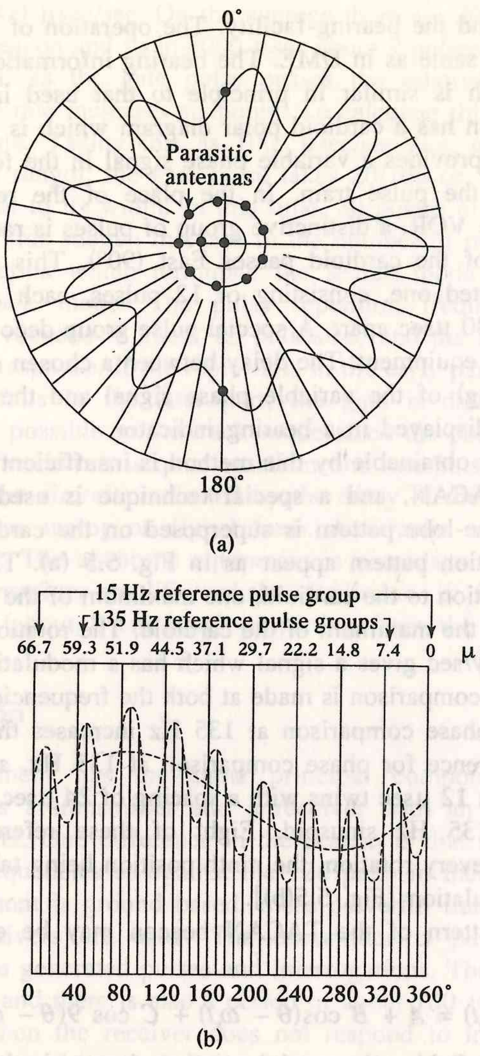
$$\varepsilon(t) = A + B\cos(\theta - \omega_s t) + C\cos 9(\theta - \omega_s t)$$

where $\varepsilon(t)$ is the field at the receiving point, situated in the direction corresponding to θ; A, B, C are constants and ω_s is the angular velocity of pattern rotation ($2\pi \times 15$ radians/sec). On demodulation of the pulse train, two sinusoids are obtained:

$$E_1 = 1 + \mathcal{K}_1 \cos(\theta - \omega_s t)$$

and $$E_2 = 1 + \mathcal{K}_2 \cos 9(\theta - \omega_s t)$$

The reference pulse groups may, in effect, be regarded as providing the reference sinusoid cos $\omega_s t$ and cos $9\omega_s t$. Comparison of phases at the frequency ω_s gives the bearing θ with limited accuracy but without ambiguity, as in the VOR. Comparison of phases at the frequency $9\omega_s$



(a)

(b)

Fig. 5.5 TACAN radiation pattern [(a) polar diagram, (b) pulse sequence at the receiver]

would give the phase angle 9θ, but as phase measuring devices do not measure angles greater than 2π without ambiguity, direct computation of θ from this phase measurement is not possible. At the frequency $9\ \omega_s$, there is a phase change of $2\ \pi$ for every $40°(2\pi/9)$ change in the bearing. Let the bearing be expressed as follows:

$$\theta = n\frac{2\pi}{9} + \phi$$

where n is an integer and ϕ an angle less than $2\pi/9$. The phase measurement at $9\omega_s$ gives actually the angle 9ϕ, which has some value between

zero and 2π. If this angle is measured with the same accuracy as the phase of ω_s, the error in 9ϕ is the same as the error in θ and so the error in ϕ is reduced by a factor of 9. The bearing is computed as the sum of an integral multiple of $2\pi/9$ and ϕ, and thus the accuracy is the same as in the measurement of ϕ. This technique also leads to the reduction of site errors. As was stated in Chapter 3 Sec. 3.4(b), site errors are caused by reflections (or re-radiations) from nearby objects. These combine with the direct ray to change the phase of the modulation envelope. But each degree change in the electrical angle (which must necessarily be between 0 and ± 180°) at 135 Hz corresponds to $\frac{1}{9}°$ change in the geographical angle. The error in the geographical angle is, therefore, reduced by a factor of nine. In the receiving equipment, the phase angle measured at 135 Hz is geared down in the ratio 9 : 1 and connected to the bearing indicator which is initially set by phase measurement at 15 Hz. The ability of TACAN to work from poor sites has led to its use on ships.

5.4 TACAN EQUIPMENT

The beacon equipment is similar to the DME except for the provision of the synchronizing pulse groups. The block diagram is shown in Fig. 5.6. The antenna is common to the receiver and transmitter and a duplexer is employed to ensure that the receiver and transmitter are isolated. The duplexers consist of tuned cavities which reject the undesired signal. The antenna of TACAN differs from that of the DME as the equipment has to provide bearing information. The radiator is made up of stack of discone antennas.[13] Around this are two coaxial plastic cylinders in which parasitic elements are embedded. The inner cylinder which has a diameter of about 15 cm has one parasitic element and the outer cylinder of diameter about 90 cm has nine parasitic elements. These modify the horizontal radiation pattern of the antenna (as shown in Fig. 5.5), which would otherwise be circular, by superposing on it two sinusoidal variations, having one cycle and nine cycles respectively. The two cylinders are rotated together at 900 rev/min by a speed controlled motor. The discone radiators have a broadband to accommodate the range of frequencies (960–1215 MHz) employed. The stack of radiators typically gives a vertical polar diagram, which has a maximum at an angle of 5° above the horizon.

A disc of non-ferrous metal is coupled to the rotating cylinders. Embedded in this are two sets of soft-iron slugs, nine in one set and one in the other. As these pass over a magnetic coil system, they give rise to a pulse, which is made to generate the groups of timing pulses from which reference sinusoids are generated in the TACAN receiver. One of these pulse groups which gives a reference for the 15 Hz modulation, is emitted when the maximum of the antenna pattern is pointing East, and consists of

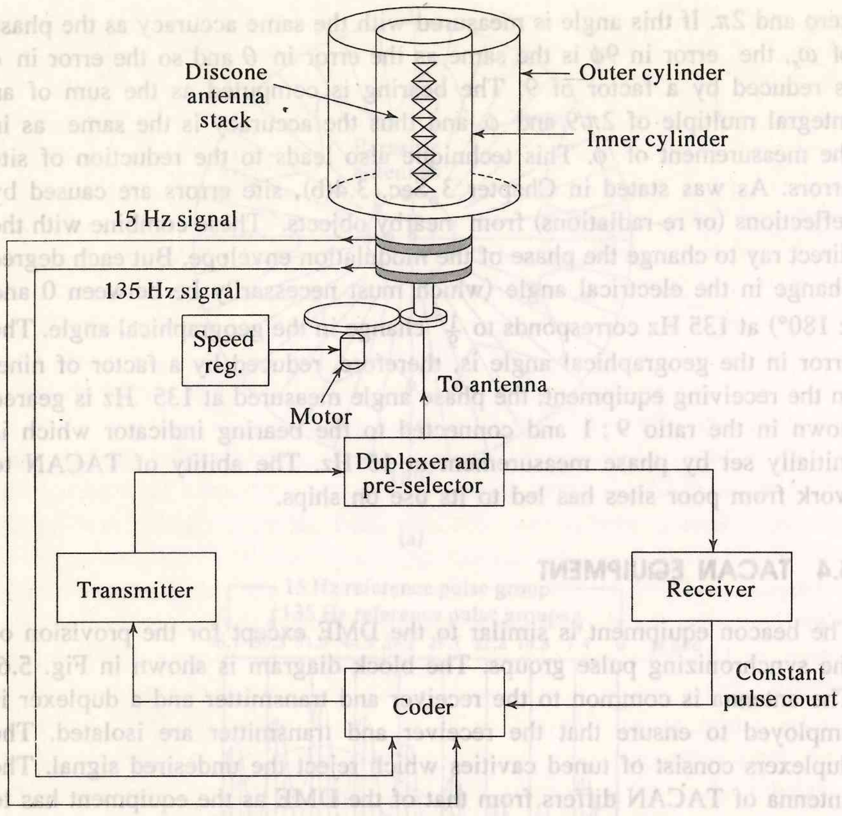


Fig. 5.6 TACAN beacon equipment

24 pulses, the spacing between pulses being aternately 12 and 18 μsec. There is one such group for every revolution. The 135 Hz reference pulse group is emitted eight times per second (the ninth group coincides with 15 Hz reference and is suppressed). These pulse groups consist of 12 pulses spaced 12 μsec apart. When reference pulses are radiated, the normal constant-duty cycle pulses are omitted. Provision is also made for an identity pulse group to be emitted as in DME beacons.

TACAN airborne equipment—This comprises the DME interrogator to which the bearing facility has been added. The block diagram of Fig. 5.3 is, therefore, applicable as far as the range facility is concerned. The output to the bearing circuitry is taken from the decoder. Automatic gain control of the DME receiver must be such as to accommodate a wide variation of the input signal while preserving the amplitude modulation.

The block diagram of the bearing circuit of the receiver is shown in Fig. 5.7. The train of video pulses is applied to peak-riding detector which extracts the envelope of the pulse train consisting of the variable phase 15 Hz and 135 Hz signals. These signals are then separated by filters. The

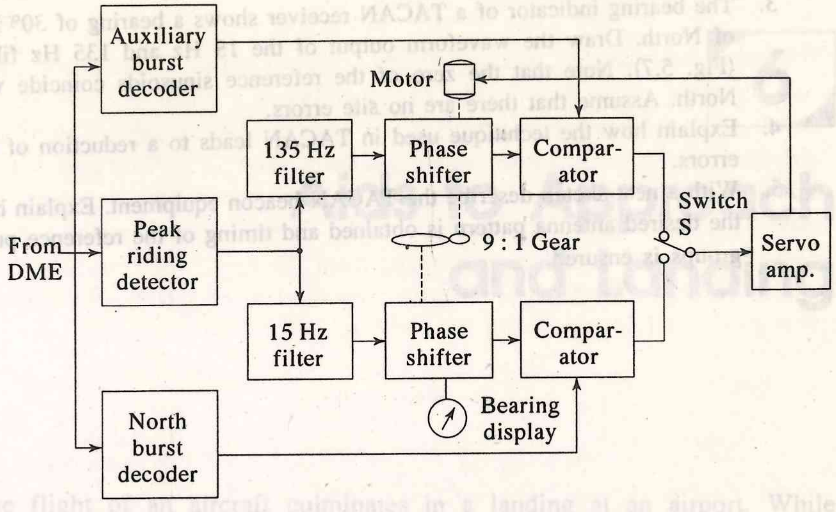


Fig. 5.7 Block diagram of the bearing circuit of TACAN

reference signals are obtained by decoding the reference pulse bursts in the North burst decoder (for 15 Hz reference) and in the auxiliary burst decoder (for the 135 Hz reference). Phase comparison is then effected between the variable and fixed phase signals in a manner which is similar in principle to that employed in the VOR receiver. This function is performed by a servo system which reduces the phase difference between the two signals to zero by servo driven phase-shifter. A single motor drives the two phase shifters, but there is reduction gear of 9 : 1 ratio between the two. The error signal may be obtained either from the 15 Hz loop or the 135 Hz loop. Whenever the 135 Hz signal is present and the phase error is less than ± 20° in the 15 Hz chain, the 135 Hz loop takes over (i.e. the switch S is moved up). If the 135 Hz signal is absent or the phase error in the 15 Hz chain is more than ± 20°, the 15 Hz loop is completed (switch S moves down). By this means, ambiguity (which phase comparison at 135 Hz entails) is eliminated. The bearing is typically displayed on a compass-type indicator. The TACAN receiver, in its modern version is typically transistorized.

QUESTIONS AND PROBLEMS

1. (a) Why are the transmitted and received frequencies different in the interrogator and transponder beacon in DME?
   (b) Suppose 50 aircraft are interrogating a DME beacon and of these, 10 are in search mode. How many response and filler pulses does the beacon transmit per second?
2. Describe the operation of the DME beacon transmitter. The beacon has a delay of 50 μs and a recovery period 100 μs after each transmission. How

3. The bearing indicator of a TACAN receiver shows a bearing of 30° East of North. Draw the waveform output of the 15 Hz and 135 Hz filters (Fig. 5.7). Note that the zero of the reference sinusoids coincide with North. Assume that there are no site errors.
4. Explain how the technique used in TACAN leads to a reduction of site errors.
5. With a neat sketch describe the TACAN beacon equipment. Explain how the desired antenna pattern is obtained and timing of the reference pulse groups is ensured.

6

Aids to Approach and Landing

The flight of an aircraft culminates in a landing at an airport. While approaching the airport, the aircraft takes a path in line with the runway and from a certain distance begins to descend until it touches the ground at a point near the runway threshold. When visibility is good, whether in the day or at night, this operation is carried out by visual observation of the ground and the landing lights, etc. The landing is then performed under 'visual flight rules' (VFR) conditions. Usually this is taken to indicate a horizontal visibility of 5 km or more and vertical visibility or ceiling of 300 m. When these conditions are not satisfied, the landing is under 'instrument flight rules' (IFR) conditions.

Special aids are provided at airports to enable the aircraft to execute landings under bad visibility. Such aids have to provide information to the aircraft about its exact position in relation to a desired path of descent. This implies that information both about any deviation of the position in the vertical and horizontal positions of the aircraft is to be given.

Two types of aids will be dealt with here: the Instrument Landing System (ILS) and the Microwave Landing System (MLS) being the first type, and the Ground Controlled Approach being the second type. (At present, in the first type, only ILS is used in India but is likely to be substituted by MLS in course of time). There is a fundamental operational difference between these two. The former presents the pilot with information about his position in relation to a prescribed approach path, continuously, by an instrument carried in the aircraft. The GCA (or more particularly, its component, the precision approach radar), employs operators on the ground who determine the position of the aircraft and instruct the pilot on the course he is to follow, i.e. they exercise control, through the pilot, on the movement of the aircraft. Clearly, this facility does not require the aircraft to carry any special navigational equipment. Only a communication set, which is required even for other purposes, is

6.1 INSTRUMENT LANDING SYSTEM

The Instrument Landing System (ILS) comprises the units localizers, glide-path (or glide-slope) and marker beacons (Fig. 6.1). The localizer defines a vertical equi-signal plane which passes over the centre line of the runway and the glide-slope, and equi-signal plane inclined to the horizontal at the desired angle of descent, generally between 2° and 4°. The intersection of these two planes gives the approach path. Three marker beacons are also installed at certain specified distances from the end of the runway. They give an indication in the aircraft as it flies over them and thereby help the pilot to check his position in the approach path.

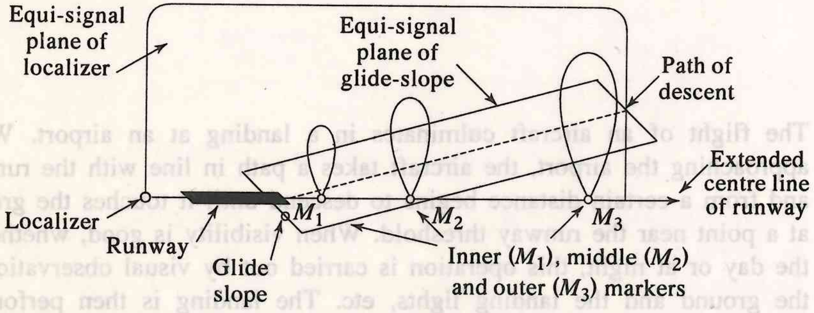


Fig. 6.1 Location of the components of the instrument landing system (ILS) with respect to the runway

(a) The Localizer

The localizer operates in the VHF band (108–110 MHz) and consists of a transmitter with an antenna system, the radiation of which has two lobes, one with a predominant modulation of 90 Hz and the other with a predominant modulation of 150 Hz, as shown in Fig. 6.2 (c). Along the line marked XOX′, the two signals are equal and this equi-signal course is aligned with the centre line of the runway.

The antenna array by means of which this pattern is obtained consists of seven, or sometimes eight, Alford loops, placed on a line at right angles to the extended centre line of the runway and about a 300 m from the end of the runway. These loops make up three arrays, two of the three loops each on either side and the remaining one (or two) in the centre. The former are called side-band loops and the latter the carrier antenna. The carrier, modulated to the same depth by sinusoids of 90 Hz and 150 Hz, is fed to the central antenna, which has a polar diagram as shown in Fig. 6.2 (a). To the other two arrays, only the side-bands of 90 Hz and 150 Hz modulation are supplied. At the same time, the following phase relations of the side-band with respect to those of the central antenna are established and maintained.

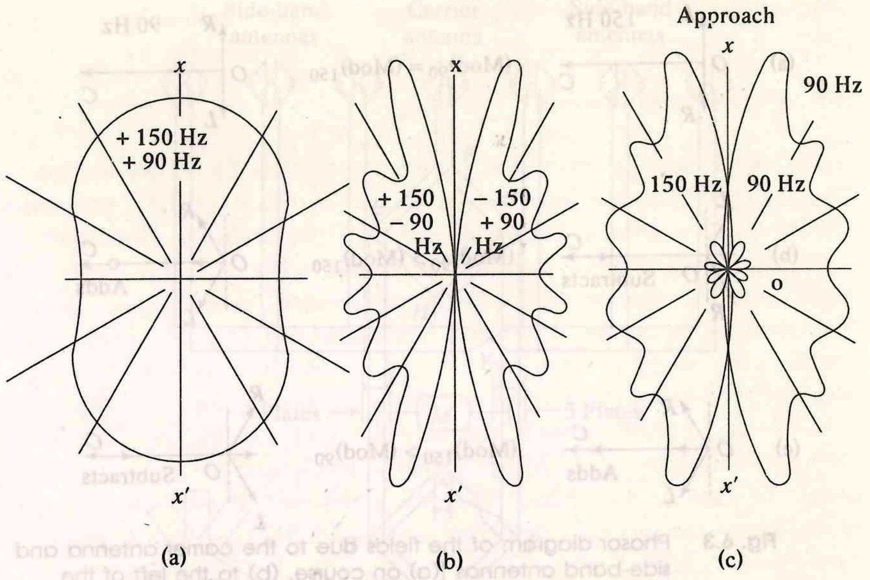


Fig. 6.2 Polar diagrams of the localizer [(a) carrier antenna, (b) side-band antennas, (c) the combined pattern; note the minor lobes generated by the array]

(a) The 150 Hz side-bands are reversed in phase with respect to those in the central antenna.
(b) The side-bands of both the modulating signals are phase shifted by 90°.
(c) The side-band power is split into two equal parts and fed to the two side-band arrays, but a phase-shift of 180° is introduced into one of them.

In addition, the spatial arrangement of the loops is designed to give a polar diagram of the 'butterfly' type shown in Fig. 6.2 (b). As a result of the phase relations given above, the fields produced by the two side-band antennas at a distant point are in phase quadrature to that produced by the central one, in addition to being mutually in anti-phase. At any point along the line XOX′, the fields cancel, as the two antennas radiate in anti-phase and the path lengths are equal. There is thus a null along this line. On either side of it, the fields will not cancel as the path lengths are different and the resultant field is the phasor sum of the two. The combined field pattern of the central and side-band antennas is as shown in Fig. 6.2 (c) and has 90 Hz modulation predominant on one side and 150 Hz modulation on the other. The manner in which this arises is explained below with the aid of the phasor diagrams in Fig. 6.3. Only the side-band phasors are represented for the sake of clarity, those of 150 Hz modulation on the left and those of 90 Hz modulation on the right.

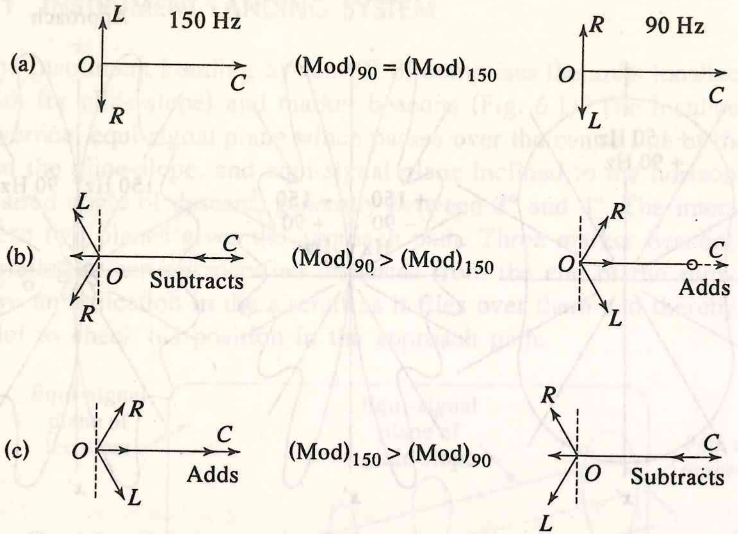


Fig. 6.3 Phasor diagram of the fields due to the carrier antenna and side-band antennas [(a) on course, (b) to the left of the course, (c) to the right of the course]

Figure 6.3 (a) represents the situation along the line XOX'. *OC* is the phasor of the field due to the central antenna, and *OR* and *OL* those due to the side-band antennas on the right and left of the central antenna. *OR* and *OL* are in phase quadrature to *OC* and mutually in phase opposition. As they are equal, they cancel, leaving only the central antenna field. The same applies to the 150 Hz side-band signal, as shown on the right. Note, however, that the phasor *OR* and *OL* are reversed in position. This can be brought about either by the reversal of the modulating signal of 150 Hz in the side-band generators in electronically modulated equipment or by introducing a phase shift of 180° in the side-band signal in mechanically modulated equipment.

In Fig. 6.3 (b), the situation on the left hand side of the centre line is shown. The signal from one antenna (*OL*) is phase advanced and that from the other (*OR*), phase retarded by the same amount. In the case of 90 Hz modulation, the two phasors give a resultant which adds to the signal from the central antenna. The same phase changes, in the case of the 150 Hz modulation give a resultant which subtracts from the 150 Hz phasor of the central antenna. The 90 Hz modulation thus predominates on the left hand side. Similarly it is shown in Fig. 6.3 (c) that the 150 Hz modulation predominates on the right hand side.

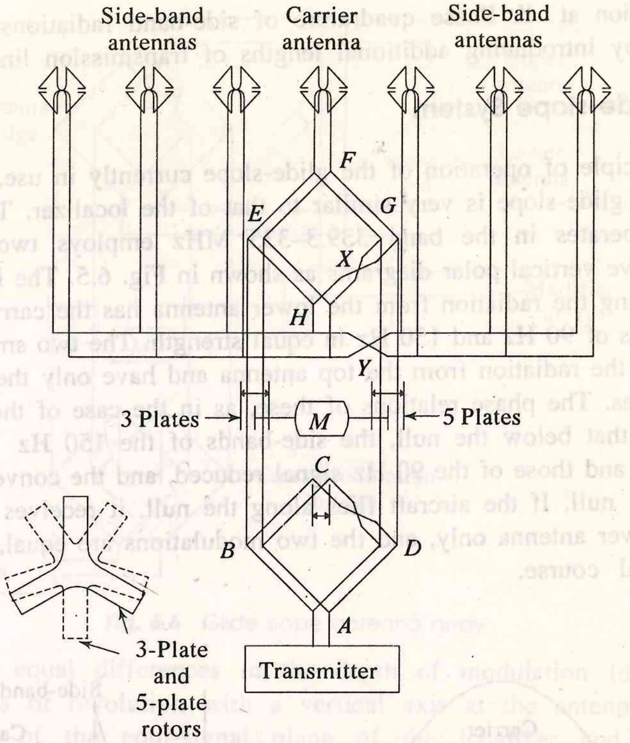


Fig. 6.4 Localizer antenna array

The means by which the modulation is brought about depends upon the type of equipment. This may be done either electronically or by mechanical means.[13] In the earlier models and also in some later ones, mechanical modulation is employed in the manner explained below. The antenna system and the modulators are shown in Fig. 6.4. The signal from the transmitter is divided into two parts by the modulation bridge *ABCD* and goes by two paths to the antenna bridge *EFGH*. Modulation at 90 Hz and 150 Hz is achieved by mechanical modulators. These consist of two quarter-wave transformers coupled to the lines *BE* and *DG*. One end of the quarter-wave line is short-circuited and the other end terminated by two plates in the centre of which is a specially shaped plate rotated by the motor *M*. The plate in the *BE* branch has three and the one in the *DG* branch has five lobes. The rotation of these plates presents a varying impedance across the line and, therefore, changes the power transmitted in the lines. The motor rotates at 1800 rev/min., producing modulation at 90 Hz and 150 Hz. The plates are shaped to obtain sinusoidal modulation. The bridge, in one arm (*CD*) of which a phase change of 180 is introduced, ensures that the modulations on the two sides do not interact.

At the antenna bridge, the carrier + 90 Hz side-bands from *E* and the carrier + 150 Hz side-bands from *G* add at *F* and go to the central antenna, which, therefore, radiates the carrier and all the side-bands. Power comes to *H* also from two paths, *EH* and *GH*, but owing to the transposition at *X*, the carriers cancel and the 150 Hz side-band frequencies get reversed. The power at this point divides into the two paths going to the two side-band arrays and the phase reversal of one is brought about by the transposition at *Y*. Phase quadrature of side-band radiations is accomplished by introducing additional lengths of transmission lines.

(b) Glide-slope System

The principle of operation of the glide-slope currently in use, called the null-type glide-slope is very similar to that of the localizer. The system, which operates in the band 339.3–335 MHz employs two antennas, which have vertical polar diagrams as shown in Fig. 6.5. The larger lobe, representing the radiation from the lower antenna has the carrier and the side-bands of 90 Hz and 150 Hz in equal strength. The two smaller lobes represent the radiation from the top antenna and have only the side-band frequencies. The phase relations of these, as in the case of the localizer, are such that below the null, the side-bands of the 150 Hz signal are enhanced and those of the 90 Hz signal reduced, and the converse occurs above the null. If the aircraft flies along the null, it receives the signal of the lower antenna only, and the two modulations are equal, giving an equi-signal course.

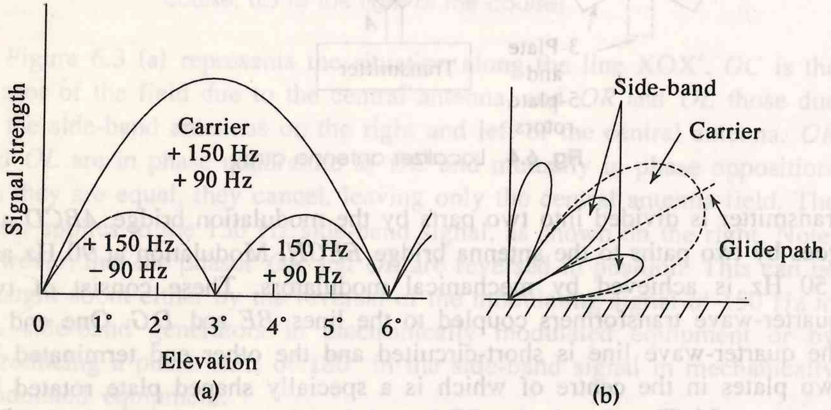


Fig. 6.5 Radiation diagram of the glide-slope equipment [(a) in cartesian coordinates (b) and in polar coordinates]

The essential elements of the null-type glide-slope system are shown in Fig. 6.6. The arrangement of the cross-modulation bridge and the antenna bridge are similar to those of the localizer shown in Fig. 6.4. The carrier and side-bands are radiated by the lower antenna and the side-bands by the upper antenna, both of which are dipoles with a reflecting screen at the back. There is, in addition, the array called the modifier array, the function of which is explained in the following paragraph.

The glide-slope equipment and antenna have to be sited away from the runway so that they do not constitute a hazard. Generally the installation is sited 450 ft away from the centre line of the runway. The surfaces

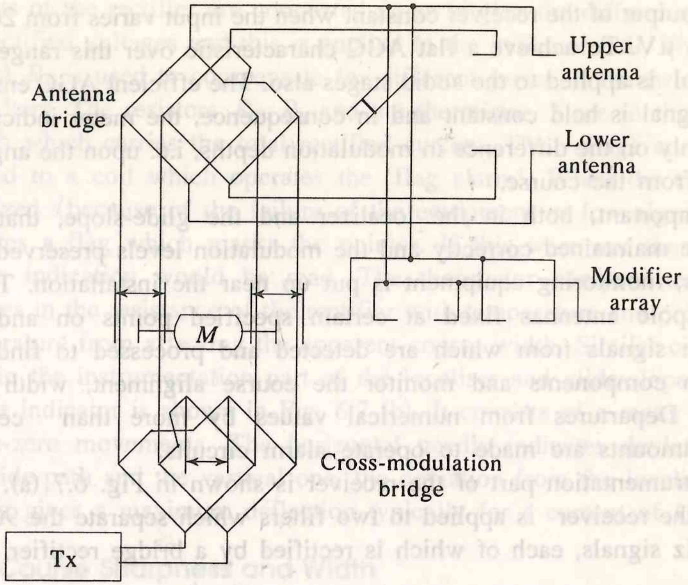


Fig. 6.6 Glide-slope antenna array

defined by equal differences in the depth of modulation (ddm) are hyperboloids of revolution with a vertical axis at the antenna.[20] The intersection of the equi-signal plane of the localizer and of this hyperboloid is another hyperbola which does not touch the runway. The preferred path of descent is, however, a straight line. At appreciable distances from the runway, the hyperbola approximates a straight line, but near the runway it tends to flatten out. To make the path nearly straight up to the touch-down point, a modifier antenna is some times used to correct for this, but the utility of this has been questioned and its use has generally been discontinued. The glide-slope antennas give several lobes of the type shown in Fig. 6.5 at higher elevations and it might appear that these might give rise to a number of false courses at higher angles. However, an examination of the modulation at each lobe shows that the first false course gives reversed indications, i.e. above the course, the 150 Hz modulation predominates and below the course the 90 Hz modulation predominates. Therefore, this cannot be mistaken for the correct course. The next false course, at three times the glide angle gives correct indications, but it is so steep that a pilot can easily make out that it is not the correct one.

(c) Receiving Equipment

The receiver is typically a crystal controlled multi-channel receiver. Separate receivers are required for the localiser and the glide-slope facilities, as they operate in widely different bands. One of the features of keeps the output of the receiver constant when the input varies from 20 μV to 100,000 μV. To achieve a flat AGC characteristic over this range, the gain control is applied to the audio stages also. The efficient AGC ensures that the signal is held constant and in consequence, the meter indication depends only on the difference in modulation depths, i.e. upon the angular deviation from the course.

It is important, both in the localizer and the glide-slope, that the courses are maintained correctly and the modulation levels preserved. To ensure this, monitoring equipment is put up near the installation. These employ dipole antennas fixed at certain specified points on and off course, the signals from which are detected and processed to find the modulation components and monitor the course alignment, width and clearance. Departures from numerical values by more than certain specified amounts are made to operate alarm circuits.

The instrumentation part of the receiver is shown in Fig. 6.7 (a). The output of the receiver is applied to two filters which separate the 90 Hz and 150 Hz signals, each of which is rectified by a bridge rectifier. The

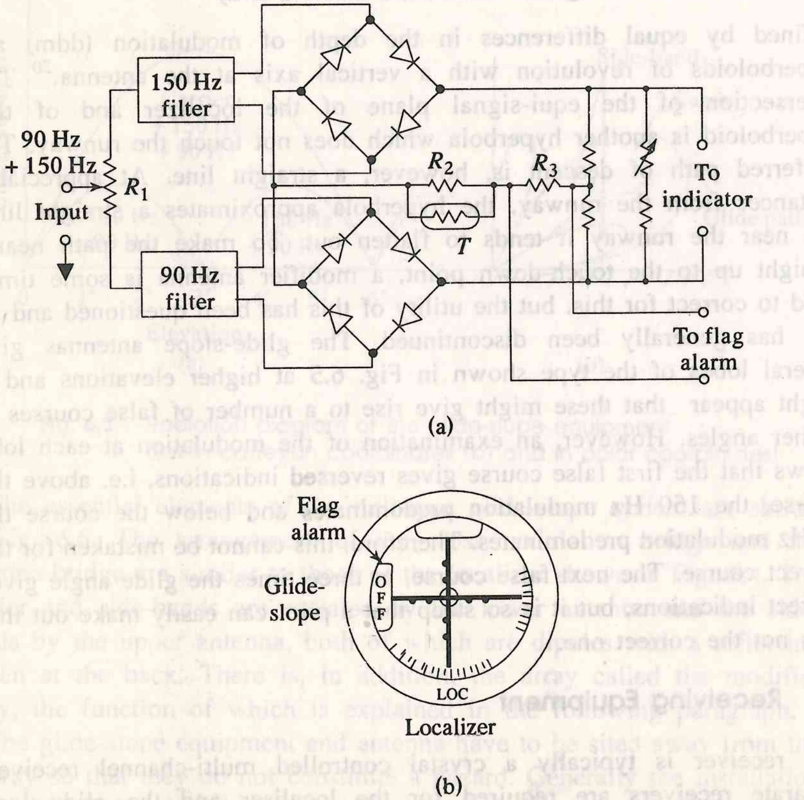


Fig. 6.7 Instrumentation part of ILS receiver [(a) Rectifier circuits

outputs of the rectifier are connected so as to give the difference between the rectified voltages and this is applied to the indicator coil. The balance control R_1 is used to compensate for different losses in the two rectifiers and filters. The resistors R_2, R_3 and the thermistor T are in the common branch which carries the total rectified current. The voltage across R_3 is applied to a coil which operates the 'flag alarm'. When the coil is not energized (because of the failure of the equipment or low signal, etc.) it operates a flag which masks the pointer. If this were not there, an on-course indication would be read. The thermistor compensates for the changes in the resistance of the rectifier with temperature and prevents the temperature from affecting the apparent course width. Similar circuits are used in the instrumentation part of the localiser and glide-slope.

The indicator is shown in Fig. 6.7 (b). It consists of a meter with two centre-zero movements. The horizontal needle indicates deviation from the glide-path and the vertical one, the deviation from the localizer. Each pointer gives a maximum deflection typically for a current of 150 μA.

(d) Course Sharpness and Width

The sharpness and width of the course are dependent on the relative depths of modulation of the 90 Hz and 150 Hz signals. The total signal modulation is defined by the relation: $M = (A + B)/C$, where M is the total signal modulation, A and B are the amplitudes of the 150 Hz and 90 Hz signals respectively and C is the carrier amplitude. The difference in the depth of modulation (ddm) of the two signals is given by $(A - B)./C$. A current proportional to this quantity drives the needle of a pointer, which, typically, has a full scale deflection of + 150 μA. On-course, whether in the localizer or the glide-path, the ddm is zero. Off the course, one or the other of the modulations predominates and a deflection is obtained in the meter. In the localizer, full scale deflection corresponds to a ddm of 0.155, which occurs when the aircraft is 2° off the equi-signal course. In the glide-slope, a ddm of 0.175 is made to give a full scale deflection when the glide-angle deviates by a fifth of the slope angle (e.g. ± 0.6° for 3° slope of the glide-path). In the neighbourhood of the null, the ddm is a linear function of the deviation from the equi-signal path.

The sharpness of the course, both in the localizer and glide-path is measured in terms of the ratio of the 90 Hz and 150 Hz side-band signals, the ratio being expressed in dB. This measure is called the 'clearance'. In the localizer, the clearance at ±1.5° off the course is called 'course sharpness'.

(e) Site Effects in the ILS

The localizer and glide-slope courses are affected by the nature of the site on which they are installed. The operation of both these facilities being continuous wave, the presence of surface irregularities, hills, vegetation as well as the nearby location of other aircraft affect the equi-signal course. So long as this does not introduce sharp bends, the course may still be 'flyable'. In difficult locations, it may be necessary to use special arrays which radiate as little energy as possible in directions other than those required. But as this may make it difficult for the aircraft to come within the beam, a subsidiary low-power transmission of the facility is made by the aid of which the aircraft can come into the beam of the more directive main transmitter. When it does so, the main beam takes over. The two transmissions differ in frequency by a small amount (a few kHz) and no retuning of the receiver is necessary. The stronger signal of the main beam takes over, i.e. the receiver responds to the stronger signal only. This phenomenon is called capture effect. The low power signal is called the 'clearance signal' and the high power one the 'directional signal'.

The polar diagram of a directional localizer ('capture effect localizer') is shown in Fig. 6.8. The clearance array acts as a low power localizer, using an eight loop array with a power output of 90 to 180 W at a frequency 4 kHz below the main localizer frequency. This pattern can be used at all azimuths and gives unambiguous information (i.e. whether to fly right or left). The directional array provides guidance within ± 10° of the centre line of the runway. The power radiated by this is low at other azimuth angles and any site irregularities in these directions will not cause course bends. At large azimuths, the clearance signal is stronger and the receiver locks onto it, and gives proper guidance.

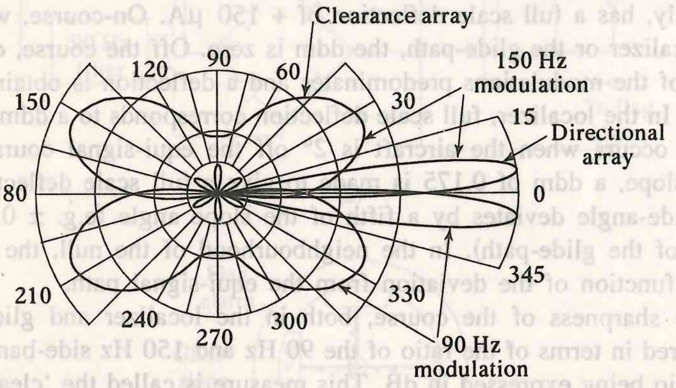


Fig. 6.8 Polar diagram of capture-effect localizer

(f) Marker Beacons

The ILS employs three marker beacons (Fig. 6.1) which give an indication in the aircraft when it passes over them. All of them operate at 75 MHz and work with an antenna which gives a fan-shaped beam which is typically ±40° wide along the approach path and ±80° perpendicular to it. The most distant one (from the end of the runway, called the outer marker (OM) is approximately 7 km from the touch down point on the runway. The radiation is modulated at 400 Hz, giving two dashes per sec. The second one, called the middle marker (MM) is placed where the glide path is 200 ft (approx. 60 m) which generally is about 1 km from the touch-down point. The modulation is at 1300 Hz with one dash every $\frac{2}{3}$ sec. The inner marker (which is not used at all airports) is placed where the glide-path is 100 ft (approx. 30 m) above the ground. It is modulated at 3000 Hz, six dots per second. In the aircraft, a single receiver tuned to 75 MHz is employed. The output is available as an audio signal and also actuates three lamps, one for each marker beacon.

6.2 GROUND-CONTROLLED APPROACH SYSTEM

This is a high-precision radar system sited near the airport runway, with the help of which a controller on the ground can bring the aircraft into approach zone and then guide it along the path of decent to a point very near the runway. The system consists of two separate radars, one called the surveillance radar element (SRE), and the other called the precision approach radar (PAR). The former is a search radar with a PPI display which helps to locate the aircraft at a relatively distant point and bring it to within a few miles from the approach end of the runway from the proper direction. It is, therefore, not a part of the precision approach system and its functions could be performed by other facilities such as airfield control radar. The PAR generally operates in conjunction with the ILS.

(a) Surveillance Radar Element

As the SRE is not an essential part of the approach system, it will not be dealt with here. The following data relating to an early version of SRE may however be noted.

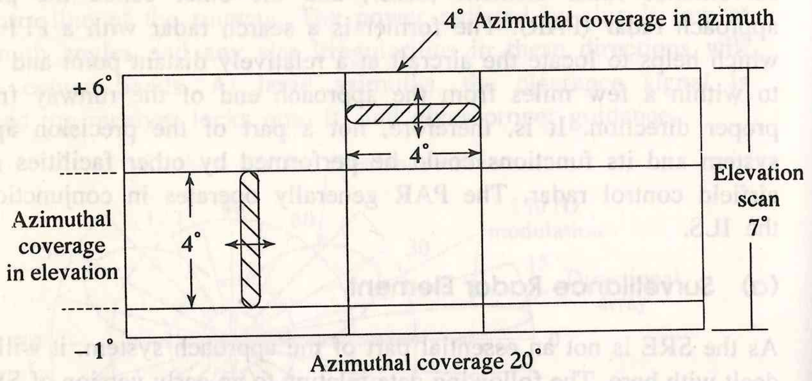
Wavelength:	10 cm
Peak power:	80 kW
Pulse length:	0.5 μ sec
Pulse repetition frequency:	2000 pulses/sec.
Scan rate:	30 rev/min.
Beam width in the horizontal plane:	approx. 0.5°

The fan-shaped beam covers about 20° in the vertical plane.

(b) Precision Approach Radar

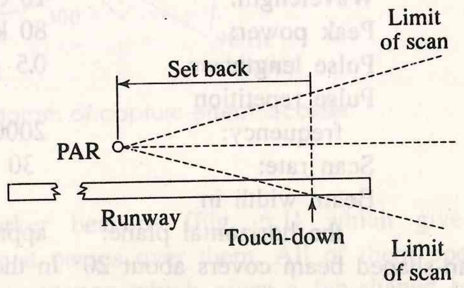
This precision radar has a maximum range of about 15–20 km and scans the approach zone both in azimuth and elevation. The precise performance and display details depend to some extent on the manufacturer of the equipment and the data given below pertain to some equipment developed by the Standard Telephones and Cables.[21]

The radar has to scan a 20° azimuth sector and a 7° elevation sector to meet the operational requirements. The accuracy demanded in respect of the determined azimuth and elevation angles requires a beam width in the scanning direction of 0.5°. Therefore two separate antennas are used for azimuth and elevation scannings. The antenna coverage in the dimension not scanned could theoretically cover the whole of the unscanned sector but practical considerations (e.g. limited transmitter power) preclude this and coverage is limited to 4°. This means that the elevation scan should be capable of azimuthal movement of 16° and the azimuthal scan an elevation movement of 3°. The latter is rarely required if the coverage is kept between 1° and 5° as few aircrafts are likely to come at a greater angle of descent. The coverage of the antennas is shown diagrammatically in Fig. 6.9 (a) and the location of the PAR in respect of the runway is shown in Fig. 6.9 (b).



Shaded rectangles show section of beam [4° × 0.5°]

(a)



Since the precision of the PAR depends upon the precise determination of the beam position, it is required that the true beam position must be known at every instant with an accuracy better than 5' of arc.

The PAR uses a single radar transmitter which is connected alternately to the two antennas, i.e. the two scans are interlaced. The data pertaining to the equipment mentioned are as follows:

Transmitter power (peak)	..	50 kW
Frequency	..	9080 MHz
Pulse width	..	0.18 μsec
Pulse repetition frequency	..	3.825 kHz
Range discrimination		200 ft
Azimuth discrimination	..	0.6°
Elevation discrimination	..	0.6°

Rapid scanning of the antenna beam is required in the PAR as the information has to be rapidly renewed. The narrow beam requirements given above dictate a large antenna aperture and, therefore, a physically large antenna (13 ft × 1.625 ft in the above equipment). Scanning by movement of the whole antenna presents practical problems and a different method which does not require the movement of the antenna system is adopted. This method, employs an array of dipoles fed from and mounted on a wave-guide the width of which is varied. The array consists of 209 dipoles spaced 1.92 cm apart which are mounted on the side of the wave-guide and terminate in a probe which couples with the wave-guide and draws a certain calculated amount of power. Radio frequency power is fed at one end of the wave-guide and its far end is terminated with a resistance load so as to prevent reflections. The array produces a beam the width of which is nearly constant and the orientation of which is dependent on the wavelength in the guide. This wavelength can be altered by altering the width of the wave-guide. Figure 6.10 shows a section of the wave-guide indicating how the width of the wave-guide is altered. The change in the wavelength changes the relative phases of the current fed to the antennas and this has the effect of changing the direction of maximum radiation. The principle is similar to that

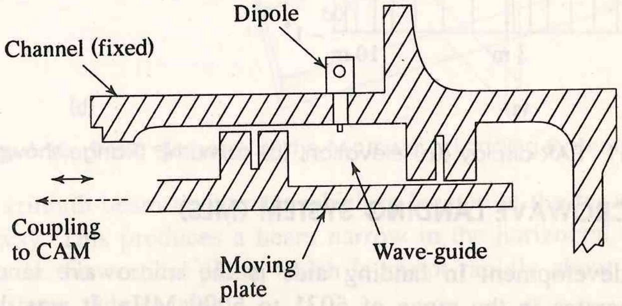


Fig. 6.10 "Squeezable" wave-guide