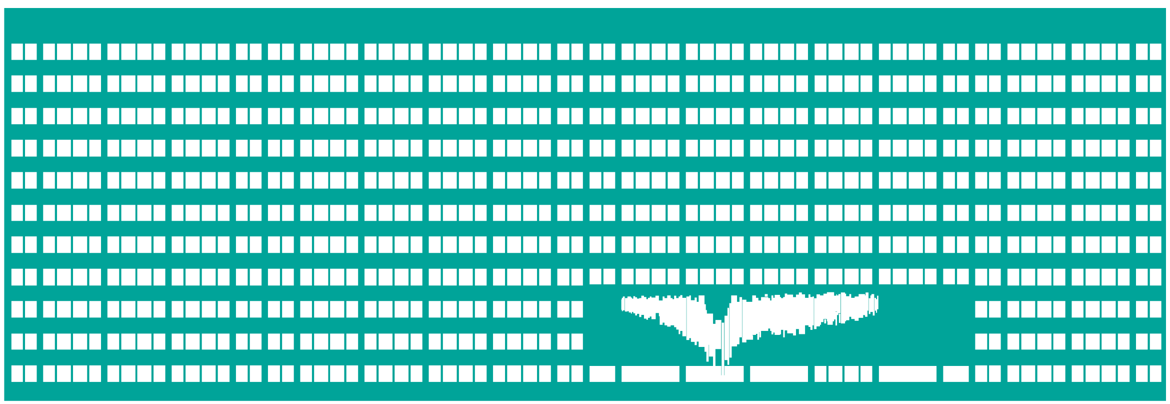
VSB TECHNICAL UNIVERSITY OF OSTRAVA
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE
DEPARTMENT OF COMPUTER SCIENCE

Navigation Systems



MS (Mobile Computing)
Lecture 7

Introduction

- Navigation is the process of **reading**, and **controlling** the movement of a craft or vehicle from one place to another.
- Most modern navigation relies primarily on positions determined electronically by receivers collecting information from satellites.
- As of 2019, four navigation systems exist:
    - The United States NAVSTAR **GPS** is fully operational GNSS of first choice. (extended by QZSS for JP and NZ)
    - The Russian **GLONASS** is in full operation.
    - China **Beidou** navigation system is operational, main orbits are above Asia, however.
    - The European Union's **Galileo** positioning system is in initial operational phase, but constellation is not complete.

Introduction

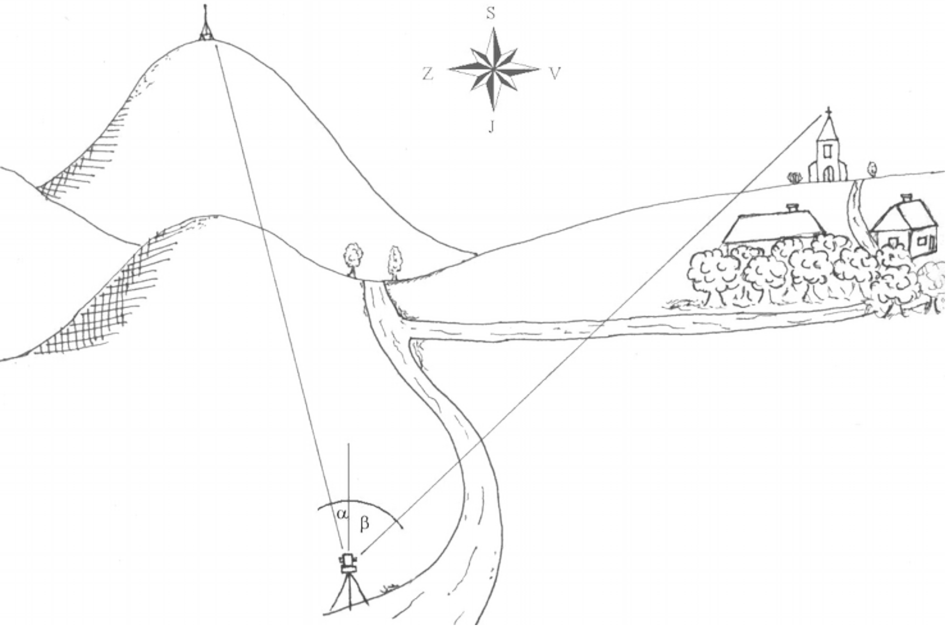
Navigation is divided into four primary areas:

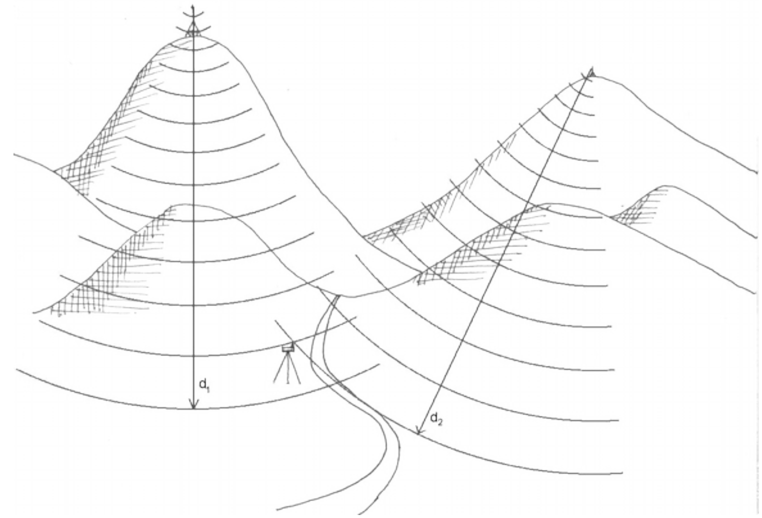
- **Piloting**
  - movement of a vessel with continuous reference to landmarks, aids to navigation, depth sounding, and radionavigation
- **Dead reckoning**
  - projecting an intended course and speed from a known point
- **Celestial navigation**
  - practice of observing celestial bodies to determine the ship's position
- **Radionavigation**
  - determination of position by the use of radio waves.

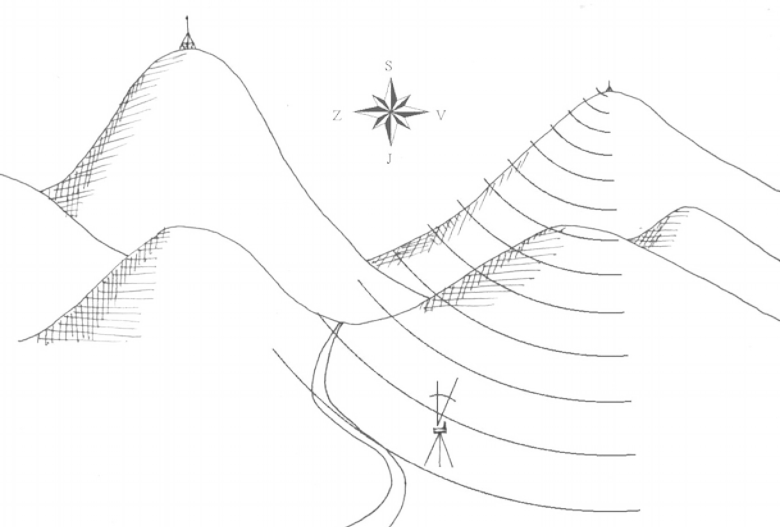
Navigational problems

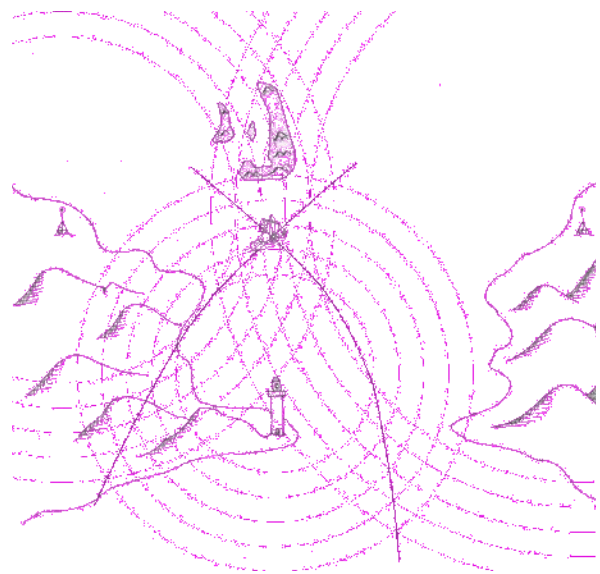
- How to determine **position.** The term position refers to a known point on Earth.
- How to determine the **direction** to get from point A to point B. Direction is the orientation of a line drawn or imagined joining two positions without any regard to the distance between them. Maps are measured in angular units using a polar-coordinate system.
- How to determine the **distance** between points, the **time** it will take, and the **speed** as the navigator proceeds.

Indirect Position Measurement









Source: Petr Rapant, Institute of geoinformatics

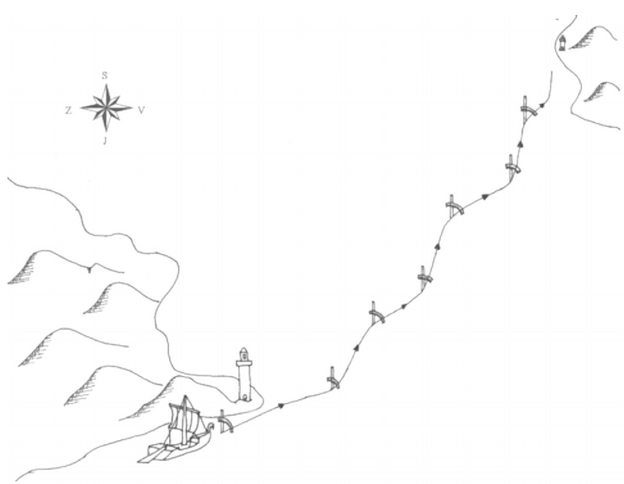
Types of Navigation

- Sea Navigation
- Submarine Navigation
- Ground Navigation
- Air Navigation
- Space Navigation

- Differences in
    - Speed
    - Precision
    - Equipment

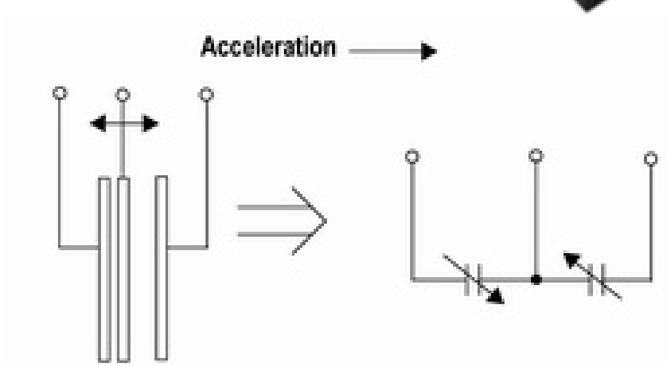
Celestial Navigation

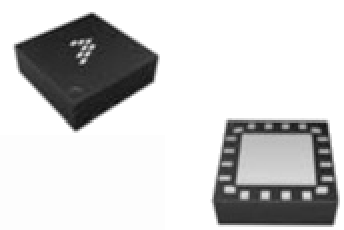
Practical celestial navigation usually requires a marine **chronometer** to measure time, a **sextant** to measure the angles, an **almanac** giving schedules of the coordinates of celestial objects, a set of sight reduction tables to help perform the height and azimuth computations, and a chart of the region.



Inertial Navigation

An inertial navigation system includes at least a computer and a module containing **accelerometers**, **gyroscopes**, or other **motion-sensing devices**. The initially position is provided from another source (a human operator, a GPS satellite receiver, etc.), and thereafter computes its own **updated position** and velocity by integrating information received from the motion sensors.

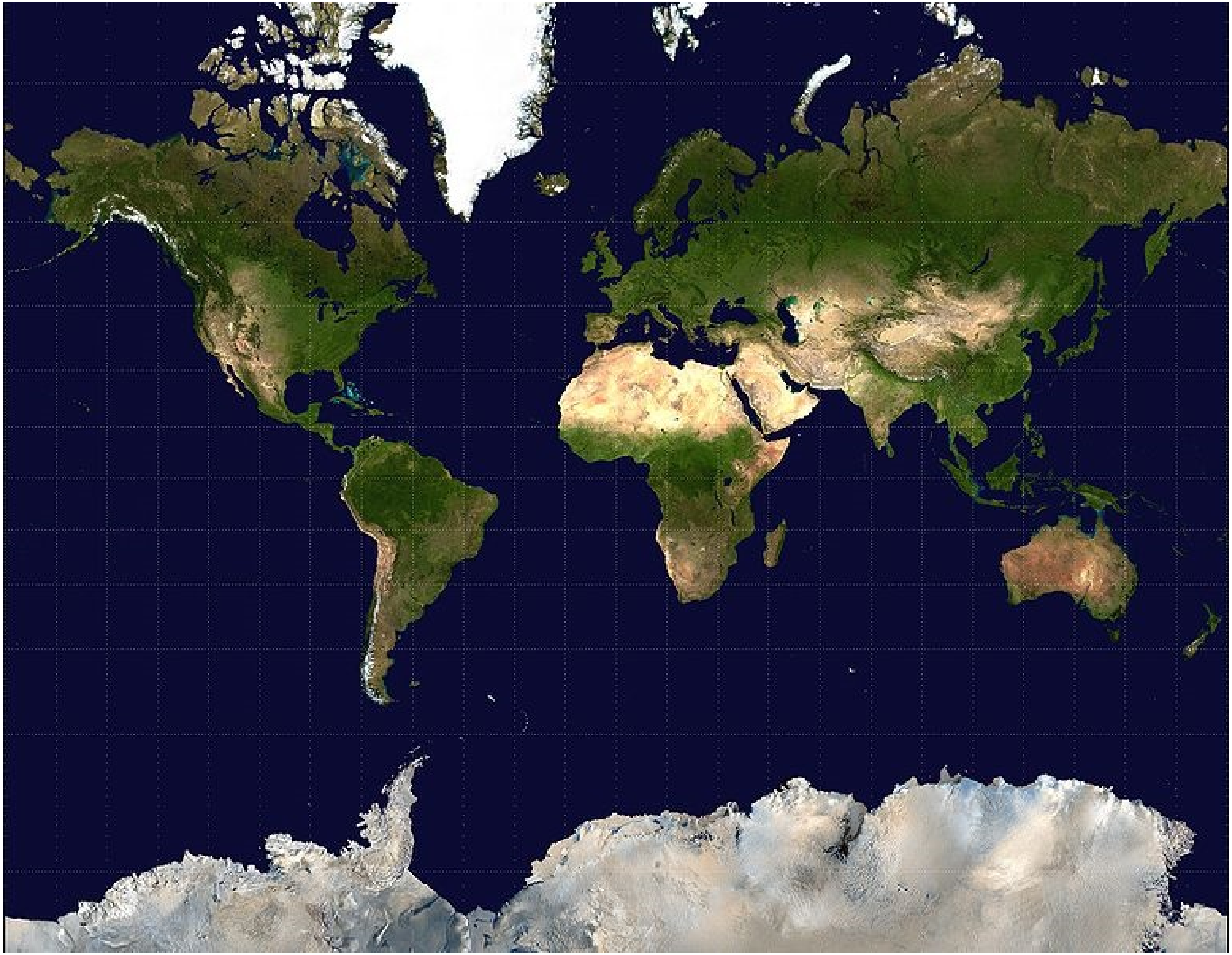




Brief History of Navigation

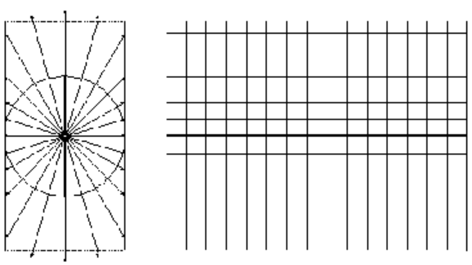
- Development connected with **ship transport**
  - First navigation based on landmarks and other aids. Sailing during the day and good weather. Later information passed in written form and charts.
- **Astrolabe** used in Western Europe (11th century)
- Magnetic **compass** (13th century)
- First **charts** – Portolano Charts (13th century)
- Celestial navigation used during the sails along African coasts (15th century)
  - Problems with longitude precision (precise time was needed)
- **Chip log** used speed measurements (16th century)
- First detailed **maps** were published.

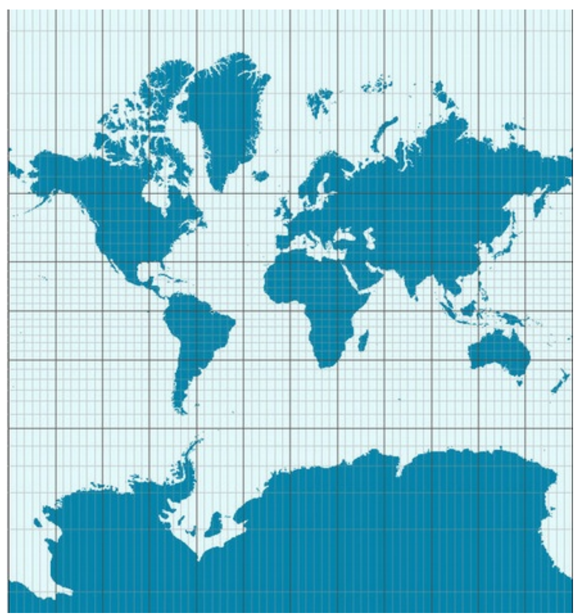
Mercator Projection

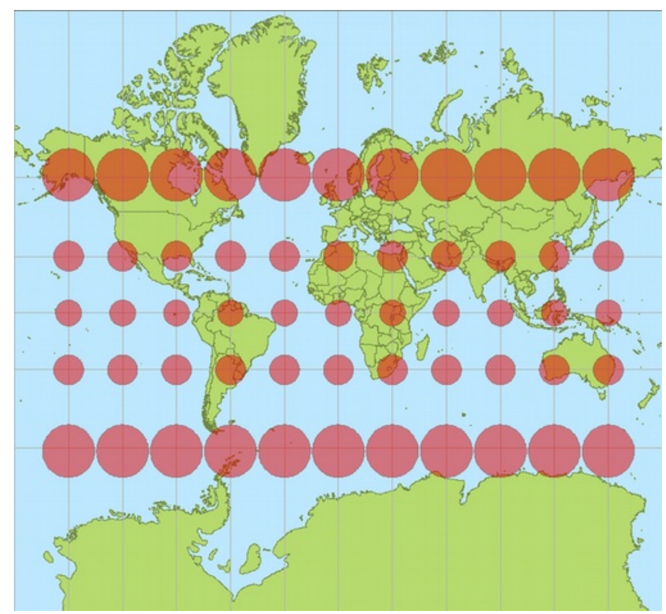


Mercator Projection

- **Cylindrical map projection** presented by the Flemish geographer and cartographer Gerardus Mercator, in 1569.
- Lines of constant course, known as rhumb lines or **loxodromes**, as straight segments.





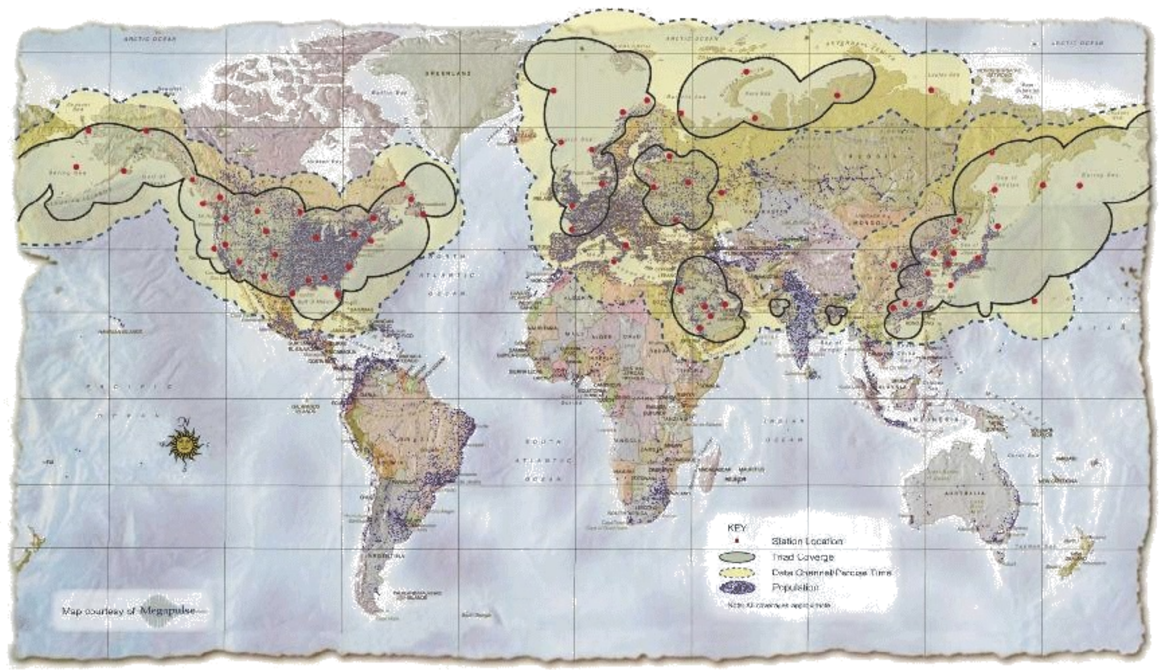


Brief History of Navigation

- **Nautical Chronometr**, Harrison 1764
  - James Cook logged only 8 mile error during his voyage.
- Greenwich **Meridian**, based at the Royal Observatory, Greenwich, established by Sir George Airy in 1851
- **Gyrocompass** compass that finds true north by using an (electrically powered) fast-spinning wheel, 1907
- **Radar**, an object detection system, 1935
- **Radionavigation**, navigation by radio waves, since 1934
  - **Lorenz** – civil airport approach system – two switched lobes sending „dots“ and „dashes“. When in centerline, the signal was continuous
  - **Knickerbein, X-Gerät** – German military system, two geographically remote transmitters directed on target.
  - **GEE** – British navigation, hyperbolic, system: Master + 2 slaves
    - **LORAN**, a terrestrial radio navigation system using low frequency radio transmitters, 1940s, one master, 4-6 slave units. Accuracy about 1% of the distance, range up to 1100 km

LORAN (LOng RAnge Navigation)

- The principle is the **time difference** between the receipt of signals from a pair of radio transmitters.
- A given constant time difference between the signals from the two stations can be represented by a **hyperbolic line** of position.



History of Satellite Systems

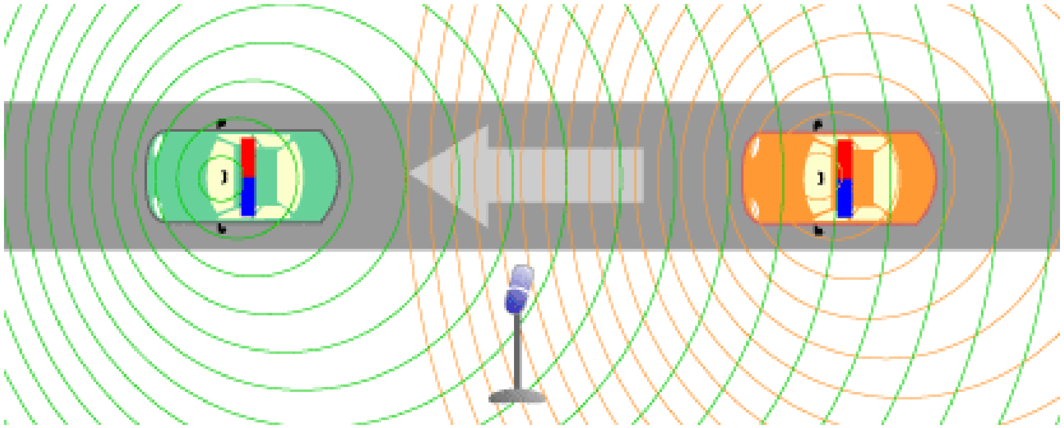
- **TRANSIT**, first satellite navigation system, developed in 1958. The critical information that allowed the receiver to compute location was a unique frequency curve caused by the **Doppler effect.**
- **GPS**, started in 1973. By December 1993 the GPS achieved initial operational capability. The receiver measures the transit time of each message and computes the distance to each satellite.
- **GLONASS**, satellite navigation system, developed by the former Soviet Union. Development began in 1976, with a goal of global coverage by 1991.
- **Galileo**, currently being built by the European Union, under development.
- **Beidou**, Chinese navigation system

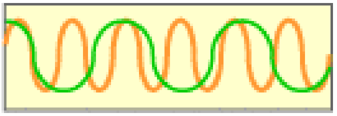
Principles of Radionavigation

- The basic principles are measurements based on
  - **directions**, e.g. by bearing, radio phases or interferometry
  - **distances**, e.g. ranging by measurement of travel times
  - **velocity**, e.g. by means of radio Doppler shift
- The first system of radio navigation was the Radio Direction Finder
- Hyperbolic systems are based on the measurement of the difference of signal arrival times from two or more locations. They are called due to the shape of the lines of position on the chart.
- Position can be determined in 2D or 3D space.

Dopler effect

- **Change in frequency** of a wave for an observer moving relative to the source of the waves.
- Can be used for **satellite systems**.
- Using signal of a given frequency with optional **time stamps** and additional parameters.





Principles of GPS

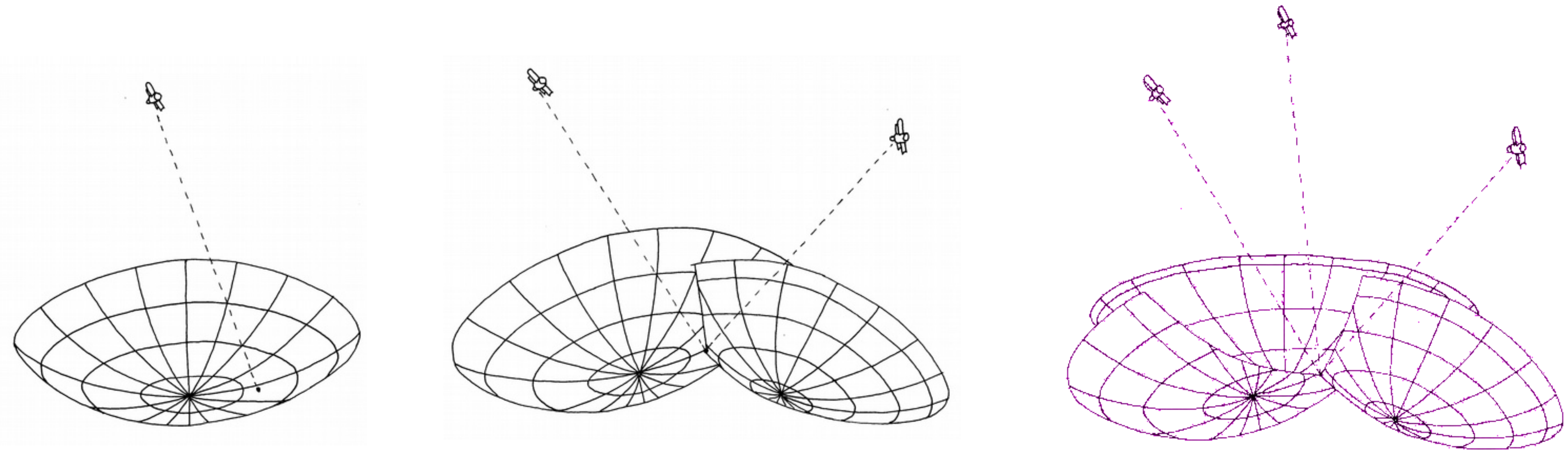
- GPS is made up of **three parts**:
  - 24 - 32 **satellites** orbiting the Earth,
  - 4 control and **monitoring stations** on Earth
  - **GPS receivers** owned by users.
- GPS satellites broadcast signals from space that are used by GPS receivers to provide **3D location** (latitude, longitude, and altitude) plus the **time**.
- Initially the highest quality signal was reserved for military use, and the signal available for civilian use intentionally degraded. **Selective availability** was ended in 2000, improving the precision of civilian GPS from about 100m to about 20m.

Principles of GPS

- Position is calculated by precisely timing the signals sent by the GPS satellites.
- Each satellite continually transmits messages which include the **ephemeris** (precise orbital information), the **almanac** (system state and rough orbits), the **time** the message was sent.
- Geometric **trilateration** is used to combine these distances with the satellites' locations to obtain the position of the receiver.

Trilateration

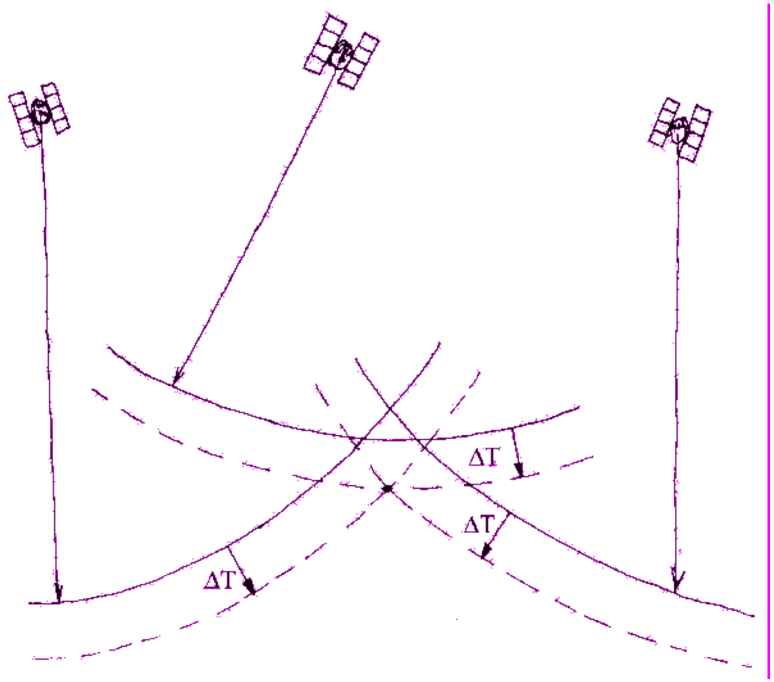
Trilateration is a method for determining the **intersections of three sphere surfaces** given the centers and radii of the three spheres.



Correction Clock Error

Even a very small **clock error** multiplied by the very large speed of light results in a large positional error. Therefore receivers use **four or more** satellites to solve for the receiver's location and time.

$$r_1 = \sqrt{(X - x_1)^2 + (Y - y_1)^2 + (Z - z_1)^2} - c \cdot \Delta T$$
$$r_2 = \sqrt{(X - x_2)^2 + (Y - y_2)^2 + (Z - z_2)^2} - c \cdot \Delta T$$
$$r_3 = \sqrt{(X - x_3)^2 + (Y - y_3)^2 + (Z - z_3)^2} - c \cdot \Delta T$$
$$r_4 = \sqrt{(X - x_4)^2 + (Y - y_4)^2 + (Z - z_4)^2} - c \cdot \Delta T$$

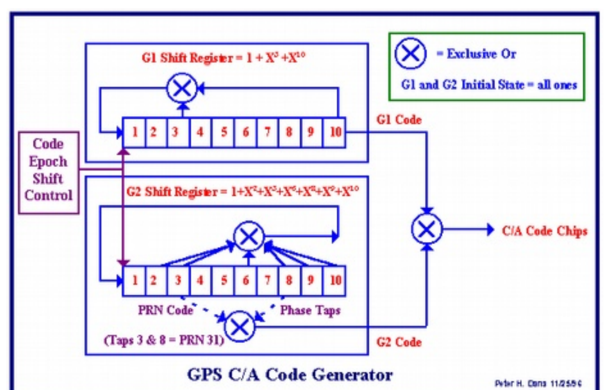


Transmitted Signals

- Each GPS satellite transmits two carrier signals in the microwave range, designated as **L1** and **L2**
- Civil GPS receivers use the **L1** frequency with 1575.42 MHz. The L1 frequency carries the navigation data as well as the SPS code (standard positioning code).
- The **L2** frequency (1227.60 MHz) only carries the P code and is only used by receivers which are designed for PPS (precision positioning code). Mostly this can be found in military receivers.

C/A and P-Code

- **C/A code** (coarse acquisition). This code is a 1023 “chip” long code, being transmitted with a frequency of 1.023 MHz. By this code the carrier signals are modulated and the bandwidth of the man frequency band is spread from 2 MHz to 20 MHz, limiting the interference.
- The C/A code is a **pseudo random code** (PRN) which looks like a random code but is clearly defined for each satellite. It is repeated every 1023 bits or every millisecond.

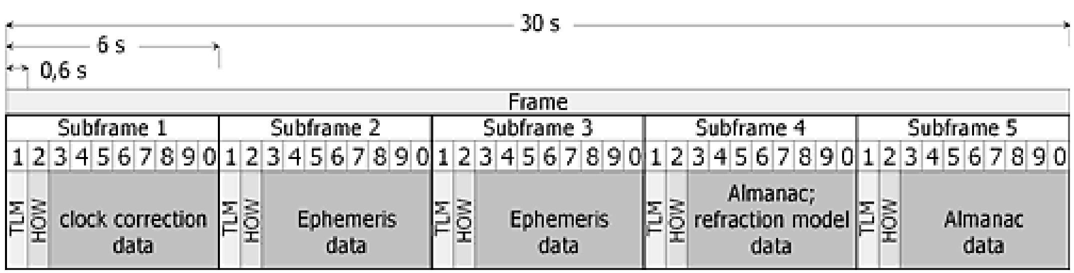


Pseudo Random Numbers (PRNs)

- The satellites are **identified** by the receiver by means of PRN-numbers.
- The **C/A code** is the base for all civil GPS receivers. The **P code** (Precise) modulates the L1 as well as the L2 carrier frequency and is a very long 10.23 MHz pseudo random code.
- For protection against interfering signals transmitted by an possible enemy, the P-code can be transmitted **encrypted**.
- During this anti-spoofing (AS) mode the **P-code** is encrypted in a **Y-code**.

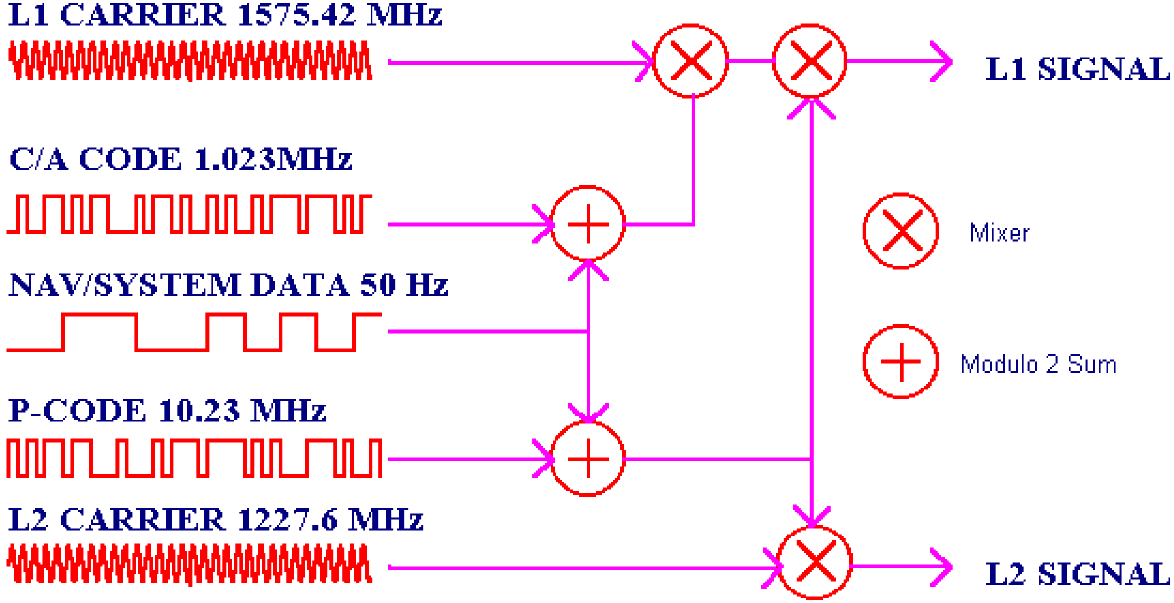
Navigational Information

- In addition to the C/A code **navigational information** is modulated into the L1 signal.
- The information consists of a 50 Hz signal and contains data like **satellite orbits**, **clock corrections** and other system parameters.
- The complete data signal consists of 37500 bit and at a transmission rate of 50 bit/s a total of **12.5 minutes** is necessary to receive the complete signal.



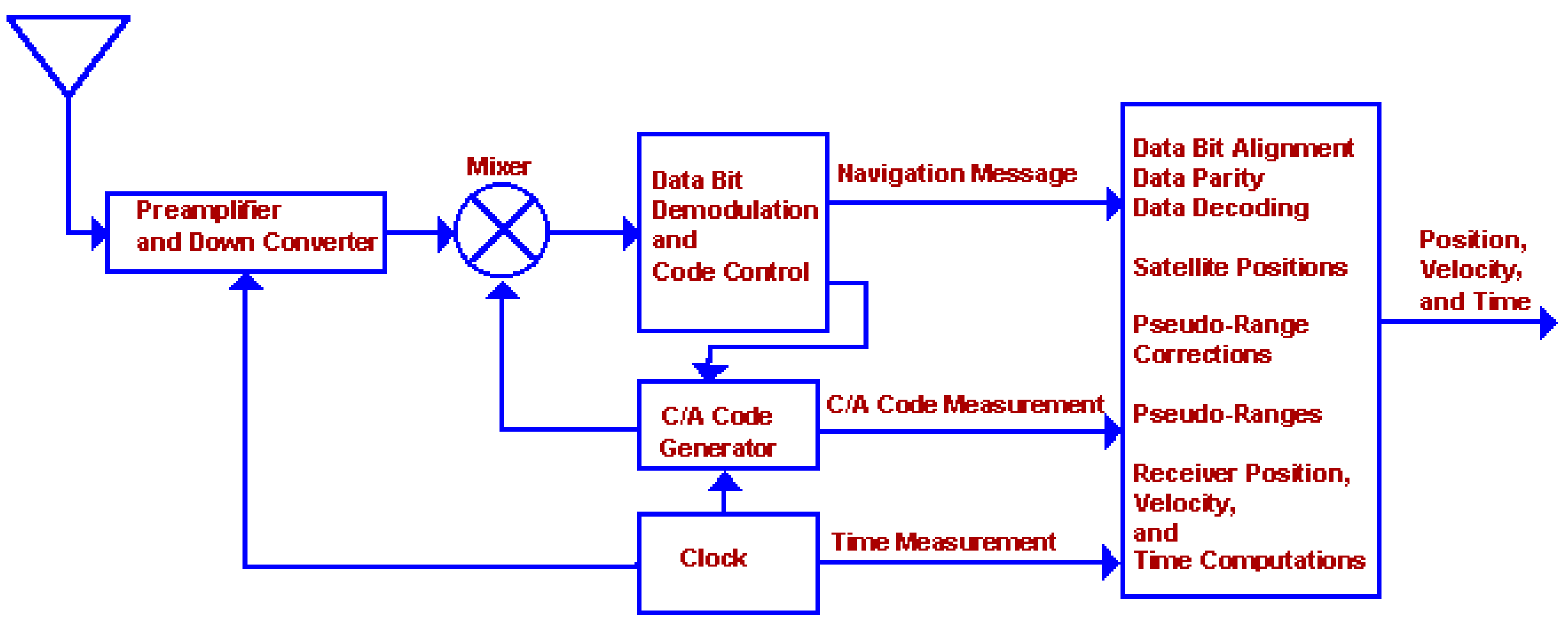
Transmissions

- In the GPS system data are modulated onto the carrier signal by means of **phase modulations**.
- When a data signal shall be modulated onto a carrier signal by phase modulation, the sine oscillation of the carrier signal is interrupted and restarted with a phase shift of e.g. 180°.



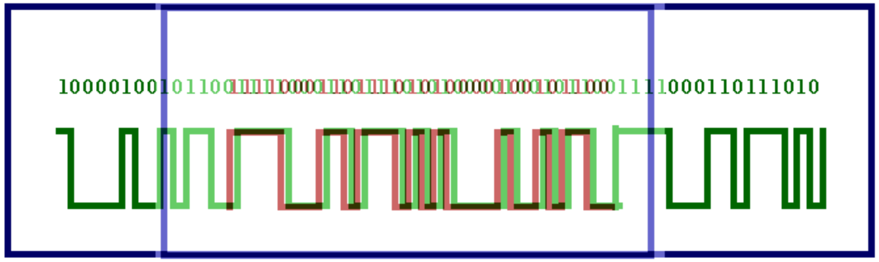
GPS Receiver

- The receiver consists of three parts
  - Antenna
  - Navigational Receiver
  - Navigational Computer

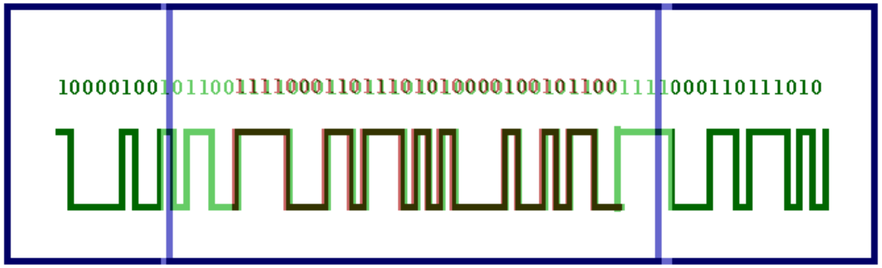


GPS Receiver

- Each satellite transmits a pseudo random code (PRN) which is known to the receiver. The receiver can compare the PRN in its memory with the PRN it just received.
- **Cross correlation** is used to match the code.



Partial Correlation of Identical Receiver and Satellite PRN Codes



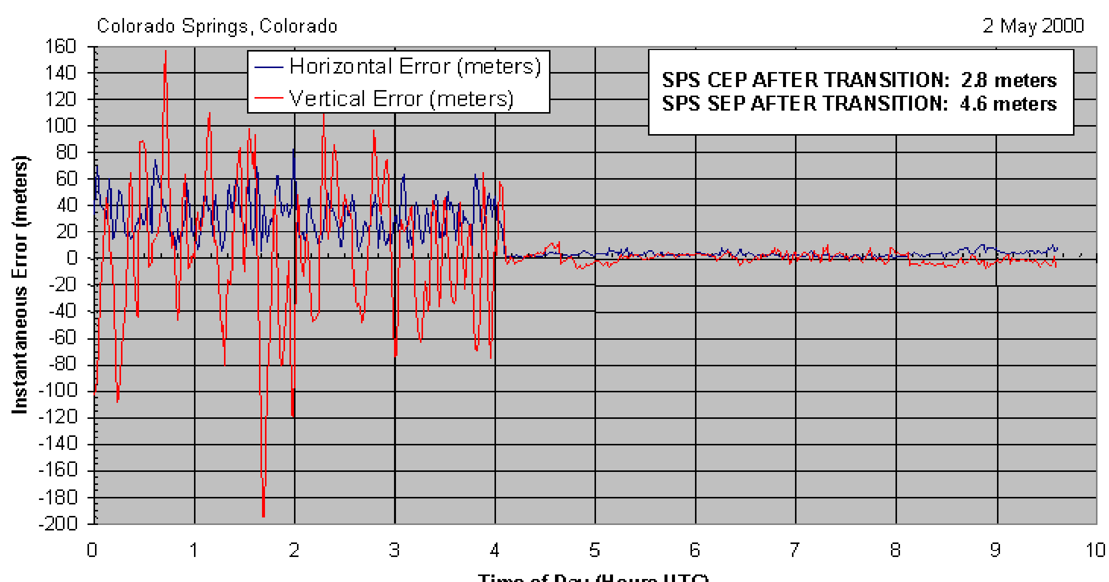
Full Correlation (Code-Phase Lock) of Receiver and Satellite PRN Codes

Source of Errors

- Signal arrival time measurement
- Atmospheric effects
- Multipath effects
- Ephemeris and clock errors
- Geometric dilution of precision computation (DOP)
- Selective availability
- Relativity
- Natural sources of interference
- Artificial sources of interference

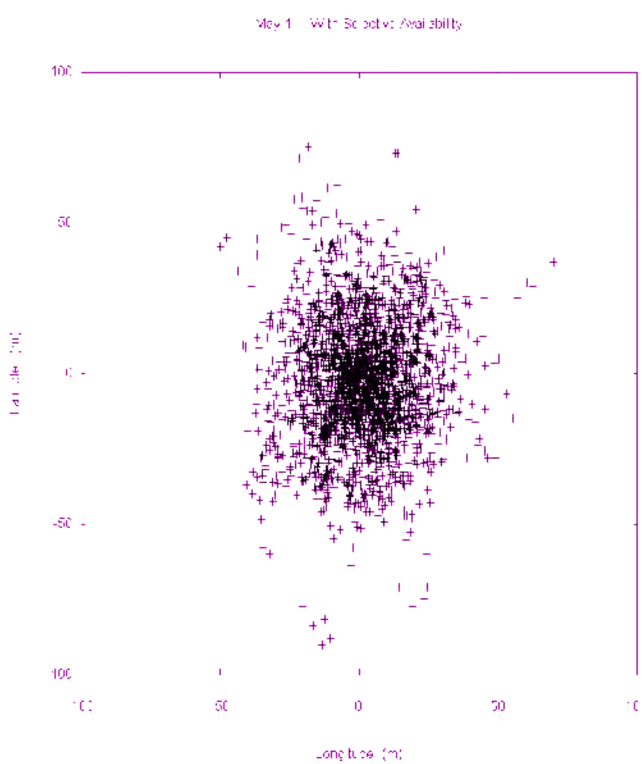
Selective Availability

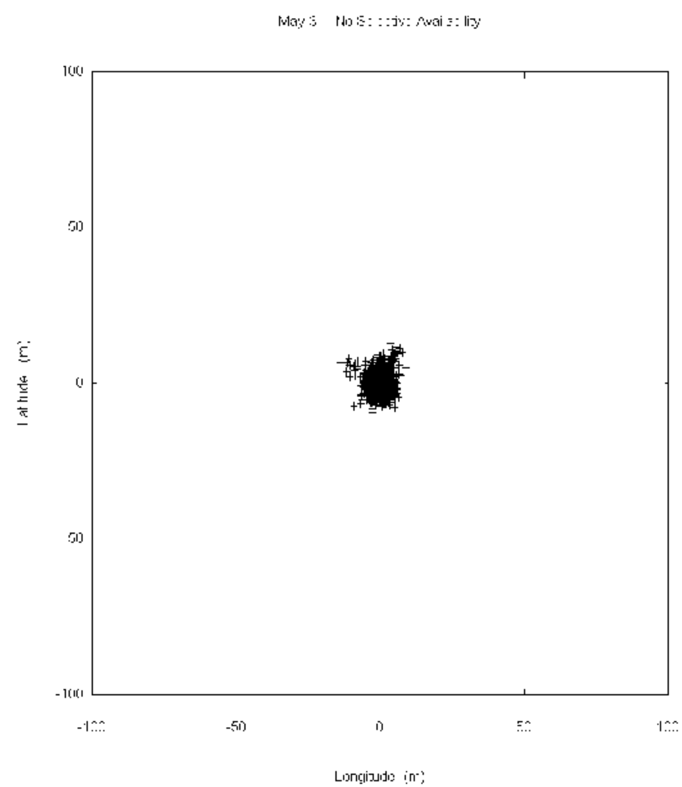
- GPS includes a (currently disabled) feature called **Selective Availability** (*SA*) that adds intentional, time varying errors of up to 100 meters to the publicly available navigation signals.
- This was intended to deny an enemy the use of civilian GPS receivers for precision weapon guidance.



SA Impact on Precision

Before it was turned off on May 1, 2000, typical SA errors were 10 meters horizontally and 30 meters vertically.





Enhancing Accuracy

- **Augmentation**
  - Wide Area Augmentation System (WAAS)
  - Differential Global Positioning System (DGPS)
  - Inertial Navigation System (INS)
  - Assisted GPS (AGPS)
- **Precise monitoring**
  - TEC, measuring ionospheric delay at each frequency
  - Comparing P(Y)-code on L1 and L2 frequencies
- **Timekeeping**
  - Correction of relativistic effects

Maps

- Maps that depict the surface of the Earth also use a **projection**, a way of translating the three-dimensional real surface of the **geoid** to a two-dimensional picture.
- Example of World map projection is the **Mercator projection**, originally designed as a form of nautical chart.
- A **vector map** is a database that describes the area by geometric objects.
- A **raster map** is a picture with world coordinates.

World Geodetic System

- The World Geodetic System is a standard for use in cartography, geodesy, and navigation. It comprises a standard coordinate frame for the Earth, a standard **spheroidal reference surface** (the datum or reference ellipsoid) for raw altitude data, and a gravitational equipotential surface (the geoid) that defines the nominal sea level.
- The coordinate origin of WGS 84 is meant to be located at the Earth's center of mass.
- In WGS 84, the meridian of zero longitude is the IERS Reference Meridian. It lies 5.31 arcsec east of the Greenwich Prime Meridian, which corresponds to 102.5 metres at the latitude of the Royal Observatory.

S-JTSK

S-JTSK is Czech national coordinate system. It’s different in many aspects to standard WGS system used by GPS.