Introduction

- **Navigation:** The art of directing the movements of a craft (object) from one point to another along a desired path is called navigation.
- In short navigation is process to finding a short & secure path to travel.
- **Aids of navigation:**
  - Compass
  - Chronometer
  - Sextant
  - The Sun, The Moon, The Stars & The Winds
  - The Theodolite & Charts (Maps of known world)

- **The Compass:**
  - A compass is a navigational instrument that shows directions in a frame of reference that is stationary relative to the surface of the Earth.
  - The frame of reference defines the four cardinal directions (or points) – north, south, east, and west.
  - Intermediate directions are also defined. Usually, a diagram called a compass rose, which shows the directions (with their names usually abbreviated to initials), is marked on the compass.
  - When the compass is in use, the rose is aligned with the real directions in the frame of reference, so, for example, the "N" mark on the rose really points to the north.
  - The magnetic compass was first invented as a device for divination as early as the Chinese Han Dynasty (since about 206 BC).
  - A simple compass is shown in figure 1.
- **The Chronometer:**
  - A chronometer is a clock that is precise and accurate enough to be used as a portable time standard; it can therefore be used to determine longitude by means of celestial navigation.
  - When first developed in the 18th century, it was a major technical achievement, as accurate knowledge of the time over a long sea voyage is necessary for navigation, lacking electronic or communications aids.
  - The first true chronometer was the life work of one man, John Harrison, spanning 31 years of persistent experimentation and testing that revolutionized naval (and later aerial) navigation and enabling the Age of Discovery and Colonialism to accelerate.
  - Figure 2 shows the Chronometer.
• **The Sextant:**
  A sextant is an instrument used to measure the angle between any two visible objects. Its primary use is to determine the angle between a celestial object and the horizon which is known as the object's altitude. Using this measurement is known as sighting the object, shooting the object, or taking a sight and it is an essential part of celestial navigation. The angle, and the time when it was measured, can be used to calculate a position line on a nautical or aeronautical chart. Figure 3 shows the Sextant.

![Figure-3](image)

• **The Theodolite:**
  A theodolite is a precision instrument for measuring angles in the horizontal and vertical planes. Theodolites are used mainly for surveying applications, and have been adapted for specialized purposes in fields like metrology and rocket launch technology. A modern theodolite consists of a movable telescope mounted within two perpendicular axes—the horizontal or trunnion axis, and the vertical axis. When the telescope is pointed at a target object, the angle of each of these axes can be measured with great precision, typically to seconds of arc. Figure 4 shows the Theodolite.

![Figure-4](image)
Magellan circumnavigated the Globe in the early sixteenth century with the aid of listed instruments.

In 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.

Navigation became science as well as art.

In twentieth century, electronics entered the field.

Time signals were broadcast by which the Chronometers could be corrected.

Direction finders and other navigational aids which enable the navigator to obtain a fix using entirely electronic aids were developed and came into extensive use.

Our aim is to study about all navigational aids which employ electronics in some way.

To start with a brief account of other methods of navigation.

Other Reading:
Four Methods of Navigation:

- Navigation requires the determination of the position of the craft & the direction in which it has to go to reach desired destination.
- The currently used methods of navigation may be divided into four classes:
  - **Navigation by Pilotage (or Visual Contact)**
  - **Celestial or Astronomical Navigation**
  - **Navigation by dead-reckoning**
  - **Radio Navigation**
- **Navigation by Pilotage (or Visual Contact):**
  - In this method, the navigator fixes his position on a map by observing known visible landmarks.
  - For e.g., in air navigation when the ground is visible the navigator can see the principal features on the ground such as rivers, coastlines, hills etc. and thereby fix his position.
  - Even at night, light beacons, cities and towns provide information about position of the craft.
  - Pilotage navigation requires good visibility.
  - With aid of air-borne radar it is called as Electronic-Pilotage.
  - The radar used for this purpose is microwave search radar provided with PPI display on which the terrain is mapped.
  - The PPI picture has poor resolution compared to human eye because the angular resolution is typically 3°.
  - Electronic-Pilotage has the range of 50 to 100kms that is advantageous in poor visibility.
  - Can’t applicable over sea.
  - Both methods of Pilotage depend upon the availability of accurate maps of the terrain.

- **Celestial or Astronomical Navigation:**
  - Also called as 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 GMT.
  - The navigator measures the elevation of 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.
• Sometimes the 3rd observation may have to be made to remove the ambiguity.
• Figure 1 illustrates the celestial navigation.

![Image](image.png)

**Figure-1**

• Its advantage is relative independence of external aids.
• Its disadvantage is that the visibility should be good enough to take elevation angles of 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 is totally dependent on measured elevation of the body and generally correct to 1 min. of arc.

**Navigation by dead-reckoning:**
• In this method, the position of craft at any instant of time is calculated from the previously determined position, the speed of its motion w.r.t. Earth along with the direction of its motion and the time elapsed.
• Abbreviated as DR stands for “Deduced Calculation”.
• This is the most common and widely used method of navigation.
• This method requires the direction of motion of the craft and speed of motion.
• First requirement may be met by magnetic compass & second by an instrument such as 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.
• In air navigation, wind velocity is generally obtained in the course of flight from weather broadcasts or by communication with ground station.
• In long flights over water, modern air operations resort to minimal flight paths i.e. the paths which require min. flying time.

**Radio Navigation:**
• This method is based on Electromagnetic waves to find the position of the craft.
• All these systems depend upon transmitters & receivers at known locations on earth’s surface & transmitters & receivers working in conjunction with them in the vehicle.
• These systems are not self-contained systems of navigation like the DR system because it is dependent on the installation of instruments on the craft as well as on the earth.
• These systems generally give the navigational parameters like distance, direction & time by measuring the delay directly or indirectly in reception.
• The positional information is related to the
  o The measurement of direction
  o The measurement of distance
  o The difference in distance of two transmitters
• These give locus of the craft on a
  o Line
  o Circle
  o Hyperbola
  Respectively.
Radio Direction-finding:

- The earliest method of electronic navigation was by direction finding i.e. the determination of the direction of arrival of EM waves at the receiving station.
- EM waves travel along great circle path so it helps to locate the transmitter along the great circle path.
- Oldest method but still use in both ships & aircraft.
- Transmitter & direction finder may be located on ground or on the craft & vice-versa.
- If direction finder located at ground then it obtain the bearing & passes on the information to the craft by a radio communication channel.
- Direction-finding may be carried out in any region of the radio spectrum but certain frequencies are specifically allotted for navigational purpose in the LF/MF, HF & VHF bands.

Loop Antenna & its emf equation:

- Consider a rectangular loop antenna as shown in figure 1 of length \( a \) & width \( b \) with its plane vertical, mounted so that it can be rotated about the vertical axis.

![Figure-1 Loop Antenna](image)

- Let vertically polarized electromagnetic wave incident on it making an angle \( \theta \) with the plane of the loop as shown in figure 2.

![Figure-2 EM wave arriving with the angle \( \theta \)](image)
• Voltages are induced in the vertical members of the loop but not in horizontal members as the wave is vertically polarized.
• Magnitude of the voltage induced in two vertical members is \(ae\).
• The voltages in the two members will not be in phase can be seen from phasor diagram as shown in figure 3.

![Figure-3 Phasor diagram](image)

- The voltage induced in AB is lags by an angle \(\Phi\).
  \[
  \Phi = \frac{2\pi}{\lambda} \frac{1}{2} b \cos \theta
  \]
  \[
  \Phi = \frac{\pi}{\lambda} b \cos \theta \quad \text{-------------- (1)}
  \]

- If the electric field at the centre of the loop is \(\varepsilon(t) = \sqrt{2} \varepsilon \cos(\omega t)\)
- Voltages induced in AB & CD are
  \[
  e_1 = \sqrt{2} a \varepsilon \cos (\omega t - \frac{\pi}{\lambda} b \cos \theta)
  \]
  \[
  e_2 = \sqrt{2} a \varepsilon \cos (\omega t + \frac{\pi}{\lambda} b \cos \theta)
  \]
- So the resultant output is \(e_L\) & it is given by,
  \[
  e_L = e_1 - e_2 = \sqrt{2} \varepsilon \frac{2\pi}{\lambda} a b \cos \theta \sin \omega t \quad \text{--------------(2)}
  \]
- From equation (2) the output amplitude is proportional to \(\cos \theta\).
- The polar diagram of the loop antenna is, therefore a ‘figure of eight’ as shown in figure 4.

![Figure-4 Polar diagram](image)
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 input of direction finding receivers to obtain a voltage which is larger than the loop voltage and to establish the desired phase relation between the loop out of the loop circuit and the output of the vertical antenna for sense finding.
- Some of these circuits discussed here, as shown in figure 1 the inductance of loop is tuned out by a capacitor and making a series tuned circuit and the voltage across capacitor or half of it is used as input of the receiver.

**Figure-1 Series tuned circuit**

- The series tuned circuit provide the certain amount of circuit magnification of the loop voltage.
- As the current in a series tuned circuit is in phase with applied voltage the voltage across the capacitance lags by 90° with respect to the input voltage.
- Figure 2 & 3 shows developments of the same circuit to achieve a better balance than is possible with the first circuit.

**Figure-2 Balanced circuit**
The balanced circuit shown in figure 3 is used to overcome the effect of antenna effect. The loop antenna is earthed and its output is thereby balanced. 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 may be introduced by input capacitance. To remove such unbalance either a compensating capacitor as shown in figure 2, in all adjustments aimed at eliminating antenna effect, a check is made to see whether the minima correspond to opposite bearing by turning in a station and turning the loop. Ideally 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 as shown in figure 4.

An aural null direction finder:

1. The input circuit of a manually operated loop direction-finder is shown in figure 5.
2. This circuit illustrates one method by which the voltage required for sense finding may be obtained and introduced in to the loop circuit.
3. There is 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.

The loop circuit consisting of the loop antenna, $L_I$, $C_I$ and $L_2$ is a series tuned circuit for the loop voltage.

In the ‘balance’ position of the switch S, an additional voltage is introduced through the variable inductive coupling between $L_3$ & $L_1$.

This voltage is obtained from the vertical antenna & the components $C_2$, $L_5$ & $C_3$ are so adjusted that this voltage is in phase quadrature to the loop voltage.

With the variation in magnitude & sign permitted by the variable coupling between $L_1$ & $L_3$, 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 in phase with the vertical antenna voltage & 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 following steps
  - With the switch S in position balance, the bilateral bearing of the signal source is found.
  - The loop is then turned by 90° & the switch is thrown to the ‘sense’ position. Then by noting whether the signal strength increases or decreases the sense can be determined.

Proper mechanical arrangement is provided for both measurements i.e. sense & direction.

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**Figure 5 Input circuit of an aural null direction finder**

- The loop circuit consisting of the loop antenna, $L_I$, $C_I$ and $L_2$ is a series tuned circuit for the loop voltage.
- In the ‘balance’ position of the switch S, an additional voltage is introduced through the variable inductive coupling between $L_3$ & $L_1$.
- This voltage is obtained from the vertical antenna & the components $C_2$, $L_5$ & $C_3$ are so adjusted that this voltage is in phase quadrature to the loop voltage.
- With the variation in magnitude & sign permitted by the variable coupling between $L_1$ & $L_3$, the quadrature component arising from antenna effect can be cancelled out.
- For sense finding, the switch S is thrown to position 2.
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  - With the switch S in position balance, the bilateral bearing of the signal source is found.
  - The loop is then turned by 90° & the switch is thrown to the ‘sense’ position. Then by noting whether the signal strength increases or decreases the sense can be determined.
- Proper mechanical arrangement is provided for both measurements i.e. sense & direction.
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 figure 1.

![Goniometer Diagram](image)

**Figure-1 Sketch of the goniometer**

- 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 figure 2, let the two loops be oriented N-S and E-W and let the incident electromagnetic wave (vertically polarized) make an angle $\theta$ with the North.
Figure-2 Plan of the Loop antennas & The magnetic field within the goniometer

- The currents flowing in the two loops are then proportional to \( \cos \theta \) (N-S Loop) and 
  \( (\cos 90 - \theta) = \sin \theta \) (E-W loop).
- For convenience, let the corresponding stator coil be called N-S coil E-W coil.
- The magnetic flux in these coils produced by the loop currents are proportional to 
  \( \cos \theta \) and \( \sin \theta \) respectively (figure-2) and the resultant magnetic flux has the same 
  direction with respect to 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 
  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 the vertical antenna 
  for sense finding.

Errors in Direction Finding:

- The analysis of loop direction finder 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 this is not possible so the wave may not be normally polarized, it may be 
  incident at an angle at the antenna and the direction of its arrival may not be the same 
  as that of the transmitter.
- Errors will arise in direction-finder due to this condition.
- These may be divided into four broad classes as given below,
  - Errors due to abnormal polarization
  - Errors due to abnormal propagation
  - Site errors
  - Instrumental errors

Polarization Errors:

- This type of errors was mainly observed at night time,
- Which was characterized by displace minima, rapid changes in their position, a poor 
  null, etc.
- The cause of this proved to be the abnormal polarization associated with inospheric 
  propagation.
- As sky waves were more prominent at night in low frequency band.
This phenomenon is known as ‘night effect’.
Abnormal polarization also occurs in radiation from aircraft transmitters and hence called as ‘aero plane effect’.

Errors due to abnormal propagation:

- It was earlier assumed that the EM Waves travelled along the great circle path from transmitter to the direction-finder.
- This is generally true but some time the path deviates from the great circle plane.
- When the propagation is via the ionosphere, such deviation can occur owing to scattered reflections and tilt of the reflecting regions.
- As both these phenomena are associated with propagation via ionosphere, they are more evident at high frequency.
- Abnormal propagation can also occur at low and medium frequencies under certain condition.
- 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 appears to be more towards the sea than it actually is.
- This phenomenon is sometimes called ‘coastal reflection’.
- These errors are generally small and generally constant and could be corrected by calibration.
- A similar phenomenon may be observed in mountain terrain this is called as mountain effect’”.

Site Errors:

- An ideal site for a direction-finder must be flat and must have high conductivity.
- In practice these conditions are not full filled 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 berried cables , spikes ,etc, can produce errors because the soil conductivity is low and EM waves penetrates the soil to some depth.
- If the direction-finder is placed near the large objects that introduces site errors.
- In a mobile installations such as on a ship-board the choice of site is vary restricted and the direction-finder is invariably surrounded by objects which absorbs the some of the energy from the wave and re-radiate it.
- Site errors can be minimized to some extant but not eliminated completely.

Instrumental Errors:

- Imperfections of the components used in direction-finders generates the errors, these errors are instrumental errors can be compensated by calibration.
Adcock Direction Finder:

- It was shown in the last lecture 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 error by dispensing with the horizontal members.
- It consists of pair or more of vertical antennas, the signals from these being taken to the receiver either by underground conductor 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 voltage are induced in the two horizontal members tend to cancel out.
- Several forms of the Adcock antenna are shown in figure 1.

(a) $2^\circ - 6^\circ$  (b) $6^\circ - 10^\circ$  (c) $< 5^\circ$  (d) $1^\circ$

Figure-1 Adcock direction finders (the standard wave error is indicated in each case)

- These are generally called U-type or 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 size the output of Adcock antenna is higher compare to loop antenna.
- 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 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.
• 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 figure 1.
• In antennas of the type shown in figure 1(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.

Advantages over loop antenna:

• The loop antenna direction finder suffers from vertical & polarization errors but in Adcock direction finder system these errors are minimized.
• The loop direction finders are suitable at lower frequency, whereas Adcock direction finder is suitable for higher frequency.
• The induced voltage in Adcock system is less in comparison to loop.
Direction Finding at very high frequency:

- 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.
- Adeck 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) but the receiver in the hut.
- Modern direction-finders are commonly of automatic type and used a crossed-H Adeck antenna with a capacitor goniometer.
- The principles of operation a “phase - comparison” direction-finders are described in previous lecture. An alternative type is employing modulation techniques.
- Recently, a direction-finding employing a new technique has been developed.
- This is commutated Aerial Direction-Finder (CADF).
- As VHF propagation is confined essentially to line odd 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 in spite of using vertical H-Adeck 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.

Automatic Direction finders:

- Manually operated direction finders are simple in construction, but needs an operator always, in aircrafts this is not possible.
- Also it has the disadvantage of speed of operation at very high speed it cause errors in direction finding.
- So the automatic direction finders are introduced here we have two types
  1) The Radio Compass
  2) A VHF Phase-comparison
The Radio Compass:

- The radio compass uses a loop antenna in a servo feed-back system.

- The equipment provided with a pair of loop and a gonio which is mechanically coupled to a motor & a synchro-generator.
- The motor is a two phase one, actuated by two input one from switch oscillator & other one from servo amplifier.
- 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.
- 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 & 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 super-heterodyne 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.

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 same as loop antenna.

Figure-2 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.
• The goni rotor is coupled to a motor and rotated at 25 rps.
• To the same shaft is attached an ac generator which gives a 25Hz 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 25Hz 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.
• Which consists of two coils mounted on a spindle to indicate the direction.
Range and Accuracy of Direction Finders:

- Ground-based direction-finders are generally of the Adcock type and are relatively free from polarization errors.
- In daytime, 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, error 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'.
Radio Range:

- Radio ranges are navigational aids which are mainly used by aircraft.
- There are two types of radio ranges in used, 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 be tuned 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.

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 (figure 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.

![Diagram of four-course radio range](image)

Figure-1 (a) polar diagram of the four-course radio range and (b) interlacing A and N transmissions

- These are 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 interlocked as shown figure 1(b).

Both these transmissions are modulated by an audio frequency note of 1020Hz.

When the aircraft is on course, the two signals being equal, a continuous note of 1020 Hz is heard.

At point 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 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 figure 2.

![figure-2](image-url)  
**Figure-2** (a) Course shifting & (b) Course bending in LF/MF Radio range

- 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.

**Disadvantages:**
- Limited number of courses are available
- Poor SNR
- Continuous listening of sound may hurt operator’s ear
- Difficulty to identify the course
VHF Omni Directional Range:

- 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**

- 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 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 1 shows how the phase difference between these is equal to the bearing of the receiving point from the beacon transmitter.

![Figure-1 Reference (R) and variable-phase (V) signals of VOR received at various points](image-url)
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 \( \omega_c \).

The equation of the cardioid (taken as representing the magnitude of the electric filed) in polar coordinates is:

\[
\varepsilon = 1 + K \cos \theta \quad (k<1) \quad \text{-------------------------\( (1) \)}
\]

Where \( \theta \) is the angle measured from North.

This is shown by the full line cardioid in figure 2, where the maximum of the cardioid \( (\theta = 0) \) is in the direction of the north.

At a time \( t \), when the cardioid has turned by angle \( \omega_st \), the filed magnitude in a direction \( \phi \) is given by the same equation but with \( \theta \) replaced by \( \phi - \omega_st \), as is clear from the cardioid shown by the broken line in figure 2.

**Figure-2 Production of variable phase signal by rotation of the cardioid pattern**

- The signal received by a receiver in the direction \( 0 \) is therefore proportional to \( 1+k(\cos \phi - \omega_st) \), which has a sinusoidal component of angular frequency \( \omega_c \).
- By comparing the phase difference between this and a signal \( \cos \omega_st \), the angle \( \phi \), 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.
- As the Omni-directional and figure-of-eight patterns have the same carrier frequency, the reference sinusoid cannot be made to directly amplitude modulates 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-direction 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 figure 3.
- The figure pertains to the equipment developed by Federal telecom laboratories.
• This differs from the earlier equipment developed by the Civil Aeronautics Administration (CAA), 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 equipment’s 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 nt. this part of the equipment will be descrby bed latter.
• Figure 3 block diagram of the VOR ground equipment.

![Block diagram of the VOR ground equipment](image)

• Referring to figure 3, the transmitter consists of a crystal controlled oscillator, frequency multipliers and 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 pa (about90%) 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.
• It consists of a disc-type antenna with four slots which gives the Omni-directional pattern and a rotating dipole which produces the figure-of-eight pattern.
• 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 wave length long but because of its position within the waveguide.
• It presents resistive impedance. The outer of the two cages enclosing he 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 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 figure 4.

![Figure-4 Detail of the Tone Wheel](image_url)

• The tone wheel is like a gear wheel, made of magnetic material.
• A permanent magnet with a coil around it is placed closed 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.
• The importance of maintain 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.
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 and the demodulated output is switched to the required instrumentation and display circuits.
- The frequency band over which the receiver works is 108.0 to 135.95 MHz covering 560 allocations each separated from the adjacent 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.
- Transistorized circuits are used in modern receivers.
- The essential elements of the instrumentation part of the receiver are shown in the block diagram of figure 1.

![Figure-1 Instrumentation part of VOR receiver](image-url)
• The demodulated output of the 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.
• The two 30 Hz thus become available and the phase difference between them is to be displayed.
• This is done by a feedback arrangement utilizing a resolver, a phase detector & a motor as shown in figure 1.
• The resolver is a sine cosine generator used to produce an angular phase shift that precisely equivalent to the angular position of its shaft.
• 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 & variable phase signals.
• The shaft position of the resolver then indicates the phase difference between the reference & 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.
Range & Accuracy 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 usable 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 that the error distribution is Gaussian, with a 95% probability that the error is within 2°. 
- (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 neighborhood 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 figure 1, the signal arriving directly at the receiver has the variable phase component with a phase difference $\phi_d$, with respect to the reference signal while the reflected signal has a phase difference $\phi_r$.
- 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 \( \phi_d \) & \( \phi_r \).
• The magnitude of the error depends upon the relative strengths of the direct and reflected signals as well as upon \( \phi_d \) & \( \phi_r \).
• Because of this last quantity, the error varies as the aircraft moves along a radial line, keeping \( \phi_d \) 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.
• (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 later 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.