Navigation

SS-2004

Chapter 8 – Terrestrial radio navigation

8 Terrestrial radio navigation / Contents

8 Terrestrial radio navigation (1)

8.1 Introduction

- Main objective: **position fixing**
- Radio navigation uses radio waves transmitted by known points to determine the position of a roving receiver
- Measurements used: bearings, distances, pseudoranges
- Positioning uses **lines of position** (LOP) ➔ Sect. 3.2.3
- Elementary properties of the electromagnetic wave propagation must be considered ➔ Sect. 4.2

- Propagation characteristics
  - **Ground** waves
  - **Sky** waves
  - **Line-of-sight** waves

8 Terrestrial radio navigation (2)

8.2 Point source systems

8.2.1 Direction-finding ("radio compass")

- A **directional antenna** is used to get a bearing to a transmitter
- Transmitters can be
  - Broadcast stations
  - Communication stations
  - Navigation stations
  - Any other kind of radiating system
- Direction finding is the **earliest use of radio** for navigational purposes

8 Terrestrial radio navigation (3)

– It continues to perform a useful function as
  - Backup system, or
  - In cases where more specialized navigation aids are not available in some parts of the world
– Main drawback
  - Quite **elaborate receiving equipment** must be used if high accuracy is required

8 Terrestrial radio navigation (4)

- Classes of direction-finders for aircraft navigation
  - **Airborne direction finder** (active navigation)
    - Takes bearings from the aircraft to ground transmitters
    - Typically, only simple antenna systems can be afforded
    - Large errors must be tolerated
  - **Ground based direction finder** (passive navigation)
    - Also: **Automatic Direction Finder** (ADF)
    - Takes bearings from the ground to the airborne transmitter upon request
    - Transmits the result back to the aircraft
    - More economic and accurate but cumbersome and time-consuming
    - Requires an airborne transmitter and a communication link

8 Terrestrial radio navigation (5)

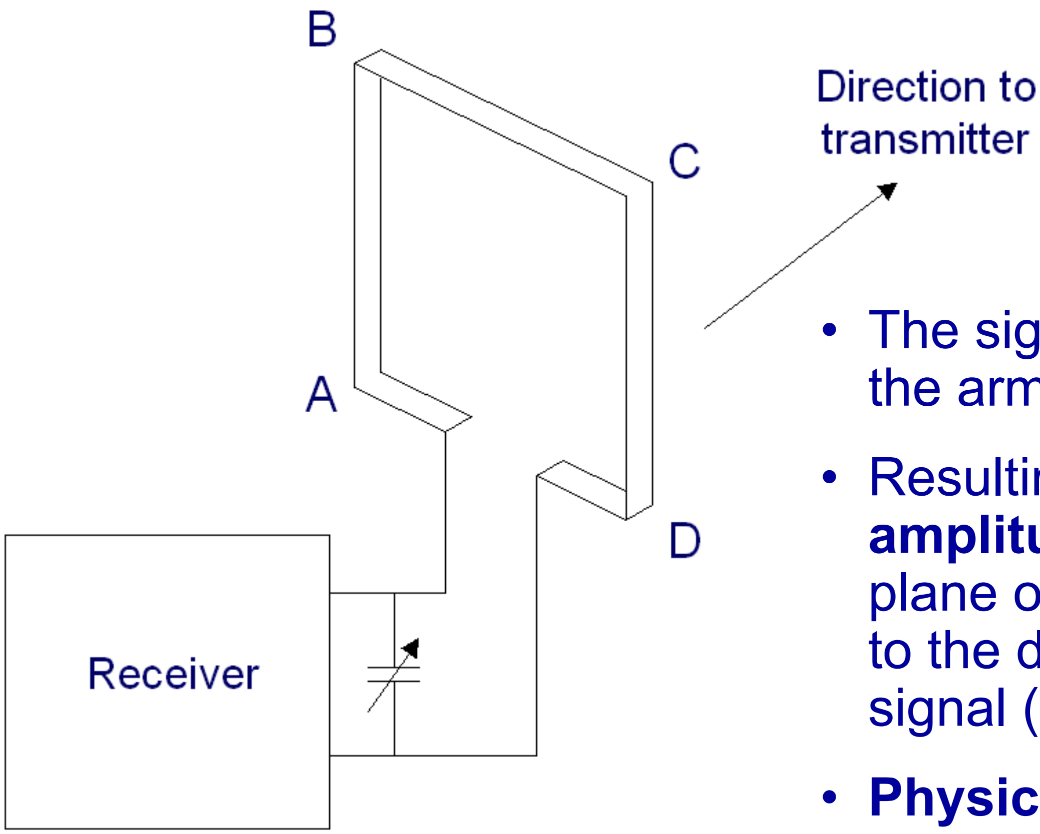
Loop antenna direction-finder principle

- No longer in production
- However, its basic principles still apply to the current generation of equipment

- Measurement of **differential distance to a transmitter** from two or more known points

8 Terrestrial radio navigation (6)

Basic principle of direction-finding loop



- The signal induces a **voltage** in the arms AB and CD of the loop
- Resulting currents are **equal in amplitude and phase** when the plane of the loop is **exactly 90°** to the direction of arrival of the signal (null position of the loop)
- **Physically rotating the loop** to the null position indicates the direction to the transmitting station

Goniometer direction-finder principle

- Two fixed loops are placed at right angles
- The goniometer translates the received radio field at the loops into a miniature magnetic field
- **Accuracy**
  - ± 2° (exclusive of errors induced by aircraft structure)
  - Including these errors, low- and medium-frequency direction-finders that use ground waves cannot produce reliable results better than ± 5°
  - Sky-wave contamination can raise this value to ± 30° or more

TUG

Airborne VHF/UHF direction-finder system

- **VHF**: 30 – 300 MHz, **UHF**: 300 – 3000 MHz
- Antennas of large aperture are required
- Many U.S. military aircraft carry direction-finding equipment
- The system is useful for air-to-air direction finding (rendezvous, refueling)

8.2.2 Nondirectional beacons (NDB)

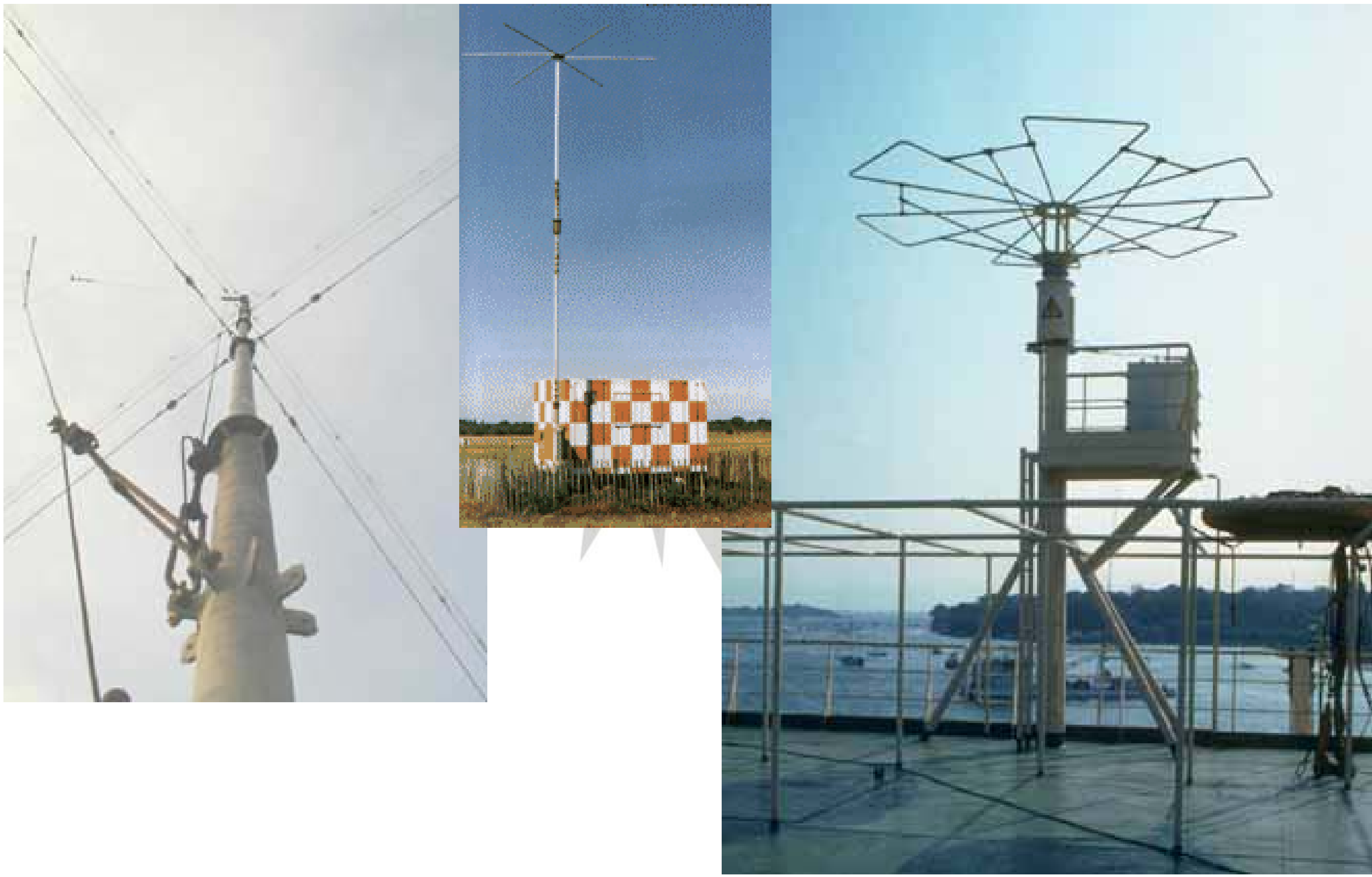
- Special transmitters are installed acting as **omnidirectional transmitters** for direction-finders
- Radio band 190 – 535 kHz is used
- NDBs are connected to a single vertical antenna
- In addition to the directional information given to direction finders some distance away, NDBs have another useful property:
  - There is a sharp reduction in signal strength as the aircraft flies **directly over the beacon** ➔ specifically defined fix for air navigation
- NDBs are used for marine and aeronautic navigation

8 Terrestrial radio navigation (10)

- Drawbacks
  - **Night** effect: vulnerability to interference from distant stations
  - **Mountain** effect: signals may be reflected ➔ fluctuations
- Nondirectional beacons have retained their popularity because
  - They are inexpensive
  - They are omnidirectional
  - They place responsibility for the quality of the bearing measurement entirely on the airborne receiver
- In 1996, the US maintained approximately 177 000 NDBs for civil aviation use with a growing rate of about 7 000 per year
- NDBs are used all around the world

8 Terrestrial radio navigation (11)

– Examples of **NDB ground antennas**



8.2.3 Marker beacons

- To provide better fixes along the airways, marker beacons were developed ➔ part of the **instrument landing system** (ILS)
- They radiate a **narrow pattern** upward from the ground
- Marker beacon transmitters imply **distance information** to the runway ➔ remind the pilot of important altitude decisions during the approach ➔ **decision height** (DH)

More information: see Sect. 8.4.1.

8.2.4 VHF omnidirectional range (VOR)

- Principle is analogous to aids to visual navigation:
  - Imagine a **rotating beam** at a lighthouse which becomes visible to the navigator if its direction coincides with his looking direction
  - When this rotating beam moves through a **reference direction**, it causes a **second light** to illuminate **omnidirectionally**; thus, vessels in arbitrary directions might see this light
  - The **time elapsed** between these two events is a measure for the angle between the vessel and the reference direction

8 Terrestrial radio navigation (14)

- VOR operates in the **VHF band** of the spectrum at 108 – 118 MHz
- VOR stations are radio beacons transmitting a signal which provides bearing information
- Lighthouse principle translated to radio waves:
  - A VOR ground station electronically rotates a directional antenna pattern at **30 rps** (round per second), generating a **30 Hz sine wave** at the airborne receiver and
  - The reference signal uses a **frequency modulation** of 30 Hz and is transmitted omnidirectionally

8 Terrestrial radio navigation (15)

- The phase difference between the two 30 Hz signals varies directly with the **bearing** of the aircraft
- The VHF carrier is also modulated by a 1020 Hz **Morse code** identification signal (➔ cf. Sect. 1.6) and by a voice signal
- Range of VORs: some 200 nautical miles (nmi)

8 Terrestrial radio navigation (16)

– **Receiver characteristics**
  - The receiver detects the 30 Hz amplitude modulation produced by the rotating pattern and compares it with the 30 Hz frequency-modulated reference signal
  - For airline-type of equipment, the two signals are brought into phase by a **motor-driven phase shifter**
  - The shaft position of this motor displays the bearing directly

– **Accuracy**
  - Around ± 1° in airline-type equipment
  - The main problem of the VOR is to measure phase shifts at 30 Hz accurately

8 Terrestrial radio navigation (17)

– Example of a (conventional) **VOR ground antenna**

8.2.5 Doppler VOR

- Compared to the conventional VOR, the only difference in the receiver is that the
  - 30 Hz amplitude-modulated signal is the reference and the
  - 30 Hz frequency-modulated signal is the variable
- The principle of wide antenna aperture is used to reduce site errors
- Compared to VOR, Doppler VOR does not require any change of the airborne equipment
- Doppler VORs are preferred in **mountainous areas**

8 Terrestrial radio navigation (19)

– Example of a **Doppler VOR ground antenna array**

8 Terrestrial radio navigation (20)

– Example of **VOR onboard equipment**

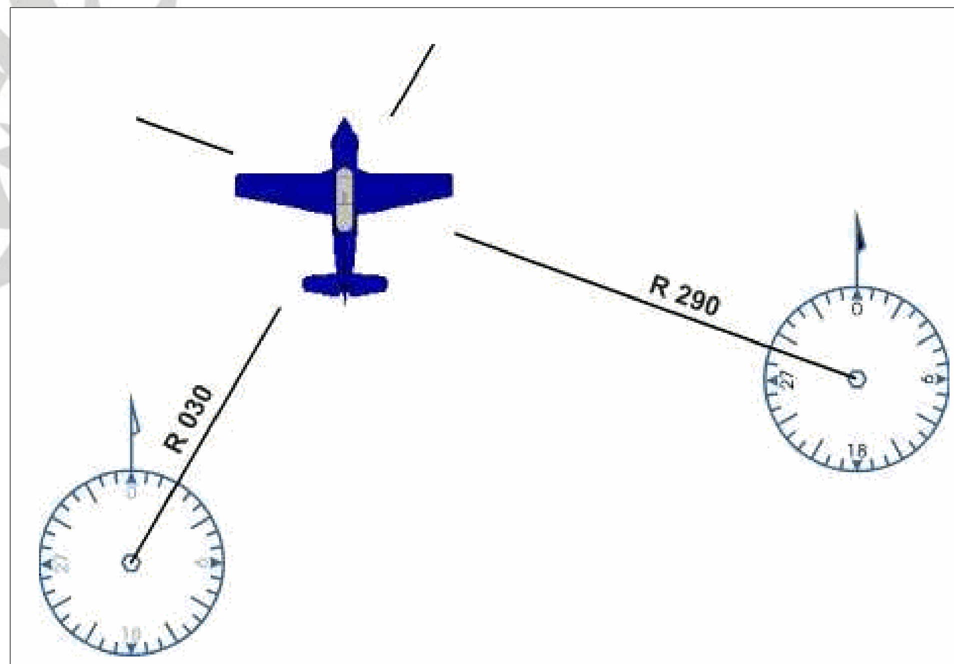
- A: course card (can be rotated by the knob B)
- B: omni bearing selector (OBS) ➔ selection of a VOR radial; here: 345°
- C: course deviation indicator (CDI); here: 0°
- D: to-from indicator; here: to

Source: www.navfltsm.addr.com

8 Terrestrial radio navigation (21)

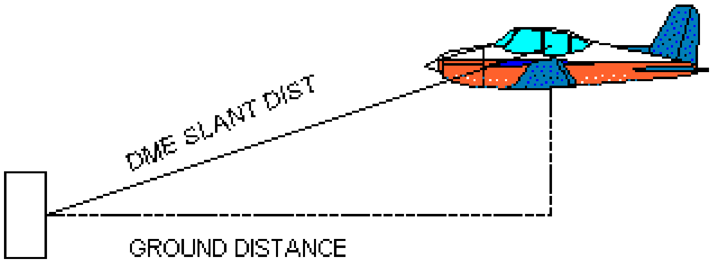
– **Navigation by VOR**

- VOR (+ DME) symbol in an aeronautical map
- Theta-theta fixing using two VOR stations



8.2.6 Distance-measuring equipment (DME)

- **Pulse-ranging system** for aircraft developed during World War II
- Commercially available since 1961
- Principle of DME: the **slant range** between the ground station and the aircraft by a two-way (interrogation-reply) run time measurement



- The aircraft transmits a signal which is received by the ground station and retransmitted
- The measured **run time** is translated to distance
- DME operates in the UHF band ➔ restriction to line of sight

8 Terrestrial radio navigation (23)

- **Principle** (a)
  - The **aircraft interrogator transmits pulses** on one of 126 frequencies, spaced 1 MHz apart (1025 – 1150 MHz band)
  - The pulses are in pairs, 12 µs apart, each pulse lasting 3.5 µs
  - Pulse-pair-repetition rate ranging between
    - 5 pulse-pairs/s
    - 150 pulse-pairs/s
  - Paired pulses are used in order to reduce interference from other pulse systems
  - The **ground beacon** (transponder) receives these pulses and, **after 50 µs fixed delay**, **retransmits** them back to the aircraft on a frequency 63 MHz **below or above** the airborne transmitting frequency

8 Terrestrial radio navigation (24)

- **Principle** (b)
  - The airborne interrogator compares the elapsed time between transmission and reception and displays the result in nautical miles (representing about 12 µs of elapsed round-trip time)
- Each beacon is designed to handle at least 50 aircraft simultaneously ➔ **capacity limitation** by two-way communication

- **Receiver characteristics** (a)
  - The reply is compared with the transmitted signal (ranging circuit)
  - The ranging circuit also gets all other pulses transmitted from the ground beacon. Therefore, it must
    - Recognize its own replies and reject all others
    - Convert these into a meaningful display

8 Terrestrial radio navigation (25)

– **Receiver characteristics** (b)

- The basic objective of all DME ranging circuits is to locate the time slot where the desired replies are actually occurring ➔ search process at the highest permissible pulse-repetition rate (150 pulse-pairs/s).
- Once the slot has been found (may vary from 1 to 20 s), the track mode commences and can be conducted at a much lower pulse-repetition rate, usually between 5 and 25 pulse-pairs/s
- **Loss of signal**
  - For about 10 s, a static memory indicates the last position or a velocity memory to get information on the last rate
  - A new search is not immediately started upon loss of signal

8 Terrestrial radio navigation (26)

- **Transmitter characteristics**
  - Whereas the airborne equipment must operate on 126 channels, the ground beacon usually stays on one channel for long periods
  - The number of aircraft that a beacon can handle is usually based on the assumption that
    - 95 % of the aircraft will be in the track mode at not over 25 interrogations/s and
    - 5 % are in the search mode at not over 150 interrogations/s
  - For 100 aircraft, this means about 3000 pulse-pairs/s

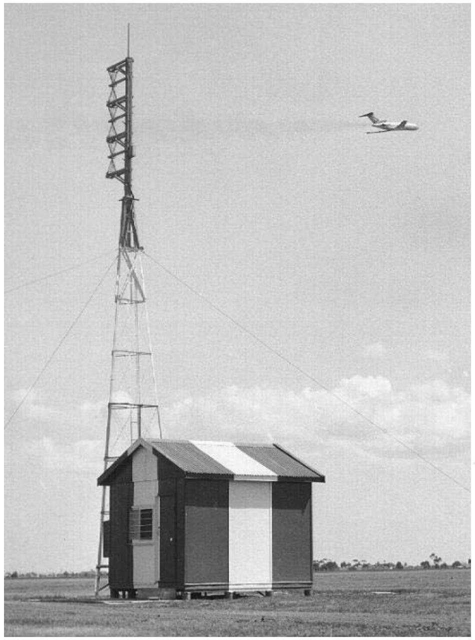
- DME (unlike the VOR) is not a passive system ➔ inherent capacity limitation of about 110 aircraft per beacon

8 Terrestrial radio navigation (27)

- Collocation of the DME ground station with a VOR station: **Standard ICAO rho-theta short-range navigation system**
- Several DMEs can be combined to form a multiple ranging navigation system
- Achievable 2-σ accuracies:
  - DME: ± 185 m (or ± 0.1 nautical miles)
  - VOR: ± 1.4°

8 Terrestrial radio navigation (28)

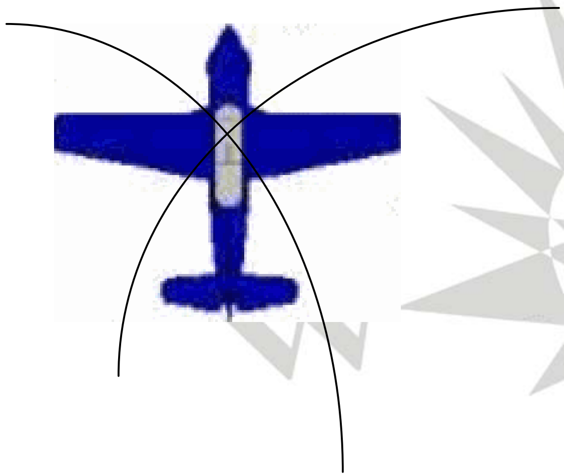
– Examples of **DME ground equipment**



– Example of **DME airborne equipment**

8 Terrestrial radio navigation (29)

– **Navigation by DME**
  - Rho-rho fixing using two DME stations



– **Navigation by VOR/DME**
  - Rho-theta fixing using a collocated VOR/DME station

8 Terrestrial radio navigation (30)

– Examples of **Doppler VOR/DME ground equipment**

8.2.7 Tactical air navigation (Tacan)

- **Military** counterpart of VOR/DME
- UHF domain, continuous bearing and distance to a station
- Airborne equipment: DME interrogator plus Tacan bearing circuits
- Distance and bearing are obtained via the same RF channel
- In 1996, over 800 facilities were maintained for the U.S. DoD

- Tacan 2-σ signal-in-space accuracy
  - Bearing: ± 1° (translates to ± 65 m at 3.75 km)
  - Distance: ± 185 m (± 0.1 nautical miles)

- Capacity
  - 110 aircraft for distance measurement (active)
  - Unlimited for bearing measurements (passive)

TUG

8.2.8 VORTAC

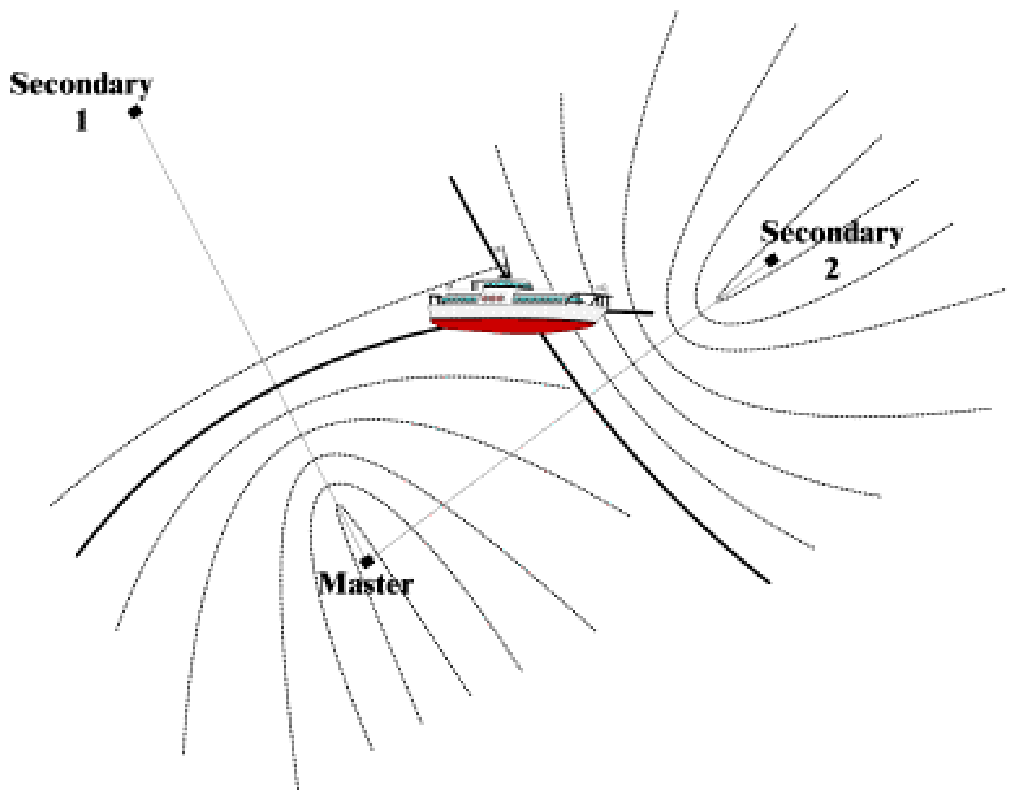
- Combination of VOR and Tacan is denoted as VORTAC
- Provides **rho-theta fixing** to both **civil and military** aircraft
- Three individual services:
  - VOR bearing
  - Tacan bearing
  - Tacan distance
- Civil aircraft read distance from Tacan and bearing from VOR
- Military aircraft get both distance and bearing from Tacan
- In 1996: more than 200 000 users in the U.S. alone

8.3 Area-based systems

- Point source systems: one transmitting source
- Area-based systems: **more than on transmitter**
- Typical representatives
  - **Hyperbolic systems** are based on **coordinated** transmissions from radio stations (Omega, Decca, Loran-C / Chayka)
  - **Other systems** (only partly covered)
    - Datatrak
    - Digital television networks
    - Cellular communication networks

Hyperbolic systems

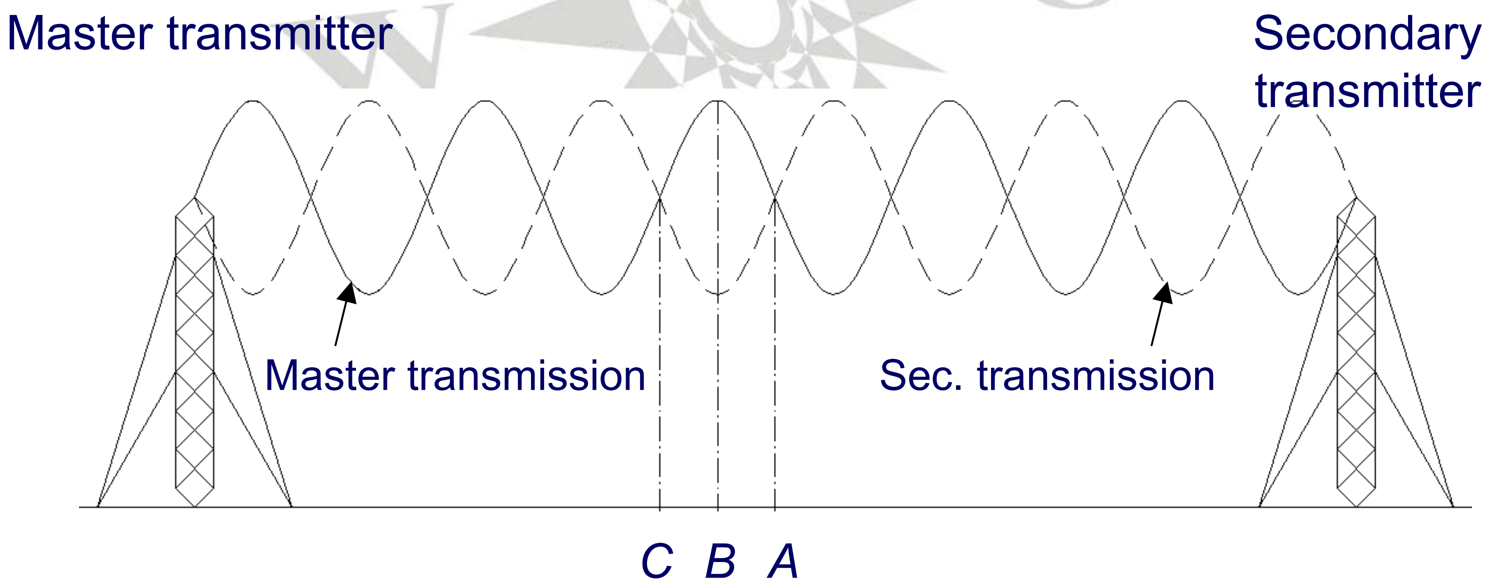
– LOP is a hyperbola ➔ all points have a **constant difference in distance** from two fixed points (i.e., the foci)



8 Terrestrial radio navigation (35)

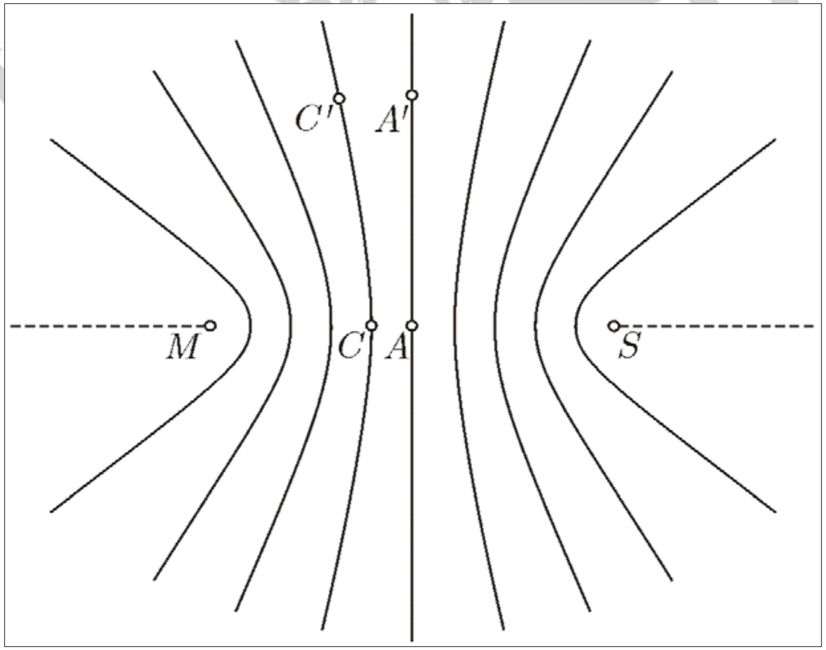
– **Figure**: two continuous wave signals (synchronized in phase)
– Simplification: an integer of wavelengths fits between the stations

- ***At A and C***: same phase **At *B***: maximal phase difference
- Moving from *A* to *C*, the receiver crosses one “**lane**”
- Width of the lane: **half wavelength** of the transmitted signal



8 Terrestrial radio navigation (36)

– **Figure**: the hyperbolas represent the LOPs for all receiver positions where the received signals from master and secondary station (the foci) are in phase
  - Receiver cannot distinguish A and A' (C and C')
  - The change of the number of traversed lanes is known because it is registered by the receiver (➔ “traditional” receiver)



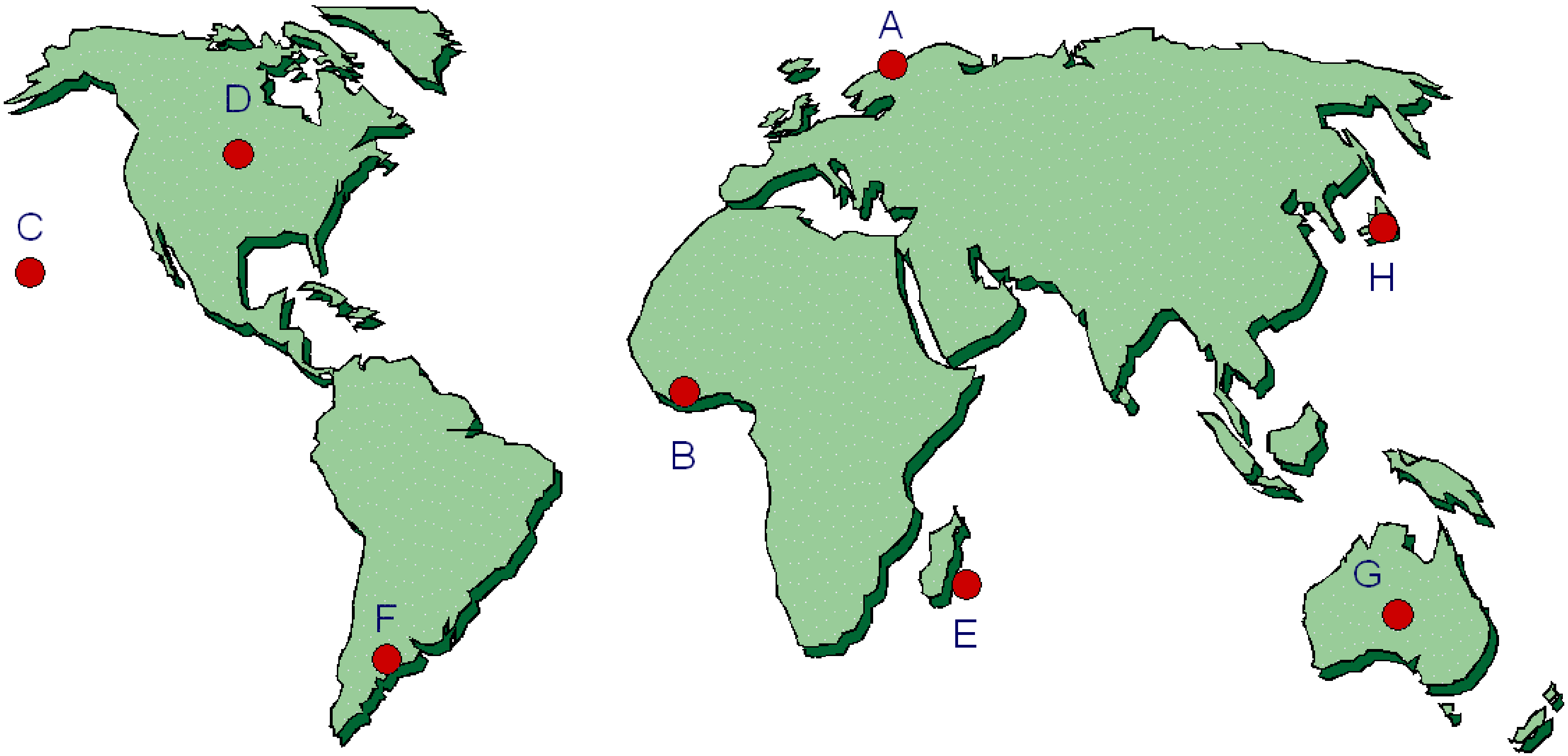
8.3.1 Phased-out systems

Omega

- Omega *was* a **very low frequency** (VLF) system using frequencies in the 10 – 14 kHz band and became operational in 1967
- Omega was based on the measurement of **phase differences**
- Since VLF signal attenuation is low, the signals propagated to **very large distances**
- On average, over a range of about 1000 km, the signal amplitude is reduced by a factor of two
- Baseline lengths of up to **6000 nautical miles** were possible
- Global coverage was obtainable with **only 8 transmitters**
- In 1997, Omega was “phased-down”

8 Terrestrial radio navigation (38)

- Omega stations
  - Norway (A), Liberia (B), Hawaii (C), North Dakota (D), La Reunion (E), Argentina (F), Australia (G), Japan (H)



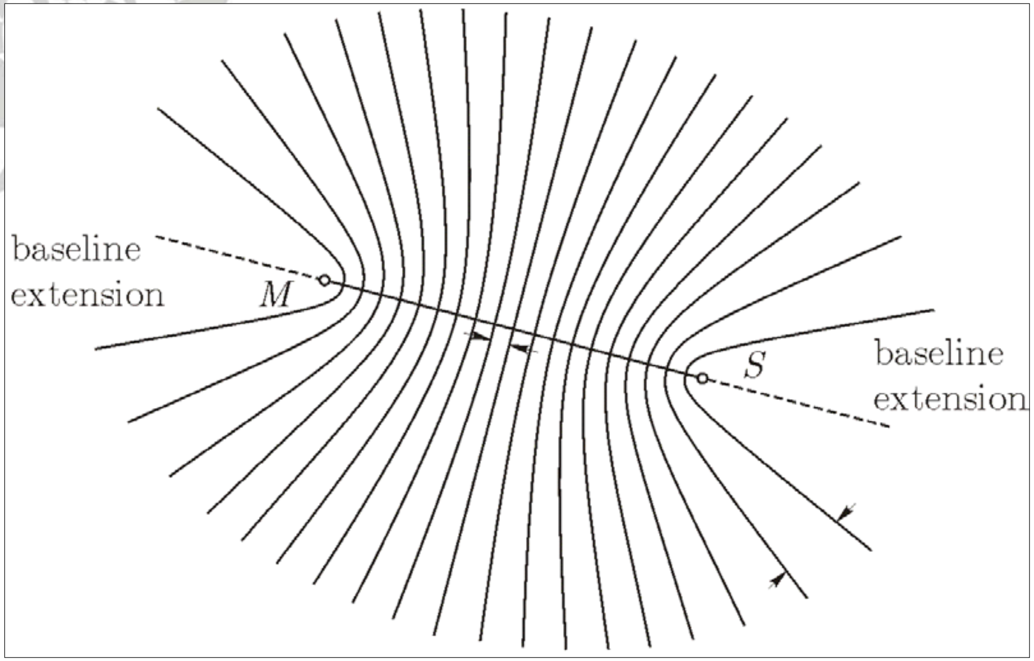
Decca

- Decca *was* a **LF system** (around 100 kHz) covering much of Western Europe, parts of Canada and other parts of the world
- The range was limited to some 800 km (day) and 440 km (night)
- Usually, Decca comprised a **central master** and **three slaves** (**red**, **green**, **purple**)
- Four stations ➔ chain
- First chain: 1946
- End of Decca: 2000

- **Achievable accuracies**

  ± 25 m in central region

  ± 250 m in outer zones



8.3.2 Loran-C

- Loran is an acronym for long range navigation
- Loran-C was designed by the U.S. DOD to provide a navigation capability with
  - **longer range** and
  - **higher accuracy**

  than predecessor Loran-A
- Loran-C was developed in the 1950's at the Radiation Laboratory of the MIT
- The Russian equivalent is called **Chayka**

8 Terrestrial radio navigation (41)

– Transmitter stations form chains (1 master, 1-5 secondaries)

– The chain coverage area is determined by

  • the **transmitted power** from each station, and

  • the **geometry of the stations**, including the distance between them and their orientation

– According to recent U.S. plans, Loran-C will be maintained and operated at least until 2008

Principle

– The transmitters broadcast low frequency (LF) pulsed signals

– The rate of pulses is denoted **pulse repetition rate**

8 Terrestrial radio navigation (42)

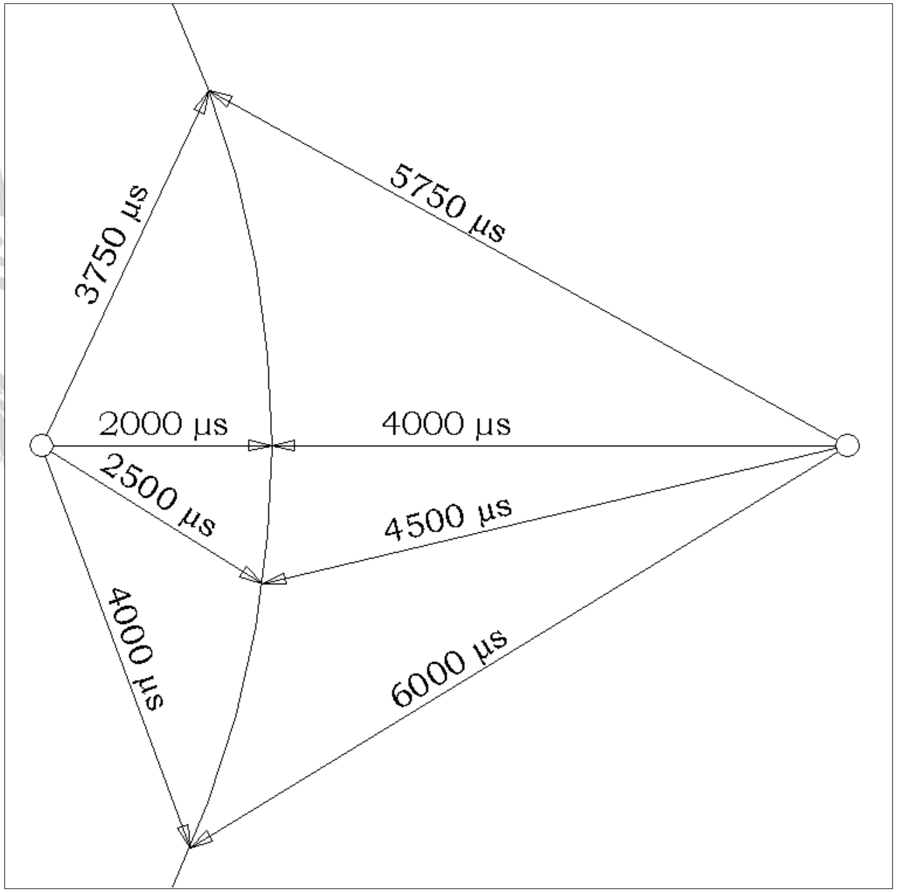
– **Example**: distance between two transmitters is 1800 km
➔ time taken to cover the distance is about 6000 µs

– LOPs may be plotted for **difference in arrival time**

– The plotted time difference in pulse reception is 2000 µs

– “Traditionally”, the LOPs were **printed on charts** showing the value of time difference for each LOP

– **Modern** receivers compute positions digitally



8 Terrestrial radio navigation (43)

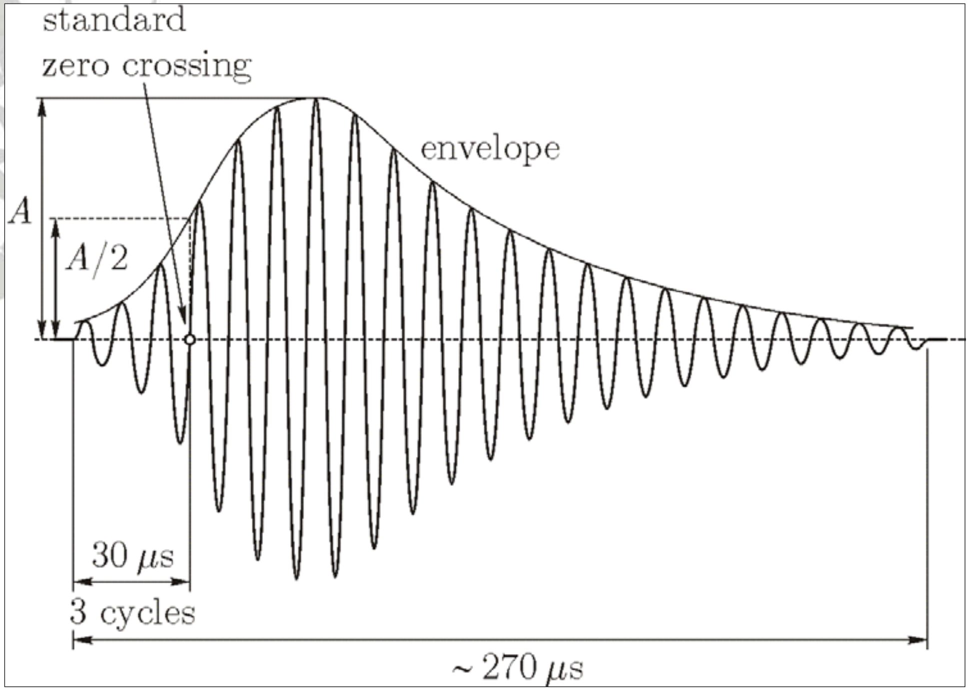
- Position fixing is possible by using LOPs from two pairs of master/secondary stations

- **Range limitation** of the system
  - The ground wave attenuates as it propagates over the earth
  - Depending on the transmission power, the range of a transmitter is limited to
    - 500 – 800 nautical miles over land
    - 800 – 1100 nautical miles over sea

Signal structure and receiver characteristics

- All transmitters are synchronized ➔ secondary signals have precise time interval relationships with the master

- Loran-C uses a carrier transmission frequency of **100 kHz** and a pulse length of **~270 µs**

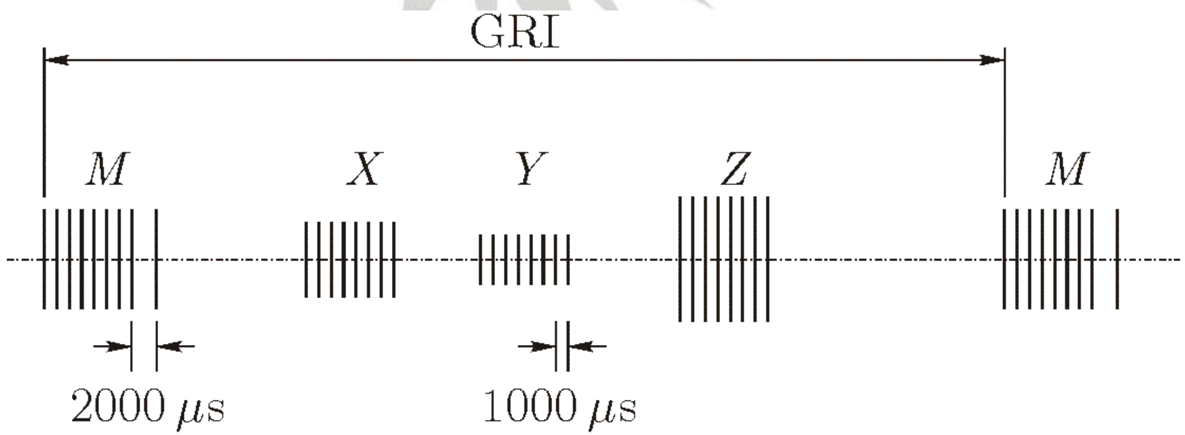


- The zero crossing times are measured with respect to the time reference (**6th zero crossing**)

- Each transmitter periodically emits a group of 8 (or 9) pulses

8 Terrestrial radio navigation (45)

- Loran transmitters are grouped into **chains**
  - Every transmitter in a given chain sends its group of pulses at the **group repetition interval** (GRI)
  - The GRI varies from **50 to 100 ms**
  - The GRI **uniquely identifies** the chain
  - Secondary pulse transmission is **delayed ➔ nonoverlapping** signals in the coverage area (➔ Figure)
- Cooperative efforts between the U.S. and Russia resulted in the implementation of a **combined Loran-C/Chayka chain** (Bering Sea)



8 Terrestrial radio navigation (46)

- **Constituents of the signal format**
  - Pulses and pulse spacing in a group
  - Carrier phase code of each pulse
  - Time of emission
  - The time between repetition of pulse groups from a station
  - The delay of secondary station pulse groups with respect to the master signal
- **Ground wave and sky wave**
  - Basic Loran-C signal: **ground wave**
  - **Sky wave** component is reflected off the ionosphere
- Travel time of the ground wave is largely predictable
- Design of the Loran pulse ➔ receiver can **separate** ground wave from the sky wave (the latter is rejected)

8 Terrestrial radio navigation (47)

- Because of the ionospheric changes, the **sky wave is unstable**
  - Temporal variations
    - Diurnal
    - Seasonal
- Receivers can derive **2D position**, **velocity**, and **time** information from the time difference of arrival of a radio wave from the master station
- **Loran-C receivers** are commonly referenced by
  - The rate (number of chains tracked)
  - The source of the time reference
  - The number of stations tracked
  - The measurement type

– **Example**
  - A single-rate, master-referenced, two-pair, time-difference receiver tracks a single chain selected by the user
  - A cross-chain receiver uses stations from two chains to define LOPs (independent of a master station)

Accuracy

– **Random errors** (atmospheric noise, man-made interference) limit the short-term **repeatable accuracy** to around ± 10 – 100 m

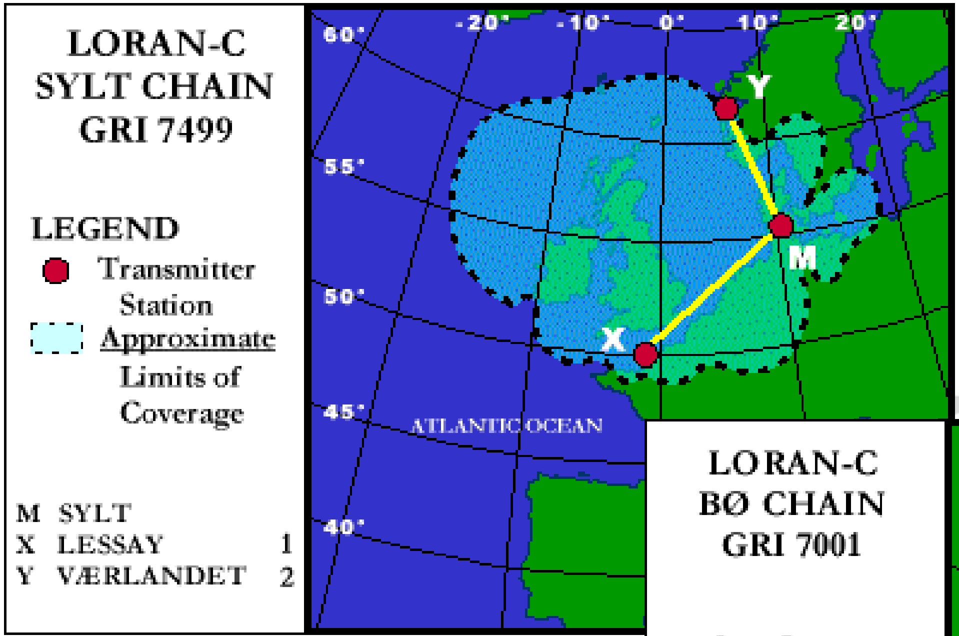
– The **biases** are mainly due to unpredicted propagation effects
  - ➔ Delay of ground wave due to ground conductivity and topographic reasons)

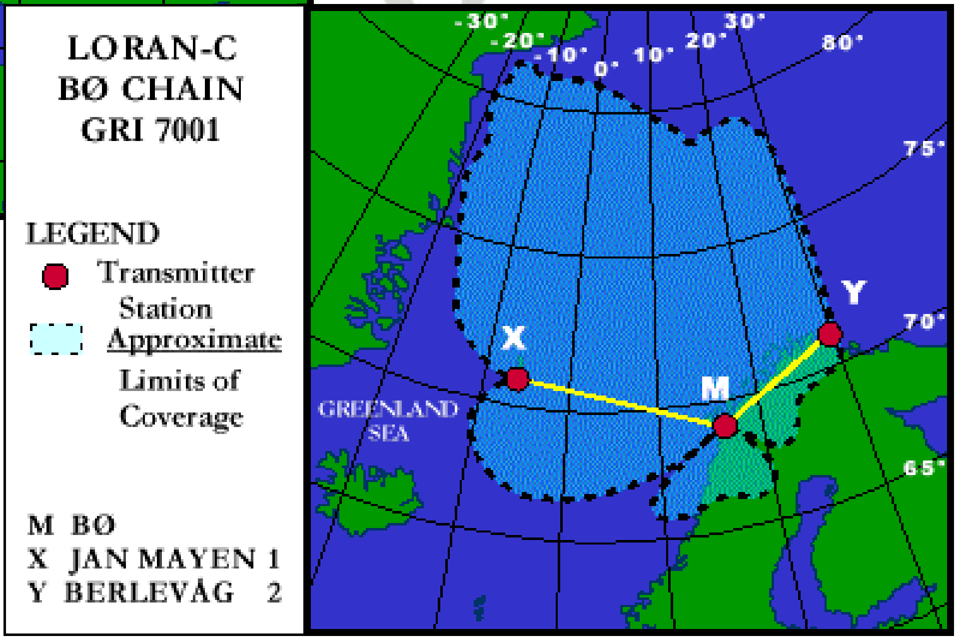
– The **absolute accuracy** (i.e., the accuracy of a position estimate with respect to a coordinate frame) is approximately ± 400 m

8 Terrestrial radio navigation (49)

– **Chain geometry**
  - Each hyperbolic LOP contains all points having the same time difference between arrival of signals from master and secondary stations
  - **Along the baseline** itself, the distance between lines of equal time difference is **smallest**, and increases to each side of the baseline
  - Since the LOPs are much closer along the baseline than they are at large distances away from it, a specific standard deviation, say 100 ns, of the time difference estimate represents much less error in position near the baseline than far offside

– Examples: **two Loran-C chains in Europe**





Differential Loran-C

- Same principle as with DGPS
  - A **reference station** is established, and a nominal set of time differences is determined
  - The reference station broadcasts the offset of the measured and the nominal values (**differential corrections**)
  - Real-time corrections to remove both **seasonal and diurnal errors** can be broadcast
- The broadcast corrections are applied to the user receiver which yields a **high absolute accuracy** in the vicinity of a reference station
- Studies show that publishing the **corrections of the previous day** is entirely satisfactory

8.3.4 Cellular communication networks

- Systems
  - Global System for Mobile communications (**GSM**)
  - Universal Mobile Telecommunications System (**UMTS**)
- Positioning techniques
  - Cell-based positioning
    - Standard vs. sector-based
  - Signal-strength measurement … rho-rho
  - Angle-of-arrival measurement … theta-theta
  - Time measurement
    - Time of arrival (TOA) … pseudorange
    - Time difference of arrival (TDOA) … hyperbolic

➔ Combinations of techniques are possible

8.4 Aircraft landing systems

8.4.1 Instrument landing system

– The instrument landing system (ILS) is designed to provide an **approach path** for alignment and descent of an aircraft

– Functionally, an ILS may be divided into three parts transmitting information to the aircraft:

- Guidance information by two directional systems: **localizer** and **glide slope** transmitter
- Range information by three (or fewer) **marker beacons** and / or **DME**
- Visual information by **approach lights**, touchdown and centerline lights, and runway lights

ILS categories

– Depending on the quality of an ILS, a category (CAT) is associated

- **CAT I**: an ILS procedure which provides for approach to a *decision height* (DH) above touchdown of no less than 200 ft and with *runway visual range* (RVR) of no less than 1800 ft
- **CAT II**: DH no less than 100 ft and RVR no less than 1200 ft
- **CAT III**
  – **IIIA**: without DH minimum and RVR not less than 700 ft
  – **IIIB**: without DH minimum and RVR not less than 150 ft
  – **IIIC**: without DH minimum and without RVR minimum
- DH: is the height above the runway at which the landing must be aborted if the runway is not visible

8 Terrestrial radio navigation (55)

- ILS components
  - **Localizer**
    - Situated at the **far end of the runway**
    - Transmits at a carrier frequency in the range 108 – 112 MHz
    - Provides **bearing** information (i.e. lateral guidance)
    - Establishes a **radiation pattern** in space that provides a deviation signal in the aircraft when the aircraft is displaced laterally from the vertical plane containing the runway centerline
    - Provides course guidance throughout the descent path to the runway threshold from a distance of **18 nautical miles** and a height range of about **1000 – 4500 feet**
    - Operational volume: **10° at either side** of the course along a radius of 18 nautical miles and **10-35° at either side** of the course along a radius of 10 nautical miles

8 Terrestrial radio navigation (56)

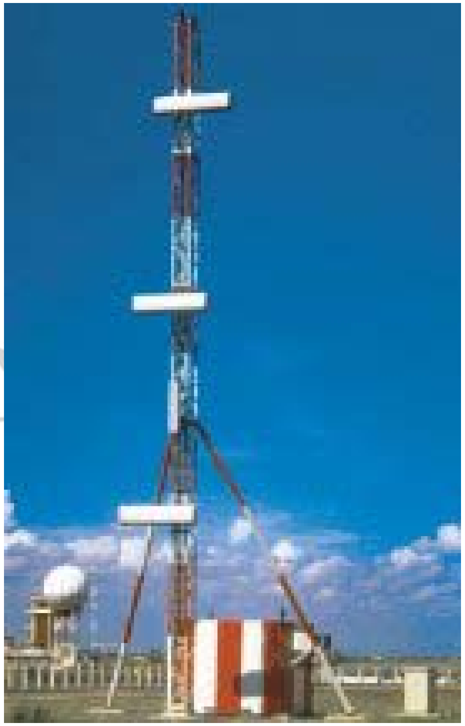
– Examples: **Localizer** ground antenna array

8 Terrestrial radio navigation (57)

TUG

– **Glide slope transmitter**
  - Transmitter located offside (left or right) the runway touch-down point providing **vertical guidance** ➔ 750 – 1250 ft from the approach end of the runway and offset 250 – 650 ft from the runway centerline
  - Operates in the UHF domain (329-335 MHz) and transmits a 1.4°-wide beam; the signal structure is similar to the localizer
  - Geometrically, the localizer and the glide slope signal form two **orthogonal planes** ➔ intersection of the planes in space is the glide path
  - Signal provides information for navigation down to the lowest authorized DH. Unfavorable conditions ➔ **missed approach procedure**

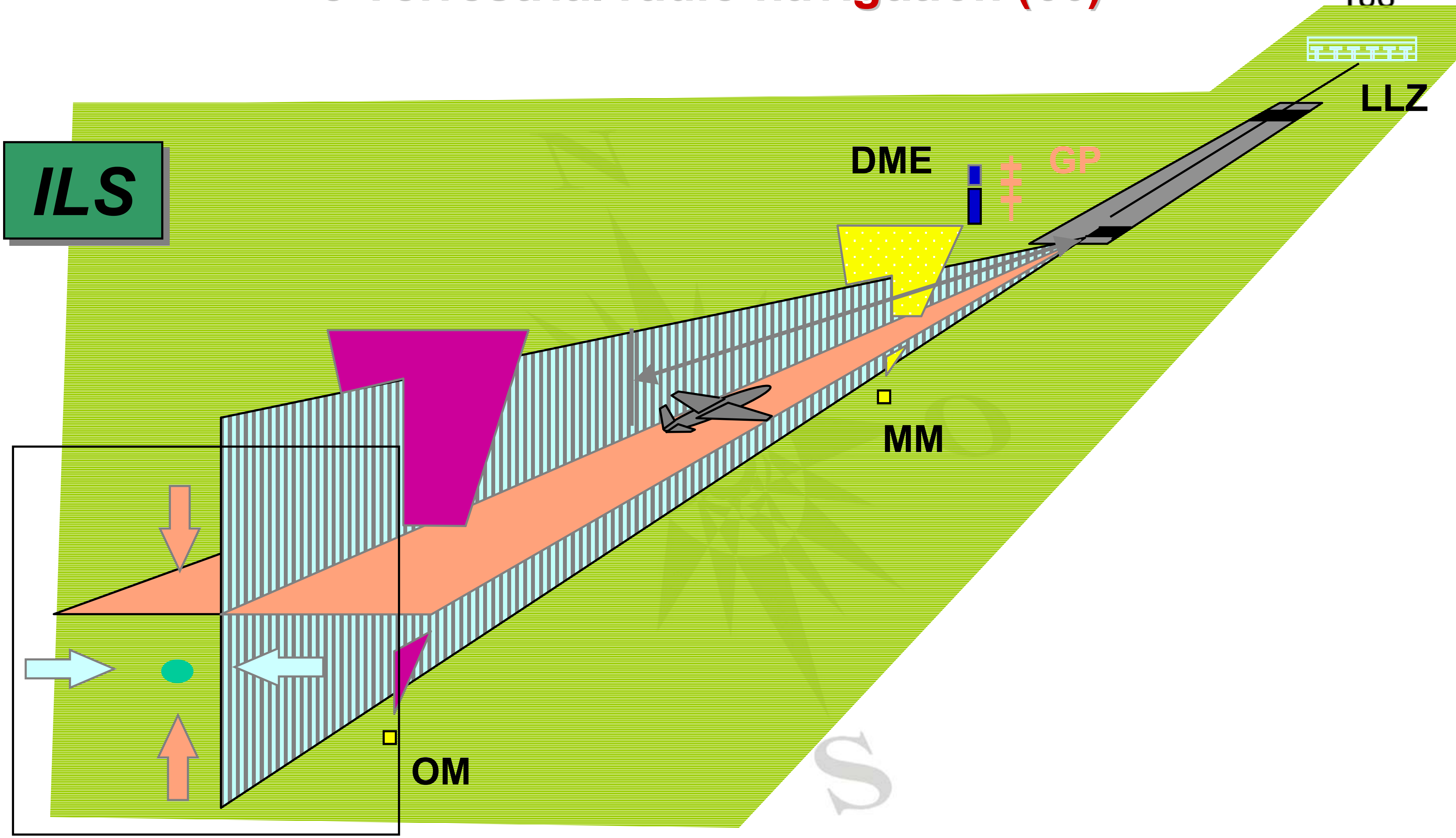
– Examples: **Glide slope** ground antenna array



8 Terrestrial radio navigation (59)

– **Marker beacons**
  - ≤ 3 markers: outer, middle, inner
  - Located about **8 km, 1 km, and 400 m from the touch-down point** giving distance information as the aircraft passes (i.e., providing information along the glide path)
  - A marker transmits a **fan-shaped vertical beam** across the approach direction
  - When passing the marker, the pilot
    - **hears** in his headset an **audio tone**
    - and **sees** in the cockpit a **visual signal** identifying the marker being passed (outer: purple, middle: yellow, inner: white)
  - The use of markers is decreasing with increasing DME

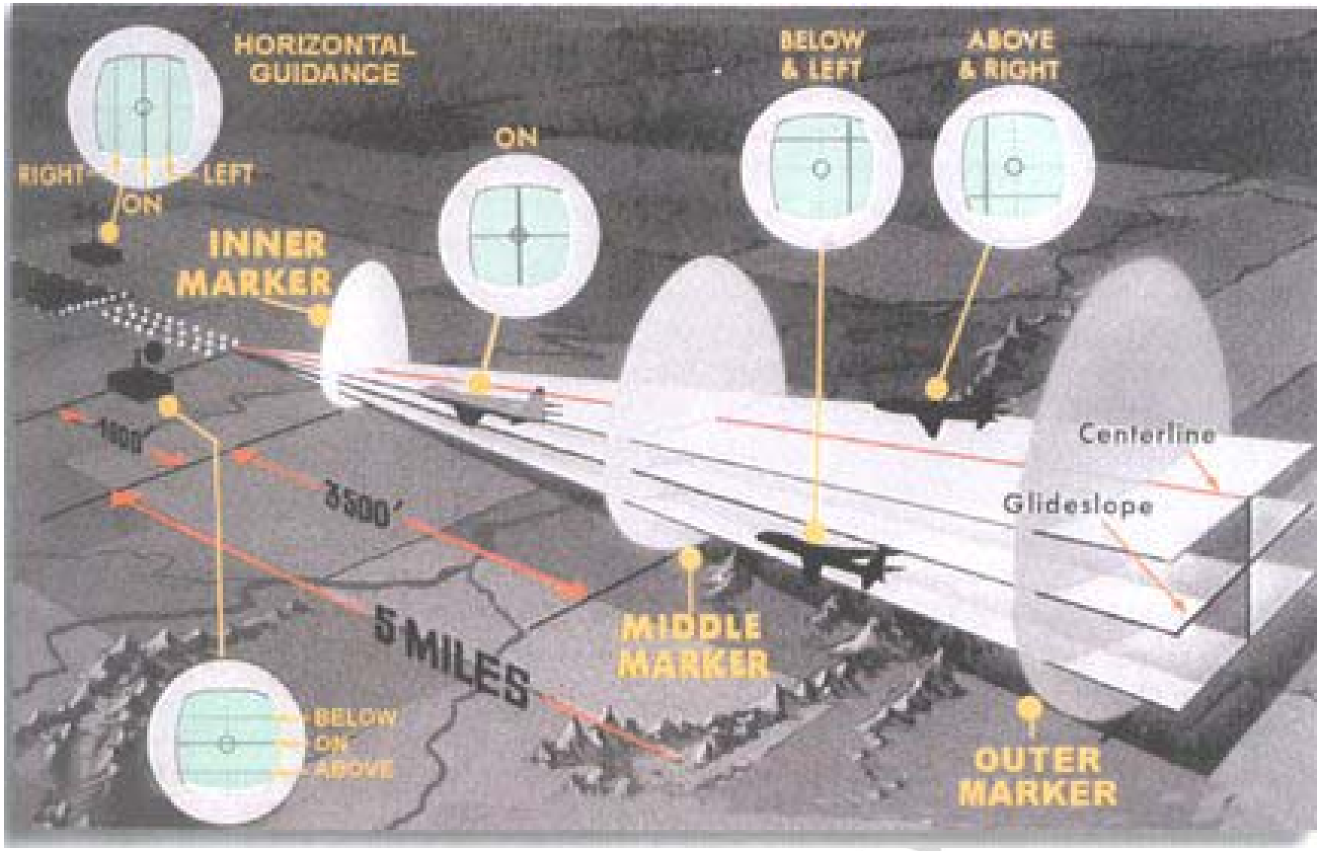
8 Terrestrial radio navigation (60)



© Austrocontrol

8 Terrestrial radio navigation (61)

– Example: **ILS use onboard the aircraft** (concept)



General problems of ILS

– Most ILS ground equipments meet the requirements for CAT I only

– Possible reasons

- Antenna problems
- Reflection problems
- Interference from FM broadcast
- Lack of available frequencies
- Inability to install an ILS at some difficult sites

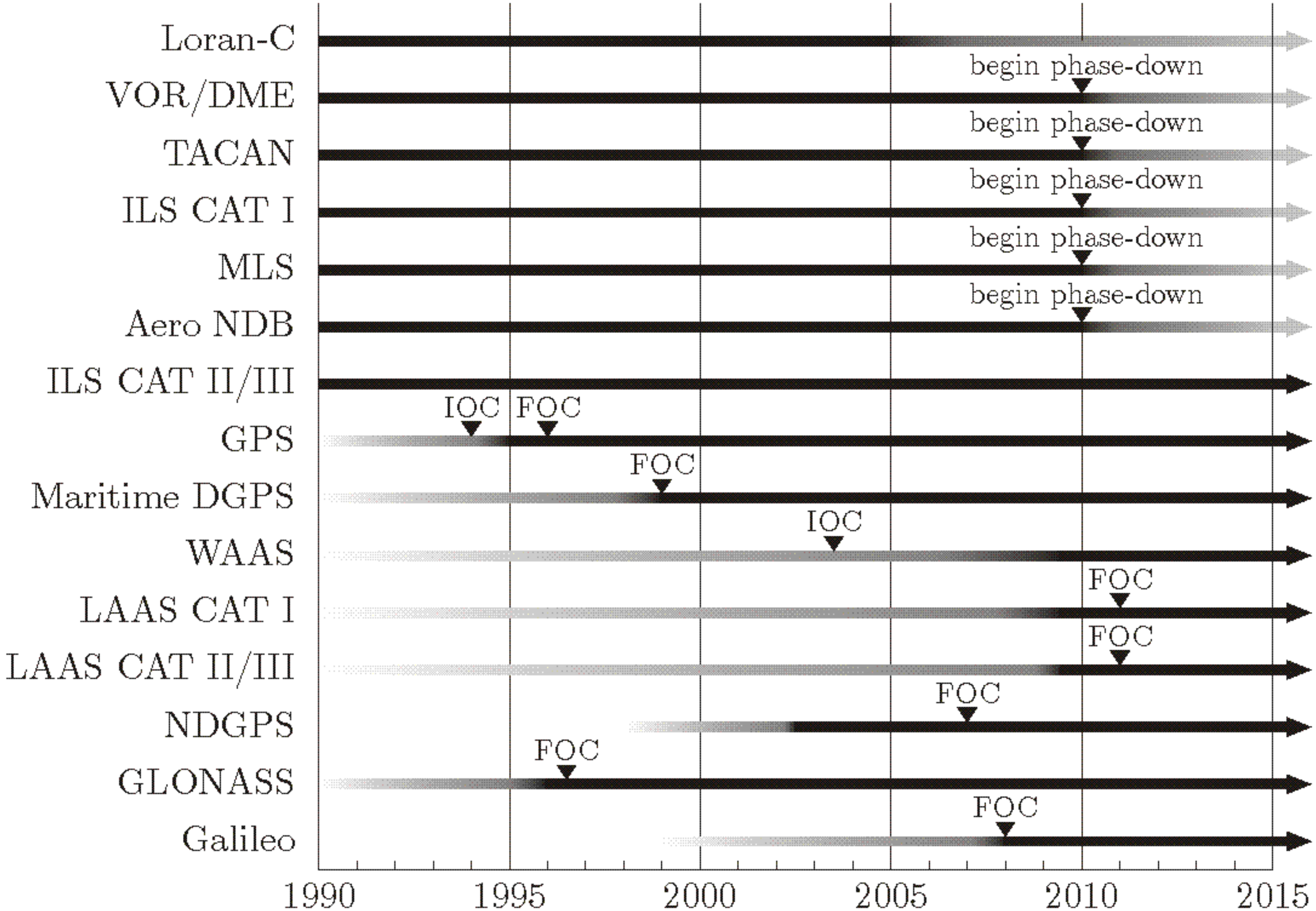
8.4.2 Microwave landing system

- ILS problems with antenna and reflection lead to the idea of systems operating at **microwave frequencies**
- After long discussions, the **time reference scanning-beam** (TRSB) MLS was selected and adopted
- MLS provides **bearing**, **height**, and **distance** information
- Particularly for military applications, MLS may be adapted for **mobile operation** and can be installed without site problems
- Rapid development of GPS faded the importance of MLS ➔ vulnerability of GPS might lead to increased importance; however, **2001 FRP expects phase-down of MLS to begin in 2010**

TRSB – a brief description

- The transmitters are located on the ground **similar to ILS**
- MLS transmits a carrier between 5.03 and 5.09 GHz
- The narrow **MLS beam sweeps across the coverage area** with constant scan velocity (± 30-40° w.r.t. the centerline)
- The airborne receiver measures the **time interval** between the sweeps (a pulse is received every time the beam is scanned)
- From the difference of pulses, the **approach angle** of the aircraft relative to the centerline can be determined
- Compared to ILS, there are **no markers**
- Distance is measured by means of **DME**

8.5 Future of radio navigation systems



References (1/2)

Caffrey JJ (2000): Wireless location in CDMA cellular networks. Kluwer Academic, Boston.

Department of Defense, Department of Transportation (2002a): 2001 Federal Radionavigation Plan. U.S. National Technical Information Service, Springfield, Virginia, DOT-VNTSC-RSPA-01-3/DOD-4650.5.

Department of Defense, Department of Transportation (2002b): 2001 Federal Radionavigation Systems. U.S.National Technical Information Service, Springfield, Virginia, DOT-VNTSC-RSPA-01-3.1/DOD-4650.5.

Enge P, Graas F van (1996): Integration of GPS and Loran-C. In: Parkinson BW, Spilker JJ (eds): Global Positioning System – theory and applications, vol. 2. American Institute of Aeronautics and Astronautics, Washington DC: 51-79.

Federal Aviation Administration (2004): Aeronautical Information Manual. www.faa.gov/atpubs/AIM/

Federal Aviation Administration (2004): Pilot/Controller Glossary. www.faa.gov/atpubs/PCG/. Forssell B (1991): Radionavigation systems. Prentice Hall, New York.

References (2/2)

Helfrick A (2000): Principles of avionics. Avionics Communications Incorporation, Leesburg.

Kriegl J (2000): Location in cellular networks – automated vehicle monitoring based on GSM positioning. Diploma Thesis, Graz University of Technology, www.iaik.at.

Lachapelle G (1998): Hydrography. Lecture Notes of the Department of Geomatics Engineering of the University of Calgary, no. 10016.

Tetley L, Calcutt D (1991): Electronic aids to navigation – position fixing. Arnold, London.

Transport Canada: www.tc.gc.ca/CivilAviation/RegServ/terminology/glossary/menu.htm

Uttam BJ, Amos DH, Covino JM, Morris P (1997): Terrestrial radio-navigation systems. In: Kayton M, Fried WR (eds): Avionics navigation systems, 2nd edition. Wiley, New York: 99-177.

Appendix

Details of phased-out systems

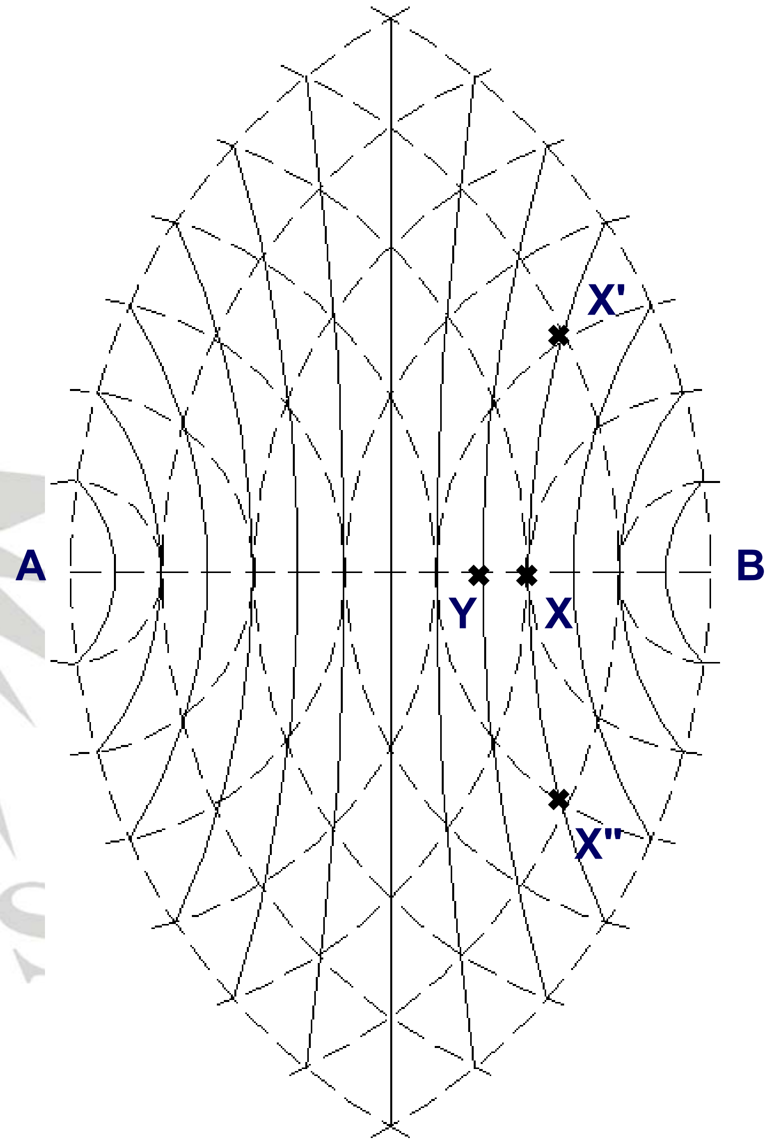
A8.1 Terrestrial radio navigation – Omega (1)

Principle

- The basic frequency is 10.2 kHz
- At each station, continuous wave signals were transmitted on
  - Four common frequencies and
  - One station-unique frequency
- The signal frequencies were time shared among the stations
- A given frequency was transmitted by only one station at any time
- The measured phase difference of phase-synchronized (to about 1 μs) time-shared signals received at a particular location with respect to two transmitting stations depended only on the actual distances between
  - The location
  - And the transmitting stations

A8.1 Terrestrial radio navigation – Omega (2)

- Figure: two transmitting stations *A*, *B* radiating phase-synchronized signals simultaneously
- Concentric circles around *A*, *B* represent one wavelength at the transmitted frequency
- Considering a receiver situated on the baseline at *X*, then signals are received from the two transmitters in phase
- If the receiver moves to *Y* the two signals are again received in phase since the receiver has moved away from *B* by half a wavelength while it has moved towards *A* by the same amount
- Thus, a **lane width** occurs every half wavelength



A8.1 Terrestrial radio navigation – Omega (3)

- In theory, the phase of the signal received from each station can be compared with a locally generated reference signal having the same wavelength and being phase-synchronized with the transmitter station
- The receiver can be anywhere along a particular phase difference hyperbola, as indicated by the points *X* and *X*. The hyperbolas are produced by joining all points of constant phase difference. Each hyperbola is known as LOP
- Repeating measurements for another pair of transmitting stations gives a second LOP
- The receiver position is established at the point of intersection of the two LOPs
- The lane width of Omega operating at 10.2 kHz is about 8 nmi (half a wavelength)

A8.1 Terrestrial radio navigation – Omega (4)

- Apart from the hyperbolic, direct ranging is also applied
  - Rho-rho
  - Rho-rho-rho
- Ranging techniques utilize phase measurements
- Two range measurements are required
- As in the hyperbolic case, it is assumed that the correct lane is initially known and successive measurements are processed so that lane changes are readily tracked
- Two stations are required (intersection of two circles) for the rho-rho method
- Rho-rho-rho type of ranging implies that the clock may have a frequency offset; signals from three stations are required

Signal structure

- The wavelengths are of the same order of magnitude as the distance between the D-region of the ionosphere and the earth surface (50-90 km)
- In the VLF band, radio propagation can be modeled as occurring within a spherical waveguide whose boundaries are formed between the earth and the ionosphere
- The lane ambiguity problem, is reduced through the use of multiple frequencies (**Moire pattern**) and is resolved for navigation through a process of continuous lane count

A8.1 Terrestrial radio navigation – Omega (6)

- Successive positions are computed from corresponding incremental phase change measurements
- If the lane count is temporarily lost, the Omega format is designed to resolve the ambiguity by using difference frequency techniques
- Modern Omega receivers process pseudorange measurements

A8.1 Terrestrial radio navigation – Omega (7)

Accuracy

- Global accuracies of ±1-2 nmi (CEP) were typical
- For aircraft, Omega accuracies of ± 2.7 to ± 3.3 nmi have been reported (95 % of the time)
- In the differential mode, the accuracy is in the hundreds of meters
- The principle (cf. DGPS)
  - A monitor station is established at a known location
  - Errors in received signals can be accurately observed
  - Any errors can be broadcast to vessels within reasonable radius

A8.2 Terrestrial radio navigation – Decca (1)

– Each chain was arranged in pairs of stations
  - Master + **red**
  - Master + **green**
  - Master + **purple**

– The stations transmitted low frequency continuous waves

– Each pair produced a pattern of hyperbolic LOPs

– The receiver consisted of three indicators (decometers), which continuously and automatically displayed the numbers of the LOPs passing through the receiver

– The intersection of any two LOPs on the chart gave the receiver position

A8.2 Terrestrial radio navigation – Decca (2)

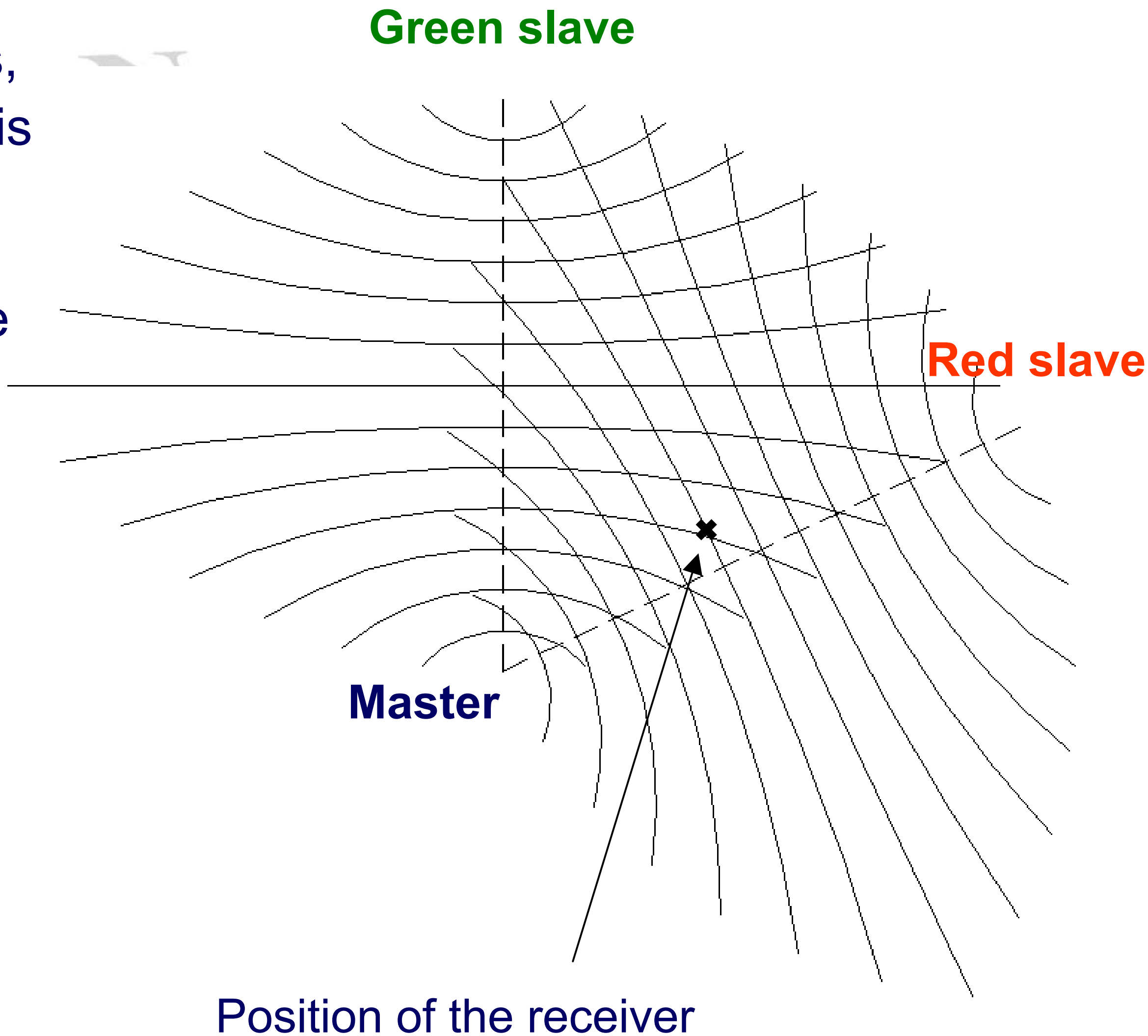
Principle

- The principle was similar to Omega
- Important difference
  - Phase comparison within Decca was achieved using a frequency multiplexing technique
  - Omega used time multiplexing

A8.2 Terrestrial radio navigation – Decca (3)

- **Figure**: Using two master/slave pairs, set of hyperbolae is obtained

- The position of the receiver may be found by the intersection of the relevant LOPs



A8.2 Terrestrial radio navigation – Decca (4)

TUG

Transmission frequencies

- In practice, all chains operated with a fundamental frequency close to the value of 14 kHz
  - Master ~ 84 kHz
  - Red ~ 112 kHz
  - Green ~ 126 kHz
  - Purple ~ 70 kHz

A8.2 Terrestrial radio navigation – Decca (5)

– **Example: SW British chain**
  - Fundamental frequency: f = 14.0466 kHz
  - The phase difference between two received signals is compared at the comparison frequency (minimum common multiple of the two related frequencies)
  - The lane width is half the wavelength of the comparison frequency
  - The given lane width is only valid along the baseline between the two transmitters because
  - The distance between points of zero phase difference increases away from the baseline

Station	Frequency [kHz]	Comp. freq. [kHz]	Lane width [m]
Master	84.280 (6 f)		
Red	112.373 (8 f)	337.120 (24 f)	444.4
Green	126.419 (9 f)	252.840 (18 f)	592.6
Purple	70.233 (5 f)	421.399 (30 f)	355.5