• Introduction
• Surveillance Radar (Transponder)
• Distance Measurement Equipment (DME)
• Non-Directional Beacon (NDB) and Automatic Directional Finder (ADF)
  - Demo and Exercises
• VHF Omni-directional Range (VOR)
  - Demo and Exercises
• Instrument Landing System
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• Global Positioning System (GPS)
Introduction

ELECTROMAGNETIC SPECTRUM
SHOWING THE RADIO FREQUENCY SPECTRUM

Electric waves | RADIO WAVES | Infra-red | Visible light | Ultra-violet | X-rays | Gamma rays | Cosmic rays

RADIO FREQUENCY SPECTRUM

9kHz 30kHz 300kHz 3000kHz 30MHz 300MHz 3000MHz 3GHz 30GHz 300GHz 3000GHz

VLF  LF  MF  HF  VHF  UHF  SHF  EHF not designated

Long Medium Short wave wave wave wave

VLF Very Low Frequency
LF Low Frequency
MF Medium Frequency
HF High Frequency
VHF Very High Frequency
UHF Ultra High Frequency
SHF Super High Frequency
EHF Extremely High Frequency
Introduction

- **Ground Waves (up to ~2MHz)**
  - Earth surface causes diffraction (bending) of beam
  - Absorption by land reduces range (better over sea)

- **Sky Waves (up to ~20MHz)**
  - Used for long distance transmission
  - Sky waves are refracted back towards ground from ionosphere
  - Can then be reflected back towards ionosphere and so on until it reaches receiver (skipping)
  - At night lower levels disappear resulting in refraction at higher levels and greater distances

- **Space Waves (> 20MHz)**
  - Penetrates ionosphere
  - Transmission is by line of sight
  - But attenuation increases as frequency increases
  - Reflections from smooth surfaces, building and hills can cause distortion of signal at receiver
# Introduction

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Aviation Frequency Bands

- **COMMUNICATIONS**: 118 – 136MHz
- **Distress Channel**: 121.5MHz

- **NDB and ADF**: 190 – 1750kHz
- **VOR**: 108 – 117.95MHz

- **ILS**
  - Localiser: 108 – 111.975MHz
  - Glidepath: 329.15 – 335MHz (frequency paired)
  - Markers: 75MHz

- **DME**: 962 – 1213MHz (frequency paired with VOR\ILS)
Typical Aircraft Antennas

- **VHF Antenna**
  - Communication

- **UHF Antenna (DME, Transponder)**

- **ADF Loop and Sense Antenna**
  - (on older aircraft sense antenna maybe a long wire from tail to cockpit)

- **Marker Beacon Antenna**

- **VOR, ILS Antenna**
Surveillance Radar

- Surveillance radar, although extensively used in air traffic control, is not confined to just controlled airspace.

- Most aircraft are now fitted with a secondary surveillance radar transponder.

- Transmits a (given) unique signal in response to a radar signal (interrogation) from the ground.

- Enables the radar controller to identify a particular aircraft.
Ground station transmits
interrogates on 1030MHz
and receives on 1090MHz
Mode A: identifies aircraft
Mode C: also includes automatic height readout
  - referenced to 1013.2mb or Flight Level
Mode S: more on this later
Surveillance Radar - ATC Advantages

- Requires much less transmitter power than primary radar for a coverage of 200 - 250nm
  - (Radar range - see next slide)

- Much less radar clutter as it does not rely on reflected pulses

- Can positively identify aircraft with unique code, can indicate track history, speed, altitude and destination

- Can indicate on controllers screen emergency situations

BAW857: Callsign
10 LL: Flight Level 10, Destination London Heathrow
S154: Ground speed (kts)
* : aircraft position
Surveillance Radar - Radar Range

- Radar uses ultra-high frequency (UHF) transmissions.
- They are basically line of sight - interruptions (blind spots and radar shadows) are caused by buildings, high terrain and the earth's curvature.
- Radar range is dependent upon many factors, the five main factors are:
  - Height of transmitter aerial, height of receiver aerial, power of transmitter, terrain or other obstructions, atmospheric conditions
  - A simple calculation can be used to find the theoretical range of radar.
Range (nm) = 1.25 \times \left( \sqrt{\text{Height of Radar}} + \sqrt{\text{Height of Aircraft}} \right)
Surveillance Radar - Transponder Operations

- **Function selector knob**: Enables various operating modes to be selected
- **Off**: Switches the transponder off
- **Sby**: On and ready for use BUT not transmitting - should be used initially to confirm code on startup and anytime you are switching code
- **On**: Transmits the selected code in mode “A” (aircraft identification mode)
- **Alt**: Altitude reporting capability mode “C” (if fitted to the aircraft)
- **Tst**: Tests the correct operation of the transponder by generating a self interrogation signal. Success illuminates the reply monitor light (some models)

- **Code selection knobs**: Should select standby when selecting or altering codes
- **Reply monitor light**: Flashes to indicate the transponder’s response to interrogation
- **Ident button (switch)**: Allows positive identification by radar controller, “squawk ident”
Surveillance Radar - Special use Codes

- 7000 : Conspicuity Code
- 7700 : Emergency Condition
  - “77 going to Heaven”
- 7600 : Radio Failure
  - “76 need my radio fixed”
- 7500 : Unlawful interference
  - “75 taken alive”
Surveillance Radar - Mode S

• Disadvantages of SSR
  - Garbling or overlapping of replies if < 2nm apart
  - Limiting codes (4096)
  - Ghosting (reflections from obstacles or high ground)

• Mode S (some of the key advantages)
  - 24 bit address → nearly 17 million codes allocated to aircraft on a PERMANENT basis
  - Data link → ground to air and air to air uplink and downlink will eventually reduce RT workload
  - Accurate height readout (25ft increments instead of 100ft)
  - Selective addressing of transponders → reducing aircraft clutter in busy airspace
Each DME ground transponder can cope with about 100 different aircraft at any one time.

The system is designed so that there is no possibility of interrogating pulses from one aircraft causing an incorrect indication to another aircraft.

DME signals are line of sight transmissions.

DME units and displays vary in type.
DME - some more information

- Operates in frequency range 962MHz to 1213MHz (UHF band)

- Can be co-located with VOR and automatically selected when VOR frequency set

- Similarly can be paired with ILS localiser

- How does it work
  - Aircraft sends a unique pulse train on the DME frequency
  - It then looks for its own pulse train being returned by the DME station spaced by ±63MHz from the DME frequency
    - DME generally can support up to 100 aircraft
  
  - Aircraft unit measures the time for the return pulse sequence
  
  - Knowing speed of radio wave is $3 \times 10^8$ m/s ......
  - Distance, speed and time to beacon can be calculated and displayed
Non-directional Beacon (NDB) Automatic Direction Finder (ADF)

ADF units vary in type and display

NDB (NON DIRECTIONAL BEACON) Transmitting on 354 kHz

RBI (Relative Bearing Indicator)

Moving Card ADF

RMI (Radio Magnetic Indicator)

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NDB - more information

• No directional information is transmitted
  - Same information in all directions

• Transmits in the LF/MF band 190 - 1750KHz
  - Range typically $2 \times \sqrt{\text{Power (land)}}$

• Accurate to within $\pm 2^\circ$ within the DOC (day)
  - DOC is designated operational coverage
  - Where would I get this information ???
  - Can be unreliable at night due to skywave propagation

• 2 or 3 letter morse code identifier
  - ENS (./-/...), FOY (..-./-.-/-...)
  - STI (Select - Tune - Identify)

• Used for enroute navigation, holds and approach

• Two types
  - Locator (L): low powered used for runway approach, typically 10 to 25nm range
  - Enroute NDB: range is typically 50nm or more
ADF – controls and operation

- Mode selector or function switch switches between different ADF modes of operation.
- **Off**: Switches the ADF off.
- **ADF**: Normal position when you want bearing information to be displayed.
- **ANT**: Antenna/receiver, in this position the loop antenna is disabled, the systems acts as a simple receiver (provides better audio reception for IDENT). Also “parks” needle in 90° position – this can be used to test operation of ADF - when you switch back to ADF mode needle should smoothly swing back to point to station.
- **BFO**: Beat frequency oscillator/crrier wave, selected when identifying the few NDB’s that use AO/A1 or A1 transmissions.
- **VOL**: With audio selected to the pilot’s headset or to the cockpit speakers, the vol can be adjusted so that the IDENT is clearly heard.
ADF - how does it work

- Electric current induced in loop aerial

- Large change in signal strength for only a few degrees rotation
- Loop position for maximum signal strength is not sharply defined
- Loop position for null signal is sharply defined (90° and 270° positions)

- Angular rotation of the loop aerial

- Loop aerial at 90° to signal

- or this way?

- This way to the NDB...
ADF - how does it work

a) LOOP
b) DIPOLE

+ =

Now only one zero current position in a complete rotation of the loop.
NDB - Flying to an NDB
NDB - Flying **from** an NDB

- Additional information is required by the pilot when flying from the NDB.

- This information can be from the magnetic compass, or more commonly, the heading indicator.
Accurate navigation can be conducted using the aircraft ADF needle which points at an NDB ground station, and a heading indicator which indicates the aeroplane’s magnetic heading.
ADF Display - Fixed Card or RBI

- A fixed-card display has an ADF needle that rotates against a fixed azimuth card.
- It indicates relative bearing to/from station.
- **QDM** =
  - \(320^\circ + 060^\circ = 020^\circ\)
- **QDR** =
  - \(320^\circ - 120^\circ = 200^\circ\)
  - \(020^\circ + 180^\circ = 200^\circ\)
ADF Display - Movable Card ADF

- As aircraft changes heading the pilot needs to manually align the ADF card with the DI
- Directly shows QDM (head of needle)
- Directly shows QDR (tail of needle)
The RMI (Radio Magnetic Indicator) display has the ADF needle superimposed on a card that is automatically aligned with magnetic north.

- Directly shows QDM (head of needle)
- Directly shows QDR (tail of needle)
8. Now that you are on course you use 5° of wind correction to maintain your course
   Heading is 355 (-5) and RB = 005 (+5) → 360 QDM

7. The wind causes you to drift back on course.

6. You return to your original heading of 360°.

5. Too much wind correction causes you to fly to the left of your course.

4. You decide to use 10° of wind correction
   Heading is 350 and RB = 010 (350 + 10 = 360)

3. Your aircraft is now back on course.

2. You turn 20° into wind (340°) to regain course - when RB is 020 then back on correct QDM

1. While on a heading of 360, your aircraft drifts off course 10° to the right due to a westerly wind.
Tracking OUTBOUND from an NDB

1. Set course.
2. Need to turn left to regain track.
3, 4. “pull the tail”. Pull the tail around
   Turn left 330, wait until tail shows RB +30
4. On QDR 360° → MH = 330, RB 030
   (QDM 180°)
5. Turn right to maintain track.
6. Maintaining track required 360° on magnetic
   heading 350° (tail shows RB +10)
7. Need to turn left to regain track.
ADF and NDB Errors

• **Designated Operational Coverage**
  - The DOC is based on a daytime protection ratio of 3:1 (S/N) ensuring required bearing accuracy of ±5° is met. Beyond the published DOC bearing errors increase

• **Static Interference**
  - Precipitation Static - generated by water droplets and ice crystals impacting aircraft causing a reduction in S/N and bearing accuracy
  - Thunderstorms - powerful electrical discharges affect the complete electromagnetic spectrum resulting in significant bearing errors
  - Night Effect - by day the D-Region (60-90km) absorbs LF and MF bands. At night this disappears resulting in skywave contamination of the ground waves.

• **Station Interference**
  - Interference due congestion of nearby stations. This can be even more significant at night because of skywave contamination from stations further away
ADF and NDB Errors

- **Mountain Effect**
  - Can cause reflections and diffraction of transmitted radio waves producing errors in the ADF

- **Coastal Refraction**
  - Radio waves speed up over water, causing the wave front to deflect away from its normal path and pull it towards the coast. Negligible at 90° but increases as angle of incidence increases

- **Angle of Bank (DIP)**
  - Results in current circulating around the loop disrupting nulls. The result is that the needle will move away from the correct QDM towards the lower wing resulting in an over-read when turning right and under-read when turning left

- **Lack of Failure Warning System**
  - No indication of false readings means special care should be taken in identifying and monitoring NDB IDENT

![Diagram of ADF and NDB errors](image_url)
NDB Demo (online)

http://www.relia.net/~george/aviation/sim/
VOR units vary in type and display
VOR - Advantages of the VOR

- **Reduced susceptibility** to electrical and atmospheric interference (including thunderstorms).
- **The elimination of night effect**, since VHF signals are line-of-sight and not reflected by the ionosphere (as are NDB signals in the LF/MF band).
- **The reliability and accuracy** of VOR signals allows the VOR to be used with confidence in any weather conditions, by day or by night, for purposes such as:
  - Orientation and position fixing (where am i?)
  - Tracking to or from a vor ground station;
  - Holding (for delaying or manoeuvring action); and
  - Instrument approaches to land.
VOR - more information

- Transmits in the VHF band 108 to 117.95MHz (160 channels)
- Range is $1.25\sqrt{(\text{Height of Tx} + \text{Height of Rx})}$
- Accurate within $\pm 1^\circ$ (site automatically monitored) within DOC, aircraft equipment accurate within $\pm 3^\circ$
- 3 letter morse code identifier transmitted every 10s
  - Shannon VOR SHA (.../..../.-)
  - STIF (Select - Tune - Identify - Flags)
- Reduced susceptibility to electrical and atmospheric interference
- The elimination of night effect, since VHF signals are line-of-sight and not reflected by the ionosphere (as are NDB signals in the LF/MF band).
- The reliability and accuracy of VOR signals allows the VOR to be used with confidence in any weather conditions, by day or by night
- Used for airfield letdowns, holding points and enroute navigation
VOR - how does it work

- VOR transmits two signals
  - 30Hz FM omni-directional reference signal (constant phase)
  - 30Hz AM variable phase (directional signal) created by a rotating transmission pattern (30 revs/sec)

- At receiver if two signals in phase then aircraft is due North of VOR
- Phase difference measured at receiver = magnetic bearing FROM VOR
- To determine position **FROM** a VOR station
- Tune to station and turn OBS knob until CDI needle centers with **FROM** indication

- To determine track **TO** VOR station
- Tune to station and turn OBS knob until CDI needle centers with a **TO** indication
VOR - Radials and Interpreting Indications

• Each dot on the VOR represents 2°

• Questions ....

• How many degrees are we off the tuned radial

• What radial are we actually on

• Now what radial are we on

• If the DME says 30nm how many miles are we off track
Aircraft moves into “zone of confusion”, CDI becomes agitated and may flick from side to side, TO/FROM flags changes indication, OFF flag flicks in and out of view.
1. While on a heading of 360°, your aircraft drifts off course to the right due to a westerly wind.

2. You turn 20° into the wind to regain your course.

3. Your aircraft is now back on course.

4. You decide to use 10° of wind correction.

5. Too much wind correction causes you to fly to the left of your course.

6. You return to your original heading of 360°.

7. The wind causes you to drift back onto your course.

8. Now that you are on course you use 5° of wind correction to maintain your course.
VOR Errors

- **Designated Operational Coverage**
  - Co-frequency protection necessitates VORs with similar frequencies to be separated by at least 500nm.
  - In the UK, this protection is denoted by the DOC (specified range and altitude):
    - 50/25 = no interference within 50nm up to a height of 25,000'.
  - DOC may vary by sectors and is valid by day and night.
  - Using a VOR outside of its DOC may lead to navigational errors.

- **Site Error**
  - Caused by uneven terrain, man-made structures, and trees.
  - Ground VOR site error is monitored to be within ±1°.

- **Propagation Error**
  - VOR scalloping is defined as deviations of the received VOR signals due to terrain, buildings, and distance.

- **Airborne Equipment Error**
  - Caused by aircraft equipment errors.
  - Maximum equipment error should be less than ±3°.
VOR Demo (online)

http://www.relia.net/~george/aviation/sim/
CDI : 0.5° per dot, max 2.5°
GP : 0.14°, max 0.7°
ILS - more information

- Localiser transmits in the VHF band 108 to 111.975MHz (40 channels)
- Glide Path transmits in the UHF band and is frequency paired
- Markers transmit at 75MHz, fan shaped pattern (OM, MM, IM)

- 2 or 3 letter morse code identifier
  - STIF (Select - Tune - Identify - Flags)

- ILS Coverage
  - Localiser 25nm ± 10°, 17nm ± 35°, +10nm > 35°
  - Glide slope 10nm ± 8° (azimuth), 0.45Θ to 1.75Θ (vertical)

- Category 1 instrument approach
  - DH not lower the 200'
  - RVR (runway visual range) not less then 550m
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**ILS - how does it work (Localiser)**

- Localiser antenna produces two overlapping lobes along the runway approach direction (QDM)

- So that aircraft ILS equipment can distinguish between lobes
  - Right Lobe (blue sector) has a 150Hz modulation
  - Left Lobe (yellow sector) has a 90Hz modulation
ILS - how does it work (Glide Path)

- Similar principle as localiser
  - Upper Lobe has a 90Hz modulation
  - Lower Lobe has a 150Hz modulation
  - Glidepath (usually 3°) is at the intersection of the two lobes

- Due to ground reflections, height and propagation properties of the aerial and number of False Glideslopes can exist (Glideslope always intercepted from below)
**ILS Display (Localiser and Glide Path)**

Full scale deflection of the needle indicates aircraft is more than 2.5° left or right of centre line.

Full scale deflection of the needle indicates aircraft is more than 0.7° above or below glidepath.
• ILS Indications can be affected by
  - Atmospheric conditions causing bending of the beam
  - Scalloping caused by reflection

• Factors affecting Range and Accuracy
  - ILS multipath interference due to large reflecting objects such as vehicles and buildings
  - Moving objects can degrade directional signals to an unacceptable level
    • ILS Critical Area: defined area about the localiser and glide path antenna where vehicles and aircraft are excluded during operation of ILS
    • ILS Sensitive Area: beyond the critical area where movement and parking of vehicles is strictly controlled
  - Snow and heavy rain can attenuate the ILS signal reducing range and accuracy
  - FM Transmitters that have frequencies just below 108MHz can overspill into the ILS band thereby causing interference with the ILS signal
Map Navigation Symbols

- VHF Omnidirectional Radio Range ........................................... VOR
- Distance Measuring Equipment .................................................. DME
- Co-located VOR and DME .......................................................... VOR/DME
- UHF Tactical Air Navigational Aid .............................................. TACAN
- Non-directional Radio Beacon ..................................................... NDB and NDB(L)
- Radio Marker Beacon or other Navigational Aid ...........................

VOR with compass Rose Orientated on Magnetic North

Aerodromes with Instrument Approach Procedures (IAP) outside controlled airspace .................

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GPS - NAVSTAR Global Positioning System

• The NAVSTAR global positioning system (GPS), is a space-based radio positioning network.
• Providing properly equipped users with highly accurate position, velocity and time (P.V.T.) information.
• The GPS system was developed by the U.S. Department of Defense (DOD) as a satellite-based radio navigation system to be the DOD’S primary means of radio navigation well into the next century.
• GPS, is designed to serve an unlimited number of users anywhere on the ground, sea, air and near space.

Note: Orbital configuration and all satellites not shown
GPS - The three Segments

- **Space Segment**, consisting of 21 active satellites (3 spare, totaling 24) which orbit the earth approximately every 12 hours, in 6 orbital planes (4 in each plane), at an altitude of approximately 11,000 nm (21,300 km).

- **Control Segment**, a satellite control ground network, responsible for orbital accuracy and control.

- **User Segment**, navigation receiver/computers in aircraft capable of receiving and identifying signals from satellites in view at a particular time and place.
GPS - How does it work (satellites)

- Each of the SV (space vehicle) transmits in the UHF band a unique PRN (Pseudo-random-noise) code

- This code contains
  - its position
  - its clock time
  - plus any clock error
  - Information on Ionospheric conditions
  - Status and almanac or position data for all other SVs
    - (downloaded hourly and is generally valid between 4 hours and several months depending on receiver)
GPS - How does it work (receiver)

- The receiver contains data (almanac) on the position and orbit of all the SVs

- If this data is valid then the receiver knows which SVs to expect and can quickly determine its position

- If the almanac is out of date or corrupted it can take longer to fix position as it must download new information
  - Time to initial fix is extended

- If the receiver position is significantly in error it will carry out a systematic search to determine which SVs are in sight ..... “skysearch”
  - This can take a while !!
GPS - How does it work (receiver)

Receiver Oscillator Produced

Satellite (Atomic Clocks)

Pseudo-Random Codes

Time Difference
GPS - How does it work (receiver)

- Intersection of two position ranges will give a circular line
- A third range will give two positions several thousand miles apart
  - one close to or on the surface of the earth
  - the other out in space (so can be eliminated)
- These 3 position ranges are known as a pseudo-range
- A fourth one is required to compensate for receiver clock errors
  - (cheap crystal vs SV atomic clock)
  - if receiver clock is 1ms fast over estimation could be about 162nm
While GPS is an extremely accurate system, small errors can be caused by a number of factors:

- Atmospheric interference
- Satellite position anomalies
- Timing inaccuracies
- Multi-path reception
- Geometric Dilution of Precision (GDOP)
The availability of any navigation system is the percentage of time that the services of the system are usable.

GPS can provide availability approaching 100% and will have continuous refinements based on orbital experience.

This figure is based upon a 24 satellite constellation with at least 4 satellites in view above a 5° masking angle. The 24 satellite constellation is designed to provide worldwide 3 dimensional coverage.
GPS - Service Availability

visible sat = 12