Radio Navigation

Radio Theory

An aerial can be described as a transducer (turns energy from one type to another) and \( c = f \lambda \)

3KHz-30KHz is Very low frequency and then Very Lovely Maidens Have Very Useful Sewing Equipment

AM produces a carrier wave and two sidebands. Single Sideband SSB transmissions suppress the lower sideband and single sideband suppressed carrier only transmits the upper sideband. HF VOLMET and two way comm use SSB with suppressed carrier as they save both power required by the transmitter and bandwidth

FM requires more power and greater bandwidth than AM and is more complex, but has less static

Pulse modulation is binary. The phase of 0 is where the amplitude is zero and rising

Radio waves are an electrical field \( E \) and an orthogonal magnetic field \( H \). Vertically polarised waves (like VHF comm) have all electrical oscillation in the vertical plane. Nav equipment (VOR) is horizontally polarised

The ideal dipole aerial is half or quarter the wavelength and has a “cone of silence” in the overhead. Parabolic aerials are used to transmit directional signals, phase array aerials are fed signals in phase with each other and create an interference pattern (works similarly to a slotted scanner)

All dish aerials produce sidelobes of wasted energy, but phase array/slotted scanners produce smaller ones. Helical antennae are wound aerials and can receive linear or circularly polarised transmissions

Propagation

Refraction is caused by a change of speed and low frequencies are refracted the most.

Diffraction is caused by sharp objects and low frequencies are diffracted the most.

Radar reflection is most likely when the wavelength is compatible with the target size.

Attenuation is the loss of power in a wave. Atmospheric attenuation is greatest at high frequencies and similar for surface attenuation. Ionospheric attenuation, however, is greatest at low frequencies.

Space waves are line-of-sight waves and maximum theoretical VHF/UHF range is \( 1.23(\sqrt{H_1} + \sqrt{H_2}) \) in ft amsl.

Surface waves are about 100NM in HF, 500NM in MF, 1000NM in LF and 4000NM in VLF.

Skywaves refract from the ionosphere which is weaker at night and most refraction in the E layer at ~125km.

Distance from transmitter to first returning skywave is minimum skip distance which decreases with frequency.

The gap between the first returning skywave and the surface wave is “dead space”. Max skip distance 1500NM.

Skywaves only reliable in the HF band, causing interference in MF and LF.

Atmospheric ducting/super-refraction in stable air masses can cause long range VHF to EHF interference. Ionospheric ducting in VLF where signals reflect off the ionosphere and are guided between earth/ionosphere.

Static comes from nature and precipitation static mainly affects LF/MF. Noise is man-made, usually on VHF.

Doppler shift formula: relative velocity (m/s) / transmitted wavelength (m) (Increase in freq is a +ve Doppler)

Communications

HF skywave long-range comms is SSB with a suppressed carrier wave and uses 2MHz-22MHz and the MUF is the Maximum Usable Frequency with night frequencies about half of day: sun’s up; frequency up.

VHF line of sight short-range comms is 118MHz-137MHz with 25KHz/8.33KHz spacing, suffering from fading.

SELCAL is HF/VHF, four letter codes and is checked on contact with each new agency.

SATCOM have geostationary satellites transmitting data, voice or pictures along the UHF band (line of sight).

ACARS/CPDLC uses VHF to send messages/ATC clearances to aircraft in flight.

VHF DF uses Adcock aerials with different phases to give: QTE true bearing from station, QDR magnetic bearing from station, QDM magnetic bearing to station, QUJ true bearing to station. A: ±2°, B (usual): 5, C: 10, D: >10

VDF letdowns/approach is interpreted by the pilot as they receive QDM on every call.

QGH is interpreted by the controller who passes steer/descent instructions (Both procedures have MDH).

121.5MHz has auto-triangulation and errors can occur due to other simultaneous transmissions/terrain error.
The NDB

NDB frequencies are 190KHz - 1750KHz and use surface waves for range of 300NM over land, 600NM over sea
The Beat Frequency Oscillator BFO or TONE selection is required to hear some idents
ADF systems use loop aerials and a sense aerial to create a carotid with a single sharp null, resolving ambiguity
The point of the needle is the QDM, the tail the QDR and for true, require variation at the aircraft
ADF has ICAO requirement of ±6° accuracy with a signal:noise ratio no less than 3:1
Static from snow/freezing rain can affect accuracy and thunderstorms direct you towards them
At night, weak skywaves can return and affect the system (hunting and fading of carrier wave) at dawn/dusk
Station interference gives erratic indications and two idents, but can be overcome with the bandpass switch
Avoid coastal refraction by taking bearings at right angles to the coast or choose beacons close to the coast
Quadrantal error is caused by the aircraft structure bending the signal path and is small/predictable
Dip error can be caused whilst turning and also you can get reflected signals from terrain if you are low
Maximum range (not accounting for ground effects etc) is roughly $3 \times \sqrt{\text{Power in Watts}}$
Locators: low power, 10-25NM usually co-located with ILS outer marker, Homing/holding: aid from en-route to
destination and around 50NM, En-route/Long range: nav aided greater than 50NM (LF for longer surface waves)
ANT for good audio and no bearing, ADF for bearing information, and TEST swings RMI pointer to 325°

The VOR

VOR uses 100KHz spacing between 108MHz and 112MHz, then 50KHz spacing from 112MHz to 117.975MHz
The VOR contains a dipole spinning at 30Hz and produces an AM signal, limacon shape, and a reference FM
signal, both in phase at magnetic north. The phase difference then indicates the radial
If true bearings are required, then here the variation is taken at the station (this is where it is referenced from)
Omni Bearing Indicator OBI is a VOR indicator with 10° deflection at full scale, and each dot is 2°
TO/FROM flag shows if the selected bearing is close as a QDM or QDR. VOR indicator independent of heading
ICAO limits of the cone of confusion are up to 50° from the vertical. Radius of cone is roughly 1.2 x height
The VOR carries a three letter Morse ident at seven words/minute repeating every ten seconds
The Designated Operational Coverage DOC of the VOR guarantees freedom from interference by day and night
The ICAO accuracy requirement for a VOR is ±5° on 95% of occasions
Scalloping causes rapid deflections as reflections from terrain or objects cause phase interference
A power output of 200W achieves ranges of up to 200NM and the VOR transmitter is monitored to ensure
bearing outputs are accurate within ±1° or it will shut down (also if signal strength reduces by over 15%)
A Doppler VOR uses a 30Hz anti-clockwise variophase FM signal and an AM reference signal (reduced site error)
VORs used for navigation in Europe are usually no more than 80NM apart
For associated VOR/DME, they must be within 600m of each other and then may share the same ident
HSI Horiz Situation Indicator will never give reverse sense indications and needs a remote indicating compass
When flying VOR approaches, the aircraft must be within 5° of the selected bearing to be considered on-track

ILS

The ILS uses separate transmitters for localiser, glidepath and markers. ILS is VHF from 108MHz to 111.95MHz
and uses odd 100KHz frequencies (plus 50KHz), the glidepath (auto-tuned when VHF channel selected) uses 40
spot UHF frequencies from 329.3MHz to 335MHz. All marker beacons operate on 75MHz and ident is a 1020Hz
tone amplitude modulated on the localiser carrier wave. Occasionally, ‘I’ precedes the code to avoid confusion
Localiser dots are 0.5° with full scale at 2.5°. Glideslope has one dot as 0.15° and full deflection as 0.75°
Localiser: two AM beams, 90Hz (fly right) and 150Hz (left), measures DDM Difference in Depth of Modulation.
Aerial usually located 300m off the upwind end. Protected to 25NM/6000ft and coverage 10° either side of the
centre line or before 17NM, 35° each side. If localiser can’t be on the centreline upwind then it can be placed
next to the runway and is “off-set”. If off-set greater than 5° then cannot be used for precision approach
Glidepath: similar, 90Hz (fly down) and 150Hz (up) and usually set at about 3° with the aerial next to the instrument touchdown point, 300m in from threshold and 120m off the centreline.

Glidepath coverage from 0.45 x GP angle to 1.75 x GP angle, 10NM and up to 8° either side of the centreline.

Glidepath steeper than 3.5° is classified as “steep” and only 8NM range.

False glideslope can appear above the real one, at about double GP angle, so come from below.

Outer marker: Blue light, 400Hz, Morse O. Middle: Amber, 1300Hz, Morse C. Outer: White, 3000Hz, Morse I.

Once established, if more than ½ scale deflection on localiser or ½ scale down on glideslope, go around.

ILS critical/sensitive areas are where movement may interfere and so everything is excluded during ILS use.

Rate of descent on a 3° glideslope is 5 x groundspeed and height = glidepath angle/60 x distance to go (ft) and add 50ft if threshold is used.

FM immune filters reduce localiser interference.

Each ILS has a monitoring system and CAT I system cuts 6 seconds after failure, CAT II/III 2 seconds.

Microwave Landing System

MLS uses two beams, one in azimuth and one in elevation, using one of 200 SHF channels in 5031-5090.7MHz.

Also uses a precision DME (DME/P) which allows the aircraft to fix its position accurately in three dimensions.

Azimuth beam starts on the left (from aircraft view) and sweeps right (TO), then back to left (FRO) and the transmitter is located at the upwind end of the runway near the ILS localiser.

Elevation transmitter is located at the downwind end near the touchdown point and works like the azimuth.

DME/P is only used with MLS and when not available, only straight in approaches are permitted.

Basic equipment, or that and a guidance computer, or that and approach path databases.

Azimuth coverage is 40° left and right, out to 20NM and elevation limits are from 0.9° from horizontal to 20°, up to 20000ft and out to 20NM. DME/P coverage goes out to 22NM.

MLS less sensitive to geographic location and can interrupt the beam to avoid reflection by stationary objects.

Radar Theory and Ground Radar

Require minimal static and atmospheric attenuation, line of sight, short wavelengths for narrow beams and wavelength chosen for target size, which puts us is UHF/VHF with some EHF (military).

Pulse radar uses a single aerial to transmit/receive and continuous wave radar has no minimum range limit.

Pulse Recurrence Period/Interval PRP is period for send/receive and PRF is Pulse Recurrence Frequency.

Max theoretical range is c/(2 x PRF) and c is about 162,000NM/sec.

Minimum range (usually in metres) is (c x Pulse length)/2. Beam width = 70 x wavelength/(antenna diameter).

So long range radar have a low PRF and so a slow scanner rotation so as not to miss the returning signals.

Super-refraction (ducting) with marked temperature inversion, sub-refraction, attenuation with distance, condition and size of the reflecting surface.

Ground radar: ASMR is Aerodrome Surface Movement Radar and works in 2-d. Moving Target Indication MTI can use Doppler shift data to distinguish moving/not and exclude clutter (can exclude objects moving across).

En-route surveillance range 200-300NM and primary radar uses UHF 600 MHz, pulse length 4μs and PRF of 270, horizontal beam width 1.7° and aerial rotation 5RPM (used together with secondary radar (no weather)).

Terminal surveillance radar up to 60-80NM on 1000-1200MHz in UHF used for transit, approach and departure.

Approach surveillance radar operate at about 3GHz with a PRF of 700 and so have pulses of about 1μs to allow them to operate at minimum ranges of 150m. Rotation rate of about 15RPM. This type of radar can be used for SRA Surveillance Radar Approach where the controller instructs the aircraft with heading changes down to about a half a mile from touchdown (no view of vertical plane, so QFE to MDH height advisories).

Military airfields have PAR Precision Approach Radar for horizontal/vertical guidance during final approach down to 200ft DHs. This doesn’t require pilot response unless requested. Must be capable of detection: range 9NM, up to elevation of 7° within 10° of centreline, target with cross-section 15m^2 or more and maximum allowable error is ±30ft in azimuth and ±20ft in elevation. Operates on 10GHz sector scans.

ASMR (or ASMI Indicators) operate on 3.8cm wavelength (SHF) with narrow beams and 60 RPM.
**Airborne Weather Radar**

Weather radar operates in SHF from 9-10GHz with wavelength 3cm, PRF 400-550 and max range 200-300NM
Aerial scans 90° left/right and can be tilted 15° up/down with beam width 3-5° (modern slotted scanners)
The scanner is gyro stabilised in pitch/roll from the IRS and the cockpit shows radar display (usually EFIS)
A narrow, conical beam is used for looking at precipitation: wet hail, rain, wet snow, dry hail, dry snow, drizzle
and the weakest is green, then amber, red and sometimes magenta
Avoid areas with close colours, fingers, hooks, u-shape and scalloped edges, and be aware of radar shadowing
MAP mode operates to 50-60NM and uses a fan-shaped beam (cosec² beam) and has manual gain control

**DME**

DME measures slant range in UHF from 960-1215MHz and transmits two pulses separated by 12μs from the aircraft, which the ground station re-transmits after 50μs. To distinguish between its own pulses and other aircraft’s, a jittered PRF is used to make the signals unique and to solve reflected ground returns, the ground transponder retransmits 63MHz off from the original signal. 252 allocated paired channels
150 PPS for 15000 pulse pairs, then 60 PPS and when locked on, drops to 24 PPS. Maximum range is 300NM
but often less and the counters count down from maximum range
Ground equipment can only handle 18 searching or 112 locked on and services the strongest 100 signals
ICAO require accuracy of 0.25NM plus 1.25% on 95% of occasions. After 1989, slant error less than 0.2NM
TACAN TACTical Aid to Navigation are military UHF and is compatible with civilian DME
Associated beacons have the same ident and VOR/DME associated if less than 100ft apart (terminal aid) or less
than 2000ft for any other purpose. Associated TACAN and VOR are VORTAC
DME memory keeps the counters turning for 8-10 seconds at the same rate after signal loss
Two DMEs permit a rho/rho fix, and a DME/VOR permit a rho/theta (range/bearing) fix
Used with ILS, DME is zeroed at the threshold and can only be used up to a maximum of 25000ft

**SSR**

Ground station interrogates at 1030MHz with one of three trio spacings and aircraft responds on 1090MHz
Pulse 2 is 2μs after 1 to suppress the sidelobe. Time between 1 and 3: 8μs civil/military ident, 21μs altitude
Response is 20.3μs long framed by two frame pulses, with space for 12 additional bits, giving 4096 idents
Altitude reporting is always to 1013.2mb and is to the nearest 100ft
SPI Special Position Identification causes the return on the radar screen to bloom for 25 seconds
Mode C is unselected when it is more than 300ft off (sometimes 200ft)
Fruiting when replies go to wrong station and garbling when aircraft are too close (reduced with mode S)
Mode S can uplink/downlink data and is required for TCAS I/II and “level 2” required >5700kg or 250KT
Elementary surveillance ELS: Mode A, pressure altitude reporting in 25ft intervals, aircraft address, flight
status, data link capability report, aircraft ident, GICB capability report (can have data requested from ground)
and ACAS RA reporting capability
Enhanced surveillance EHS must be able to respond to GICB requests with: magnetic heading, selected
altitude, IAS, Mach number, vertical rate, roll angle, track angle rate, true track angle, GS
>5700kg or 250KT require two mode S antennae on top/bottom of fuselage along the centreline and must be
capable of receiving/transmitting on both, then choosing the optimal one
Once a mode S transponder has been identified, it can be locked out to prevent it from replying to any all-
stations calls
Squitters are used for TCAS/ACAS II equipped aircraft which are sent randomly from both aerials
**Satellite Navigation**

GPS uses a notional constellation of 24 satellites in 6 orbital planes at 55 degrees to the equator at 20200km. A satellite is not visible until 5° above the horizon (mask angle).

L1 is 1575.42MHz with CA Coarse Acquisition and Precise and L2 1227.6MHz with Precise only.

Timing on satellites is controlled by 4 atomic clocks which are maintained by the MCS Master Control Station. The PRN Pseudo-Random Noise code transmits time signals on L1 every millisecond.

Ranges from 3 satellites required for a 2-d fix and for 3d, either 4 satellites or 3 with altitude information.

Receiver clock bias is resolved by the receiver, which then knows the satellite positions, their ephemeris, but their expected positions are stored in receiver memory as an almanac. GPS is referenced to WGS 84.

The almanac can be updated as the satellite sends NAV data on L1, 25 frames at 30 seconds each.

The receiver searches the sky if position changed/database outdated and can be reduced by entering pos/time.

Fixing accuracy of ±13m on 95% of occasions is quoted for raw signals.

Satellite ephemeris error from satellite being in the ‘wrong’ place gives 0.5m out, atmospheric/ionospheric error depends on $1/f^2$ and models reduce error to ±4m, instrument/receiver error ~1m, multipath signals from terrain reflection ~0.5m and clock bias can occur.

Dilution of Precision DoP can be caused by geometric dilution by a shallow cut of the position spheres, or by coverage problems due to jamming the weak satellite signals.

GLONASS will have 24 satellites in 3 orbital planes, evenly spaced and at 64.8° to the equator, operating L1 at 1.6GHz and L2 on 1.2GHz. GLONASS uses the PZ-90 system instead on WGS 84.

GALILEO will have 30 satellites in three planes at 56° with 9 operational and one spare satellite per plane.

Multi-channel receivers are used in aircraft; multiplex receivers switch between satellites in view but are susceptible to jamming. Continuous receivers are used for specialist circumstances. Aerials on top of fuselage.

ABAS is Airborne Based Augmentation Systems and is to provide integrity.

RAIM Receiver Autonomous Integrity Monitoring uses an extra satellite and if one isn’t working, require spare.

AAIM Aircraft Autonomous Integrity Monitoring uses the IRS/INS as a backup for any GPS failure.

GBAS Ground Based Augmentation Systems makes ground measurements of the signal errors and forwards those to aircraft. Min GBAS coverage is 15NM from threshold out to 35° with extension 20NM 10° either side.

A GBAS based on GPS is sometimes referred to as Local Area Augmentation System LAAS.

Differential GPS dGPS computes correction at a known ground facility and corrects to 1-3m within 30km range.

Pseudolites are ground based imitation satellites which send satellite signals and dGPS correction.

SBAS Satellite Based Augmentation Systems like Wide Area WAAS do the above over a larger area.

SBAS coverage area is where signal can be received and service area where it meets specific requirements.

GPS is approved for Basic Radio Nav, BRNAV in Europe. Needs RAIM or integrated other systems and if only GPS available, if RAIM will be unavailable for more than 5 minutes, the flight does not go.

**RNAV**

RNP 0.01/15 means 0.01NM laterally and 15ft vertically (proposed standard for CAT II approaches).

Departure: RNP 1, en-route: RNP 4, non precision approaches: RNP 0.5 initial only or RNP 0.3 for all stages.

For B-RNAV, display XTRK, distance/bearing to wpt, time to wpt or GS and capability to store at least 4 wpts.

Phantom stations are bearings/ranges from a VOR/DME.

On basic 2D RNAV equipment (KNS), one dot is 1NM in RNAV and 0.25NM in APR RNAV.

Precision RNAV P-RNAV is RNP 1 and uses DME/DME, VOR/DME (15NM range), GPS or IRS.

On a two-dot EFIS display, one dot is 2NM and in NAV mode, heading is at the top.

In EFIS VOR mode, one dot is 5° and in APR mode it is 1° or in expanded APR mode then 0.5°.

For ETA for close waypoints, GS is mainly used; for far away waypoints, mainly forecast speed used.

ETAs at waypoints are often called ETOs Estimated Time of Overflight to distinguish them.