Aircraft Navigation Systems

Introduction

- The primary purpose of an on-board navigation system in an aircraft is to know accurately, the present position to guide the aircraft along a desired path.
- The earliest navigation aid was a magnetic compass, which had its own serious limitations.
- The next improvement was the horizontal gyro, which remained stationary in an inertial space and directional orientation of aircraft could be measured referencing to this stationary gyros axis.

- Further developments of navigation aid included radio-navigation systems such as Non-Directional Beacons (NDB), VHF Omni Range (VOR) stations which served as an effective navigation aid over much of the land mass of earth; NDB and VOR systems require a large number of expensive ground stations.
- The next improvement was the development of an autonomous Inertial Navigation System (INS). INS also suffers from error build up, which has to be corrected using a reference.

- Presently, the navigation of modem aircraft use one or combination of the following:

(i) Radio Navigation aids such as NDB, VOR, DME and ILS.

(ii) Inertial Navigation Systems, and its derivatives such as MHRS-INS a well as GPS-INS, and

(iii) Satellite-based navigation systems, such as GPS, GPS-aided INS.

Radio Navigation Aids

- In 1907, Bellini and Tosi used two mutually orthogonal loops as an antenna from which directions of incoming radio waves can be determined by the relative magnitudes of current vectors in the two coils.
- Later Adcock of developed a modified direction finding system, which was widely used for the next thirty years.
- These were operating in medium frequency (300-1000 kHz) range.
- Sharper radio beams were possible by using VHF range (100-300 MHz) during 1920s. USA army developed successfully improved Bellini-Tosi loops/goniometer.

Radio Navigation Systems

- The Radio Navigation Systems depend on a network of ground-based transmitters.
- The airborne equipment receives the radio beams from transmitters, to know the direction of flight with respect to the ground station, and also fix the aircraft's present position using two separate ground stations-the so called "position fixing".

- There are three major systems currently in use today:

(i) NDB/ADF (Medium Frequency 100-300 kHz)

(ii) VOR (VHF range 100-300 MHz)

(iii) ILS (VHF range 100-300 MHz)

- There were other systems like TACAN and VORTAC, hyperbolic navigation systems (Decca), Long Range Navigation (LORAN) systems, Omega, etc., for both civil and military applications.
- All of these are now generally replaced with GPS-based systems, eliminating expensive ground network, at the same time improving accuracy.

(i) Non-directional Beacons-NDB (200-550 kHz):

A NDB transmits non-directional radio signals which are detected by an aircraft equipped with a directional antenna and receiver to determine the bearing to the ground beacon and home on to it.

NDB is similar to light house-and acts as a RF equivalent of light house.

The ground equipment consists of a transmitter operating at a frequency range of 200-500 kHz(Medium Frequency).

These beacons are modulated with 1020 Hz audio tone and as a Morse code station identification signal at least twice in a minute.

The primary function of NDB is to provide navigation during APPROACH and LANDING phase of the aircraft.

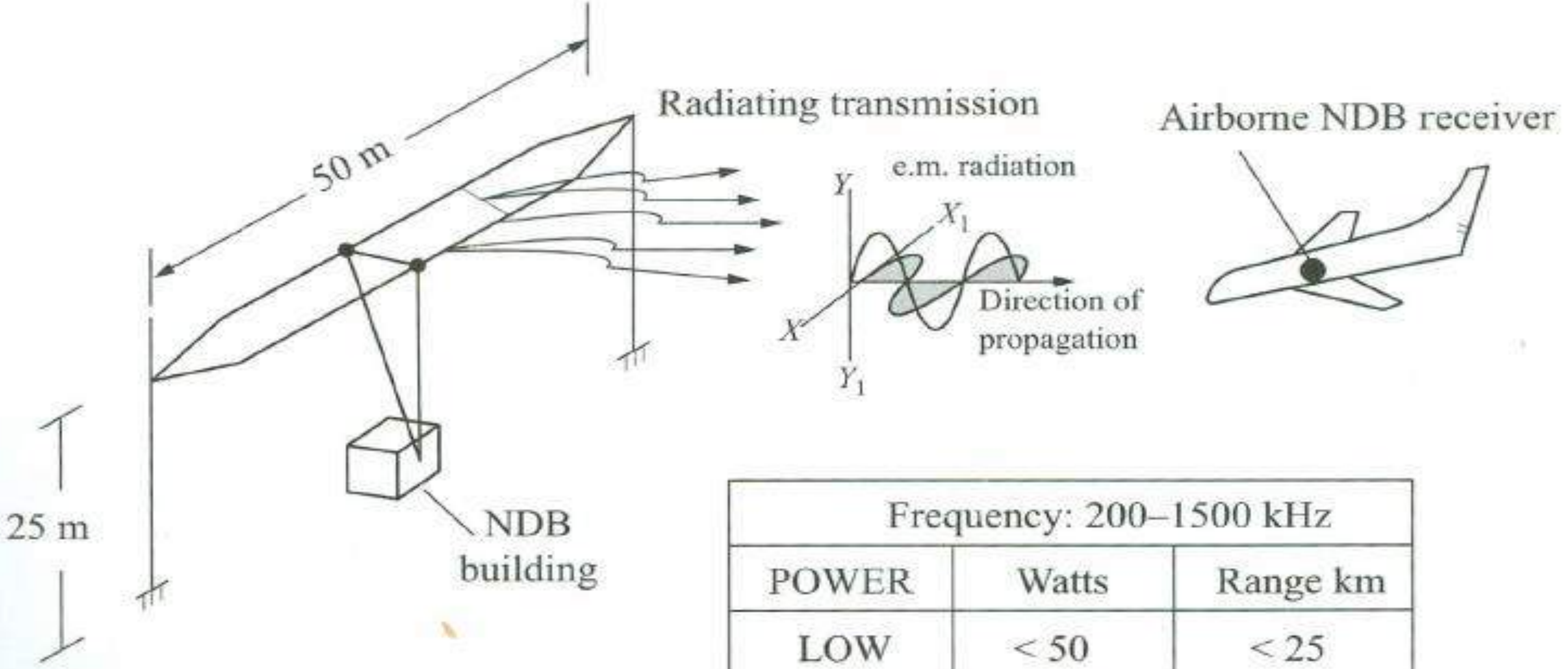
Basic Principle of Operation of NDB

- NDB has two components:

(i) Ground equipment, and

(ii) On-board equipment in the aircraft.

- The ground equipment is essentially a medium-frequency radio transmitter in the 200-500 kHz band, which radiates an uninterrupted carrier which is modulated at regular intervals by a tone keying for station identification.
- NDB is so called because it provides non-directional radiation pattern, with uniform radiation in all directions.
- This is in contrast with say ILS localiser which has a highly directed radiation pattern.



Frequency: 200–1500 kHz		
POWER	Watts	Range km
LOW	< 50	< 25
MEDIUM	< 2000	< 100
HIGH	> 2000	< 150

Fig. 9.1 NDB antenna (ground station).

The antenna is downsized to practical lengths by using discrete inductor coils and capacitors to achieve resonance—the so called "loaded" antenna. Otherwise the antenna length in metres for 300 Hz would be impractically long $\left(\lambda = \frac{c}{v} = \frac{3 \times 10^8}{300 \times 10^3} = 1000 \text{ m}\right)$ distance of 1 km.

The radiation pattern is circular and has same intensity in all directions. Proper grounding and its maintenance is required for efficient radiation as the earth resistance comes in series with the antenna.

Airborne NDB Receiver

- The most recent NDB receiver consists of:

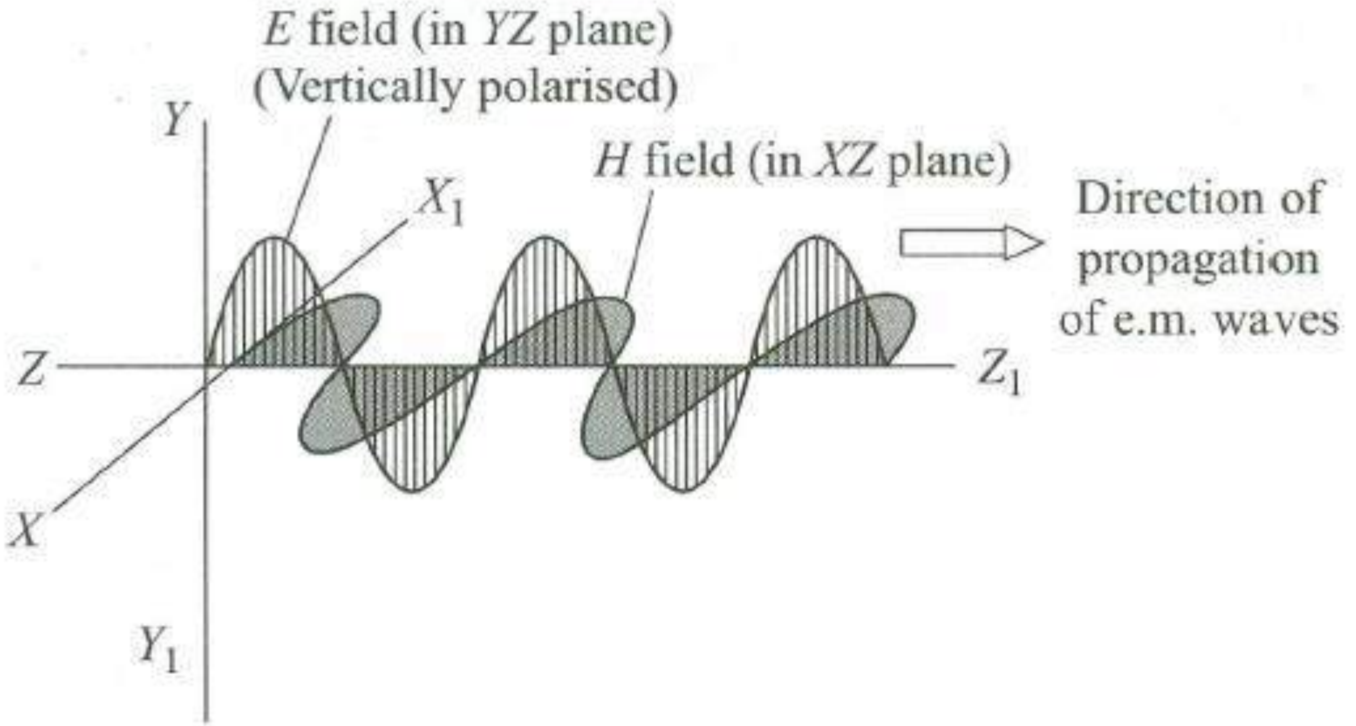
(i) Fixed antenna wound on ferrite slabs, projecting only about 3 Cm from the aircraft skin, and extending horizontally by about 30 cm.

(ii) Fixed cross-loop system working in conjunction with a motor-driven goniometer (angle measuring device).

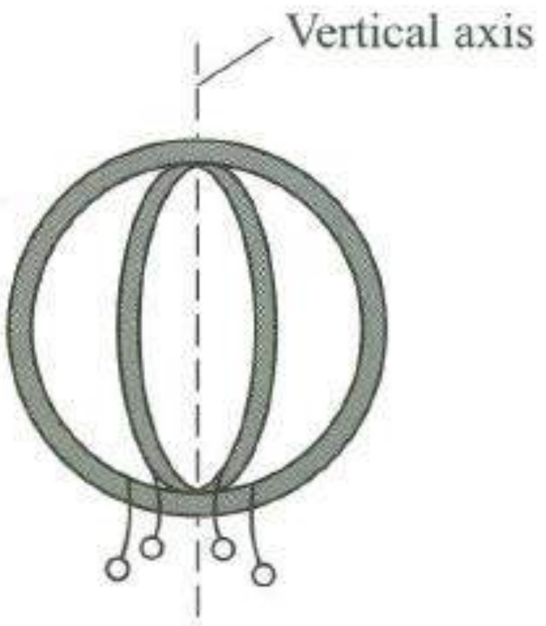
- The operation starts with the pilot selecting the transmission frequency of the NDB station located on ground.
- The airborne NDB receiver picks up this signal and the goniometer + fixed cross loop system hunts for minimum signal to give the bearing of the NDB.
- The NDB station radiates electromagnetic energy with electrical field vertically polarised. The associated magnetic field of electromagnetic wave will be horizontally polarised. Both waves will be perpendicular to the direction of propagation as shown in the Figure (a).
- Two antennas are required which are known as the LOOP antenna and the SENSE antenna.

LOOP Antenna

- This is an inductive antenna in the aircraft, consisting of one or two loops of wire, to sense the magnetic field component of the radiated field.
- Loop aerial is a simple directional antenna used as a receiver for receiving radio signals transmitted from a NDB transmitter. It consists of a number of turns of wire which forms the antenna loop.
- If the loop is perpendicular to the plane of propagation, then the horizontal magnetic component of a vertically polarised electromagnetic radiation couples into the loop, and induces voltages in the sides of the loop.



(a) Electric and magnetic fields of e.m. field radiated



(b) Two loops antenna in the aircraft

Fig. 9.2 (a) E and H fields radiated off the NDB ground station, and **(b)** a fixed 2-loop antenna within the aircraft.

Sense Antenna

- This is a long wire (in older aircraft) seen mounted from the aircraft cabin roof to the tail fin.
- For modem aircraft, both loop and sense antenna are located in the same tear drop-shaped case mounted as near the centre line of aircraft as possible. The omnidirectional SENSE antenna captures the electrical field component of the electromagnetic field radiated from the NDB beacon.
- The radiation pattern of sense antenna will be circular.

VHF Omnidirectional Range (VOR)

- VOR stands for VHF Omnidirectional Range, which is a type of a ground based electronic aid to short range (200 km) navigation for aircraft. Each VOR operates between 108.0-117.5 MHz (VHF range).
- A VOR signal received in the aircraft provides the pilot bearing data in degrees from the VOR station to the current position of the aircraft The bearing is generally referenced to magnetic north. VOR furnishes only the bearing (in degrees).
- Many VOR stations have another co-located nav-aid called DME (Distance measuring equipment) to obtain range data also. VOR and DME together give both bearing and slant range of aircraft.

- VOR requires a network of expensive ground stations. Each ground station broadcasts a VHF radio (at ~ 100 MHz) composite signal including:
- (i) ground stations identity in Morse code (and some times in voice identification as well), and
- (ii) bearing data which is received by the VOR receiver to deduce a magnetic bearing from the station to the aircraft-i.e., the direction from the VOR ground station with respect to the earth's magnetic north at the time of installation.

- VOR provides 360 courses to and from the VOR station selectable by the pilot.
- The VOR's main advantage is that the radio signal furnishes a reliable and unambiguous radial line from the VOR ground station, which is selected by the pilot, to follow the correct course.
- Thus the aircraft can be made to fly from station to station by tuning in successive VOR stations in the on-board VOR receivers.
- VOR data can also be displayed on Horizontal Situation Indicator-a more sophisticated RMI.

- VORs are more accurate and reliable than ADFs for a variety of reasons:

(i) Less course bending around hills and coastlines

(ii) Less interference from thunderstorms

(iii) More accurate bearing (degrees) information, as radials (one of 360 radials)

(iv) Surrounding radio stations do not affect VOR

(v) More reliable than NDB/ADF, due to all-solid-state electronics.

- VOR's main disadvantage is, since it works in VHF band, a direct line-of-sight (LOS) to VOR station from the aircraft must exist, to obtain the bearing data from the station.
- VOR itself is now being replaced by fully autonomous GPS aided INS; autonomous because the navigation system uses on-board GPS receiver and INS, and does not rely on ground-based radio stations.

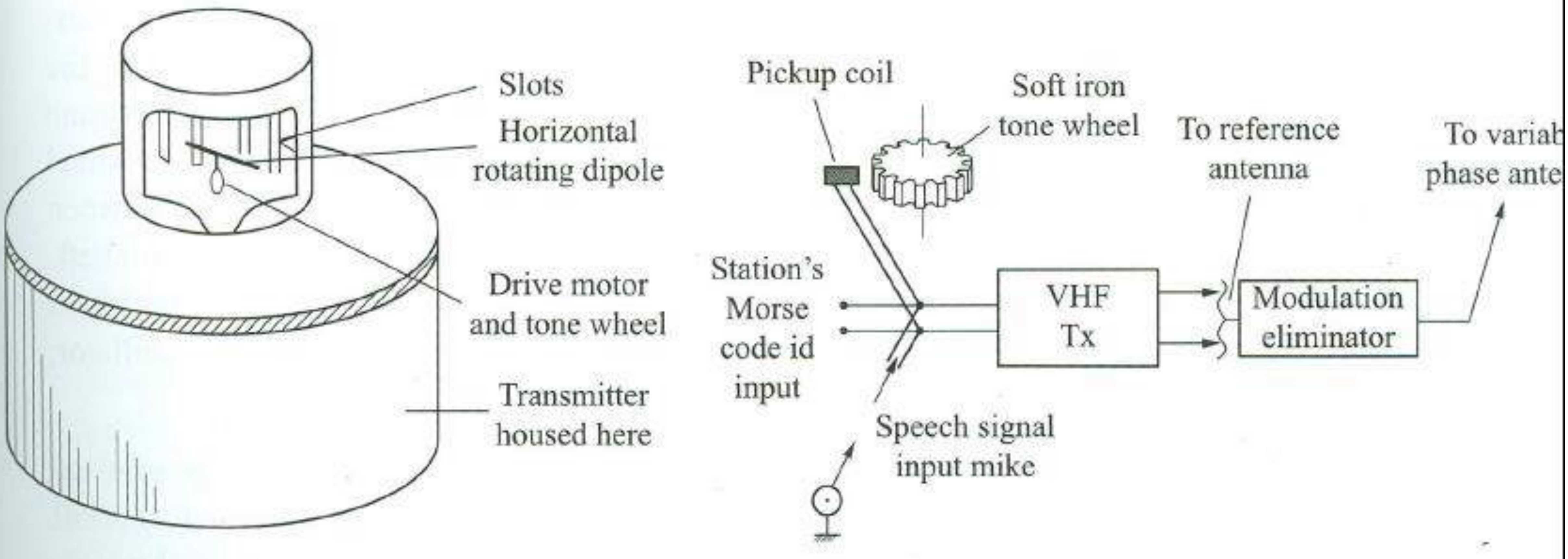
Principle of VOR Operation

- VOR stations have VHF frequency allocations between 108.0 MHz and 117.95 MHz, with a spacing between successive stations of 50 kHz .
- VOR issues two signals:

(i) Reference-phase-a 30 Hz signal is frequency modulated on a sub-carrier of 9960 Hz.

(ii) The second-phase is also 30 Hz modulated, but this time, amplitude-modulated, and it is derived from the rotation (mechanical/electronic) of a directional antenna array-30 times per second.

A highly directed beam is radiated out of VHF station, over the entire 0-360° at an interval of each degree.



(a) VOR housing room

(b) Block diagram of transmitter

Fig. 9.5 VOR transmitter station and block schematic.

- **Transmitter:** The ground station consists of a standard AM transmitter. A high-power (~200 W) is used for enroute VOR, covering a range of several hundred kms.

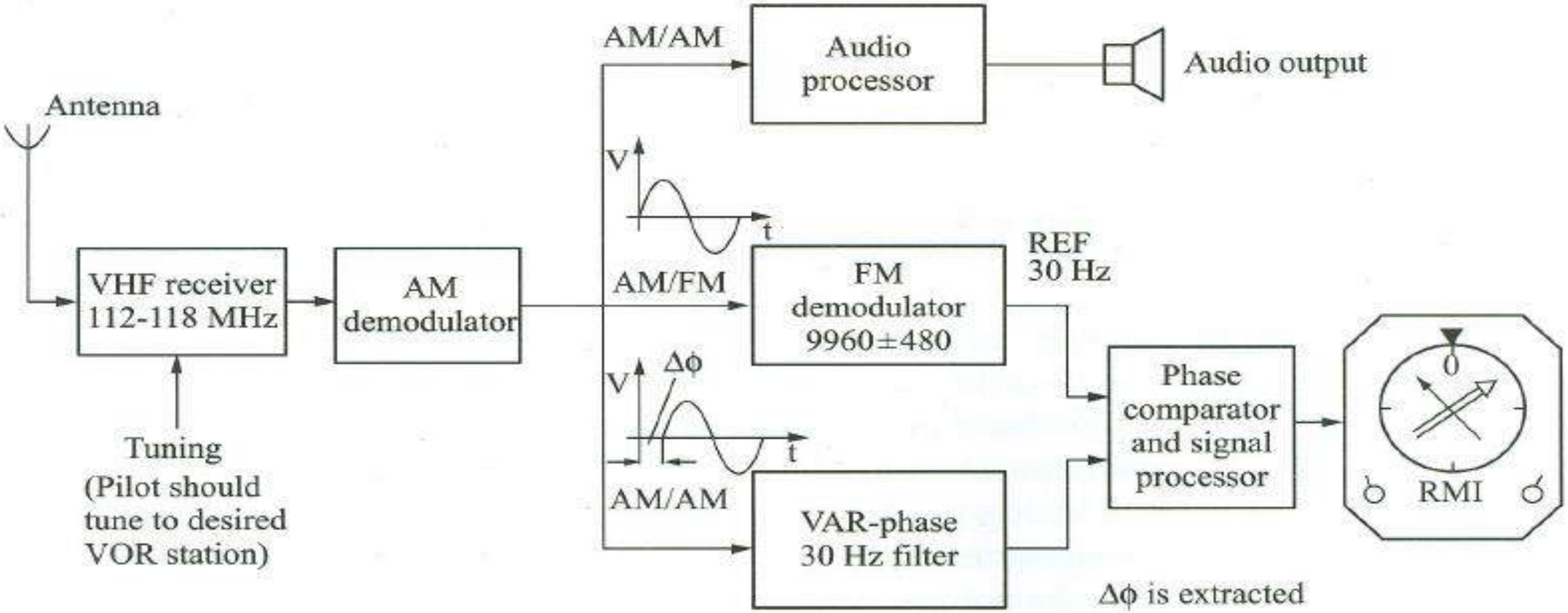
- The transmitter modulator gets its input signals from three sources:

(i) Reference phase generator

(ii) Variable phase generator

(iii) Station identification signals .

VOR Receiver



Note: Phase delay between reference wave (magnetic north) and variable phase signal is used to display the magnetic bearing of aircraft to the VOR station

Fig. 9.7 Airborne VOR receiver.

1. Audio Signal is extracted from the demodulator output and processed in the Audio Processor to give an aural output through a loudspeaker.

2. Reference Signal is derived from the output of the AM demodulator. The frequency-modulated, 9960 Hz subcarrier is recovered to yield 30 Hz reference signal ~ (9960 ± 480 Hz).

3. Amplitude modulated Variable phase signal is obtained in the 30 Hz filter. A phase comparator compares the relative phase difference ΔΦ between the reference wave and the lagging variable signal to obtain the bearing information.

Thus, the VOR receiver tells the pilot in what direction he is located with reference to the VOR station-referred to as RADIAL. By comparing two such radials, from two different VOR ground stations, he can "fix" his position on the navigation

- **Major advantages of VOR are:**

1. It provides more information, allowing pilots to follow a line in the sky more easily that withNDBs.

2. It offers greater accuracy and is more reliable than NDBs.

- **Disadvantages of VORs include:**

1. It is very expensive to buy, install and maintain VOR ground station.

2. Performance of VORs are affected by obstructions or when the aircraft fly over mountaineous *terrain-(site and enroute errors).*

This error is mitigated by Doppler VOR-DVOR.

Doppler VOR (DVOR)

- DVOR enhances the bearing accuracy particularly when the VOR ground stations (beacons) an installed in the vicinity of obstructions, or when the aircraft using VOR signals fly over mountainous terrain.

DVOR resolves this problem by using:

1. A wide-base antenna array for suppressing the effects of multipath propagation, and

2. Doppler effect for determination of bearing.

- In DVOR, the ground station consist of an omnidirectional antenna located at the center, surrounded by a circular array of loop antenna. The array has about 48 antennas arranged along the circumference of a large diameter 0 44 feet.
- The peripheral antennas are supplied with switched RF power displaced 9960 Hz away from the central antenna feed.
- Each aerial is switched ON, one at a time in sequence to radiate VHl energy-starting from the antenna at North of the VOR station.
- The antenna is either mechanically switched sequentially as in earlier DVORs, or by using solid-state switches.

When the antenna "moves" towards the aircraft, the radiating frequency f increases to $f + \Delta f$ where Δf is the Doppler shift. Doppler shift Δf, depends the velocity of "rotating" antenna:

$$\Delta f = \frac{f_c V}{c} \tag{9.2}$$

where, f_c = VHF carrier frequency ≈ 114 MHz

V = tangential velocity in m/s = πDN

D = diameter of outer antenna array, 13.4 m

N = "rotation" per second of the directional beam

c = speed of light = 3×10^8 m/s

$\Delta f \approx 480$ Hz, with an array diameter of 13.4 m and speed of 30 rotations/second. The 9960 Hz thus varies by ±480 Hz at 30 Hz sine wave. This will be equivalent to frequency modulating the subcarrier frequency of 9960 Hz. The modulating signal, as noted above is a sinusoidal wave of 30 Hz.

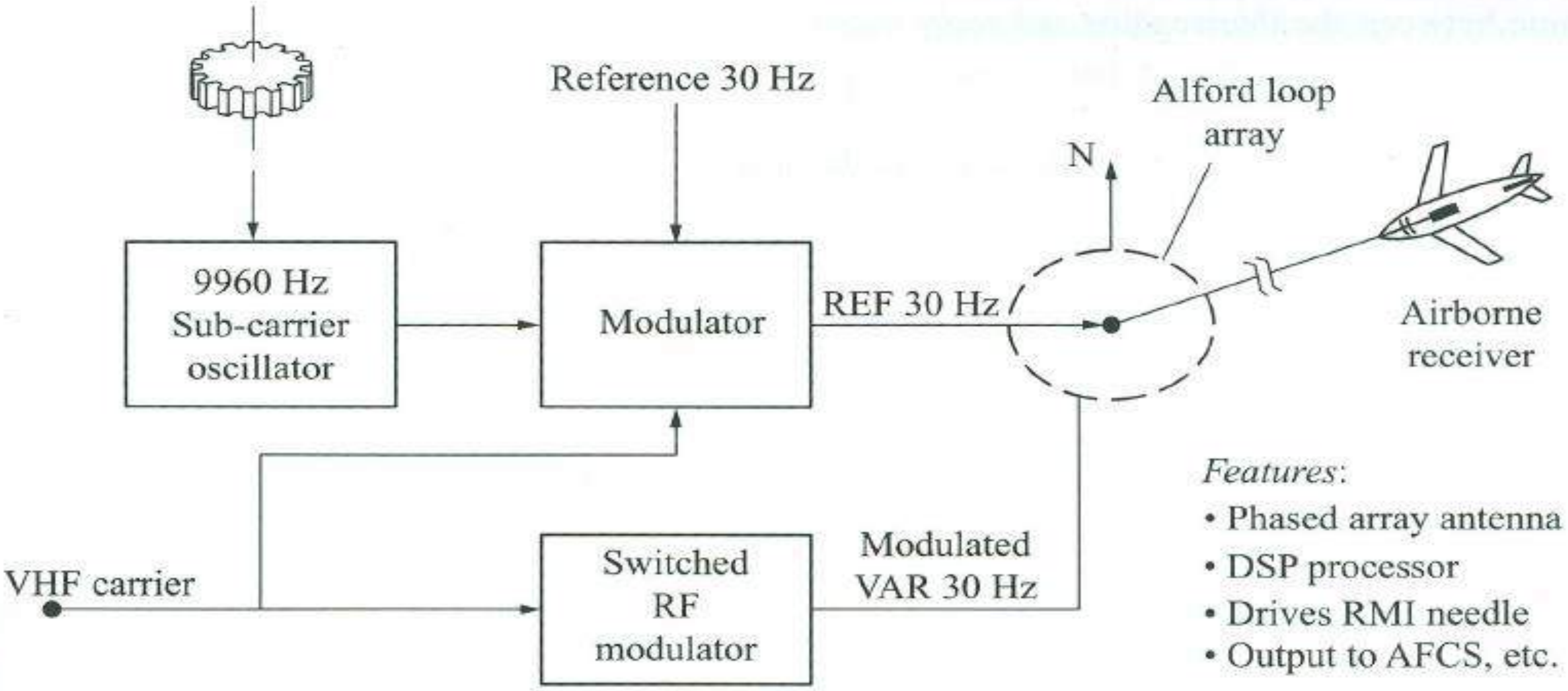


Fig. 9.9 All solid-state VOR system.

Distance Measuring Equipment, DME

- DME is the equipment which measures the range (slant) distance between the aircraft and DME station-usually colocated with VOR station. Ground distance is computed using altitude data and slant range.

DME consists of: (i) an airborne interrogator pulse generator modulated with an r.f. frequency ranging any where between 960–1215 MHz, and (ii) a ground-based Transponder which receives the pulse and retransmits an amplified pulse after a fixed delay of about 50 μs. The on-board DME receiver acknowledges this pulse, subtracts the fixed delay of 50 μs to determine Δt, the difference in time between the interrogator and reply pulses, which is a measure of the slant range, given by

$$R = c\,\Delta t$$

where, c = speed of electromagnetic wave, the speed of light $\approx 3 \times 10^8$ m/s.

This is the basic principle used in the DME.

1. Operating frequency: 960-1215 MHz.

2. DME Onboard equipment consisting of a Transmitter-Receiver pair, blade antenna and Range Computer to display range distance

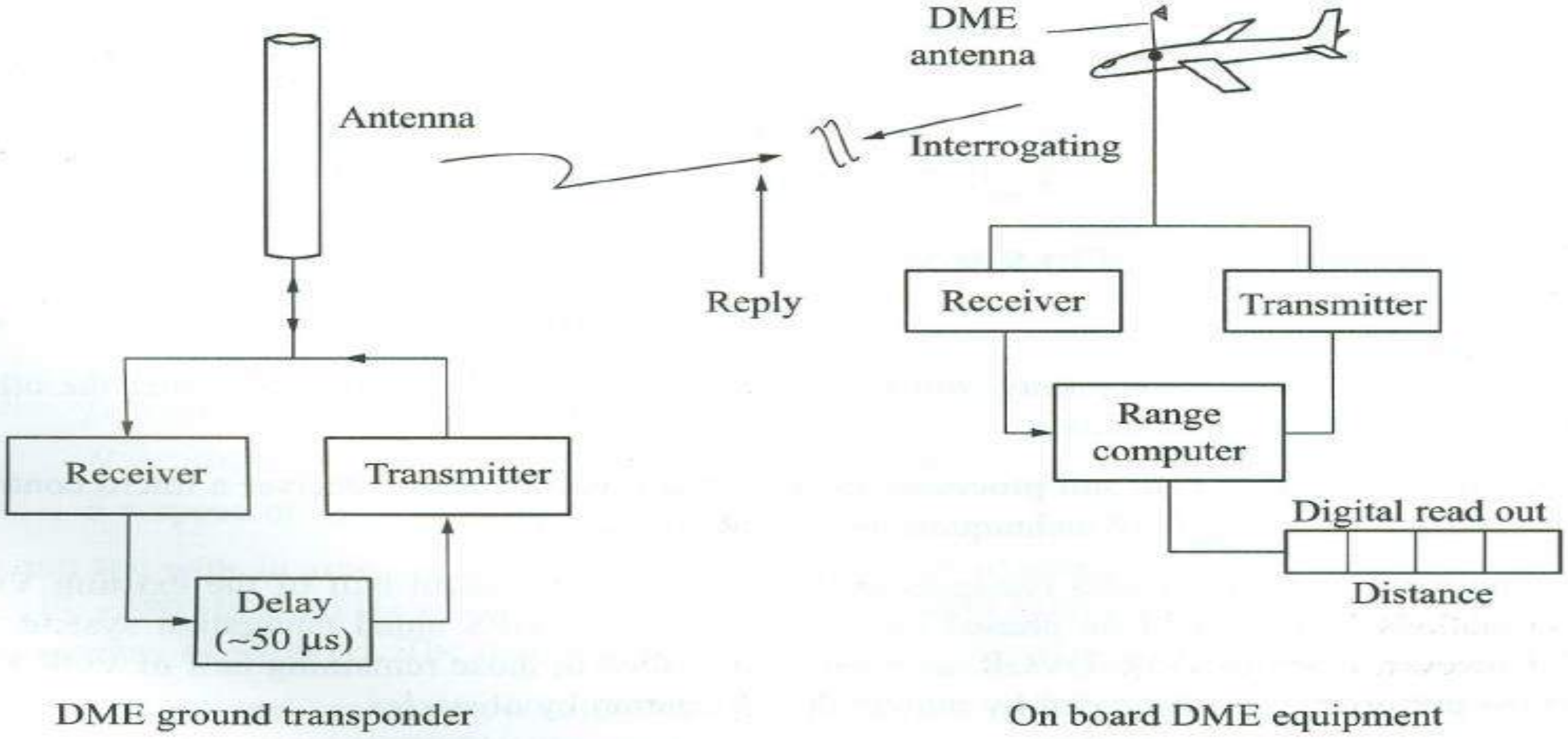


Fig. 9.10 DME system—onboard and ground equipment.

Instrument Landing System (ILS)

- ILS is a ground-based approach and landing aid used throughout the world today. It provides precision guidance to an approaching aircraft.
- ILS comprises of 3 main subsystems:

(i) Localiser for horizontal guidance to line up the aircraft with the centreline of the runway

(ii) Glideslope for vertical guidance along a safe 2-30 glide slope right up to runway, and

(iii) Two or three RF Marker Beacons to provide "distance to run" for approaching aircraft.

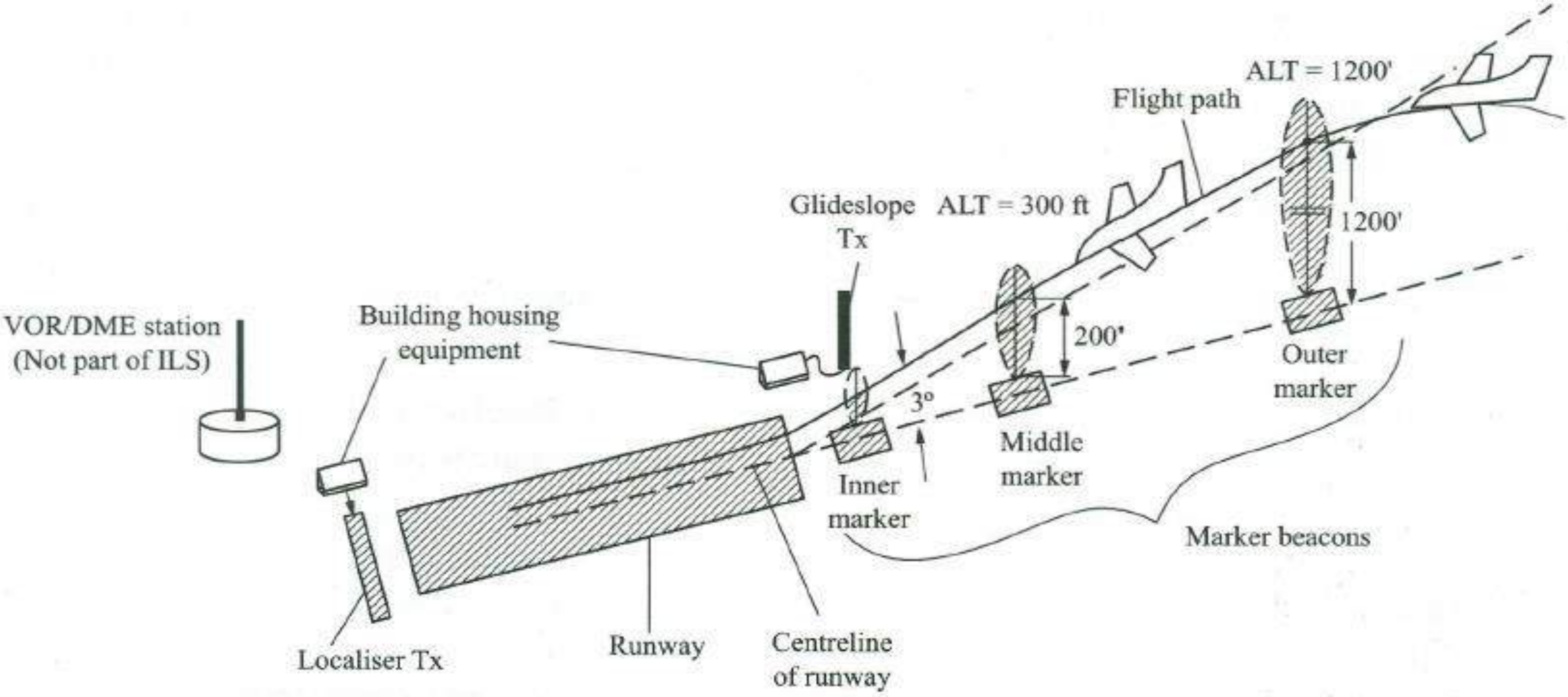


Fig. 9.11 ILS system for approach and landing of aircraft.

(i) Localiser (LOC):

Localiser provides guidance in the horizontal plane (in the lateral direction). Aircraft guidance is provided by localiser receiver in the aircraft and the LOC display, located at the bottom of FDS or EFIS display.

The on-board LOC receiver measures the Difference in Depth of Modulation (DDM-an ILS terminology) of the 90 Hz and 150 Hz signal.

Depth of modulation-also known as modulation index is a measure of how much the modulated signal changes around its original value as given by the expression:

D, depth of modulation = M/A

where, M = peak amplitude of modulating audio frequency signal

A = another chosen constant of the carrier frequency

M and A are defined by $y(t)$, the instantaneous value of modulated carrier:

$$y(t) = \underbrace{A \sin \omega_c t}_{\substack{\uparrow \\ \text{Carrier}}} + \frac{M}{2}\left[\underbrace{\sin\{(\omega_c + \omega_m)t + \phi\}}_{\text{upper side band}} + \underbrace{\sin\{(\omega_c + \omega_m)t - \phi\}}_{\text{lower side band}}\right] \tag{9.3}$$

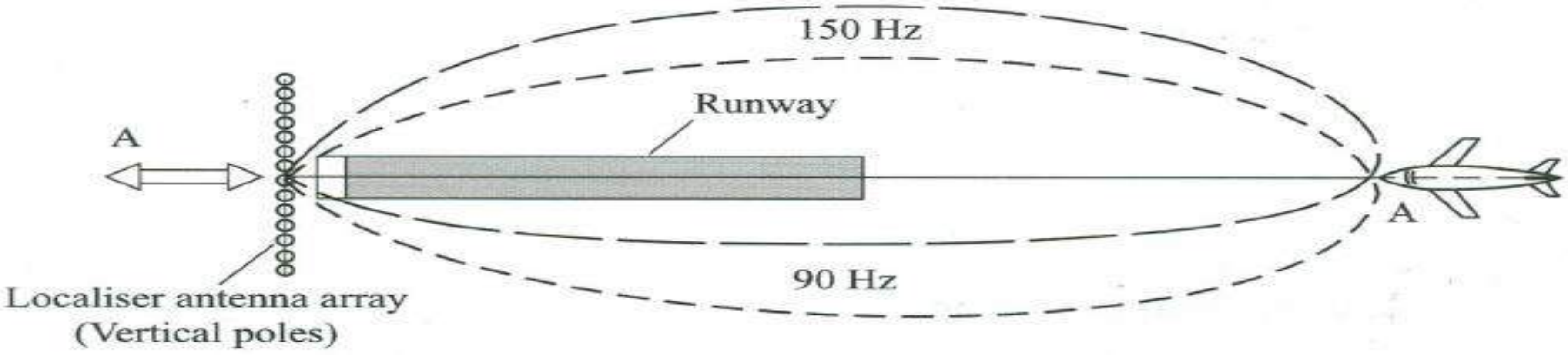
where, A = related to carrier wave, unmodulated amplitude

ω_c = angular frequency of the carrier VHF

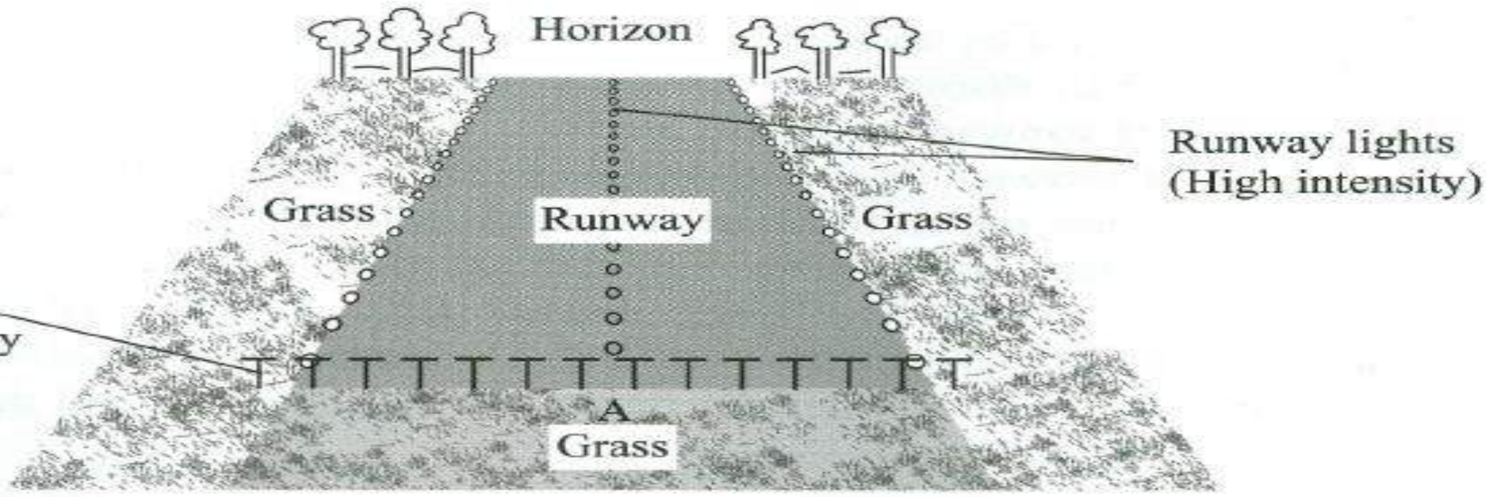
ω_m = modulating 90 or 150 Hz signal

ϕ = phase constant

If $D = 0.5$ (or 50% modulation), the carrier amplitude varies by 50% above and below the unmodulated level of carrier wave, as shown in Figure 9.13.



(a) Radiation pattern of LOCALISER beam



(b) Runway view from an observer at A

Fig. 9.12 Localiser antenna, pattern.

(ii) Glide Slope (GS):

While the localiser provides information to the pilot about horizontal-plane guidance to line up the aircraft to the centre line of the runway, glide slope (GS) gives vertical guidance.

A radio-frequency beam at an angle of 3° to the horizontal plane of runway, is fanned out. The standard glide-slope path is 3° downhill to the approach-end of the runway.

The glide-path projection is normally adjusted to 3° above horizontal so that it intersects the Middle Marker (MM), at about 200 ft altitude and the Outer Marker (OM) at an altitude of about 1200 .ft above the runway elevation.

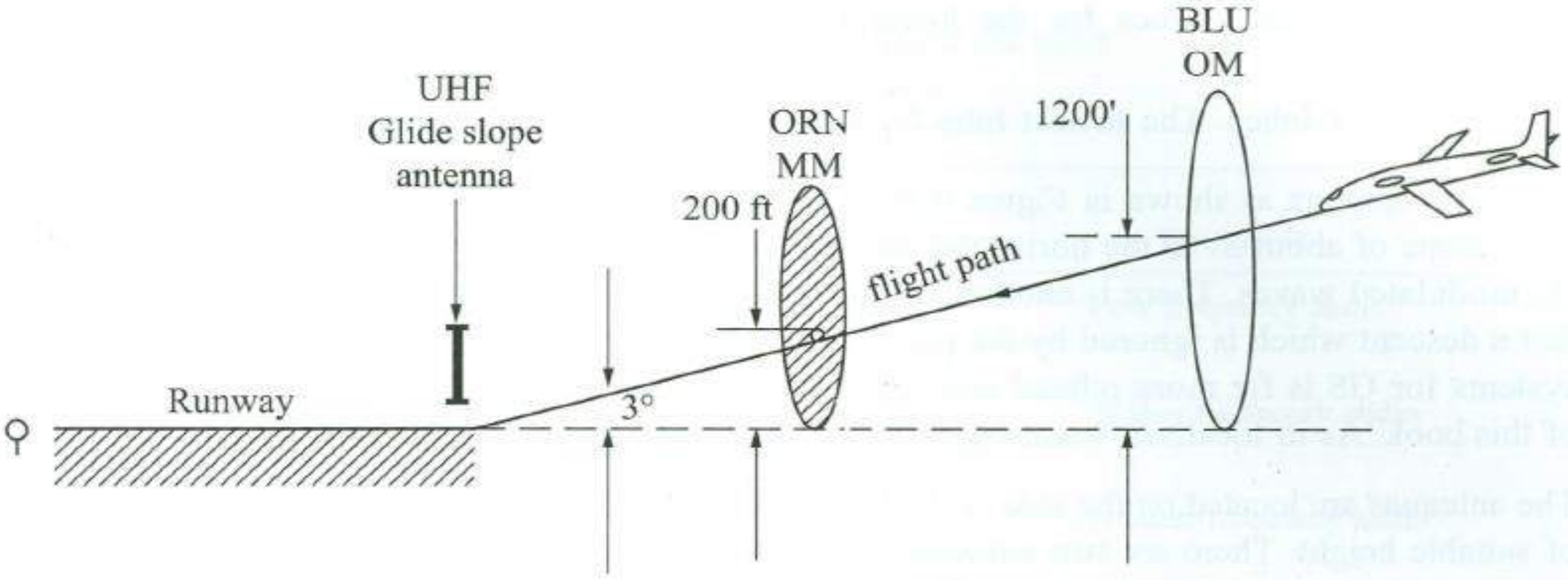


Fig. 9.15 Glide slope details for an approaching aircraft.

- The principle of operation is very similar to localiser operation. Here also there are two beams, one, the lower beam is modulated on a UHF carrier (this is always paired up with localiser frequency) with 90 Hz audio modulating wave.

Marker Beacons, MB

- Marker beacons are used to alert/warn the pilot during landing, that an altitude check by him is required when the aircraft passes over Marker Beacons. Both visual (coloured flashing lights) and audible alerts are issued to him, whenever the aircraft overflies the Marker Beacon stations. ILS has three Marker Beacons enumerated as:
- Inner Marker, I (optional)
- Middle Marker, M, and
- Outer Marker, O.

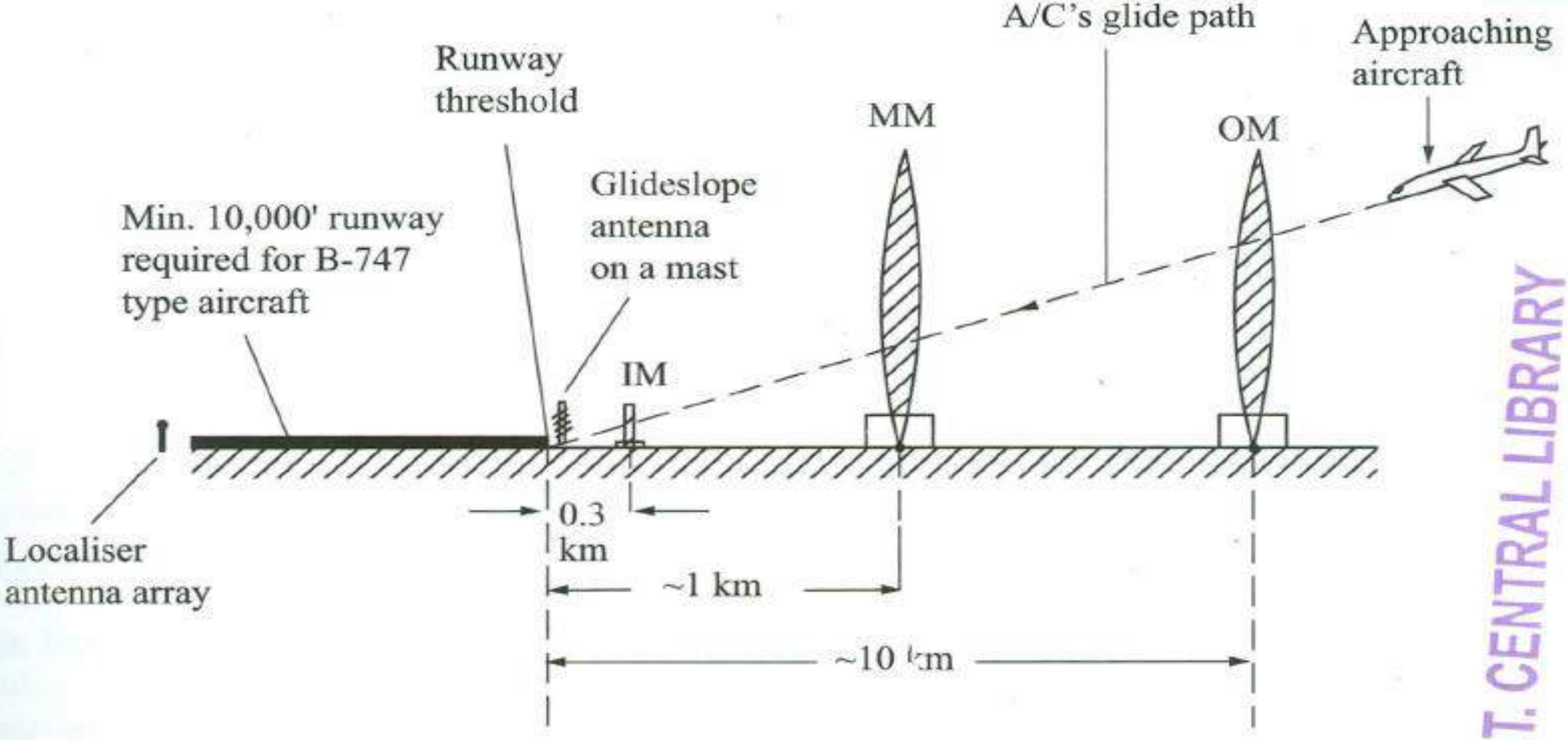


Fig. 9.17 Marker Beacons near and typical airport.

- Outer Marker [OM] is located on ground, at a distance ranging from 7-10 km from the runway threshold.
- When the aircraft intercepts this outer Marker Beacon, the event is indicated by a blue lamp that flashes in sync with the received audio code.
- Middle Marker (M) The Middle Marker (MM) is located so that a missed approach can be initiated by pilot, during poor visibility conditions. A missed approach means, pilot does not land, but pitches the aircraft up with full thrust wings level, so that aircraft is put to Go Around (GA) mode.

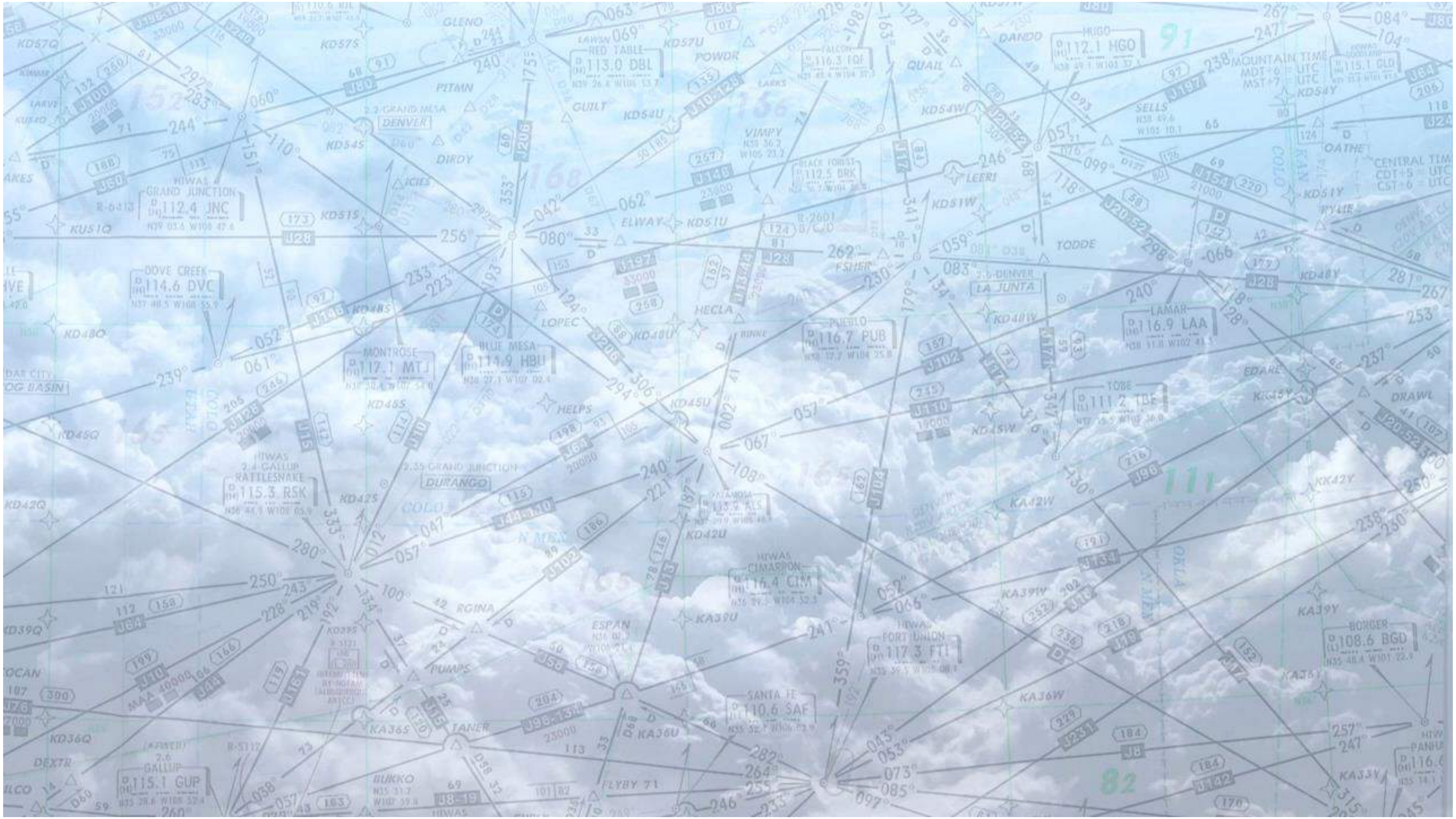
- *Inner Marker* (I) This is an optional installation. When installed, it is located such that, under poor visibility conditions, the arrival at the runway threshold is about to happen.

Table 9.1 Audio/visual alerts to the pilot

Marker	Coded as	Colour of Lamp	Audible Frequency	Comment
OM	— — —	BLUE	400 Hz 2 dashes/s	Low frequency audio
MM	•–•–•–•	AMBER	1300 Hz Alternate dots and dashes	Higher frequency audio
IM	• • • •	WHITE	300 Hz Dots only	Highest frequency audio

Attitude and Heading Reference System (AHRS

- AHRS uses all-solid-state 3-axis sensors to provide heading (directional/yaw) data and attitude (pitch and roll) for use by Electronic Flight Instrument System, (EFIS), Flight Control System (FCS), Flight Management System (FMS) and other avionics equipment.
- AHRS consists of an Attitude Heading Computer (AHC) , Flux Detector Unit (FDU) , Deviation Compensator Unit (DCU).
- ARC contains a solid-state, inertial sensor cluster, whose low-level outputs are amplified and then converted to digital form.
- The digital output is processed, using a resident software, to compute pitch, roll and heading Euler angles, along with accelerations along three axes.



RED TABLE
113.0 DBL
HUGO
112.1 HGO
FALCON
116.3 FQF
BLACK FOREST
112.5 BRK
GRAND JUNCTION
112.4 JNC
DOVE CREEK
114.6 DVC
MONTROSE
117.1 MTJ
BLUE MESA
114.9 HBU
PUEBLO
116.7 PUB
LAMAR
116.9 LAA
TOBE
111.2 TBE
RATTLESNAKE
115.3 RSK
ALAMOSA
113.9 ALS
CIMARRON
116.4 CIM
FORT UNION
117.3 FTI
SANTA FE
110.6 SAF
BORGER
108.6 BGD
GALLUP
115.1 GUP
DURANGO
LA JUNTA
DENVER
MOUNTAIN TIME
CENTRAL TIME

Doppler Navigation System (DNS)

- Doppler navigation system (DNS) is also a fully autonomous system like INS, not relying on any ground stations for its functioning.
- DNS is a low-cost, but coarse alternative to INS.
- DNS finds applications in very small aircraft and helicopters, where use of INS is an overkill, and prohibitively expensive.

- Doppler effect (named after Austrian Scientist Christian Doppler) is the shift in frequency which occurs when there is a relative motion between the source of an electromagnetic wave and an observer. The frequency shift t1f is given by:

$$\Delta f = \pm \frac{V_a f_0}{c}$$

where, V_a = Velocity of the aircraft

f_0 = Transmission frequency

and c = Speed of light (3×10^8 m/s)

- The velocity of the aircraft, and the angular measurements obtained either using gyros or magnetic compass, will be used to obtain the position of the aircraft.
- All the computations-like integration of velocity to obtain displacement data, adding this displacement to start up value, etc., are done in a dedicated digital computer.
- It is possible to obtain the position data in both longitudinal and lateral directions at any point of time, i.e. LATILONG data.

- The on-board equipment consists of:

(i) A transmitter (Tx) at about 10 GHz with a minimum of 30 MW power

(ii) A receiver (Rx) comprising a balanced mixer, an IF amplifier and an audio stage. This receiver time shares multiple beams sent out by the antenna and

(iii) Transmitting/Receiving antenna for the multiple beams towards the earth. If any of the usual 3 beams is lost, a warning flag drops to view in the data display to discard the data.

- The receiver also has built-in-test feature to check the system health.

- Let us first consider a single beam measurement as shown in Figure for an aircraft flying straight and level.

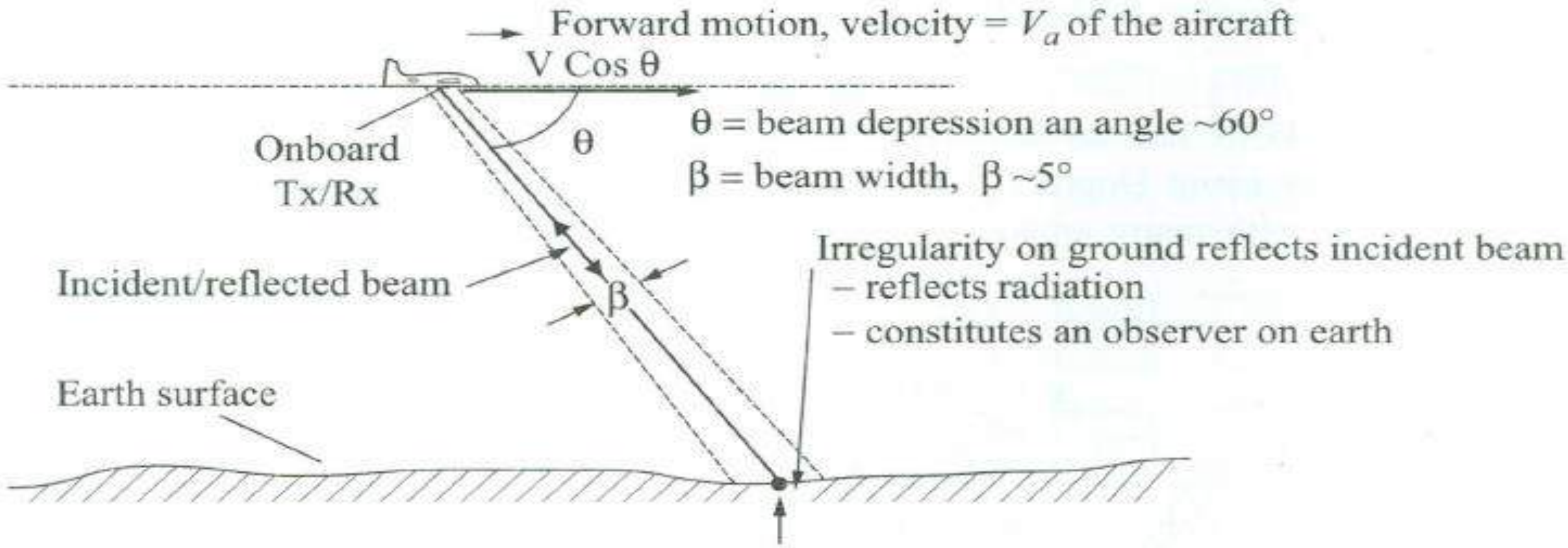


Fig. 9.32 Forward beam of Doppler transmitter.

- The onboard transmitter/antenna sends a radio frequency beam (X band-Microwave frequencies 7-11.5 GHz) towards the forward direction, at a depression angle e of about 60°.
- The r.f. beam is back scattered by ground irregularities or reflected back towards the airborne receiver (Rx) which is colocated with the transmitter in the same LRU-a line replaceable unit.
- When the aircraft is approaching the reflecting irregularity, there will be an increase in radiated frequency due to Doppler effect.

$$\Delta f = \frac{2 f_0 V_a}{c} \cos\theta \tag{9.5}$$

where, Δf = Doppler shift one way (Tx to irregularity)

f_0 = Microwave frequency ~ 10.00 GHz

V_a = aircraft velocity in the level flight, in metres/sec

$\cos\theta$ = included to compute the velocity component of the observed Doppler shift along the flight path. Doppler velocity is measured in the direction of the beam, and since the aircraft is not flying along the beam, we have to consider Doppler velocity component in the flight direction.

c = speed of light (3×10^8 m/s)

Factor 2 in the numerator arises due to two Doppler shifts caused by (i) Tx to irregularity and (ii) from irregularity to Rx.

Aircraft velocity is then given by:

$$V_a = \left[\frac{c}{2 f_0 \cos\theta}\right] \Delta f \tag{9.6}$$

Augmentation Systems

- Global Navigation Satellite System (GNSS) can be made to yield even higher performance by several types of augmentation to improve accuracy, reliability and availability of service. Calculation process is augmented with external information to reduce the total error significantly as follows:

(i) Some systems transmit additional information about common error sources such as ionospheric delay, ephemeris errors, clock drift, etc.

(ii) Other augmentation systems provide direct measurements of how much the signal was off previously, and

(iii) Yet other augmentation system provides additional data to be integrated into the calculation process.

since the Doppler shift Δf is measurable, V_a is readily computed.

Sensitivity factor is given by Doppler shift (Hz)/knot. (Recall knot is a unit of speed and 1 Knot = 1.825 km/hr).

i.e.

$$\frac{\Delta f}{V_a} = \frac{2 f_0 \cos\theta}{c} \tag{9.7}$$

- The principle of augmentation for calculation of precise position of the airborne GPS receiver is a very simple.
- Accurately-surveyed ground stations, LAT/LONGS are compared with those obtained from GPS. The error thus computed is broadcast, using either a satellite (SBAS) or ground station (GBAS), to the aircraft's receiver to minimise its position error

- Basically, there are two augmentation systems:
- 1. Satellite-Based Augmentation System (SBAS)/wide area/WAAS
- 2. Ground-Based Augmentation System (GBAS)/localised.

Augmentation Systems

Satellite Based Augmentation System (SBAS)/Wide area use Implementations by :

1. WAAS, FAA, USA
2. EGNOS, Europe
3. MSAS, Japan
4. GAGAN, India

Ground based Augmentation System (GBAS)/Localised use near airports

LAAS (Local Area Aug. System)

* Range = 20 km
* VHF and UHF band transmission

DGPS (Differential GPS)

* Range ~ 100 km
* VHF band

1. Satellite Based Augmentation System (SBAS)- Wide Area Augmentation System

- SBAS is a satellite-based system to support wide enroute areas, through the use of additional satellite-broadcast messages.
- SBAS systems consist of 6-10 ground stations located at accurately known reference points around the earth.
- These reference points are established after detailed surveying, and provide seamless error correction around the earth selected region of earth.
- The ground stations take measurements of one or more GPS satellites and ionospheric data which affects the signal received by the user.
- Using these measurements, correction messages are computed by the ground stations and up linked periodically to minimum of three geostationary satellites, which in turn broadcast the error corrections to the user aircraft receiver, anywhere around the earth.

2. Ground Based Augmentation Systems (GBAS)

- GBAS is primarily localised to a smaller area near the airports. As in SBAS, GBAS system has one or more accurately surveyed ground stations which take measurements from the GNSS and use couple of radio transmitters to send the correction data directly to the aircraft.
- In Local Area Augmentation System (LAAS), the ground stations transmit correction messages using Line-of-Sight (LOS) VHF or UHF bands of electromagnetic spectrum, directly to the end user.

Thank You