Off-board navigation systems

Department of Aerospace Engineering

Navigation Content

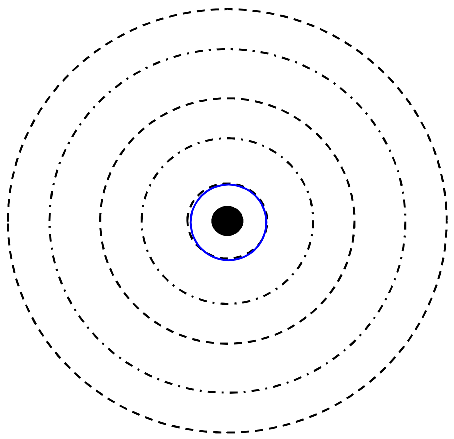
- Historical perspective
- External systems
  - ADF
  - VOR
  - DME
  - LORAN
  - GPS
- Combined systems
- Landing systems - ILS

External navigation systems

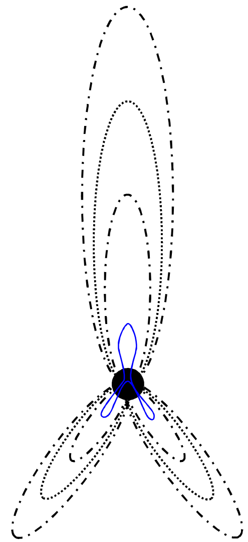
- In contrast to the self contained INS, some navigation systems use a network of ground infrastructure to help determine position.
- These systems are typically based on radio transmission
  - It is important to remember about the propagation of differing RF waves
- The radio navigation systems were developed to guide aircraft in the 1930's and developed extensively for military use in WWII.
- Thus they appeared before INS was widely used, and their development has continued alongside, mainly because they have differing error characteristics

Directional antennas

- Many radio navigation systems exploit directional antennas.

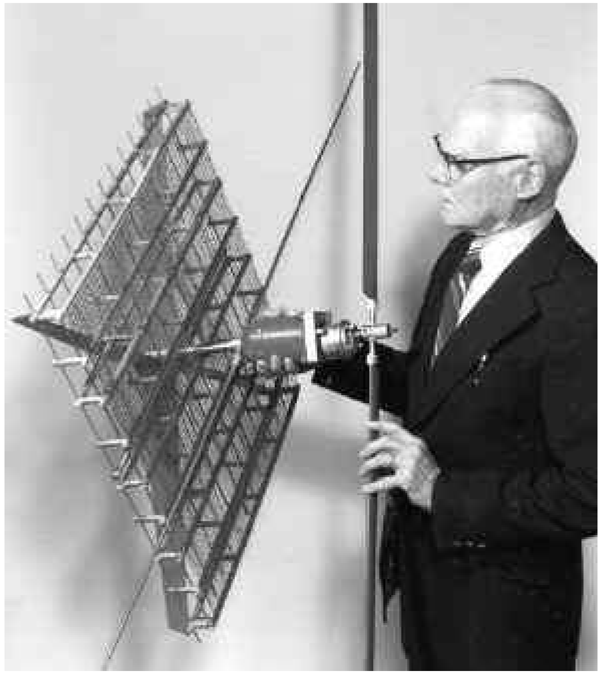


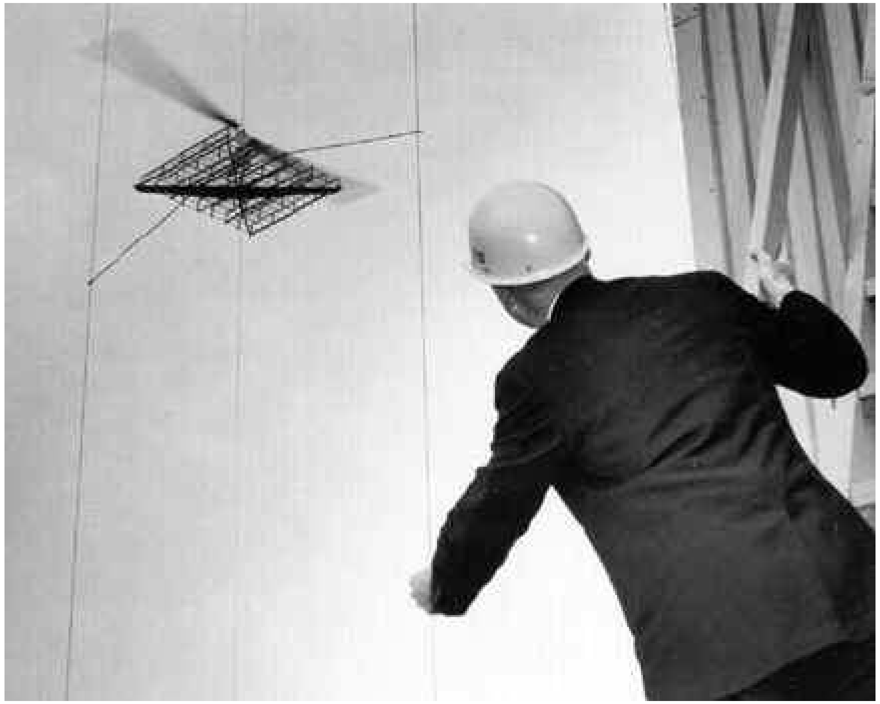
Omni-directional antennas broadcast/receive in all directions



Directional antennas antennas broadcast /receive with a particular beam pattern

Directional Radio Frequency- High Power

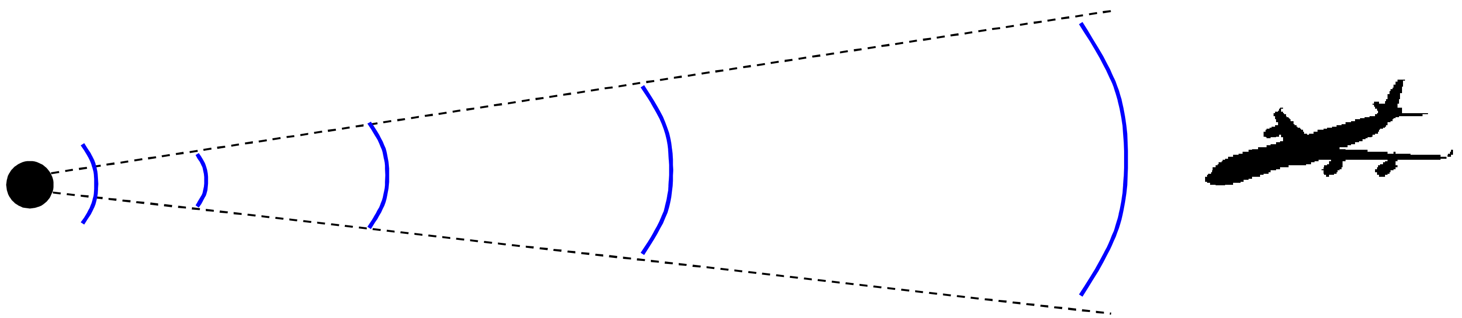




- Directional radio frequency systems have been proposed to power all sort of things: UAVs, satellites etc.
- As long ago as the 1960's they have been used to power helicopters!

Beam riding

- In the 1930 aircraft navigation systems exploited ‘beam riding’ - flying along a radio beam.

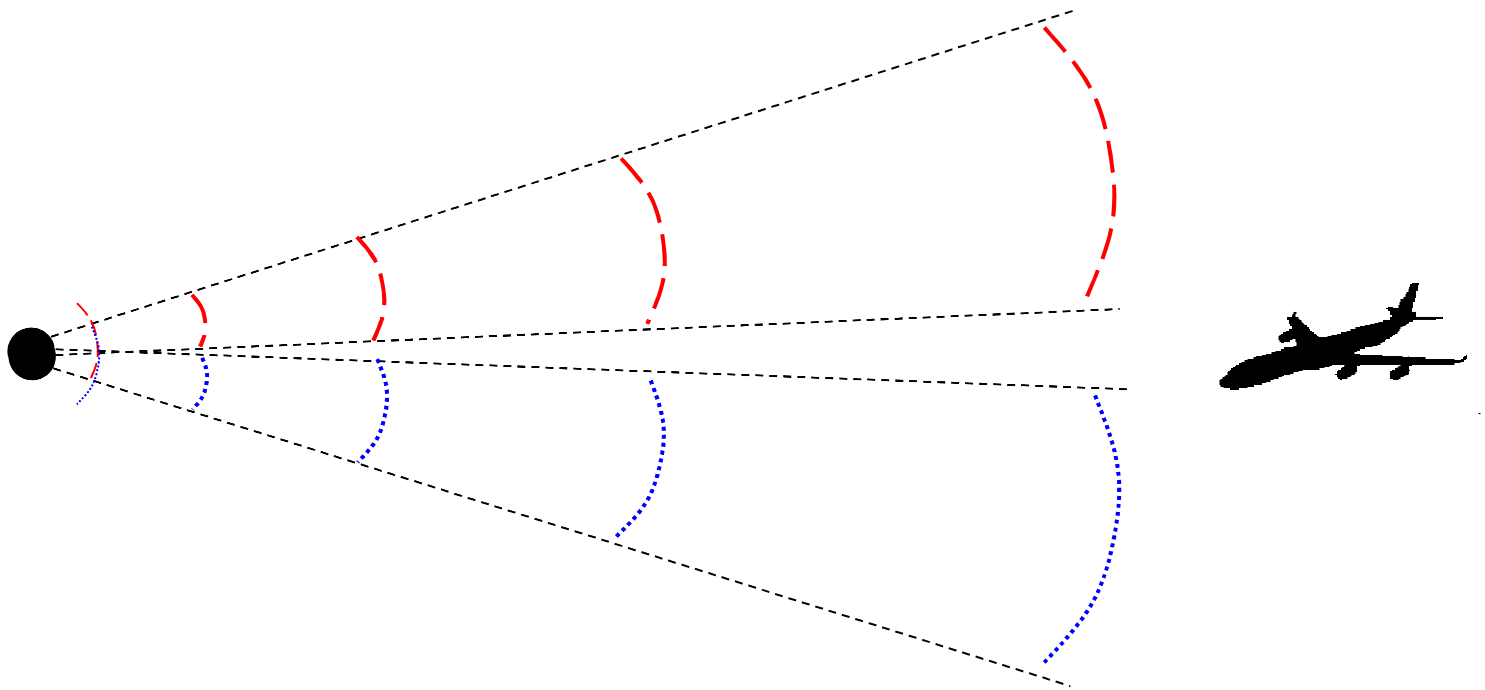


The aircraft tries to maximise the received signal to stay on course

Unfortunately the beam width of practical antennas limits this to short distances

Beam riding

- Practical systems got around the problem of beam spreading by combining multiple antennas.
  - Following the narrow beam between two wider beams



Beam riding

- This technique was used in the ‘Lorenz beam blind landing system’ (1930’s) – the first instrument landing system.

- Around the same time a similar system – ‘low frequency radio range’ or ‘four course radio’ was used in the US. This system broadcast waves into four quadrants giving the pilot four possible headings from each beacon.

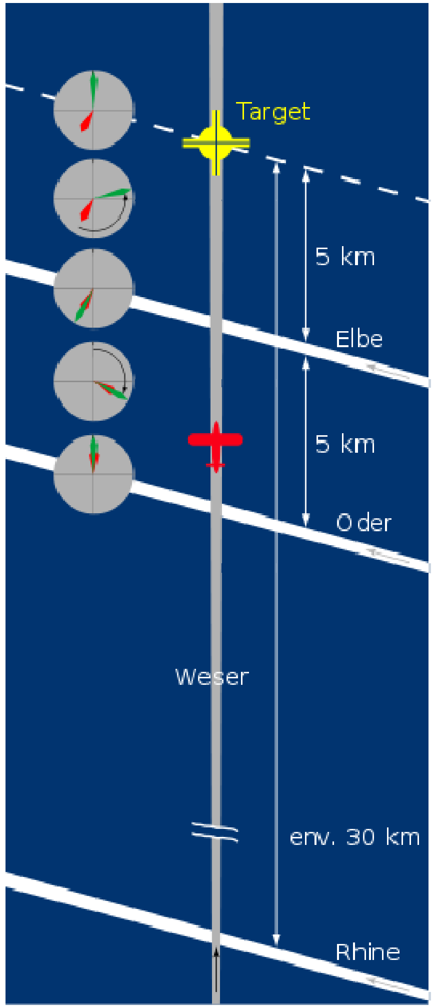
- Both systems also provided some position information;
  - Lorenz system had antennas broadcasting vertically at defined locations
  - LFR used the ‘cone of silence’ above each station to indicate position.

Beam riding - military

- Beam riding was developed extensively during WWII.
- The ‘Battle of the Beams’ saw increasingly sophisticated systems to extend the range and accuracy of beam riding systems.

Beam riding - military

Transmitter locations - Knickebein



X-Gerat

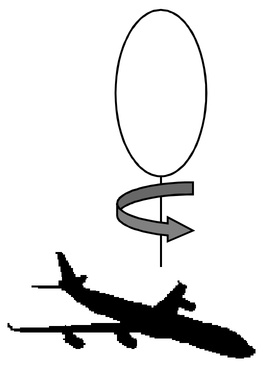
Beam riding - military

- Beam riding was developed extensively during WWII.
- The ‘Battle of the Beams’ saw increasingly sophisticated systems to extend the range and accuracy of beam riding systems.

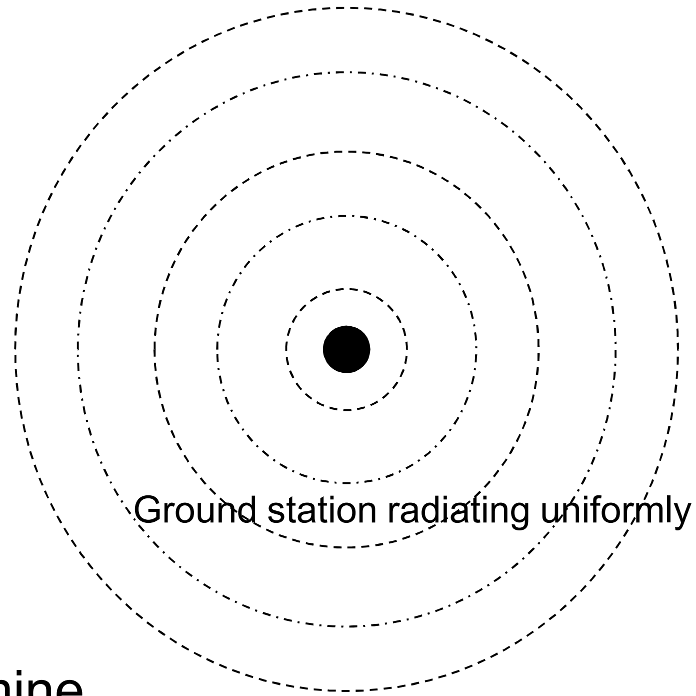
  but also countermeasures….
- Y-Gerat or ‘Wotan’ was effectively foiled since the operating frequency inadvertently was the same as the powerful TV transmitter at Alexandria Palace and could thus be interfered with easily.

ADF – Automatic direction finder

- One basic principle of radio navigation can be illustrated by ADF.



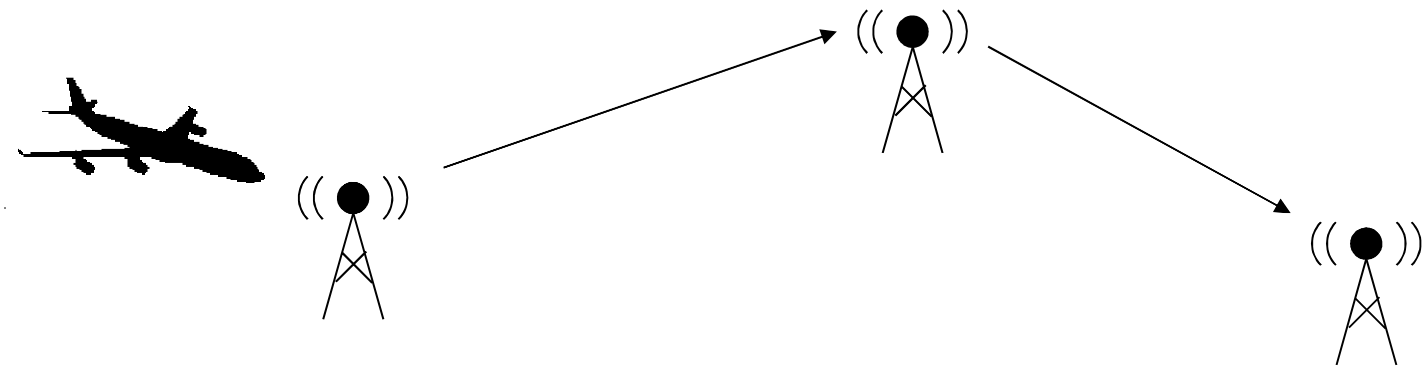
Aircraft with moveable directional antenna



Ground station radiating uniformly

- By rotating the antenna and seeking maximum signal the ADF can determine the bearing to the ground station (of known position)

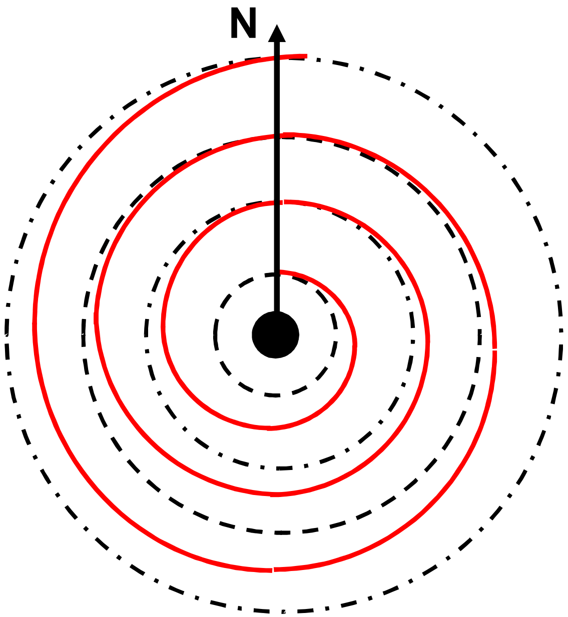
ADF – Automatic direction finder



- ADF allows point to point navigation following predetermined flight paths (as is normal in civil airspace).
- Operating in the LF bands it has a range <75NM
- ADF has been around for some time – it became compulsory for commercial flights in the US in 1937.
- Low cost and the technique has applications today

VOR – VHF omni-directional Range

- The more recent (1950's on) 'no moving parts' version of ADF is known as VOR.
- In the VOR scheme the aircraft antenna is fixed, but the base station transmits a more complex signal consisting of a rotating pencil beam and an omni-directional pulse.



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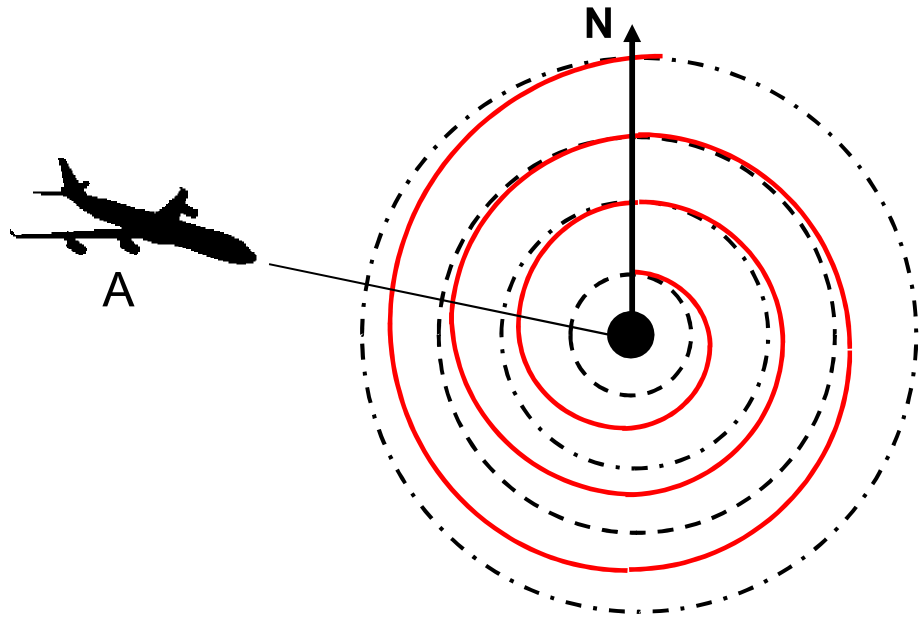

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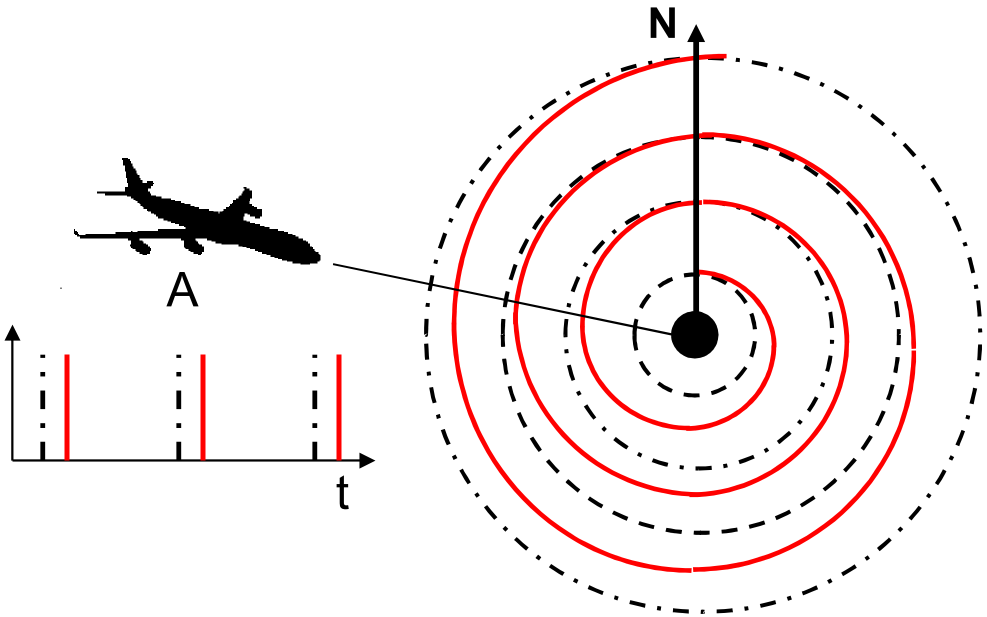

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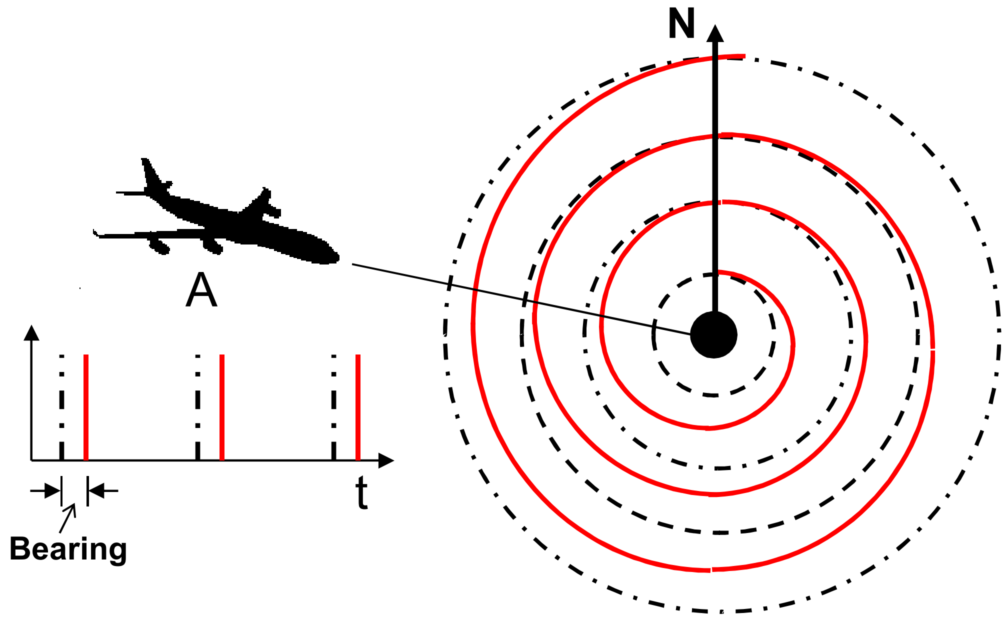

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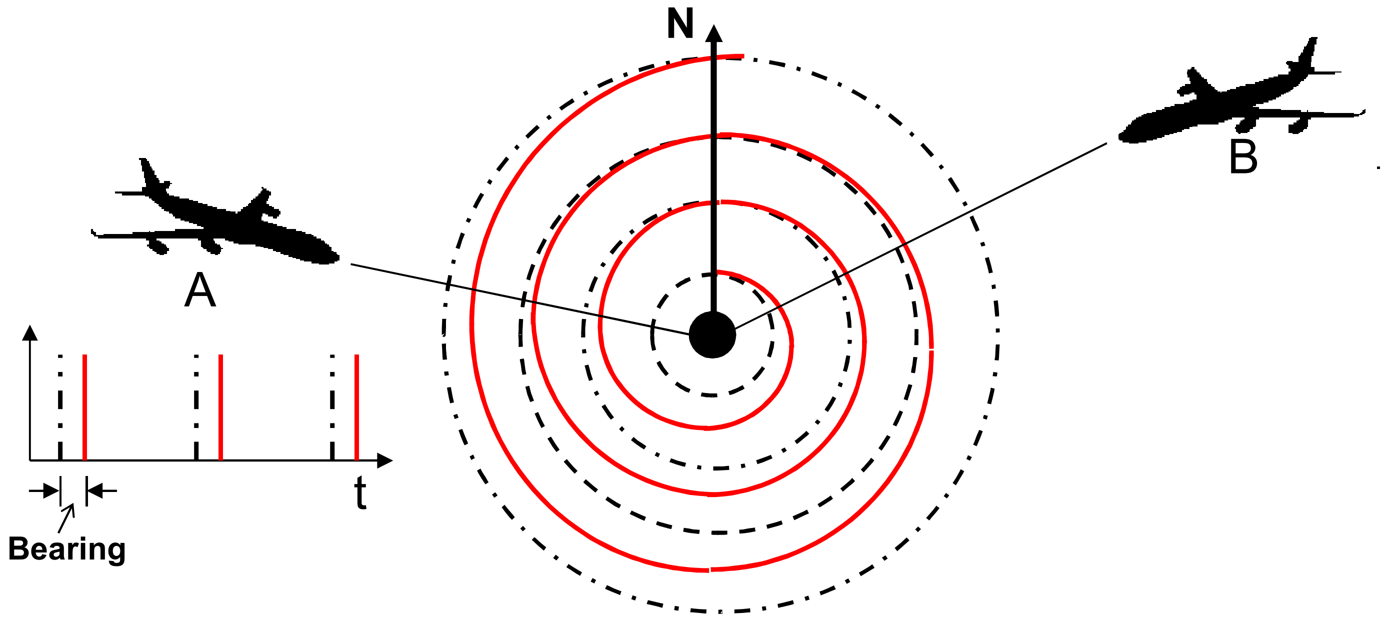

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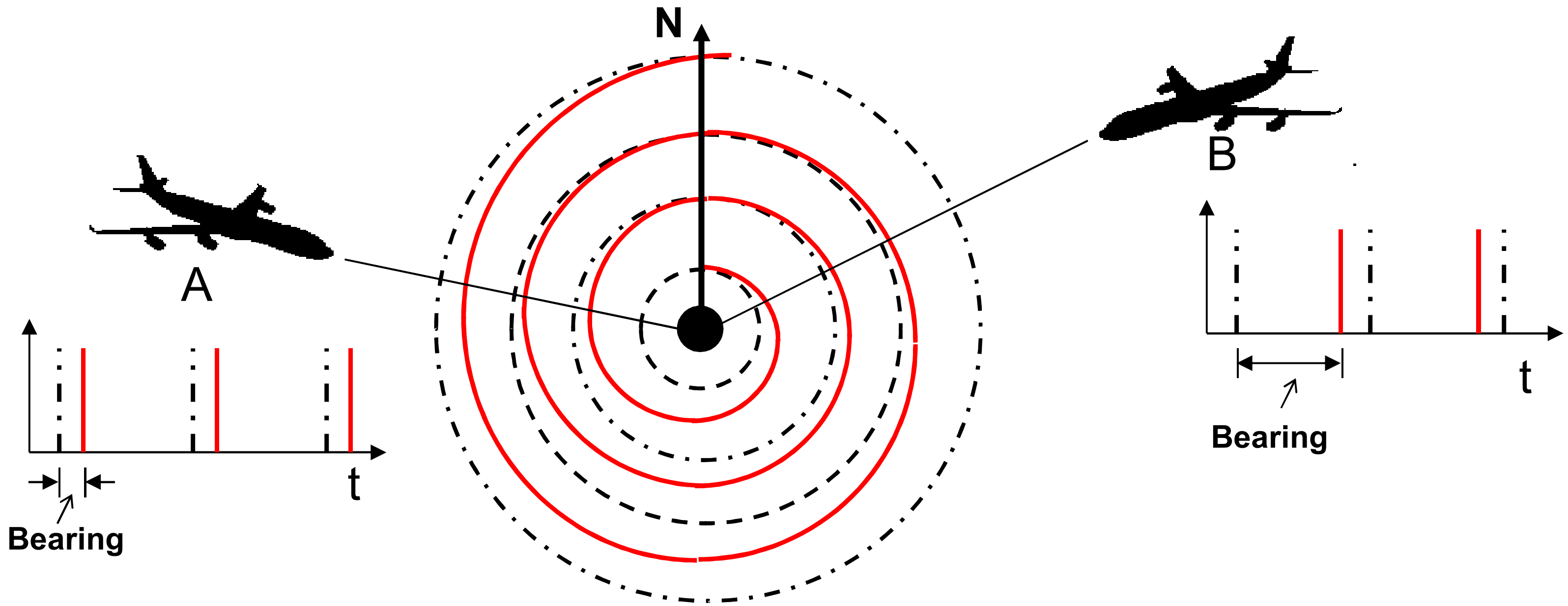


VOR beacon

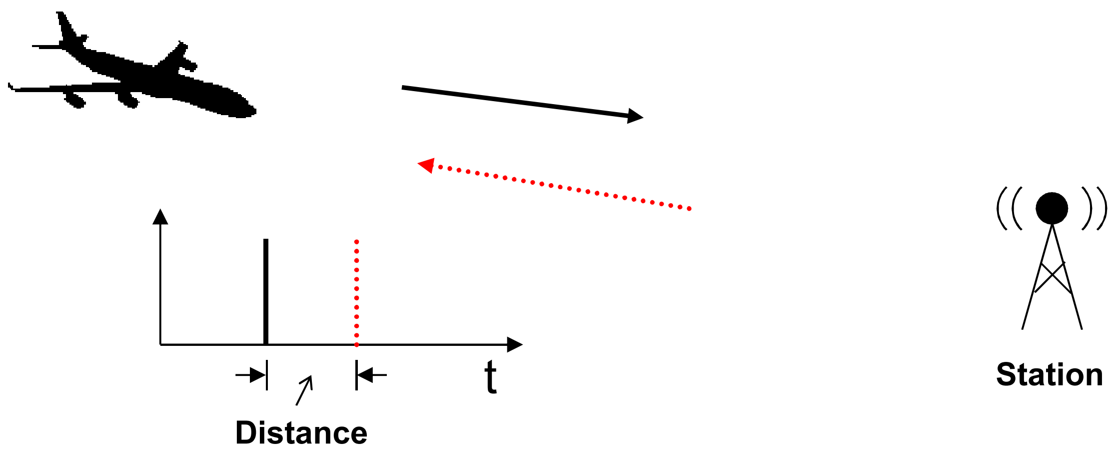
VOR Station

VOR

- VOR is currently the most widely used and important radio navigation aid.
- The transmitted signals are actually Morse Code or a voice signal to identify the station. (this is also the case with ADF)
- In addition other communications can piggy-back on the transmission, e.g. air traffic control.
- Operating in the VHF band it is limited to line of sight – thus VOR requires a high number of stations located along flight paths.
- VOR stations are expensive, although they have almost entirely replaced LF ADF type stations for civil aviation since VOR offers improved accuracy and less interference than ADF.

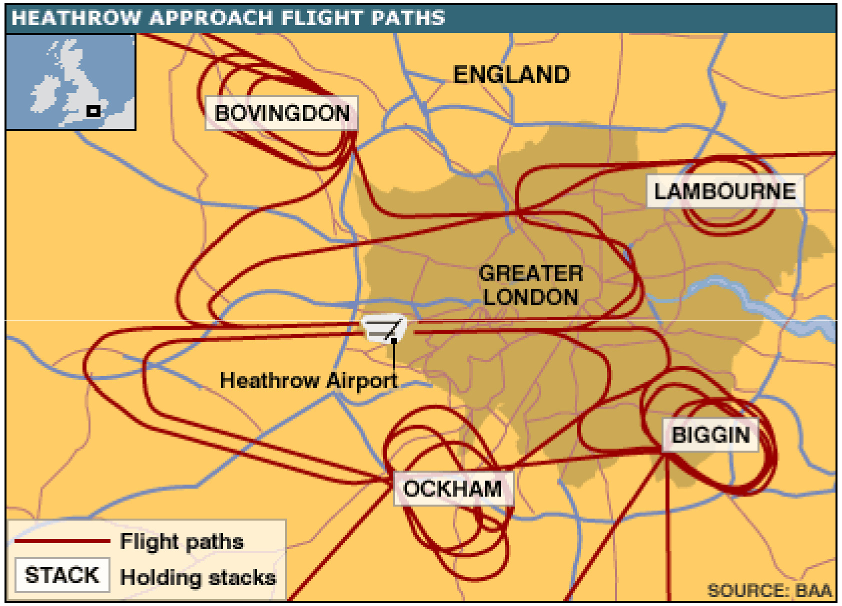
DME – Distance measuring equipment

- Some systems supplement the bearing information of VOR with the information about the distance of the aircraft from the station.
- The system used is actually part of TACAN (TACtical Air Navigation) – a military system similar to VOR.
- The aircraft sends an interrogation signal to the station and times the response – the time is proportional to the distance.

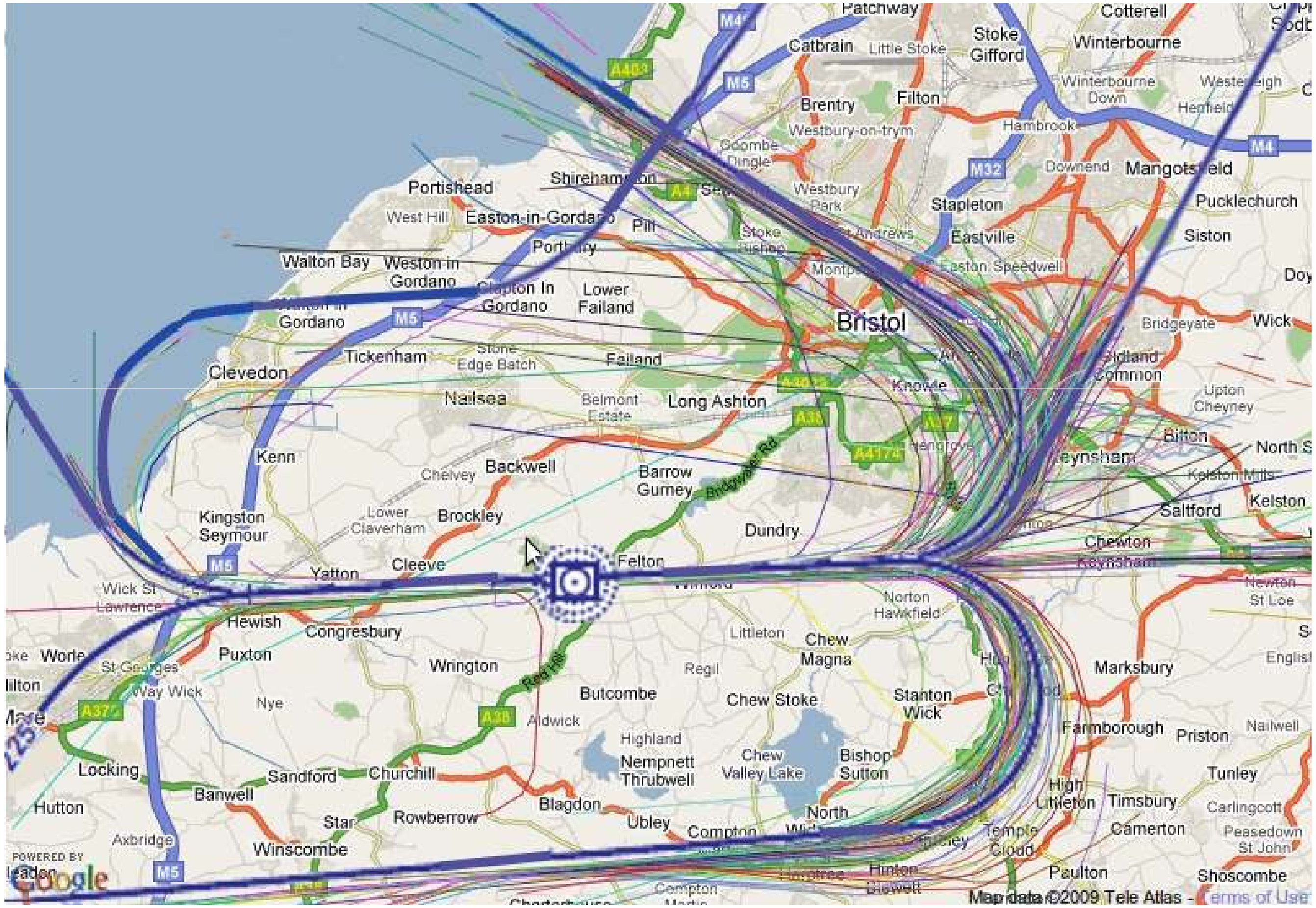


Air traffic control - Flight Paths

- Air traffic control was developed in response to mid air collisions.
- It started off (limited by technology) as controllers at airports.
- It is a system of centralised control so it makes sense to fly aircraft along pre-determined corridors at defined flight levels.
- The navigation infrastructure reflects this, e.g. VOR beacons along flight paths.



Bristol flight paths



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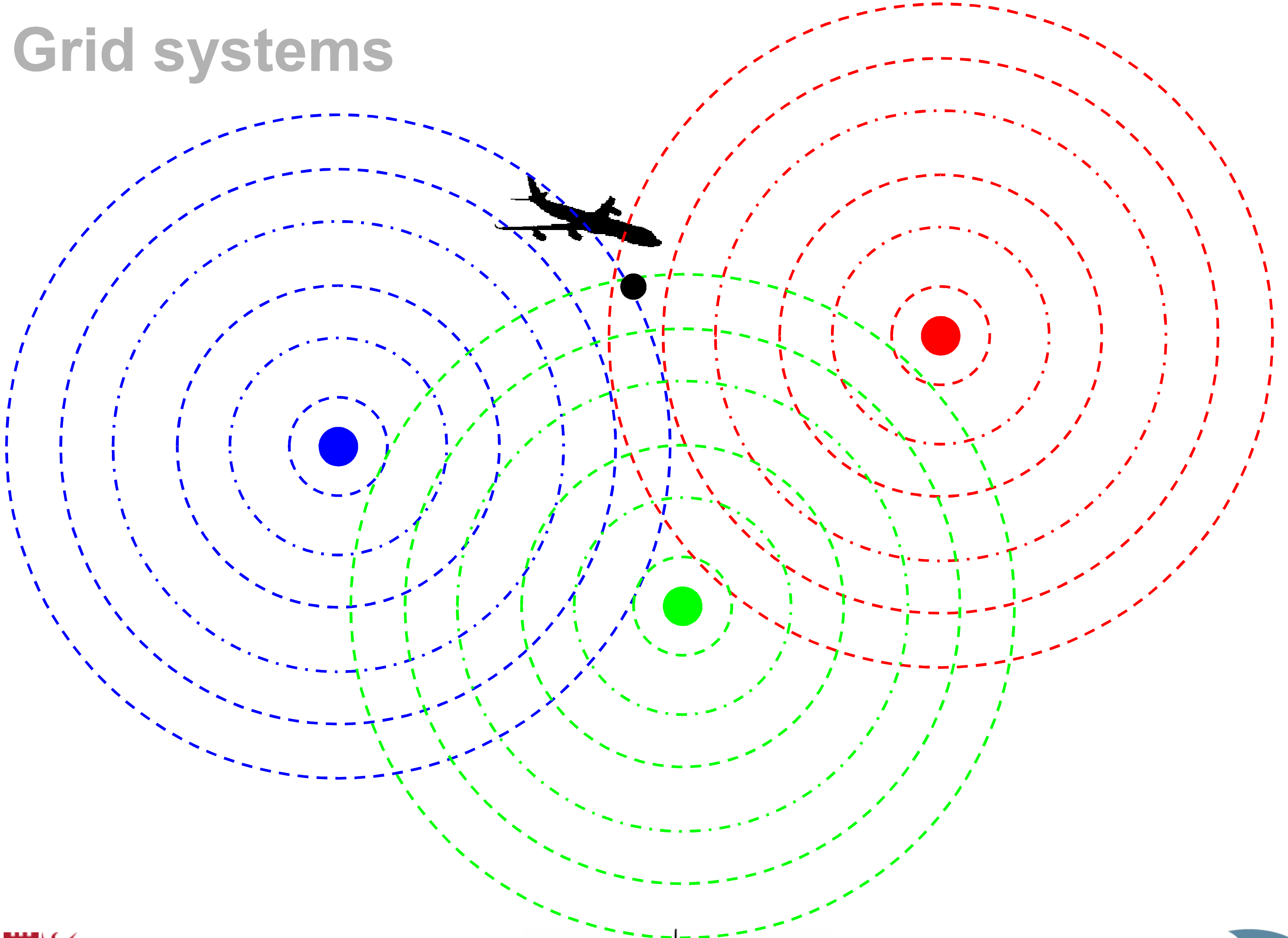
Grid systems

- The systems we have looked at so far are point systems – ideal for flying along pre-determined ‘corridors’.
- It is possible to use the bearing information from 2 or more VOR stations to determine location in 2D space – a so called ‘grid system’ (or hyperbolic) but the usefulness is limited by the short range of the VHF transmissions and to provide more extensive coverage would be prohibitively expensive.
- To overcome this several grid systems were developed using LF RF.

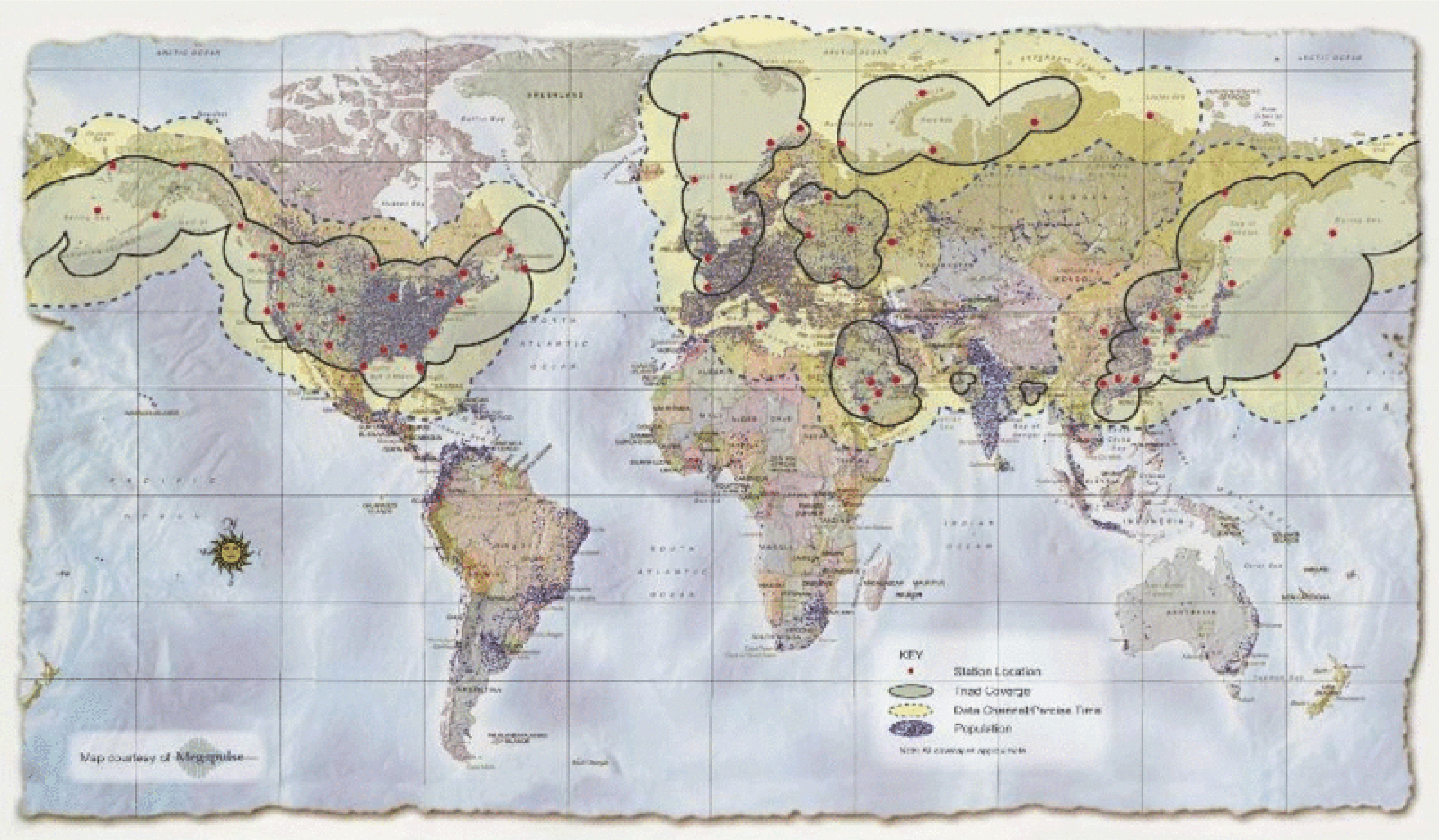
Grid systems



Grid systems

- DECCA – developed by the British during WWII. DECCA is actually a company name. Used in latter years for shipping and switched off in march 2000
- OMEGA – US military system using VLF and the only system that provided coverage over the entire globe. Operational 1971 - 1997.
- LORAN C (LOng RAnge Navigation) – Developed in the 1950's and the only just shut down (2010). Widely used for shipping and aviation. LORAN transmitters are arranged in 'chains' (a master and 2 or more slave stations) that give overlapping areas of coverage.

LORAN coverage



Satellite navigation systems

- Ground based radio grid systems have now been superseded by satellite navigation systems.
- These are essentially the same concept as other grid systems, just with the transmitters are satellites: triangulation from a minimum of 4 satellites at known locations, establishing distance from a synchronised clock signal.
- By having the transmitting stations orbiting, it was possible to have many more of them and give line of sight coverage over the world
  - National boundaries restrict ground based infrastructure
  - Ground based systems needed low frequencies =
    - Long antennas, low information rates

NAVSTAR GPS

- When most people say GPS, they refer to NAVSTAR GPS, a US military system with access granted to other users.
- For many years this was the only fully functioning satellite navigation system, and has made most impact in commercial and domestic markets.
- The system uses differing encryption codes for differing classes of user and employs more than one frequency to help mitigate for atmospheric propagation errors.
- Originally the civilian codes were deliberately degraded – this policy was officially abandoned in 2000 allowing the system to find many more applications.

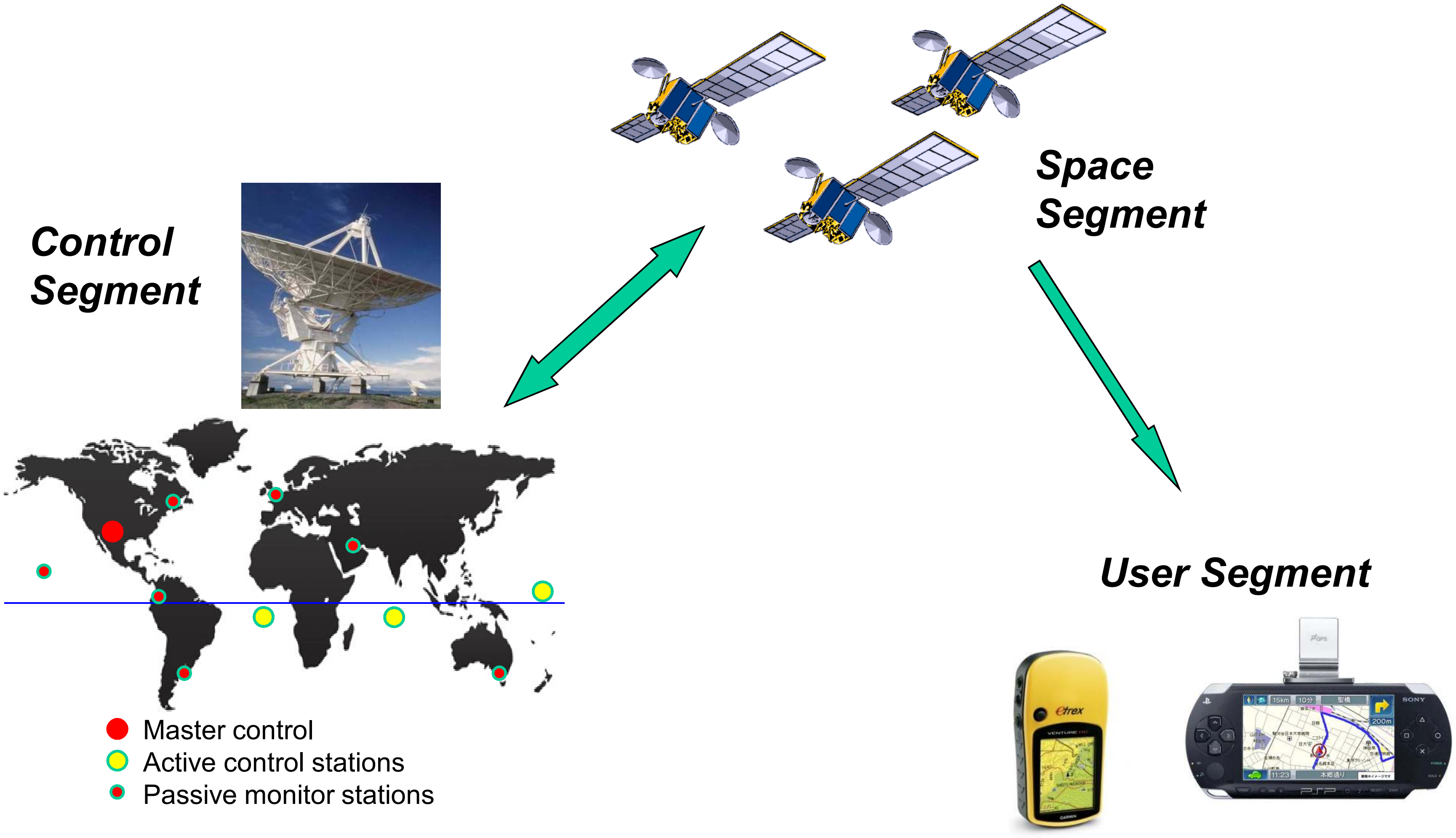
NAVSTAR GPS

- On its own a civilian GPS system can achieve accuracy of around 10’s m.
- This is limited by the fundamental accuracy of the code – how ‘coarse’ it is, and by propagation errors.
- Military systems use a finer code and two channels to minimise both sources of error.
- Resourceful civilian users improved on this by;
  - Creating differential systems – corrections from a known point
  - Using the two encrypted military channels to give limited information to correct propagation errors – typically used for surveying

Other satellite navigation systems

- GLONASS
  - Russian System, recently resurrected.
  - First fully operational (24 satellites) in 1995 (a year behind GPS).
  - Fell into disrepair: two new satellites were needed each year to keep the system operational.
  - System back fully operational in 2011
- Galileo
  - EU system, planned to come on-line many times!
  - Currently 4 satellites, fully operational 2019?
- Compass
  - Chinese system, currently covers Asia
  - Fully operational 2020.

GPS segments



GPS – on aircraft

- GPS is increasingly used alongside other navigation aids – although it may never completely replace RF technologies because of concerns over robustness, accuracy and service-denial.

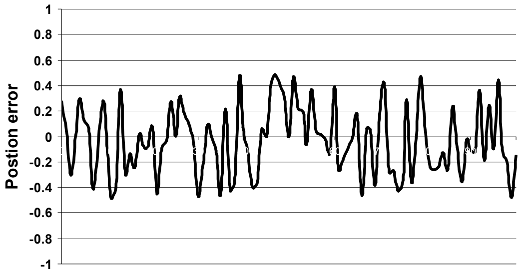
- Originally restricted for civil aircraft;
  - Must be supplemented by other navigation aids,
  - Not used for approach guidance,
  - Constructed and maintained to FAA regulations,
  - Have RAIM (Receiver Autonomous Integrity Monitor)

- New implementations are widening use – WAAS (wide area augmentation system) and LAAS (local area augmentation system) : essentially aircraft-specific differential systems with integrity monitoring.

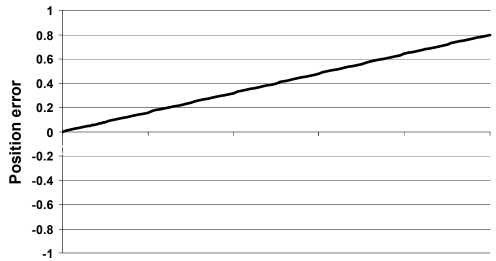
Combined systems

- INS and external type systems have different error dynamics
  - INS, High short term relative accuracy, long term drift.
  - External systems short term errors, long term accuracy.

GPS, VOR, LORAN, ADF



INS



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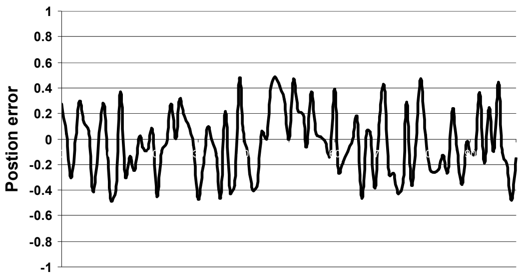
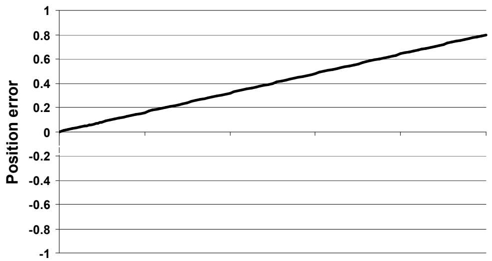
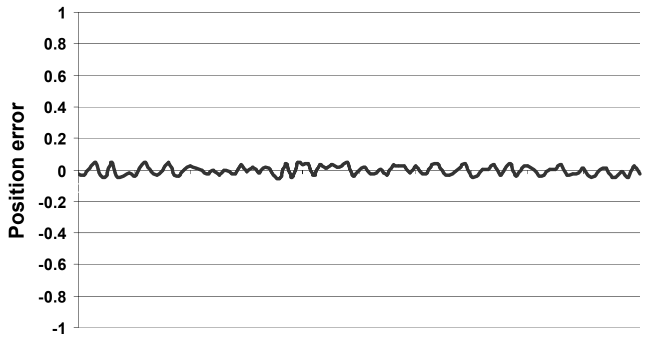


INS





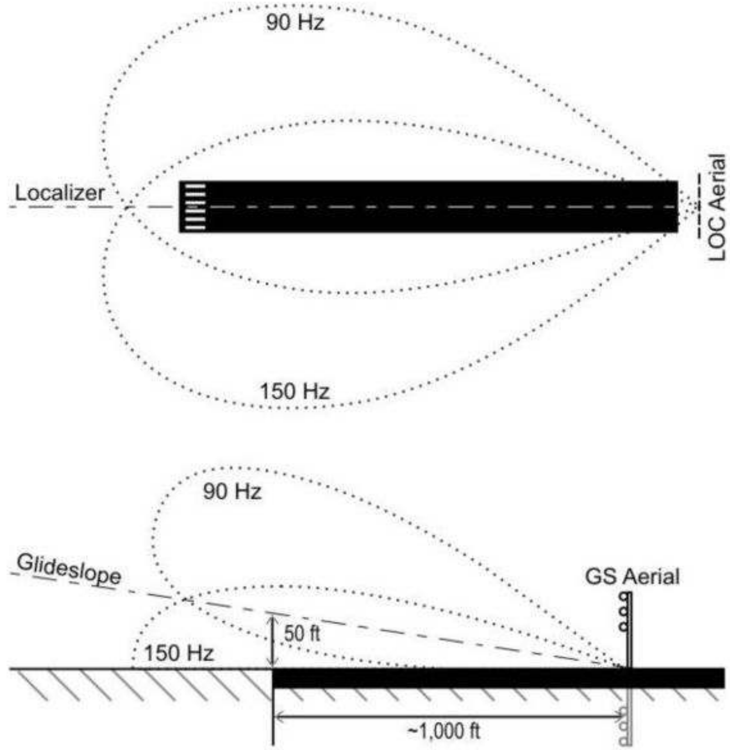
'Sensor fusion' can combine the positive properties of each system to provide overall enhanced performance.

ILS – Instrument landing system

- Navigation is most critical during the final part of the flight, the landing. The most common civil system is the ILS, a RF based system.

- The localiser provides lateral position

- The glides slope altitude information

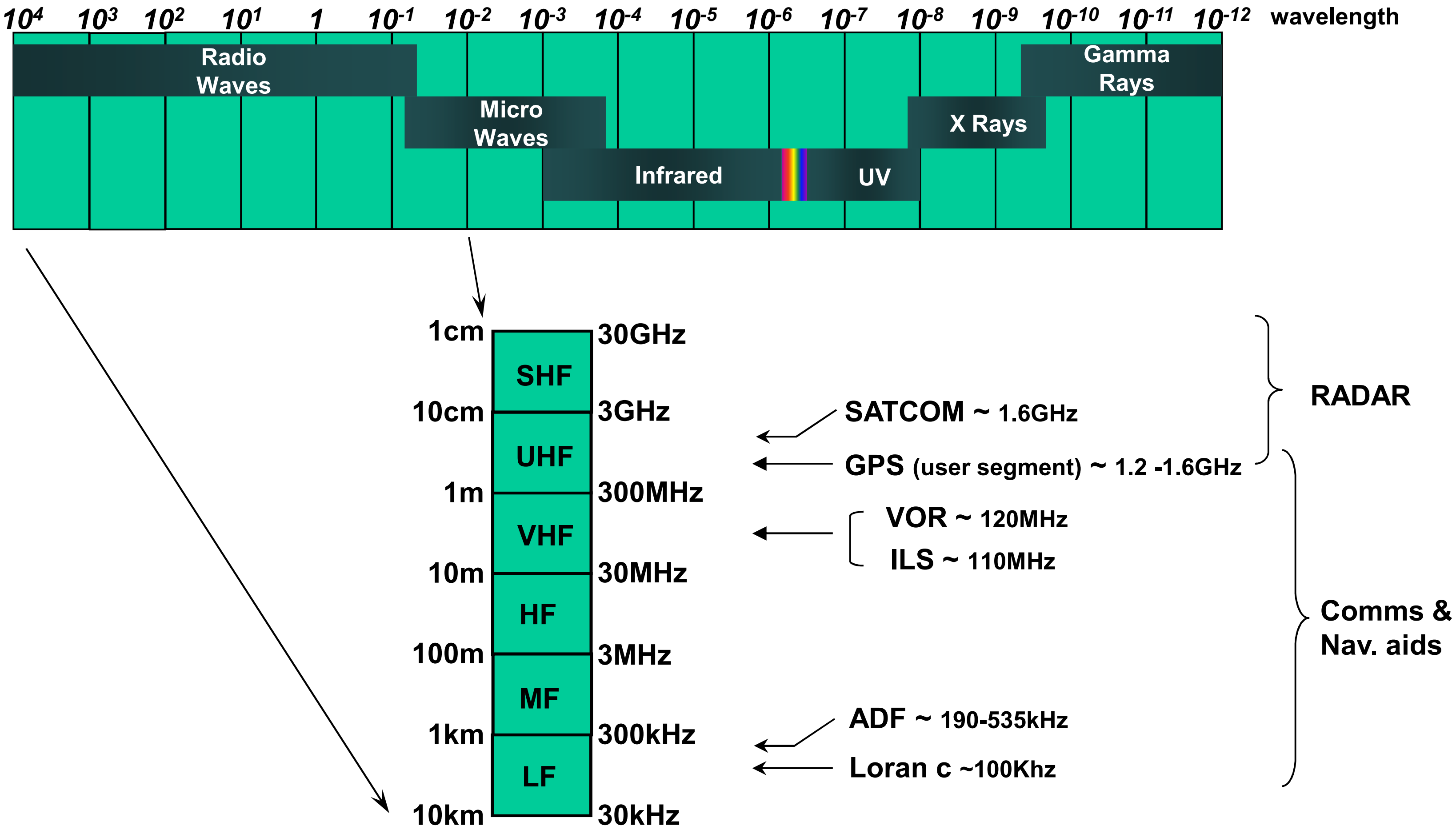


Glide slope and localiser antenna

ILS – Instrument landing system

- Depending on the equipment fitted to the aircraft (and airport) different categories are defined;
  - CAT1 This permits the pilot to land with a decision height (where pilot takes over from autopilot) of 61m and forward visibility of 800m.
  - CAT2 Permits pilot to land with a decision height of 30m and forward visibility of 350m.
  - CAT3a No decision height, visibility 200m
  - CAT3b No decision height, visibility 50m.
  - CAT3c No decision height, no visibility – also guides plane along runway after landing.

RF Spectrum – Aircraft



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Antenna on a civil airliner