Chapter 2

Various Navigational Aids for Aviation

2.1 Introduction

Navigation is a process of directing a vehicle from one known point to other known point. Navigational aids are essential for safe and smooth flow of air traffic. The pilot of an aircraft is provided with various types of navigational aids for positional guidance in the space with reference to the ground references. Navigation systems can be classified into two types. They are primitive methods of navigation systems and modern navigation systems.

Piloting, Dead reckoning, Celestial and Inertial navigation are four primitive methods for navigation, which give approximate ‘position fix’. Modern navigation systems use transmission and reception of electromagnetic waves for position fixing. These are classified as, i) Ground based navigation systems and ii) Satellite based navigation systems. The ground based navigation systems are: VHF omni directional range navigation system (VOR), Distance Measuring Equipment (DME), Instrument Landing System (ILS), Microwave Landing System (MLS), Long Range Navigation aid C (LORAN C), DECCA and Non Directional Radio Beacon (NDB). Each navigation aid serves a different purpose. The primary navigational aids used in India are VOR and ILS. The satellite based navigation systems are: Navy Navigation Satellite System (TRANSIT), Global Positioning System (GPS), Globalnaya Navigatsionyya Sputnikovaya Sistema (GLONASS), Wide Area Augmentation System (WAAS) and GPS Aided GEO Augmented Navigation System (GAGAN).

In India, Airports Authority of India (AAI) has the statutory authority to establish, operate and maintain navigation facilities and to prescribe standards for the operation of any of these aids. Presently the primary navigational aids used in India are DVOR and ILS. These are used for instrument flight in the controlled airspace over the Indian subcontinent (PANSRAC Doc4444, 1998). Using the ground field test receiver and flight calibration aircraft (AVRO HS-748) data, the performance of the existing DVOR and ILSs of Hyderabad airport are investigated. The measured and calibrated data is analyzed for a period of one year starting from January 2002 to Dec 2002. The results confirm that environmental changes cause a
change in the ILS course structure and increase in the VOR error spread to 0.30° in a particular direction (300°). In this chapter, VOR theory, salient features of landing, ILS signal format and the effect of environmental changes on primary navigational aids performance are presented.

2.2 Primitive methods of navigation systems

There are four important primitive methods. These are briefly described in this section (Kayton and Fried, 1997). i) Piloting: Position fix in this method is with respect to familiar landmarks.

ii) Dead reckoning: Position fix in this method is by extrapolation of series of measured velocity increments.

iii) Celestial navigation: Position fix in this method is accomplished by measuring the angular position of celestial bodies such as stars, moon etc. 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 chromo meter. ‘Position fix’ is made with these two measurements.

iv) Inertial: Inertial Navigation Systems (INS’s) are autonomous electromechanical systems that provide the altitude, velocity, and position of any vehicle on which the systems are mounted. The major components of INS are: (a) Gyros or Gyroscopes provide information on the altitude or angular velocity of the vehicle with respect to a reference system. (b) Accelerometers: It is a device that measures the specific force. Specific force is the sum of all inertial accelerations.

2.3 Modern ground based navigation systems

Modern navigation systems use transmission and reception of electromagnetic waves for position fixing. The ground based navigation systems are: VOR, ILS, MLS, LORAN C, DECCA and NDB. The primary navigational aids used in India are VOR and ILS (Kayton and Fried, 1997).

a) VOR

VOR provides azimuthal guidance to the aircraft. True bearing can be determined from comparison of two signals (carrier mode signal and side band mode signal). It operates in
108-118 MHz frequency range. There are two types of VORs, namely conventional VOR (CVOR) and Doppler VOR (DVOR). Even though both VORs serve the same purpose as far as the aircraft is concerned, the selection of the CVOR and DVOR depends upon various site conditions in an airfield. Presently DVORs are only in use in India.

b) ILS

ILS effectively guides the aircraft both in elevation and azimuth. Lobe switching is employed for both elevation guidance in a straight path and for azimuthal guidance. It operates in the frequency range of 110-330MHz.

c) MLS

The MLS uses two narrow beams which are scanned to and from in the azimuth and elevation sectors. The various elevation and azimuth scanning beam signals are time multiplexed into an allotted time frame. It operates in 1-5 GHz frequency range. MLS was designated by ICAO (International Civil Aviation Organization) to be the new world standard for precision landing, beginning 1998. But because of the reluctance of both service providers and aircraft operators to equip with MLS (because of its high cost), and the advent of satellite based guidance technology (i.e. GPS), ICAO recommended that ILS be retained as an alternate until satellite based precision landing technology could be fully evaluated.

d) LORAN C

LORAN C is medium to long-range low frequency time difference measurement system. A master and four secondary transmission stations transmit a set of radio pulses centered around 100 KHz in precisely time sequences. Receiver measures the difference in time interval between these transmissions from different stations. Then it produces a hyperbolic line position based on time difference.

e) OMEGA

OMEGA is a very long-range, very-low-frequency (VLF) radio navigation system operating in the internationally allocated navigation band between 10-14KHz. Omega is based on phase differencing techniques rather than time differences. A pair of transmitting stations provides the navigation with a family of hyperbolic lines of position. Eight transmitting stations with 5000-6000 nmi baselines give a global coverage. Omega is used primarily because as ‘Stringer’ observed at a meeting of the British Institute of Navigation, ‘It satisfies the three R’s – Reliability, Redundancy and Range’ (Kayton and Fried, 1997).
f) DECCA

DECCA works through taking observations to pairs of six transmission stations using phase differencing techniques. These give rise to hyperbolic lines of position. It operates in 70-130 KHz frequency range.

g) NDB

NDB is an oldest form of radio navigation still in use. It transmits nondirectional signals in low frequency (LF)/medium frequency (MF) range (190-535kHz). There are 4 types of NDB usages: i) Compass locators ii) Approach aids (25 nm), iii) Enroute beacon, iv) High power beacons- used in some coastal areas. NDB is used for enroute navigational aid. When NDB is used in conjunction with the ILS markers, it is called a Compass Locator. The airborne equipment used for receiving the NDB signal is called Automatic Direction Finder (ADF). The ADF consists of Amplitude Modulation (AM) receiver, Sense Antenna, Loop Antenna (directional antenna) and Indicator (fixed or movable card). The magnetic bearing to the station is determined in the following way using the fixed card:

\[ MB \text{(to the station)} = MH + RB \]

Where, \( MH \) = aircraft magnetic heading, \( RB \) = Relative bearing and \( MB \) = Magnetic Bearing

NDBs are subject to disturbances that may result in erroneous bearing information. The main limitations are: i) Fading, ii) Night effect, and iii) shoreline effect. Fading usually occurs at night when ground wave and sky wave interact and going in and out of “phase” causing the signals to be either cancelled or reinforced as the atmosphere changes. During fading, pilots will notice a rhythmic swinging of the needle and a volume fluctuation of the identifier.

Shoreline Effect: Ground waves change direction as they pass from land to water and vice versa; they are bent slightly. Pilots should note potential bearing indication errors when flying in the vicinity of coastal areas (Kayton and Fried, 1997).

2.3.1 DVOR Concept

Navigation systems assist pilots in flying from one airport to another. These systems help both pilots and air traffic controllers (ATCOs) to determine the aircraft's position relative to the ground and to other aircraft. DVOR is the basic electronic navigation, which is being widely used. The primary function of a DVOR is to provide aircraft with a continuous and automatic presentation of bearing information. That is an aircraft can fly from one DVOR
station to another DVOR station. The system operates in the VHF frequency band, from 108.0 to 117.95 MHz.

DVOR radiates two 30 Hz sinusoidally varying modulation signals. DVOR operation is based on the phase difference between these two 30Hz signals modulated on the carrier. These signals are called reference phase and the variable phase. Reference phase has a constant phase at all angles of azimuth at unit time. Variable phase is in phase with the reference phase at magnetic north and leads the reference phase modulation on a degree for degree basis throughout the 360° of azimuth, i.e. if an aircraft is flying a track of 090° away from the DVOR, the variable phase will lead the reference phase by 090°.

i) Reference phase

The reference phase is produced by amplitude modulation (AM) of the carrier with a 30Hz sinusoid to a depth of 30%. The modulated carrier is radiated omni-directionally in the horizontal plane by the Alford Loop antenna located at the center of the sideband aerial ring. The radiation pattern is a circle.

ii) Variable phase

The variable phase modulation is produced by frequency modulation. The sideband signals ($f_c \pm 9960$ Hz) are radiated from a ring of antennas and are commutated around the ring at 30Hz rate. The 9960 Hz is called subcarrier (Fig. 2.1). The distant observer sees a doppler frequency shift of these sideband frequencies varying at 30Hz with a maximum deviation determined by the diameter of the ring (Fig 2.2) (AWA DVOR Technical Manual, 1989). Since the effective path length between the rotating sideband sources and the distant point of reception varies at a 30Hz rate, the observed frequency of the sideband signals also varies at a 30Hz rate. The radial velocity of the sidebands around the aerial ring is such that the doppler shift of the subcarrier is $\pm 480$Hz.

iii) Space modulation

The frequency modulated subcarrier amplitude modulates the main carrier in space to a depth of 30%. The amplitude modulation is obtained in space by adding the omni directionally radiated carrier and the separately radiated upper and lower sideband signals radiated from the ring of sideband antennas. This modulation is called the space modulation. The resultant signal radiation pattern is cardioid wave pattern.
2.3.1.1 Doppler effect on the carrier and sideband frequencies of DVOR

The doppler effect causes a change in the received frequency when there is a relative change between transmitting and receiving points. Doppler frequency observed in the aircraft receiver ($f_0$) is given by (AWA DVOR Technical Manual, 1989).
\[ f_o = f \frac{V + V_o}{V + \omega r \sin \theta} \tag{2.1} \]

where, \( V \) = velocity of the EM wave, \( V_o \) = velocity of the observer moving towards the source and \( f_o \) = frequency of the source, \( r = \) radius of the antenna ring, \( \omega = 2\pi f \), \( f = \) orbital frequency, \( \theta = \) angle measured counter clockwise from observer \((O)\) to the source \((S)\). The velocity of the source \((S)\) moving towards the observer \((O)\) is \( (V_S) = \omega r \sin \theta \) \tag{2.2}

### 2.3.1.2 Doppler effect on carrier and sideband frequencies

The Doppler effect is investigated for the case when the aircraft is approaching from the East side (see Fig. 2.2). To illustrate this an example estimation is considered.

Hyderabad airport DVOR beacon data is considered in this estimation. The parameters are: i) Carrier frequency: 114.7 MHz, ii) Sideband frequency: 114.709960 MHz rotating at 30cycles/sec., iii) Sideband antenna ring diameter = 13.5m, ii) Aircraft speed = 1000m/sec., iv) \( v = 3 \times 10^8 \text{ m/s} \) and v) \( \omega = 2\pi \times 30 \text{ rad/sec}. \) Doppler effect on carrier and sidebands are estimated and presented in Table 2.1 (Eq. 2.1).

<table>
<thead>
<tr>
<th>Carrier frequency observed (MHz) (Eq.2.1)</th>
<th>Doppler effect ((\Delta f)) on carrier (Hz)</th>
<th>( \theta = 0^\circ )</th>
<th>( \theta = 90^\circ )</th>
<th>( \theta = 270^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed sideband (MHz)</td>
<td>Observed sideband (Hz)</td>
<td>Observed sideband (MHz)</td>
<td>Observed sideband (Hz)</td>
<td>Observed sideband (MHz)</td>
</tr>
<tr>
<td>114.700382</td>
<td>382</td>
<td>114.7103424</td>
<td>9960</td>
<td>114.709856</td>
</tr>
</tbody>
</table>

From Table 2.1, it is noticed that the sideband frequency observed = \( f_o + (9960 \text{ Hz FM with maximum deviation of 479Hz}) \).

The frequency deviation \( (\Delta f_o) = f_o - f_o \) \tag{2.3}

By ignoring the speed of aircraft and doppler effect on the carrier in Eq.2.1, Eq.2.3 can be written as, \( \Delta f_s \text{ (in Hz)} = -4.214 f_s \cdot (MHz) \cdot \sin \theta \) \tag{2.4}

Maximum frequency deviation \( \Delta f_s \text{ max (in Hz)} = 4.214 f_s \text{ MHz} \) \tag{2.5}

For the sidebands 108.00996MHz and 118.00996 MHz, \( \Delta f_s \text{ max observed are 455.2Hz and 497.3Hz respectively. No doppler shift is observed in the sideband signals when they are radiated from a pair of antennas that lies in the line joining the central antenna to the aircraft antenna. If there is no frequency shift of the sidebands, so there is no deviation of the resulting subcarrier signal. When the sidebands are radiated from other antennas in the ring,} \)
there will be some apparent relative motion between the aircraft and the radiating source. This relative motion causes a doppler frequency shift of the sidebands with the resulting deviation of the subcarrier signal.

2.3.1.3 DVOR error analysis

There are two main errors, which cause the Doppler VOR bearing inaccuracy. The classification of errors is presented in Table 2.2 (AWA DVOR Technical Manual, 1989).

Table 2.2 VOR errors

<table>
<thead>
<tr>
<th>Name of the error</th>
<th>Error components</th>
<th>Error Budget (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumental/equipment</td>
<td>Receiver indicator error</td>
<td>0.5° to 1.0°</td>
</tr>
<tr>
<td></td>
<td>Polarization error</td>
<td>1.5° to 2.6°</td>
</tr>
<tr>
<td></td>
<td>Ground station error</td>
<td>0.1° to 0.8°</td>
</tr>
<tr>
<td>Propagational effect</td>
<td>Vertical pattern effects</td>
<td>0.1° to 0.3°</td>
</tr>
<tr>
<td></td>
<td>Terrain effects</td>
<td>0.1° to 0.7°</td>
</tr>
<tr>
<td></td>
<td>Site effects</td>
<td>0.5° to 1.6°</td>
</tr>
</tbody>
</table>

a) Receiver indicator error: The receiver indication errors are due to failure of the receiving equipment to translate accurately the bearing information contained in the VOR signal from the ground equipment. These errors are caused by unequal phase shifts in the receiver channels for the variable and reference phase signals in the phase detector. The receiver error exhibits a slow and systematic variation with bearing. A receiver indicatior error varies with individual receivers and also with ageing of components. The maximum value of the error varies from 0.5° to 1.0° (AWA DVOR Technical Manual, 1989).

b) Polarization error: This error is due to vertical polarization. VOR vertically polarized field has a directional characteristic in space quadrature with the presence of the vertical component of the field. The maximum value of error varies between 1.5° to 2.6° at an elevation angle of 11°.

c) Ground station errors: This error is due to four reasons. They are: i) Improper earthing of counterpoise, ii) Misalignment of north marking, iii) antenna phase and iv) Unbalanced sideband power.
2.3.1.4 Results and discussion of DVOR error spread estimation

The error spread of the DVOR of Hyderabad airport are estimated by collecting the one year field station data from January 2002 to December 2002. Table 2.3 shows the ground calibration data of DVOR for the month January 2002. In this table the actual bearing, observed bearing, corrected reading and the bearing error are presented. Fig. 2.3 shows the DVOR error spread from January-December 02. The maximum bearing error observed is 0.30° at 300° radial and the minimum bearing error observed is 0° at 60° radial. The error spread observed is 0.30°. The maximum error spread allowed is 1°. The present error spread falls within the allowable range. To find the best curve fit to the error spread data 4th, 5th and 6th degree polynomial curves are drawn against the actual data (Fig. 2.4). The 6th degree polynomial is exactly matching with the DVOR error spread. A maximum positive bearing error in the vicinity of 60°-300° radials and a minimum bearing error in the direction of 300°-60° radials is noticed. The mean of the error is 0.1242°. The median is 0.115° and the standard deviation is 0.0835°. The DVOR bearing error spread is due to the reflections from the surrounding high raise buildings, iron fencing and recently erected chimney in the 300° radial direction.

Table 2.3 Ground calibration of DVOR for the month January-2002

<table>
<thead>
<tr>
<th>Bearing Actual (deg.)</th>
<th>Bearing Observed (deg.)</th>
<th>Corrected reading (deg.)</th>
<th>Bearing Error (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>30.0</td>
<td>30.03</td>
<td>30.03</td>
<td>0.03</td>
</tr>
<tr>
<td>60.0</td>
<td>60.0</td>
<td>60.0</td>
<td>0.00</td>
</tr>
<tr>
<td>90.0</td>
<td>90.05</td>
<td>90.05</td>
<td>0.05</td>
</tr>
<tr>
<td>120.0</td>
<td>120.12</td>
<td>120.12</td>
<td>0.12</td>
</tr>
<tr>
<td>150.0</td>
<td>150.12</td>
<td>150.12</td>
<td>0.12</td>
</tr>
<tr>
<td>180.0</td>
<td>180.10</td>
<td>180.10</td>
<td>0.10</td>
</tr>
<tr>
<td>210.0</td>
<td>-149.89</td>
<td>210.11</td>
<td>0.11</td>
</tr>
<tr>
<td>240.0</td>
<td>-119.89</td>
<td>240.11</td>
<td>0.11</td>
</tr>
<tr>
<td>270.0</td>
<td>-89.80</td>
<td>270.20</td>
<td>0.20</td>
</tr>
<tr>
<td>300.0</td>
<td>-59.70</td>
<td>300.30</td>
<td>0.30</td>
</tr>
<tr>
<td>330.0</td>
<td>-29.78</td>
<td>330.22</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Error spread = (0.30° - 0.0°) = 0.30°
2.3.2 Instrument Landing System (ILS)

The all weather operational capability of an airport can be improved by providing ILS. ILS is the international standard for approach and landing guidance and is considered as one of the
most favourite landing aids by the professional pilots. ILS was adopted by International Civil Aviation Organisation (ICAO) in 1947 and will be in service until at least 2010. The ILS System allows an approaching aircraft to align itself with the extended centerline of the runway and descended in an area free from obstructions on a defined glide angle (ICAO DOC 9750, 1999).

2.3.2.1 Categories of ILS
ICAO defines three categories of visibility for landing civilian Aircraft with the aid of ILS. These categories differ on two factors.
1. Minimum Decision Altitude (MDA)
2. Runway visual range (RVR)- Horizontal and vertical visual ranges.
These factors for different ILS categories are specified as shown in Table 2.4 (ICAO, Annex 10, 1995).

<table>
<thead>
<tr>
<th>Factors</th>
<th>VFR</th>
<th>CAT I</th>
<th>CAT II</th>
<th>CAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDA</td>
<td>300 mt</td>
<td>200 ft</td>
<td>100 ft</td>
<td>&lt;100 ft</td>
</tr>
<tr>
<td>RVR</td>
<td>5 Km</td>
<td>1800 ft</td>
<td>1200 ft</td>
<td>700 ft</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+8 mt</td>
<td>4 mt</td>
<td>1.3 mt</td>
<td></td>
</tr>
<tr>
<td>Integrity</td>
<td>10 sec</td>
<td>5 sec</td>
<td>2 sec</td>
<td></td>
</tr>
</tbody>
</table>

The higher the category of the ILS installed at airport, i.e., the lower is the decision height, the better is the guidance to the aircraft subject to the terrain and topography conditions.

2.3.2.2 Components of ILS
Three Parameters, which are essential for a safe landing, are Azimuth Approach Guidance, Elevation Approach Guidance, and Range from touch down point. These are provided to the pilot by the three components Localiser, Glide path and Marker beacons respectively.

2.3.2.3 Aircraft ILS components: The Azimuth and elevation guidance are provided by the Localiser and Glide path to the pilot continuously by an on board meter called the Cross Deviation Indicator (CDI). Range information is provided continuously in the form of digital read out if DME is used with ILS. However range information is not provided continuously if Marker Beacons are used. In this condition aural and visual indications of specific distances when the aircraft is overhead the marker beacons are provided by means of audio coded
signals and lighting of appropriate colored lamps in the cockpit (NORMAC ILS Manual, 1991). Fig. 2.5 shows the typical locations of ILS components.

Fig. 2.5 Typical locations of ILS components

2.3.2.4 ILS signal format

ILS theory founded on the concept of Difference in Depth of Modulation (DDM), which applies to Localiser course theory and glide path theory. ILS employs amplitude modulation of a radio frequency carrier to provide the guidance information. To obtain the required coverage for localizer and glide path, two RF signals need to be radiated. These two RF signals are defined as: (a) CSB signal and (b) SBO signal

a) CSB signal

This is an RF signal in which the RF carrier is amplitude modulated simultaneously by the audio frequencies of 90Hz and 150Hz. If \( V_c \sin \omega_c t \) is the carrier signal, the resultant CSB signal is expressed by:

\[
V_{CSB} = V_c \sin \omega_c t + m V_c \sin 90^\circ \sin \omega_c t + m V_c \sin 150^\circ \sin \omega_c t
\]

(2.6)

\[
V_{CSB} = V_c \sin \omega_c t + \frac{m V_c}{2} \cos (\omega_c - 90^\circ t - \frac{m V_c}{2} \cos (\omega_c + 150^\circ t)
\]

(1) \quad (2) \quad (3) \quad (2.7)

\[
+ \frac{m V_c}{2} \cos (\omega_c - 150^\circ t - \frac{m V_c}{2} \cos (\omega_c + 150^\circ t)
\]

(4) \quad (5)

This equation gives the following frequency components:

(1) A radio frequency carrier \( f_c \)

(2) A 90Hz lower sideband \( f_c - 90Hz \)

(3) A 90Hz upper sideband \( f_c + 90Hz \)
(4) A 150Hz lower sideband  \( f_c-150\text{Hz} \)
(5) A 150Hz upper sideband  \( f_c+150\text{Hz} \)

b) SBO signal

This is an RF signal in which the RF carrier is amplitude modulated simultaneously by the audio frequencies 90Hz and 150Hz with the carrier component removed. If \( V_c\sin\omega_c t \) is the carrier signal, the resultant SBO signal is expressed by:

\[
V_{\text{SBO}} = V_c \sin \omega_c t \left[ -\sin \omega_{90} t \sin \omega_c t + \sin \omega_{150} t \sin \omega_c t \right]
\]

\[
V_{\text{SBO}} = -\frac{mV_c}{2} \cos \left( \omega_c - \omega_{90} \right) t + \frac{mV_c}{2} \cos \left( \omega_c + \omega_{90} \right) t
\]

\[
+ \frac{mV_c}{2} \cos \left( \omega_c - \omega_{150} \right) t - \frac{mV_c}{2} \cos \left( \omega_c + \omega_{150} \right) t
\]

The frequency components in the Eq. 2.9 are:

(1) A 90Hz lower sideband  \( f_c-90\text{Hz} \)
(2) A 90Hz upper sideband  \( f_c+90\text{Hz} \)
(3) A 150Hz lower sideband  \( f_c-150\text{Hz} \)
(4) A 150Hz upper sideband  \( f_c+150\text{Hz} \)

2.3.2.5 Salient features of Landing

When a flight is approaching the airport, it descends from the enroute or oceanic airspace into terminal airspace. During landing, the aircraft must transit from the terminal flight to the final approach along the extended runway centerline by using the standard instrument approach procedures, published for each runway at the airport. From minimum approach altitude, pilot will follow the final approach procedure. The precision approach of the aircraft is guided by radio beams generated by the ILS. Aircraft maintains a speed of 100 to 150knots during descent, along the glide path beginning at the final approach fix (outer marker). When the aircraft reaches the authorized decision height, pilot lands the aircraft only if the runway or its lights are visible; otherwise, he aborts the landing (ICAO PANS OPS, 1993). The airborne receiver receives both the direct radiated and the reflected signals. The reflection
coefficient is a function of the angle of incidence and dielectric constant of the reflecting surface. The RF phase between the signals is given by the difference in path lengths and the phase of the reflection coefficient. As the aircraft flies along a flight path the difference in path lengths varies which gives a change of the RF phase difference. This results in a variation in DDM of the received signal (ICAO Annex10, 1995).

ILS employs amplitude modulation of a radio frequency carrier to provide the guidance information. It radiates two RF signals namely (a) Carrier with Side Band (CSB) signal and (b) Side Band Only (SBO) signal (NORMAC ILS, 1991). In CSB and SBO signals the carrier is amplitude modulated simultaneously by the audio frequencies of 90Hz and 150Hz. The resultant CSB signal is expressed as

\[ V_{CSB} = V_{cCSB} \sin \omega_c t + mV_{cCSB} \sin \omega_{90} t \sin \omega_c t + mV_{cCSB} \sin \omega_{150} t \sin \omega_c t \]  

(2.10)

where, \( V_{cCSB} \sin \omega_c t \) is radio frequency carrier, \( m \) is the modulation index, \( \sin \omega_{90} \) and \( \sin \omega_{150} \) are the audio frequencies of 90Hz and 150Hz respectively.

In SBO signal carrier component is removed. If \( V_c \sin \omega_c t \) is the carrier signal, the resultant SBO signal is expressed as

\[ V_{SBO} = V_{cSBO} [-\sin \omega_{90} t \sin \omega_c t + \sin \omega_{150} t \sin \omega_c t] \]  

(2.11)

The SBO signals follow an RF path through the Localiser transmitter separated from the transmitter modulation (CSB) and is radiated from separate antennas or from antennas common with the CSB signal. Since the SBO is not modulated with the carrier to which they are related in the transmitter it self, they are considered to mix with the carrier in space in a process referred to as "space modulation". The total SBO component will combine with the carrier component in space either exactly in phase (180°) or out of phase or at some phase angle (\( \phi \)). \( \phi \) may vary from 0° to 360°.

### 2.3.2.6 ILS facilities at Hyderabad airport

Hyderabad airport is situated in the middle of the city surrounded by high raise buildings. Hyderabad is one of the fast developing city for both national and international air traffic. The environment has been fast changing because of the urbanisation. It is the fifth largest city in India. Localiser is situated at 09 runway stop end and glide path is located in north at 450 ft away from the runway touch down point. Outer marker and Middle markers are located at
3.9 nautical miles (nmi) and 0.57 nmi respectively from the runway threshold point. The approach direction of the aircraft for landing is from the runway 27.

Localiser at Hyderabad airport operates at a frequency of 110.1 MHz. It provides course guidance throughout the descent path up to the runway threshold, providing a maximum coverage distance of 18 nmi from the antenna location. The guidance is provided along the course line at an altitude of 1,000 ft above the highest terrain and up to 4,500 ft above the elevation of the antenna site. Localiser antenna array consists of 12 antenna elements. The elements are spaced at a distance of \( \frac{3}{4} \lambda \) of the operating frequency. The radiation pattern of the antenna array becomes the course guidance. Modulation frequencies of 90 Hz and 150 Hz are used to provide right and left indications to the pilot. When the DDM is zero, the aircraft is correctly positioned on the runway centerline. If a DDM exists, the pilot must correct the aircraft's position until the DDM is zero. The depth of modulation of 150 Hz and 90 Hz signals depend on the relative strength of SBO signal with respect to CSB signal and also on the advance or retard angle of RF phase between them. DDM can be expressed as (Kayton and Fried, 1997).

\[
DDM = M_{150} - M_{90} = \frac{E_{SBO}}{E_{CSB}} (\cos \phi_r) \tag{2.12}
\]

where,

- \( M_{90}, M_{150} \) are the degree of modulation of the 90Hz and 150Hz components respectively.
- \( E_{SBO}, E_{CSB} \) are amplitudes of the SBO and CSB signals respectively
- \( \phi_r \) is the RF phase angle between SBO and CSB signals

The \( E_{SBO} \) and \( E_{CSB} \) in Eq. (2.12) can be expressed as

\[
E_{SBO} = E_{SBO, \text{direct}} + E_{SBO, \text{indirect}} = E_{SBO}(0) + E_{SBO}(\theta) \tag{2.13}
\]
\[
E_{CSB} = E_{CSB, \text{direct}} + E_{CSB, \text{indirect}} = E_{CSB}(0) + E_{CSB}(\theta) \tag{2.14}
\]

The indirect signals represent the radiation from the reflecting object (\( \theta \)). The path structure at the course line, where \( E_{SBO, \text{direct}} = 0 \) is mainly interesting. Eq. (2.12) can be rewritten as

\[
DDM = 2 \frac{E_{SBO}(\theta)}{E_{CSB}(0) + E_{CSB}(\theta)} (\cos \phi_r) \tag{2.15}
\]

Where \( E_{CSB}(0) \) is the maximum radiation. As \( E_{CSB}(0) \) is >> \( E_{CSB}(\theta) \). Eq. (2.15) can be written as,
\[ DDM = \frac{E_{SBO}(0)}{E_{CSB}(0)} \left( \cos \phi_{r1} \right) \] (2.16)

Where \( \phi_{r1} \) is the resultant phase between the reflected \( E_{SBO} \) indirect signal and the directly radiated CSB signal. The \( \phi_{r1} \) may vary several periods along the flight path, which results in a variation of DDM through \( \pm \) values.

2.3.2.7 Evaluation of ILS course structure

The course structure of the ILS is to be checked periodically. Otherwise, the deviations can be potentially dangerous. This mandatory checking is carried out using dedicated and specially equipped test flight and ground based field test receiver system. Data acquired using these systems is analysed to arrive at the specific performance parameters such as runway centerline alignment, course width and glide angle. The details of these are described in the following section.

2.3.2.7.1 Test flight measurements

Flight Inspection Unit (FIU) of Airports Authority of India owns a fleet of 4 flight calibration aircrafts. It consists of 2 Avro HS-748 and 2 Dornier DO-228. The Avro aircrafts are fitted with manual flight inspection systems. All types of navigation aids except Category (CAT) III ILS can be inspected with the available systems. For every 4 to 5 months, the ILS facility has to be checked with the test aircraft. The aircraft is tracked by a ground based theodolite tracker. To check, whether the electronic centerline is aligned with the physical centerline of the runway or not and to check the quality of course signal, the test flight follows the procedure prescribed in NORMAC-ILS (1991). The aircraft flies an arc about runway centerline at approximately 5 nmi from localiser and 1000 ft above ground level to ensure that the course width is satisfactory. During flight inspection four major checks are carried out. They are:

i) Zero DDM on the runway centerline

ii) Course width of 2°

iii) Course bends, if any, in the course line and

iv) Signal strength in the ILS coverage sector.

However, in this thesis only the first two checks are reported.

2.3.2.7.2 Ground based field test receiver measurements
Using the NORMAC ILS signal field test receiver, which is equivalent to an ILS receiver in the aircraft, course structure measurements are taken for various radiation angles. The field test receiver measures the DDM, sum of modulation of 90 Hz and 150 Hz signals and RF signal strength of the course structure.

### 2.3.2.7.3 Results and Discussion

Course structure measurements were taken on 9th Sept. 2002 and 20th Oct. 2002 for ± 10° of course angle using the ground based field test receiver. These measurements are compared with the flight calibrated data (12th June 2002). With reference to 12th June 2002 data, it is observed from 9th Sept. 2002 measured data that the electronic centerline of the runway (0 DDM) is shifted towards 150Hz signal side by approximately 0.3° and the course width is widened by 0.15°. The DDM values of 90 Hz and 150 Hz signals are plotted against the course angle for measured data in Fig. 2.6.

A 0.3° shift in the centerline of ILS causes a horizontal error of 20.9 m at 3 km distance. The change in the course structure could be due to reflections from the recently built surrounding high raise buildings and ground surface in front of the antenna array. It may also be due to the reflection properties (from dry sand soil to a wet ground) of the ground surface, which changes during these seasons. The reflection coefficient of the ground increases when dry ground becomes wet. In this region, the hot summer ends in June and till September the area is full of monsoon rains. The DDM variation is reflected in the electronic centerline and course width changes. The variation in the runway centerline of the system is due to the $\phi_1$ variation between the reflected SBO signal ($E_{SBO}$, indirect) and the directly radiated CSB signal ($E_{CSB}$, direct) (Eq. 16). The variation of course width is due to the $\phi_1$ variation between the $E_{SBO}$ and $E_{CSB}$ signals (Eq.13 and 14). The DDM variation causes the Course Deviation Indicator (CDI) of the aircraft receiver to show false indication and is potentially dangerous. As the weather conditions did not vary significantly from Sept. to Oct. 2002, only a 0.01° shift in centerline and no significant change in the course width from 20th Oct.2002 data with reference to Sept. 2002 are noticed.
In order to overcome the environmental effects associated with the ILS radiation pattern, augmented GPS such as Wide Area Augmentation System (WAAS) can be used for navigation and landing aid. WAAS can be used to create the straight instrument approach corridors, which does not have any angular dependence as in ILS (Sasibhushana Rao et al., 2001). The source of radiation in case of ILS is at the ground whereas in WAAS, the source of radiation is from the space. Since the GPS signal is a spread spectrum signal it rejects the signals with large delays using the narrow correlator spacing resulting in better navigation performance.

![ILS course radiation patterns during different seasonal days](image)

**Fig.2.6 ILS course radiation patterns during different seasonal days**

### 2.4 Modern satellite based navigation systems

The ground based navigation systems have problems like ground reflections, electromagnetic interference and reflections from physical systems. These problems are mostly avoided in satellite based navigation systems, due to its space constellation. Satellite navigation is based on a global network of satellites that transmit radio signals in the low/medium earth orbit. The satellite navigation system have the following advantages: (i) satellite can radiate a radio frequency transmission and may also carry a transponder beacon and can provide all weather service, (ii) satellite navigation systems are potentially capable of high accuracy. The modern
Satellite based navigation systems are: TRANSIT, GPS, GLONASS and GALILEO (Misra Pratap et al, 1999).

i) TRANSIT

Transit is the first satellite aided navigation system for civilian use from 1967. Transit works on doppler principle, using seven low orbiting satellites. Each of these satellites transmits on two frequencies 150 MHz and 400 MHz. Position is calculated by measuring the change in frequency of satellite transmissions as it speeds past in low orbit. Using the satellite's position and velocity information, user position is calculated by measuring the change in frequency of satellite transmissions. The TRANSIT satellites were orbiting in polar plane at about 1100 km altitude. The TRANSIT satellites were affected by gravity field variations than higher orbiting satellites like GPS. Since their number is very limited, one does not get a 'fix' very often. Further, TRANSIT satellites transmissions at 150 and 400 MHz were more susceptible to ionospheric delays and disturbances than the higher GPS frequencies. Since GPS was fully operational, TRANSIT was discontinued on 31st December 1996 (Leick, 2004).

ii) GPS

GPS is a satellite based radio navigation system designed and developed by Department of Defense (DOD), U.S.A. The first GPS satellite was launched on February 22, 1978. GPS provides accurate three dimensional position of user anywhere in the world and under all weather conditions (Kaplan, 1996). The satellites transmit at frequencies L1 (1575.42 MHz) and L2 (1227.6 MHz) modulated by two types of codes and the navigation message. At present L1 carrier is modulated with C/A and P-codes, whereas L2 is modulated with a P-code only. The advantages of GPS are: i) intentional interference like Jamming, unintentional interference will affect GPS least, since spread spectrum techniques are used in it and ii) system accuracy can be improved to the order of centimeter's using Differential techniques like DGPS, WAAS, GAGAN etc., Full operational capability of GPS is achieved on July 17, 1995.

iii) GLONASS

The Russian GLONASS system launched its first navigation satellite in 1982. Like GPS, GLONASS was planned to contain at least 24 satellites. The nominal orbits of the satellites are in 3 orbital planes separated by 120°, with inclination of 64.8°. The nominal orbits are
circular with radius of 25,500km. The major difference between GLONASS and GPS is that each GPS satellite transmits at its own carrier frequency. If \( p \) is the channel number that is specific to the satellite, then

\[
f_1^p = 1602 + 0.5625p \text{ MHz} \tag{2.17}
\]

\[
f_2^p = 1602 + 0.4375p \text{ MHz} \tag{2.18}
\]

Similar to GPS, there are C/A codes on L1 and P-codes on L1 and L2. But the code structures are different. The GLONASS broadcast navigation message contains satellite positions and velocities in the PZ90 Earth Centered Earth Fixed geodetic system. Recently 3 GLONASS satellites are launched in 2002 and GLONASS program is undergoing a modernization.

iv) GALILEO

The European Civil Satellite Navigation Program is called Galileo. Galileo space segment is expected to consist of a global constellation of about 30 satellites, distributed over 3 planes. The nominal orbits are expected to be circular, with semi major axes being close to GPS and GLONASS systems. Galileo satellites transmit at 3 frequency bands namely, E1-L1-E2, E5A-E5B and E6. In order to make Galileo and GPS compatible, the carrier frequency for the Galileo E1-L1-E2 will be 1575.42MHz, which is the same as GPS L1. Similarly, E5A and L5 will use 1176.45 MHz as the common carrier frequency. The modulation codes and chipping rate for the various carriers is still to be finalized. The carrier frequencies of GPS, GLONASS and Galileo are presented in Table 2.5 (Leick, 2004).

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Multiple of 10.23</th>
<th>Carrier frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5 &amp; E5A</td>
<td>115</td>
<td>1176.45</td>
</tr>
<tr>
<td>E5B</td>
<td>117.5</td>
<td>1202.025</td>
</tr>
<tr>
<td>L2</td>
<td>120</td>
<td>1227.60</td>
</tr>
<tr>
<td>G2</td>
<td>See Eq.(2.18)</td>
<td>per satellite</td>
</tr>
<tr>
<td>E6</td>
<td>125</td>
<td>1278.750</td>
</tr>
<tr>
<td>L1, E1-L1-E2</td>
<td>154</td>
<td>1574.42</td>
</tr>
<tr>
<td>G1</td>
<td>See Eq.(2.17)</td>
<td>per satellite</td>
</tr>
</tbody>
</table>

For a transition period of 10 years (approximately) during, which both VOR and GPS/GLONASS/GALILEO/WAAS can be used as a sole means of navigation. This period is
a reasonable compromise between the ICAO’s desire to minimize its cost for maintaining and replacing VOR and the aircraft operator’s desire to get maximum utilization from their investment in conventional avionics. Present aircraft’s have to be equipped with ILS receivers, until the GAGAN is certified as a sole means of approach aid, which will be meeting the requirements of CAT I PA.

2.5 Conclusions

To appreciate the significance of developments in the aviation, salient features of the primitive methods and other terrestrial navigational aids are presented. The VOR provides the navigational signals for an aircraft receiver, which allows the pilot to determine the bearing of the aircraft. The error spread of the DVOR of Hyderabad airport is estimated by collecting one year field strength data (January-December 2002). The maximum bearing error observed during the period is 0.30°. The standard deviation of the error spread is 0.0835°. The DVOR bearing error spread is due to the reflections from the surrounding high raised buildings, iron fencing and recently erected chimney in the 300° radial direction. Similarly in case of ILS, the field strength data acquired using test aircraft and NORMAC ILS signal field test receiver are compared for different dates. The results indicated that during June to September 2002, the centerline of the runway is shifted and the course width is widened. Because of the change in the course structure, the horizontal accuracy provided by CAT I ILS crossed the limit of 16m. However, no significant change is noticed in the centerline of the runway and course width during Oct.2002 data with reference to Sept. 2002. To avoid the environmental effects on the ground based navigational aids, a more economical space based satellite navigation system such as WAAS may be used for aircraft landing. A system similar to WAAS can be designed and implemented for low and equatorial latitudes to achieve better accuracies.