Lecture 10:

TLT – 5606
Spread Spectrum techniques

Lecturer: Simona Lohan

Satellite-based positioning (I)

Outline

- History of satellite navigation; motivation of satellite-based positioning
- Global Navigation Satellite Systems (GNSS): classification & applications
- How GNSS works? Sources of error in satellite positioning.
- GNSS system description & overview of the navigation satellite systems nowadays (active or planned):
  - GPS
  - Galileo
  - Glonass
  - QZSS
  - Compass
  - GPS augmentation

- *Supplementary bibliography for Lectures 10-12:*

Nel Samama, 'Global Positioning- Technologies and Performance', Wiley&Sons book

K. Borre, D. Akos, N. Bertelsen &al. " A software-defined GPS and Galileo receiver- Single Frequency approach", Birkhäuser Boston Ed., 2007.

The Earth : latitude & longitude

from ***GPS Land Navigation*** by Michael Ferguson

Brief history of navigation and positioning – old times (I)

- Magnetic needle compass (4th century, Chinese origin): the oldest instrument of navigation
- Among the first navigational instruments: the latitude hook Kamal (arab origin, 9th century): it was measuring the altitude; its length was aligned with the horizon and star to show when the desired latitude had been reached
- A quadrant was used in 15th century to measure angles

Compass (circa 4th Century BC)

Brief history of navigation and positioning –old times (II)

- Astrolabe (17th century, Greek origin): The circumference of the ring is marked in degrees and the alidade (movable pointer in the middle) is pivoted in the center of the ring with pointers against the scale for measuring celestial altitudes

- Chronometers (18th century): before them, longitude computation was an unsolved problem (latitude was obtained from angle's measurements). Left: Berthoud chronometer (1782)

Brief history of navigation and positioning – radio age

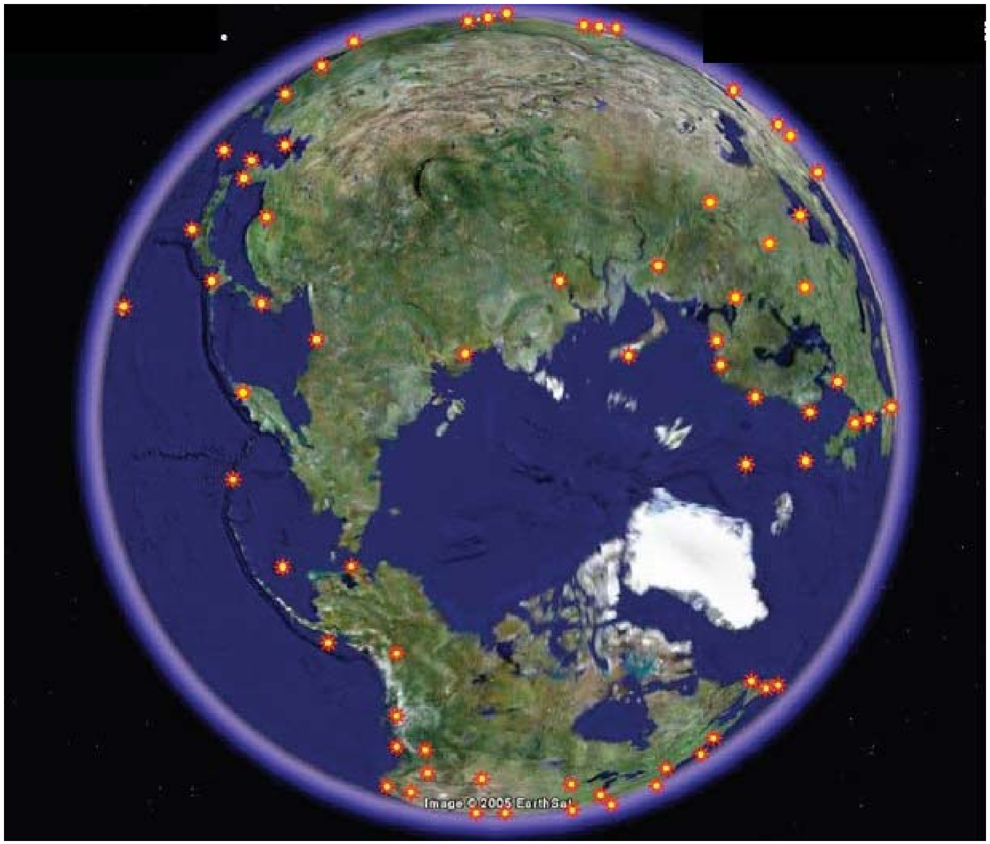
- End of 19th century:
  - Discovery of ’radio conduction’ phenomenon
  - First radio antennas
  - First wireless transmissions
- 20th century:
  - Beginnings (by 1904): time signals were being sent to ships to allow navigators to routinely check their chronometers for error
  - 1921: installation of the first radio-beacon (=a non-directional transmitter that usually transmits a constant signal on a licensed radio frequency). Beacon-based positioning is the precursor of LORAN and GPS.
  - 1937: installation of The first prototype ship-borne radar system on an US ship.
  - 1942: first LORAN (**LO**ng **R**ange **A**id to **N**avigation) system was placed in operation with 4 stations in US.

Brief history of navigation and positioning – first terrestrial positioning systems

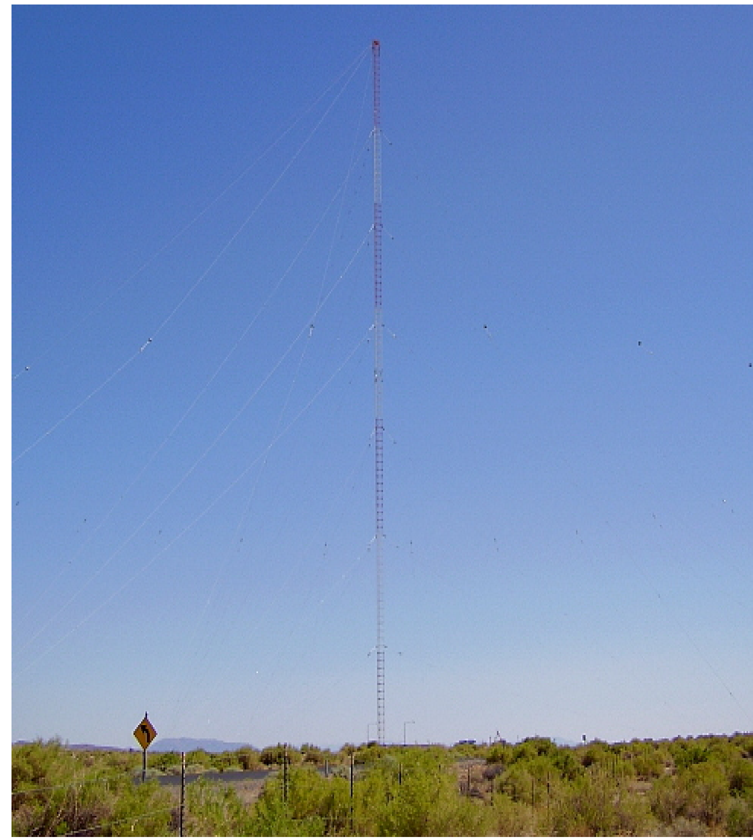
- **Principle**: all locations having the same difference of signal travel time to two fixed points (e.g., to 2 transmitters) lie on a hyperbola. The focal points of this hyperbola are the 2 transmitters. With 3 transmitters => 2 hyperbolas, whose intersection point gives the position.
- DECCA: hyperbolic low frequency (around 100 kKz) radio navigation used between 1944 and March 2000. Operational ramge was about 450 km.
- LORAN: another hyperbolic low frequency navigation system, first introduced in 1942, mainly used in US, Japan and Europe (Russia has a similar system, Chayka)
  - Current LORAN version is LORAN-C; it uses electromagnetic spectrum from 90 to 110 kHz and high power transmission (400 -1600 kW)
  - Large antenna sizes due to low frequencies (heights about 200 m)
  - Currently under modernization in US (eLoran=enhanced Loran); uncertain future

LORAN

LORAN stations worldwide (courtesy: Standford University PNT Symposium, 2007)

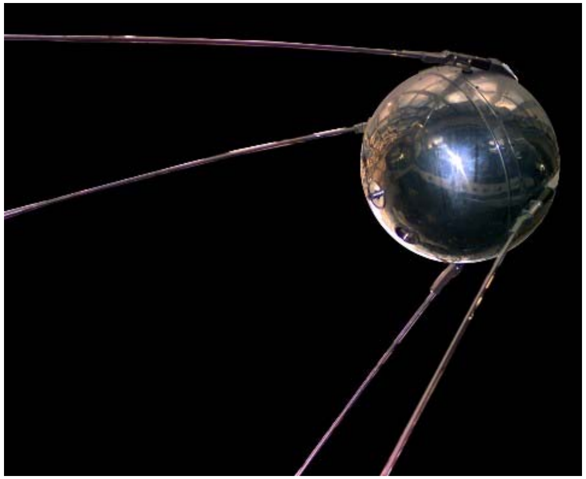


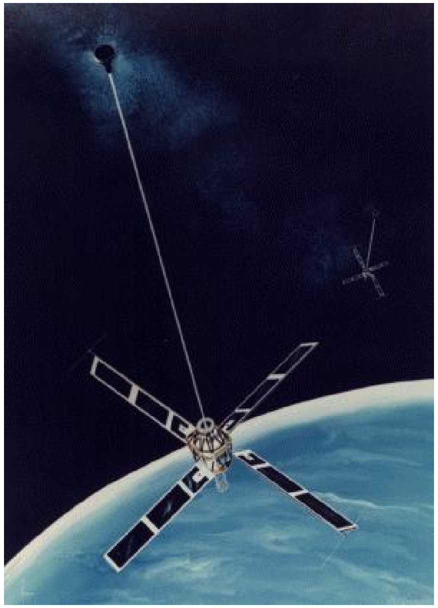
Loran C antenna



Brief history of navigation and positioning – first satellite-based navigation systems (I)

- 1957: first artificial Earth satellite "Sputnik 1" was launched (Russia). The initial approach towards the position location was based on measuring the Doppler shift of the satellite.
- 1960s: "Transit" system was introduced by US for targeting submarine-launched long-range missiles. "Transit" was effective but required expensive receiver systems





Brief history of navigation and positioning – satellite-based navigation systems (II)

- 1980s: US moved to the Navstar Global Positioning System (GPS)
- 1980s: Russia also developed a GPS-like system named GLONASS (abbreviation for the Russian "Globalnaya Navigatsionnay Sputnikovaya Sistema").
- Nowadays: both Japan and the European Space Agency (ESA) are working on GPS augmentation systems, such as MTSAT (Multifunction Transport Satellite Space based Augmentation System), EGNOS (European Geostationary Navigation Overlay System)
- Also stand-alone satellite navigation systems are developed, such as Galileo (the future European satellite system) and Compass (in China).
- Most common abbreviation for a generic satellite positioning system is **GNSS** (Global Navigation Satellite System).

Motivation for satellite-based positioning

- Various applications, both civilian & military: transportation (air, land, maritime), surveying and mapping, agriculture, telecommunications, natural resources exploration, commercial, etc.
- The current global market of applications and services of positioning systems is estimated to more than 3 billion US dollars and it is expected to grow.
- With satellite-based positioning we can acquire global coverage (with some limitations, for example indoors) and very good accuracy and integrity (especially if several GNSS systems are used together).
- Inexpensive receivers.

- However, one major limitation is still the indoor location (due to low signal powers and severe multipath environments). Joint cellular and satellite-based positioning are also possible.

GNSS classification

- **Global coverage systems**:
  - GPS (fully operational), US
  - GLONASS (operational, currently updated), Rusia
  - Galileo (planned; by 2013), Europe
  - Compass (planned; by 2010), China
- **Local/regional coverage systems**
  - DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite), France
  - IRNSS (Indian Regional Navigational Satellite System), India
  - QZSS (Quasi-Zenith Satellite System), Japan
- **GNSS augmentation**: supporting current and future global coverage navigation systems
  - EGNOS (European Geostationary Navigation Overlay Service), Europe
  - WAAS (Wide Area Augmentation System), US
  - CWAAS (Canadian Wide Area Augmentation System), Canadian
  - MSAS (Multi-functional Satellite Augmentation System), Japan
  - Differential GPS, worldwide
  - Inertial Navigation Systems (INS), worldwide
  - Pseudolites (pseudo-satellites), worldwide

GNSS applications

They can be summarized into 5 broad categories:

- Location = determining a basic position (e.g., emergency calls)
- Navigation = getting from one location to another (e.g., car navigation)
- Tracking = monitoring the movement of people and things (e.g., fleet management)
- Mapping = creating maps of the world
- Timing = bringing precise timing to the world

GNSS applications - examples

SEARCH & RESCUE

TRIP PLANNING & SAFETY

GAMES/INFOTAINMENT

MOBILE ROBOT

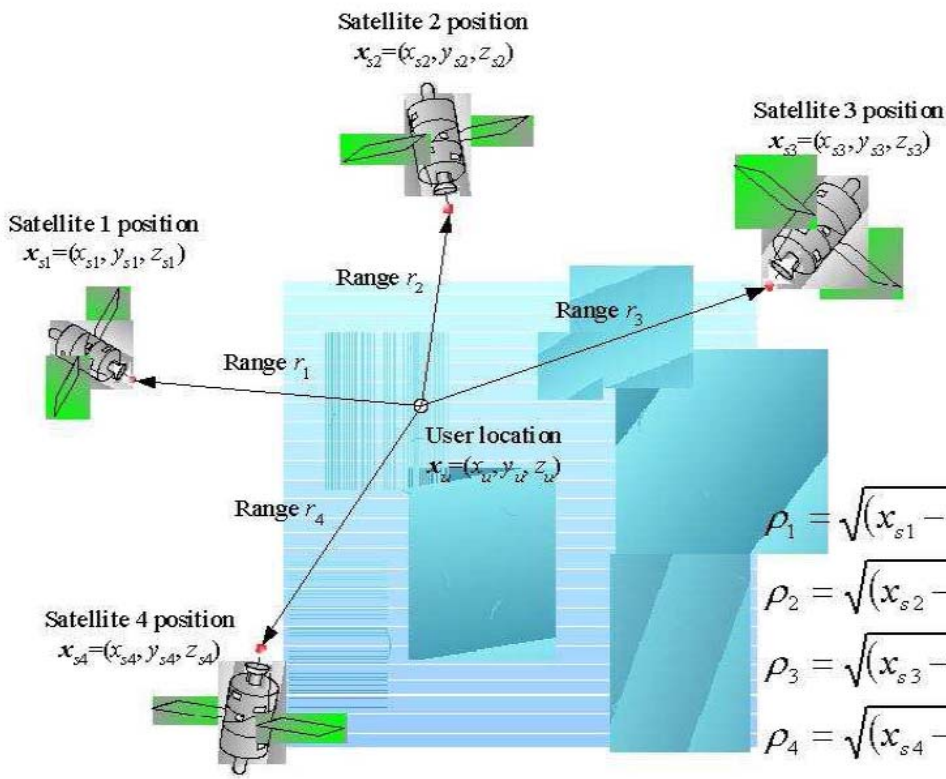
PERSONAL NAVIGATION

FLEET TRACKING

PERSONAL ASSISTANCE

How GNSS works? Position determination (I)

GNSS systems use the concept of Time-Of-Arrival (TOA) of signals to determine user position. Minimum 4 satellites needed in order to determine the user coordinates x_u, y_u, z_u (horizontal, vertical & height).



$$\rho_1 = \sqrt{(x_{s1}-x_u)^2+(y_{s1}-y_u)^2+(z_{s1}-z_u)^2}+c\cdot\Delta t$$
$$\rho_2 = \sqrt{(x_{s2}-x_u)^2+(y_{s2}-y_u)^2+(z_{s2}-z_u)^2}+c\cdot\Delta t$$
$$\rho_3 = \sqrt{(x_{s3}-x_u)^2+(y_{s3}-y_u)^2+(z_{s3}-z_u)^2}+c\cdot\Delta t$$
$$\rho_4 = \sqrt{(x_{s4}-x_u)^2+(y_{s4}-y_u)^2+(z_{s4}-z_u)^2}+c\cdot\Delta t$$

Position determination (II)

- Position determination is based on the so-called **triangulation/ multilateration principle**: the position of the user is found at the intersection of 4 spheres, each with radius equal to the pseudorange measurements ρ_i. If less than 4 satellites are visible), => uncertainties in the position (i.e., intersection is larger than one point).

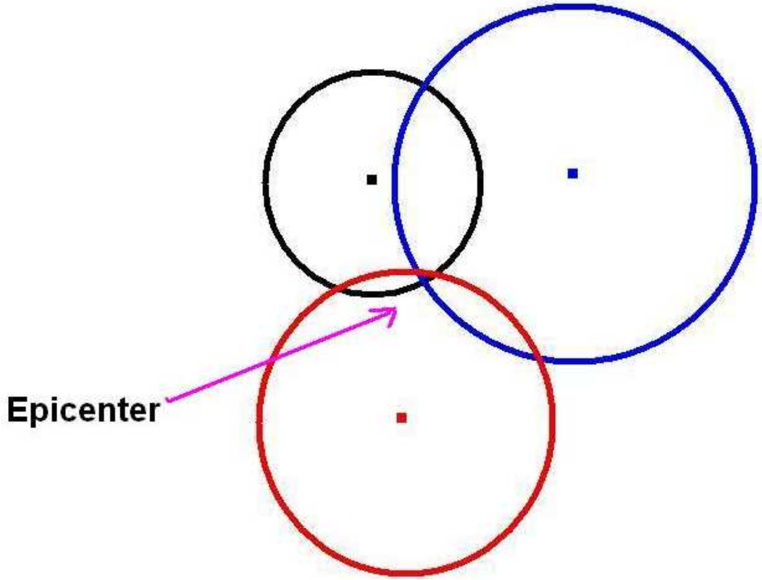
- Satellite positions are known. In the above system of 4 equations, the unknowns are: x_u, y_u, z_u and t.

- If more satellites are visible => Least Square-based solutions (similar with wireless TOA location).

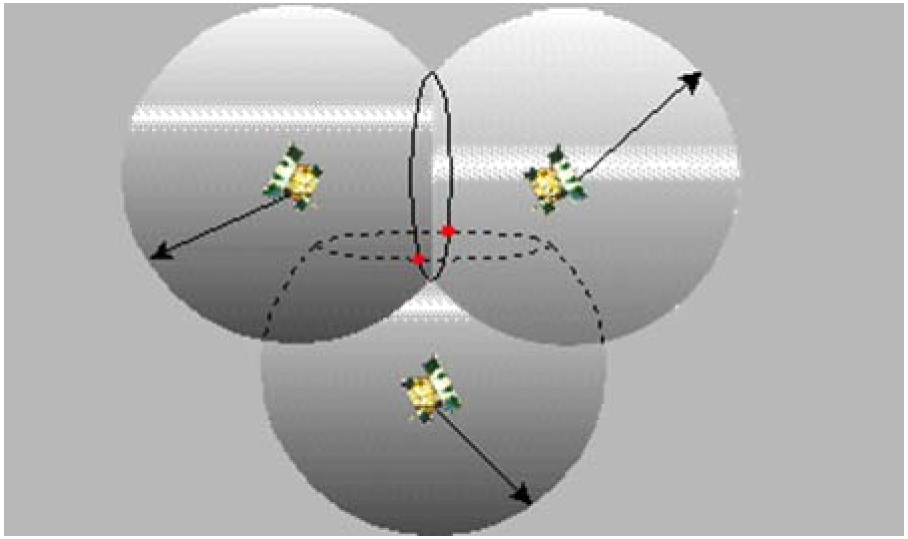
Position determination (III)

Triangulation principle:

Intersection of 3 circles=>1 point



Intersection of 3 spheres =>2 points



A 4-th measurement is needed to correct for clock error

Code measurements (Pseudorange)

- Pseudorange measurements ρ_i may be affected by various errors. Typically, pseudoranges are obtained from time delays and Doppler shift estimates; also carrier-phase based positioning is possible (to be discussed in details later).
- Accurate clocks needed (e.g., GPS satellites are transmitting synchronously) => some reference (universal) time is available.
- The receiver clock is generally not synchronized - an exact time of reception can not be determined. The pseudorange measurement is defined as:

$$\rho_i = c(t_R - t_T) = r + c\Delta t;$$

  - c=speed of light
  - t_R, t_T =times of reception/transmission
  - r=true range
  - Δ t=clock offset
  - Reception time is computed ('measured') by the GNSS receiver through the acquisition and tracking processes (discussed in the next lectures)

Relating pseudoranges to user position and time

$$\rho_1 = \sqrt{(x_{s1} - x_u)^2 + (y_{s1} - y_u)^2 + (z_{s1} - z_u)^2} + c \cdot \Delta t$$

$$\rho_2 = \sqrt{(x_{s2} - x_u)^2 + (y_{s2} - y_u)^2 + (z_{s2} - z_u)^2} + c \cdot \Delta t$$

$$\rho_3 = \sqrt{(x_{s3} - x_u)^2 + (y_{s3} - y_u)^2 + (z_{s3} - z_u)^2} + c \cdot \Delta t$$

$$\rho_4 = \sqrt{(x_{s4} - x_u)^2 + (y_{s4} - y_u)^2 + (z_{s4} - z_u)^2} + c \cdot \Delta t$$

- Many solutions available: closed-form, linearization methods, least-squares solutions, ...
- Several details (weighting for different errors, relativistic effects, ephemeris corrections, propagation effects, etc.) need to be accounted for.

Sources of error in satellite positioning (I)

- Signal multipath: This occurs when the GNSS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This increases the travel time of the signal, thereby causing errors (similar with cellular systems).
- Non Line-Of-Sight (NLOS): obstruction of the LOS wave due to thick obstacles (e.g., wave propagation indoors or in urban canyons with tall buildings).

Sources of error in satellite positioning (II)

- Ionosphere and troposphere delays: the satellite signal slows as it passes through the atmosphere; these delays should be estimated and compensated for.
- Receiver clock errors: a receiver's built-in clock is not as accurate as the atomic clocks on-board the satellites. Therefore, it may have very slight timing errors.
- Orbital errors: also known as ephemeris errors, these are inaccuracies of the satellite's reported location.
- Number of satellites visible: the more satellites a GPS receiver can see, the better the accuracy (we need at least 4).
- Other sources: intentional jamming of the satellite signals, atmospheric effects that may degrade the satellite signal quality, etc.

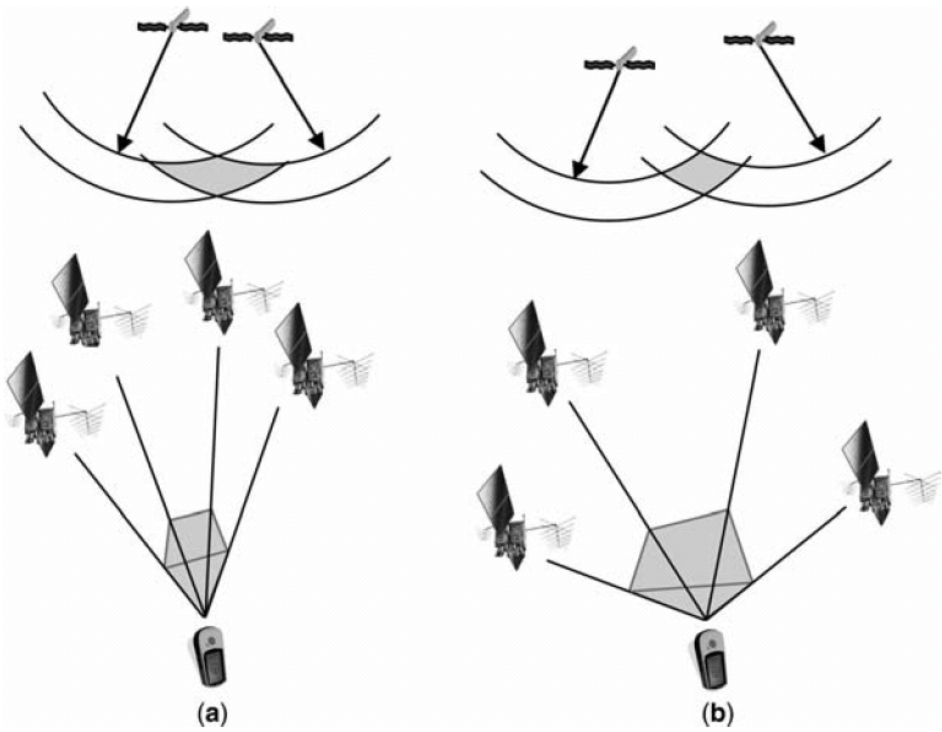
Sources of error in satellite positioning (III)

- **Geometrical distribution of satellites**: the geometry of satellites influences the position accuracy (see plot below)
- **Other sources**: intentional jamming of the satellite signals, atmospheric effects that may degrade the satellite signal quality, etc.

(a) Poor and (b) good constellation geometries

smaller intersection area =>

better precision



Ionospheric correction

-Start with pseudorange estimates from satellite k and 2 frequencies f_1,f_2:

$$\rho_{1,k} \quad \rho_{2,k}$$

-Form the ionospheric correction term:

$$\chi_k = \frac{f_2^{\,2}}{f_2^{\,2} - f_1^{\,2}} \left(\rho_{1,k} - \rho_{2,k} \right)$$

-Smooth the ionospheric corrections over time

$$\hat{\chi}_k = \frac{1}{J} \sum_{j=0}^{J-1} \chi_{k-j}$$

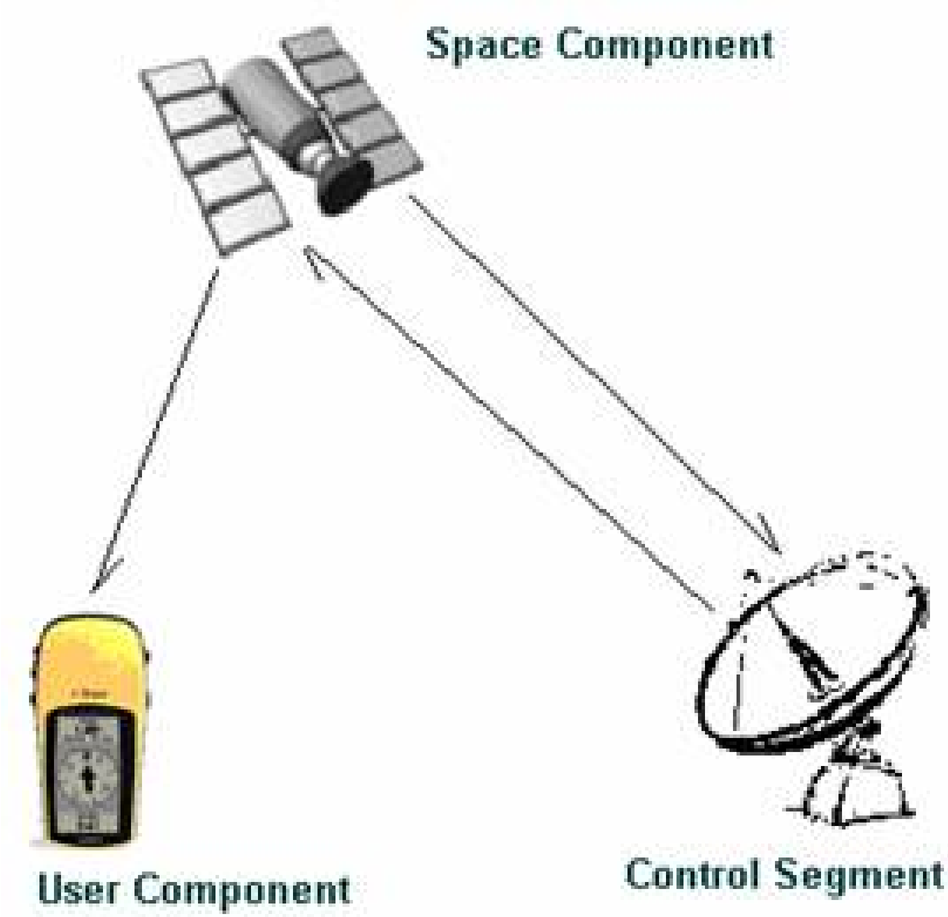
Perform the ionospheric correction

$$\rho_k = \rho_{1,k} - \hat{\chi}_k$$

GNSS system description

- GNSS systems are quite complex, involving many different components. The satellites are the most visible part, but they require a heavy ground infrastructure in order to deliver the right signals with the right parameters to the users.
- All GNSS systems are based on the same architecture (3-segment architecture):
  - Space segment: satellites
  - Ground segment: monitoring, controlling and uploading stations
  - User segment: user community/GNSS receivers
- Number of satellites and monitor stations differ according to the GNSS system (GPS, Glonass, Galileo, ...)
- The geographical placement and number of ground stations is important, especially with respect to the integrity of the positioning solution. (Integrity is the characteristic that allows a user to evaluate the confidence he can attribute to the positioning the receiver is providing)

GNSS system description – generic architecture



GNSS system description – Space segment

The space segment is formed by the satellites, also abbreviated by SV (Satellite Value). The functions of a SV are:

- It receives and stores data from the ground control segment.
- It maintains a very precise time. In order to achieve such a goal, each satellite usually carries several (e.g., 4) atomic clocks of two different technologies (e.g., cesium and rubidium), depending on the generation of the satellite.
- It transmits data to users through the use of several frequencies
- It controls both its altitude and position.
- It may enable a wireless link between satellites

GNSS system description – Ground segment

The main functions of the ground segments are to:

- Monitor the satellites;
- Estimate the on-board clock state and define the corresponding parameters to be broadcast (with reference to the constellation's master time)
- Define the orbits of each satellite in order to predict the ephemeris data, together with the almanac;
- Determine the altitude and location orders to be sent to the satellites to correct their orbits.

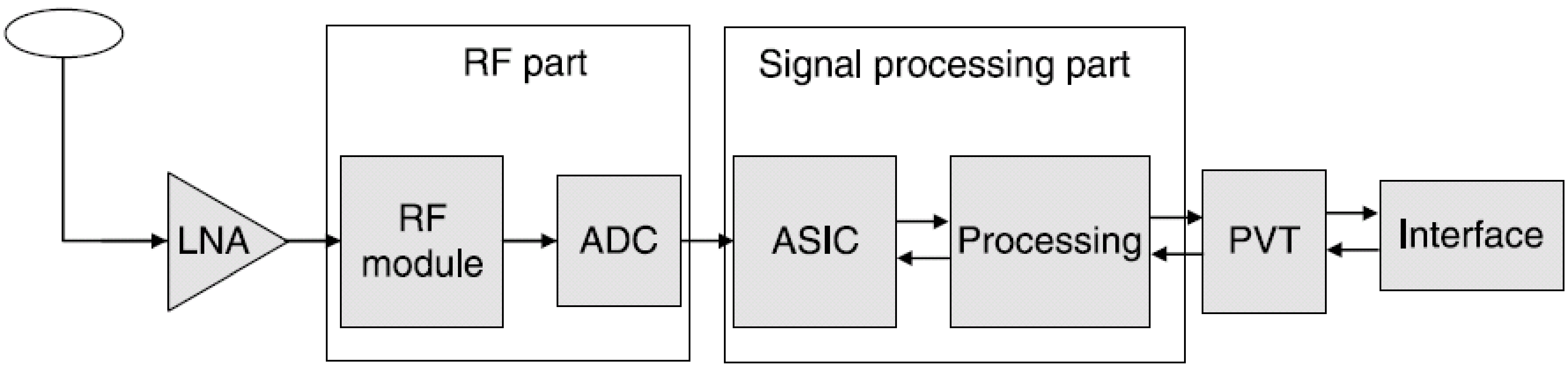
Ephemeris = precise orbit and clock corrections for the satellites. Each satellite broadcast only its ephemeris data. In GPS, ephemeris is broadcast every 30 s.

Almanac= coarse orbital parameters of the satellites (valid for up to several months)

GNSS system description – User segment

User segment = user community + GNSS receivers

- Block diagram of a GNSS receiver:



ADC= Analog-to-Digital converter
ASIC = Application Specific Integrated Circuit (Note: alternative software GNSS receivers are also possible)
PVT = Position Velocity Time computation

Overview of global satellite navigation systems:

GPS

Galileo

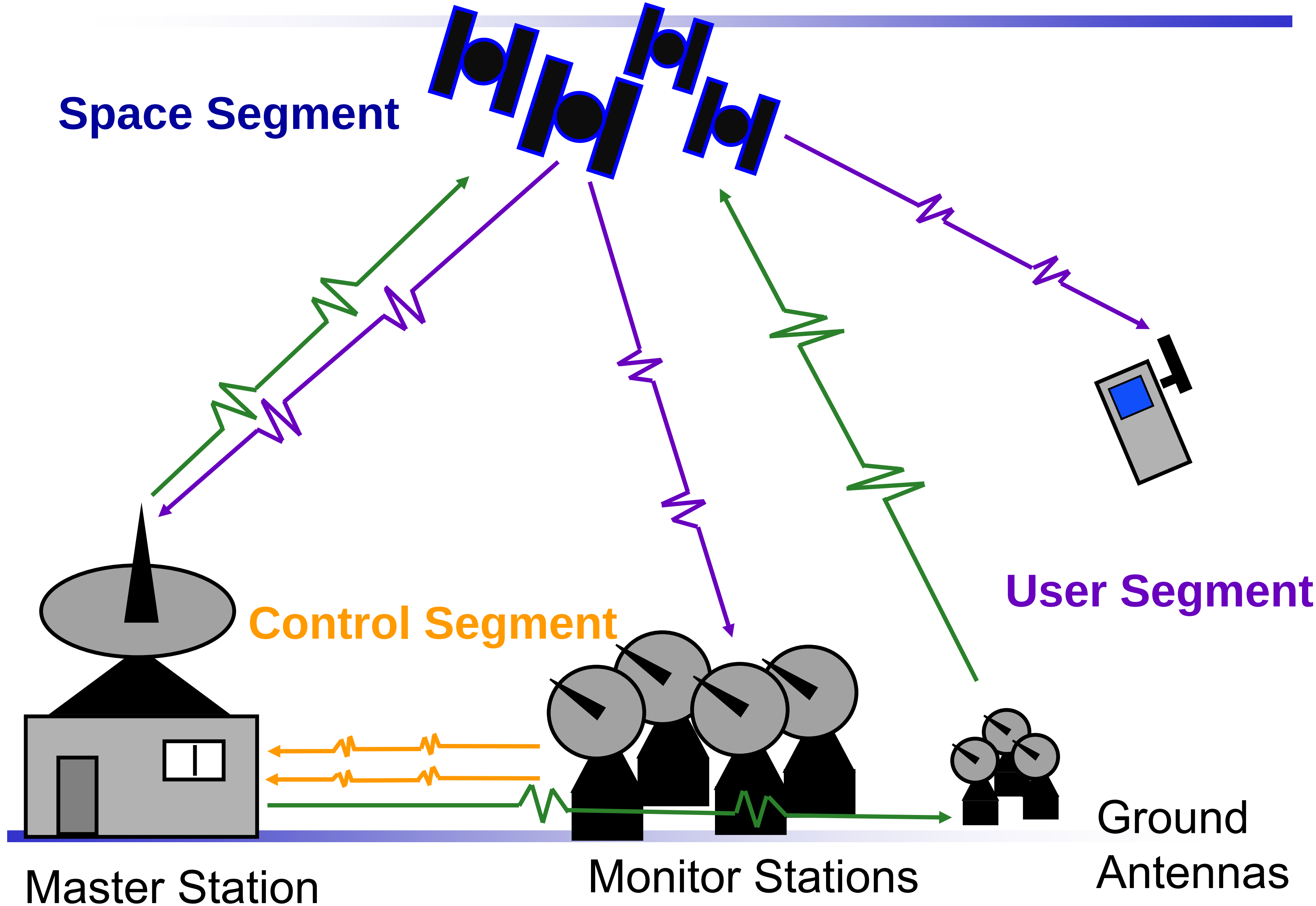
Glonass

Compass

Navstar GPS - Overview

- Controlled by US Department of Defense (DoD)
- Initially for military use only, later on/nowadays also for civilian applications
- Currently, it is the only fully functional satellite navigation system.
- Its 3 segments are as follows:
  - Satellite constellation: currently 32 satellites; they provide the ranging signals and navigation data messages to the user equipment. Originally, there were 24 satellites.
  - Ground control network: 1 Master Control Station (MCS), 3 uploading stations, and 11 monitor (surveillance) stations; this segment tracks and maintains the satellite constellation by monitoring satellite health and signal integrity, and by maintaining satellite orbit configuration.
  - User equipment: it receives signals from the satellite constellations and computes user Position, Velocity and Time (PVT).

The three segments of GPS

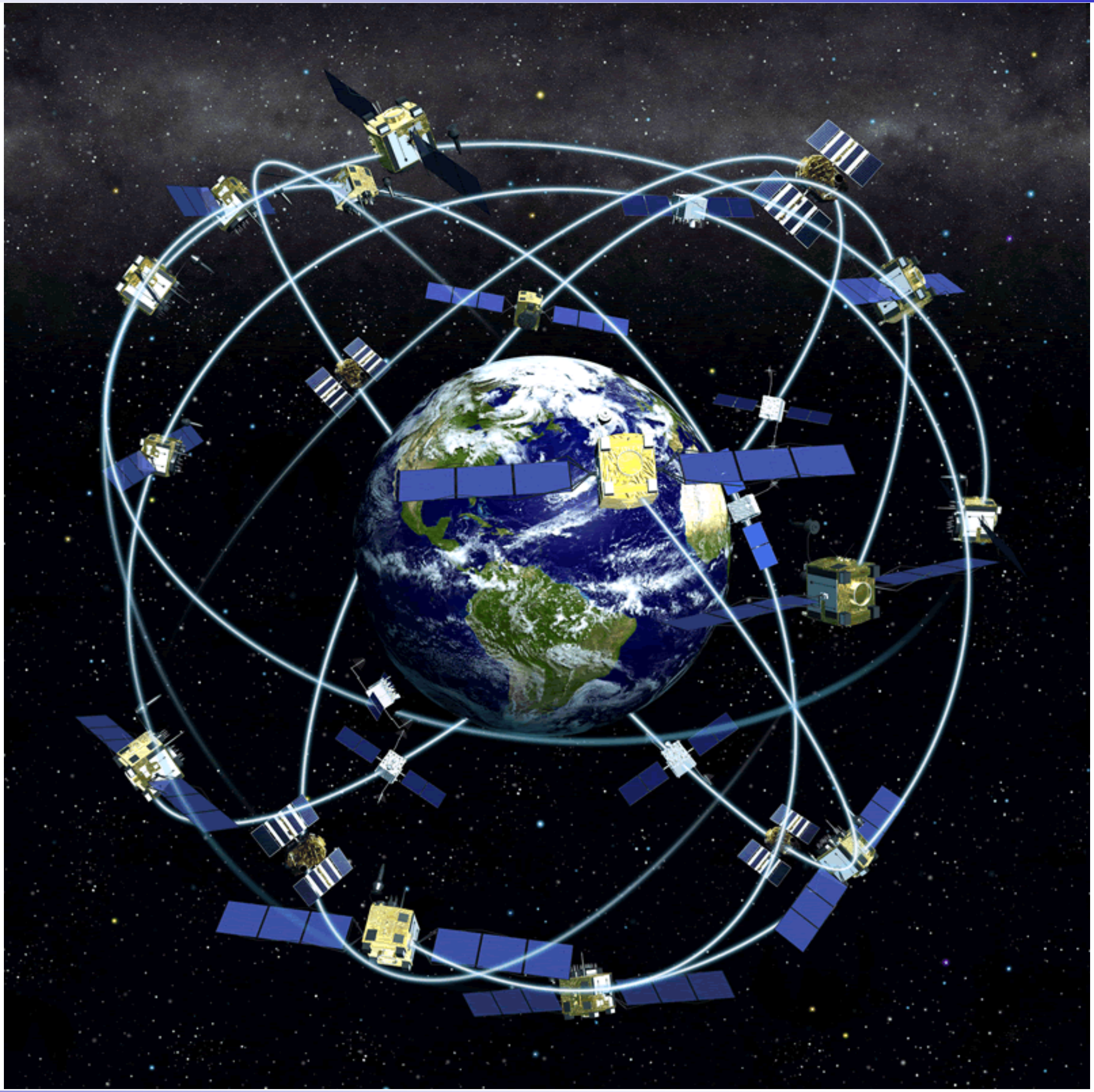


GPS constellation

Currently, there are 32 Block II/IIA/IIR/IIR-M GPS satellites on the sky.

Originally **-> Block II GPS satellites only (24)**:

- In 6 nearly circular orbital planes.
- 4 satellites/plane.
- Orbital plane inclination of 55 degrees.
- altitudes of 20200km above the earth.



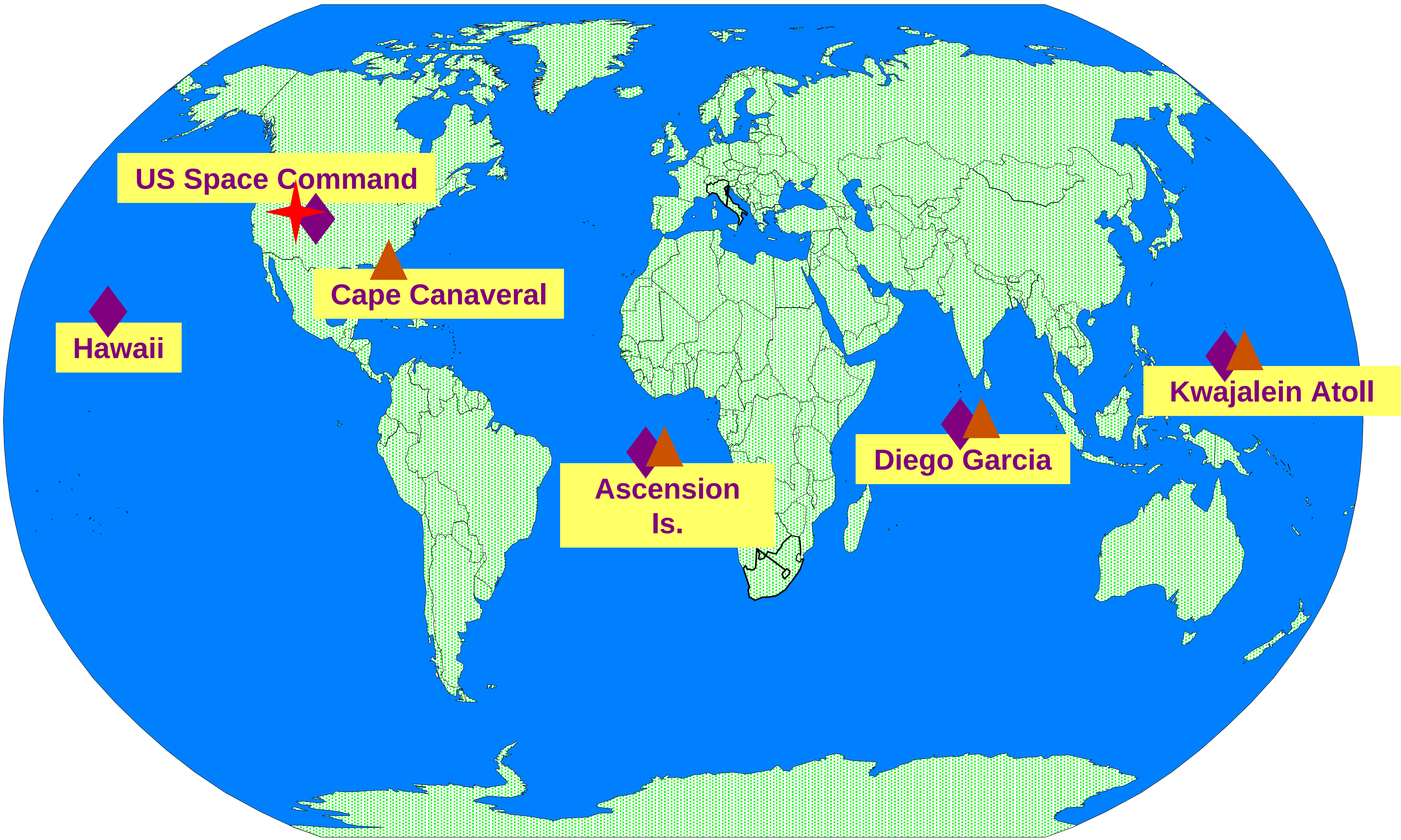
GPS ground segment (I)

- 1 Master Control Station (MCS): located at Schriever Air Force Base, Colorado; here the data from the monitor stations are processed 24 h a day in real time

- 3 uploading stations: located at Ascension, Diego Garcia and Kwajalein; they operate in S-band (2 - 4 GHz).

- 11 monitor (surveillance) stations: every satellite can be seen from at least two monitor stations; the monitor stations track all satellites in their range and collect data of the satellite signals. The raw data are then sent to the mater control station where the data are processed.

GPS Control Segment (II) – before 2005



Master Control Station located at Schriever Air Force Base, Colorado

Monitor (Surveillance) Station

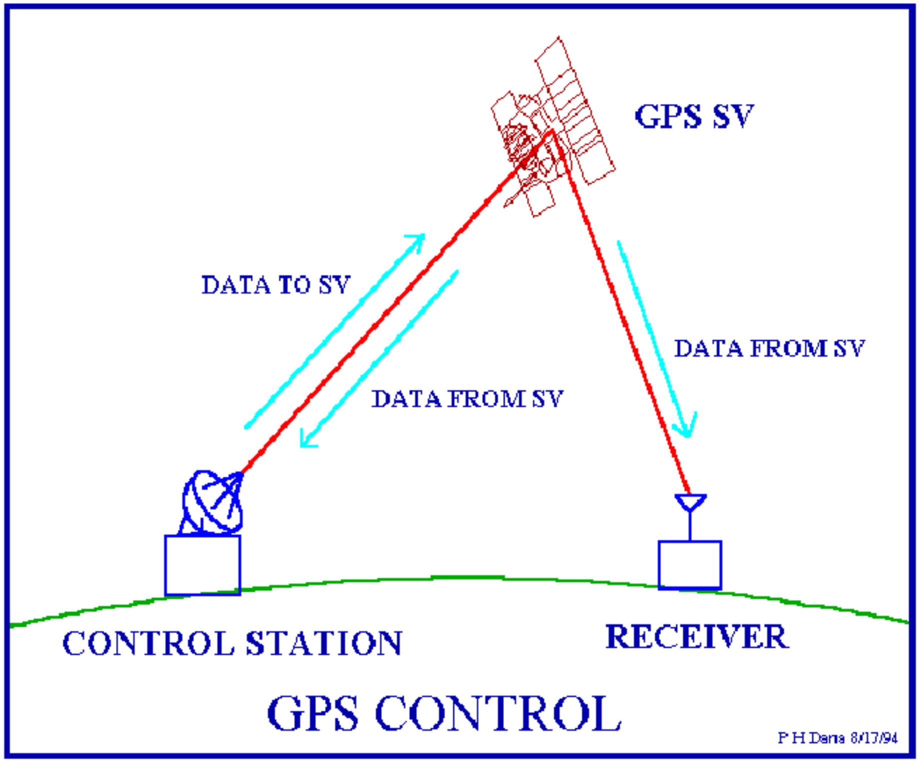
Ground Antenna (Uploading Stations)

GPS Control Segment (III) – after 2005

6 National Geospatial Agency (NGA) stations were added in September 2005 to the already existing 5 monitor stations

GPS Control Segment (IV)

The monitor stations measure signals from the Satellite Values (SV) which are incorporated into orbital models for each satellites: precise orbital data (ephemeris) and SV clock corrections.



At the Schriever Air Force base, Colorado, the back-up “master clock” of the United States Naval Observatory is located, which has a stability of less than 1 s in 20 million years.

GPS User Segment

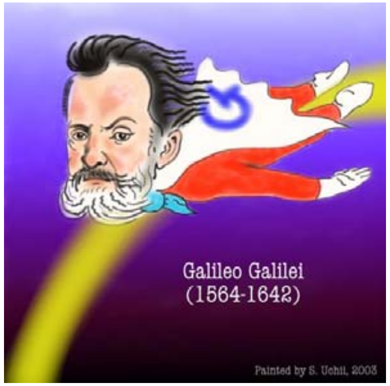
- The GPS User Segment consists of the GPS receivers and the user community. GPS receivers convert SV signals into position, velocity, and time estimates. Four satellites are required to compute the four dimensions of X, Y, Z (position) and Time, according to the triangulation principle.
- The SVs transmit three microwave carrier signals. The L1 frequency (1575.42 MHz) is for civil use. The other two frequencies are in L2 band (1227.60 MHz) and L5 band (1176.45 MHz). Three binary codes shift the L1 and/or L2 carrier phase:
  - C/A Code (Coarse Acquisition) modulates the L1 carrier phase. The C/A code is a repeating 1 MHz Pseudo Random Noise (PRN) Code of duration of 1023 chips (1 msec).
  - P-Code (Precise) modulates both the L1 and L2 carrier phases. The P-Code is a very ong (seven days) 10 MHz PRN code.
  - Navigation Message also modulates the L1-C/A code signal. The Navigation Message is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters.

Navstar GPS Positioning requirements

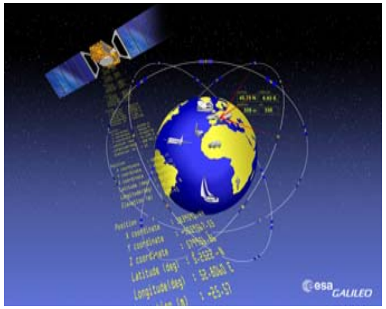
- 2 types of services specified in the US Federal Radionavigation Plan (1999):
  - Precise Positioning Systems (PPS) and
  - Standard Positioning Service (SPS)
- PPS Predictable Accuracy is: 22 meters horizontal accuracy, 27 meters vertical accuracy, and 200 nanosecond time (Universal Time Clock/UTC) accuracy.
- SPS Predictable Accuracy (for civil users; no military restriction) is: 100 meters horizontal accuracy, 156 meters vertical accuracy, and 340 nanosecond time (Universal Time Clock/UTC) accuracy.

Galileo system overview

- The Galileo Programme (so named to honor the great European scientist Galileo Galilei) is a joint initiative of the European Commission (EC) and the European Space Agency (ESA) to provide Europe with its own independent global civilian controlled satellite navigation system.



- It is an autonomous system, interoperable with GPS and globally available.
- It is based on the same technology as GPS (i.e., DS-CDMA) and provides a similar - and possibly higher - degree of precision, thanks to the structure of the constellation of satellites and the ground-based control and management systems planned.

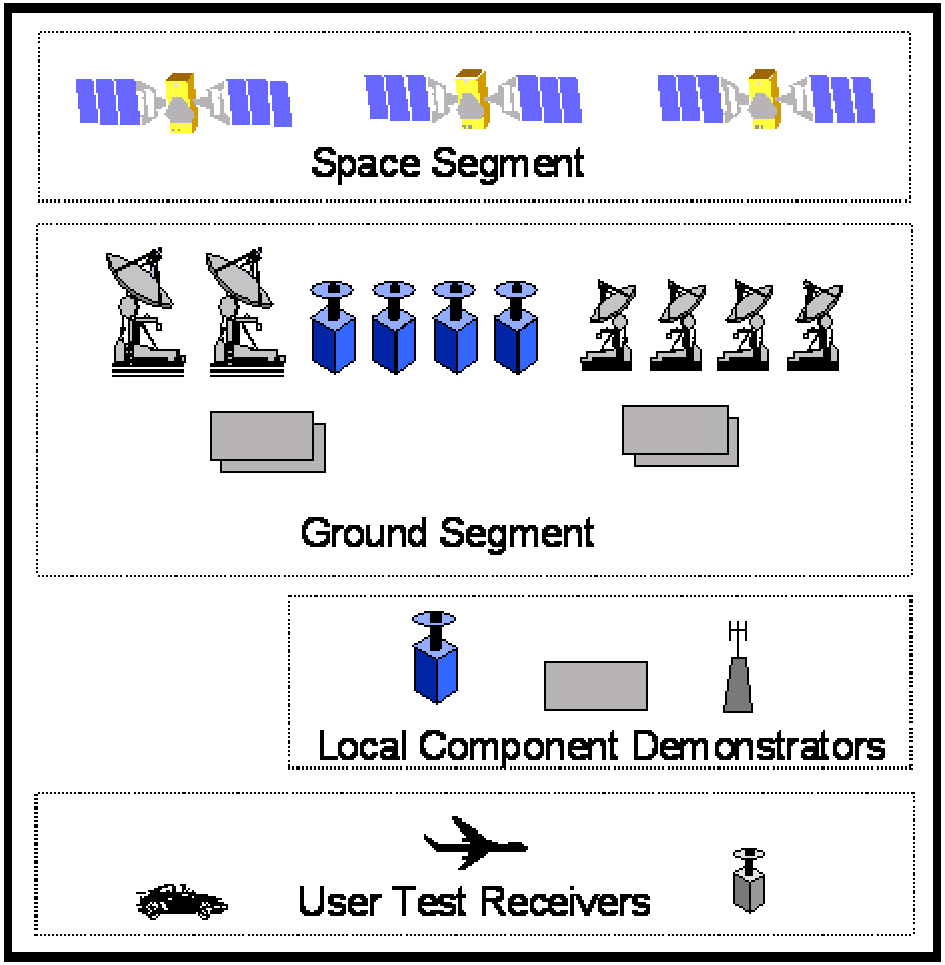


- It represents a real public service and, as such, guarantees continuity of service provision for specific applications.

Galileo history

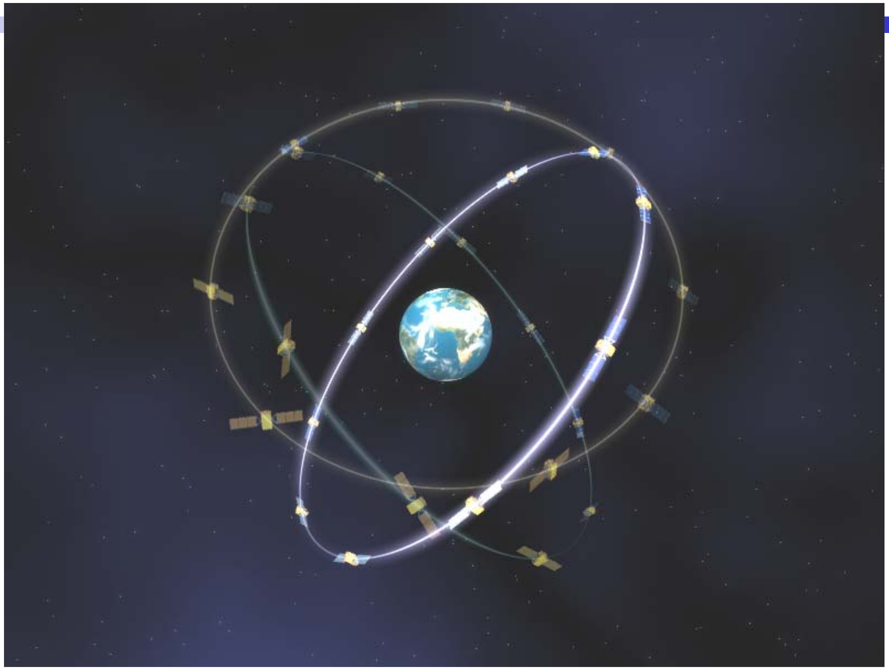
- **1998**: EU decides to develop its own satellite navigation system ”Galileo”
- **2000**: Definition phase of Galileo starts (it was completed in 2003).
- Mar **2002**: statement on GPS-Galileo cooperation; establishment of Galileo Joint Undertaking (GJU) for management and concession of Galileo.
- Nov **2003**: Joint statement between European Commission and US regarding GPS-Galileo
- 1June **2004**: EU and US signed GPS-Galileo agreement:
  - Common civil signal: BOC(1,1) modulation was selected as the baseline for both Galileo and GPS future OS signals
- July 2004: An official European Union Regulatory Authority, the European GNSS Supervisory Authority (GSA) was established. GSA replaced GJU completely in 2006.
- **2005**: first Galileo test satellite launched on orbit (GIOVE-A)
- May **2006**: First Galileo standardization documents (for OS signal only) were made available
- **2007**: MBOC modulation adopted for common GPS-Galileo signal for civilian use
- **2008**: second Galileo test satellite (Giove-B) launched on orbit

Galileo architecture



Galileo Space Segment

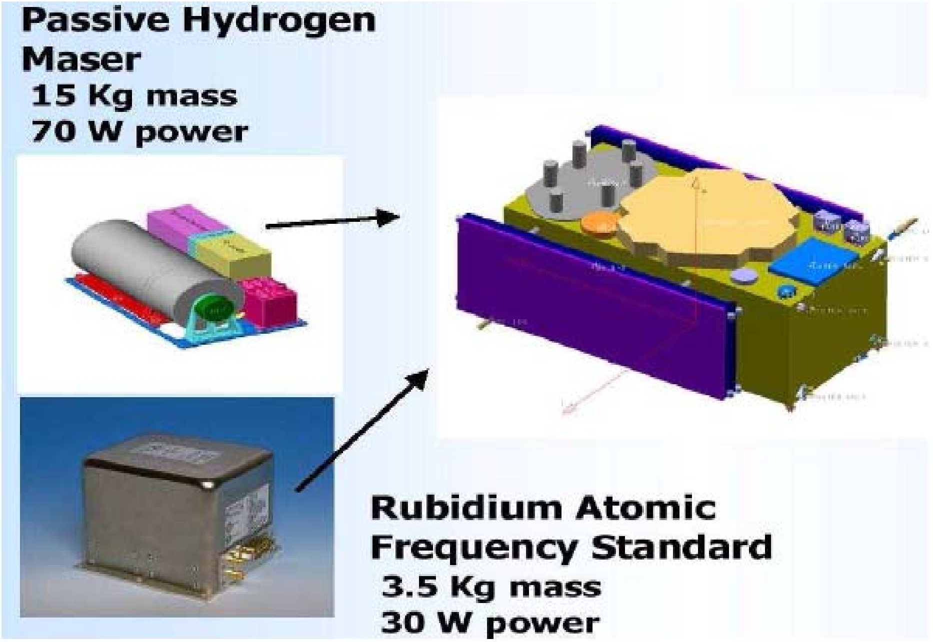
- Galileo will be based on a constellation of 30 satellites (27 + 3 reserve) and ground stations
- It uses the same principles as Navstar GPS for position location
- Constellation of 30 satellites at 23222 Km altitude (17 orbits in 10 days). 10 satellites per plane, 3 planes.
  - Only 9 satellites per plane active.
  - One satellite per plane is in-orbit spare.



Period: 14 hr 22 min
Ground track repeat cycle 3 days

Galileo space segment – clock design

- Two on-board atomic clocks are being developed for Galileo:
  - The Rubidium Atomic Frequency standard Clock: frequency around 6 GHz, 3.5 Kg mass, 30 W power
  - The Passive Hydrogen Maser Clock: frequency around 1.4 GHz, 15 kg mass, 70 W power (the most stable clock ever to fly in space)



- Rubidium clock has good short-term stability, but it is subjected to larger frequency variations due to environment.
- Hydrogen Maser Clock has both short-term and long-term frequency stability, but may suffer of small frequency drifts.

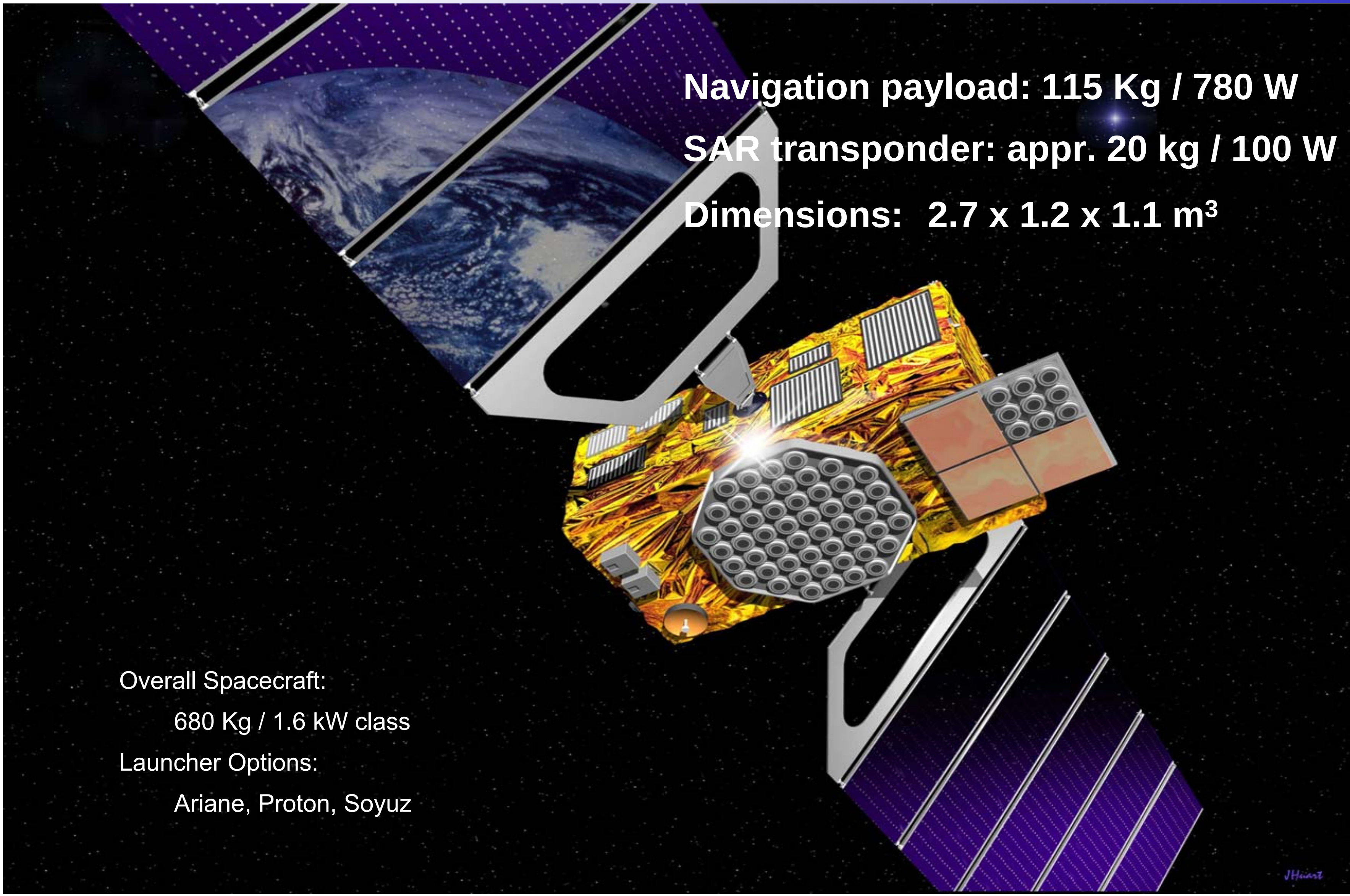
Giove-A and Giove-B launches

Left: Giove – A test satellite, launched Dec, 27, 2005

Right: Giove – B test satellite, launched Apr, 23, 2008

(both from Kazakhstan's Baikonur cosmodrome)

Galileo space segment – spacecraft design



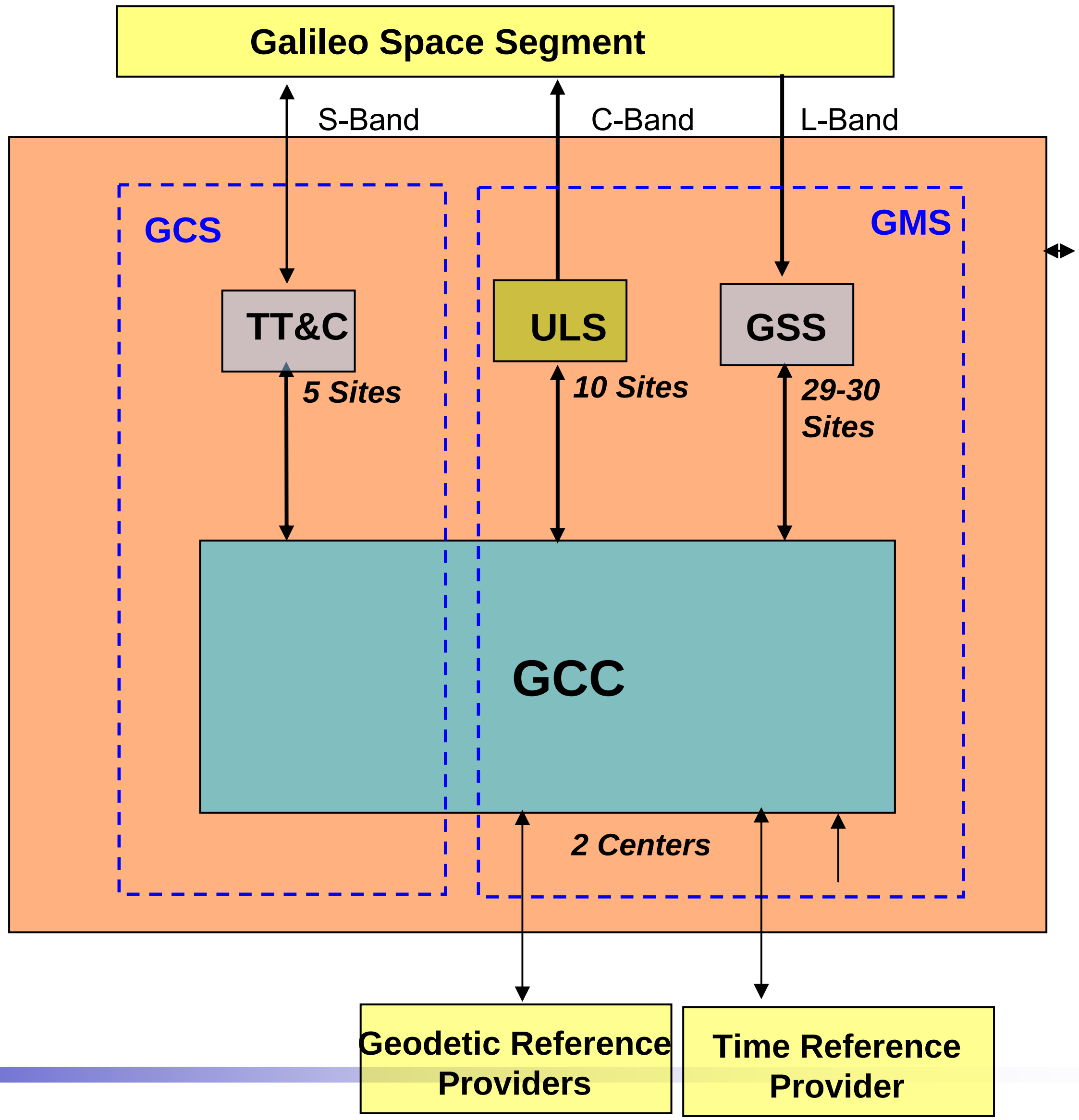
Galileo Ground Segment

- 2 Galileo Control Centers (GCS) (Europe): control of the satellites and navigation mission management
- 10 mission up-link stations (worldwide) in C-band (5.925–6.425 GHz)
- 29-30 Galileo Sensor/surveillance stations (worldwide) forming the Galileo Mission control System (GMS) together with the up-link stations: they will follow the satellite signals in order to provide the definition of the data to be uploaded
- 5 Tracking, Telemetry and Control (TT&C) stations (worldwide) in S-band (2 - 4 GHz): these TT&C stations form the Galileo Ground Control System (GCS): monitoring and control of the satellites.

- Geographical places for control stations (deployment): still to be defined (1 is in Munich, DLR site)
- The number of stations is not finalized; modifications are still possible.

Galileo architecture

GCS	Galileo Control System
GMS	Galileo Mission System
GCC	Galileo Control Center
TT&C	Telemetry, Tracking and Command Station
GSS	Galileo Sensor Station
ULS	(Mission Data) Uplink Station



Galileo services

- Galileo satellite-only services
  - Open Service (OS): free for everyone; mass market applications, simple positioning
  - Safety of Life (SoL): for professional applications; integrity; authentication of signal
  - Commercial Service (CS): for maritime, aviation and train applications; encrypted; high accuracy; guaranteed service
  - Public Regulated Service (PRS): encrypted; government-regulated; integrity; continuous availability
  - Support to Search and Rescue service (SAR): humanitarian purpose; near real time; precise; return link feasible
- Other Galileo-related services: Galileo locally assisted services (use some local elements to improve performance, e.g., differential encoding, more carriers, additional pilot tones), Galileo combined services (combination with other navigation or communication systems).

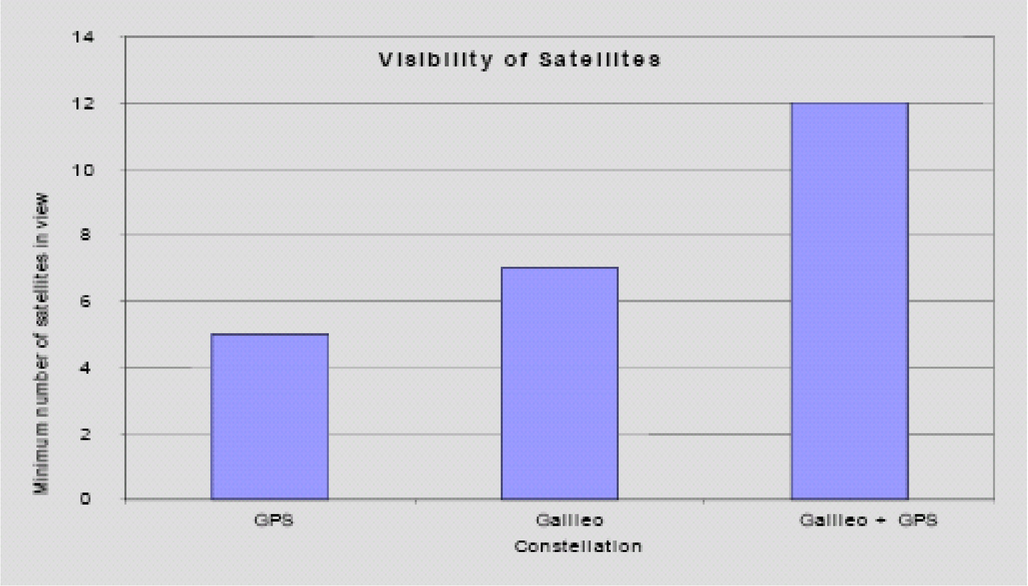
Galileo expected performance with Open Service (OS)

Source: Galileo Joint Undertaking webpages (GJU). OS are free of charge and they are meant for mass-market applications (e.g., in-car navigation, hybridization with mobile phones).

		Open Service	
Type of Receiver	Carriers	Single Frequency	Dual-Frequency
	Computes Integrity	No[11]	
	Ionospheric correction	Based on simple model	Based on dual-frequency measurements
Coverage		Global	
Accuracy (95%)[12]		H: 15 m V: 35 m	H: 4 m V: 8m
Integrity	Alarm Limit	Not Applicable	
	Time-To-Alarm		
	Integrity risk		
Continuity Risk		$8x10^{-6}$/15 s	
Timing Accuracy wrt UTC/TAI		Not defined	50 nsec[13]
Certification/Liability		No	No
Availability		99 % - 99.9 %	

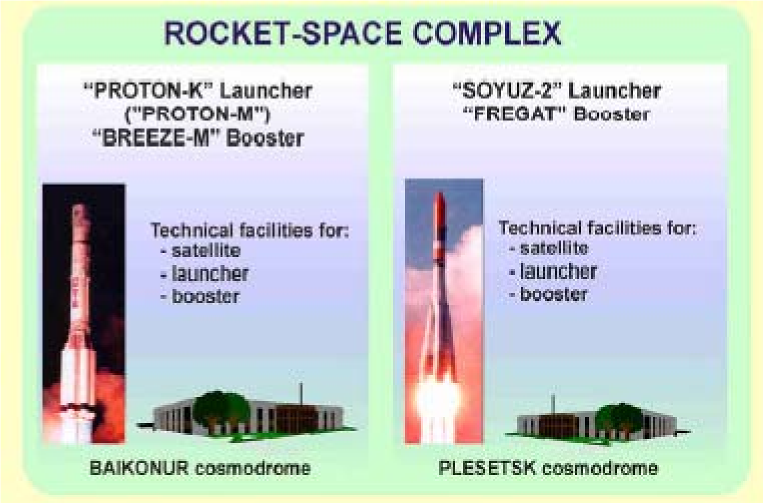
Estimated Visibility of Satellites

Source: ESA



GLONASS system overview

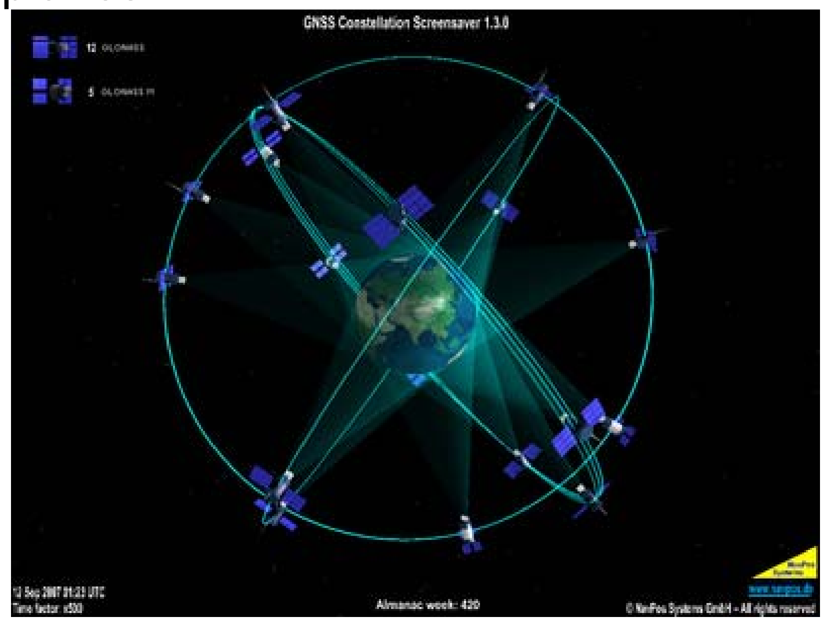
- Dual-use (civil/military) system provided by Russia
- Civil signals provided to all, free of user fees; It started in 1983; now it's updated
- GLONASS modernization directive, as of January 2006:
  - Constellation of 18 SV by end of 2007
  - Full operational capability by end of 2009
  - Comparable performance with GPS and Galileo by 2010



Glonass uses FDMA (different from all the other CDMA-based satellite navigation systems); many say that FDMA signals are less suitable for accurate positioning than CDMA. However joint Glonass-GPS might improve accuracy and availability in the future.

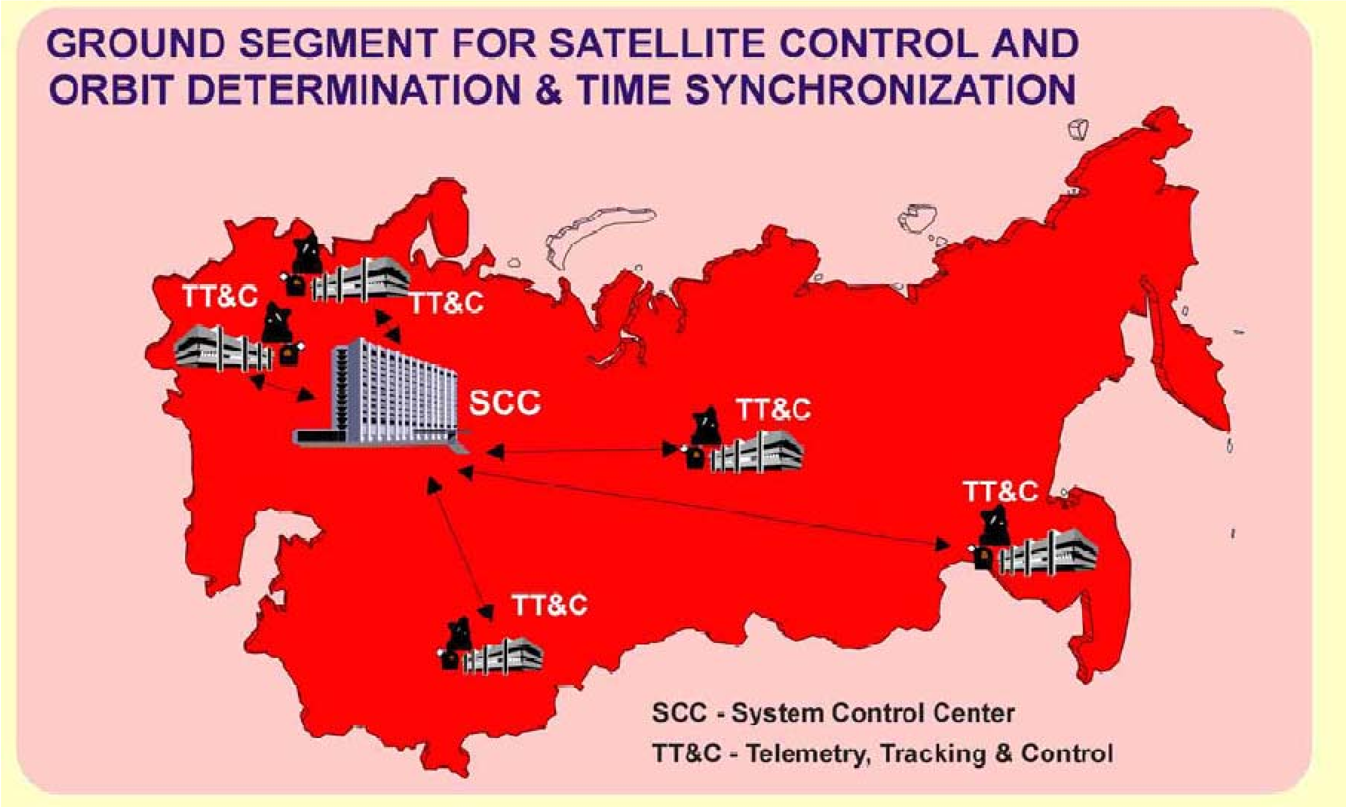
GLONASS space segment

- 24 active satellites when operational
  - altitude - 19100 km
  - inclination - 64.8 degrees
  - period - 11 hours 15 minutes.
  - 8 satellites per plane; 3 orbital planes



GLONASS ground segment

- 1 system control center (SCC) located in Krasnoznamensk, Moscow region
- 5 TT&C stations, all located in Rusia

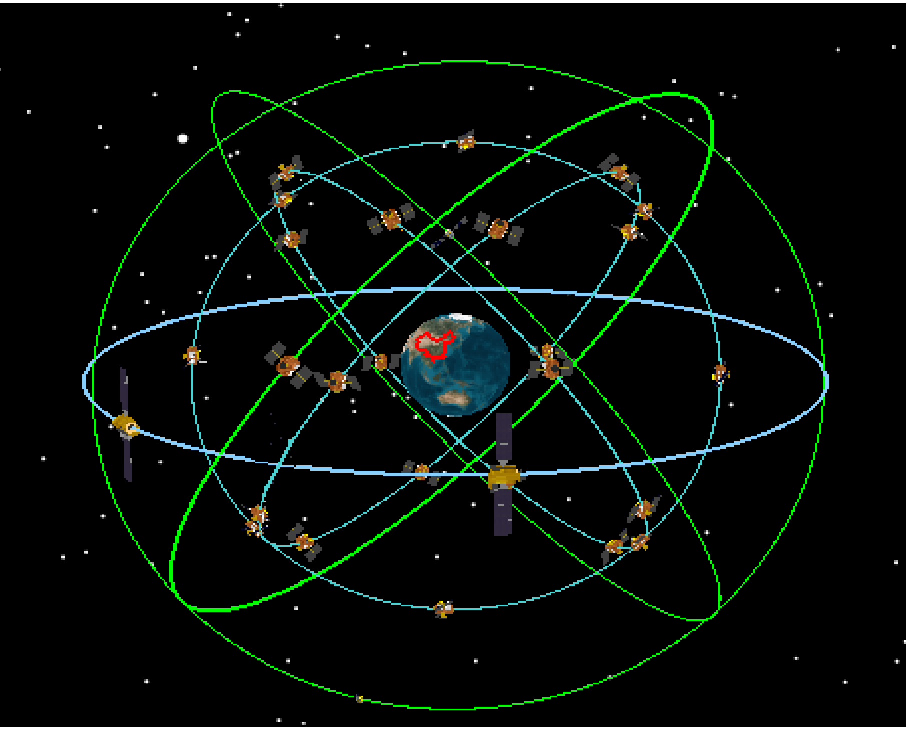


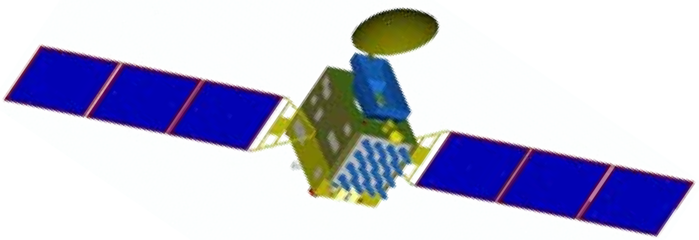
COMPASS system overview

- System under development by China; starting point was BEIDOU, later renamed as Compass
- 30 MEO satellites + 5 GEO satellites (MEO= Medium Earth Orbit; GEO= Geostationary Earth Orbit)
- Claimed accuracy: positioning 10 meters, velocity - 0.2 meter per second timing accuracy - 50 nanoseconds.
- Could institute user charges

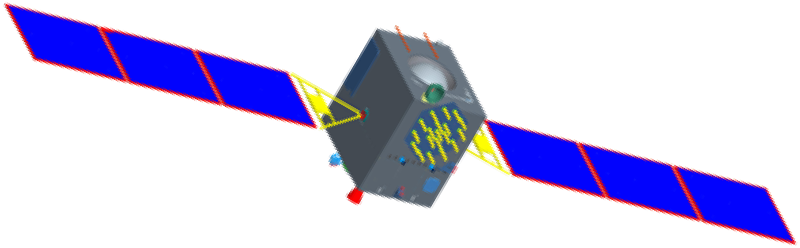
COMPASS space segment (I)

Maximum 30 MEO satellites and 5 GEO satellites





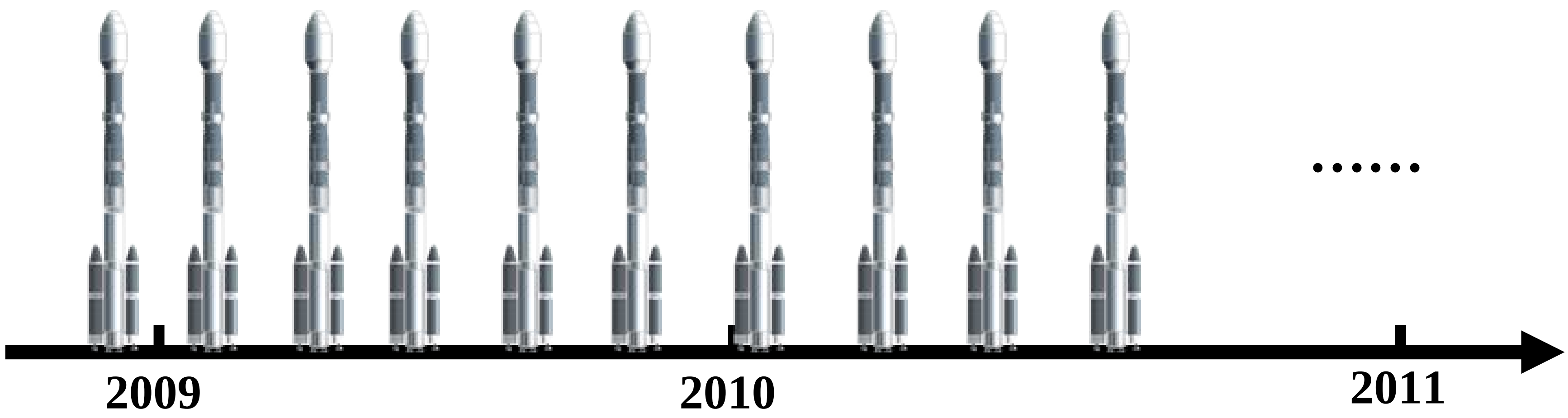
GEO Satellite



MEO Satellite

COMPASS space segment (II)

10 rockets are planned to be launched in the next 2 years => more than 10 satellites will be put into use by 2011, after that the system can offer services regionally.



COMPASS ground segment

The ground segment consists of Master Control Station, Upload Stations and Monitor Stations.

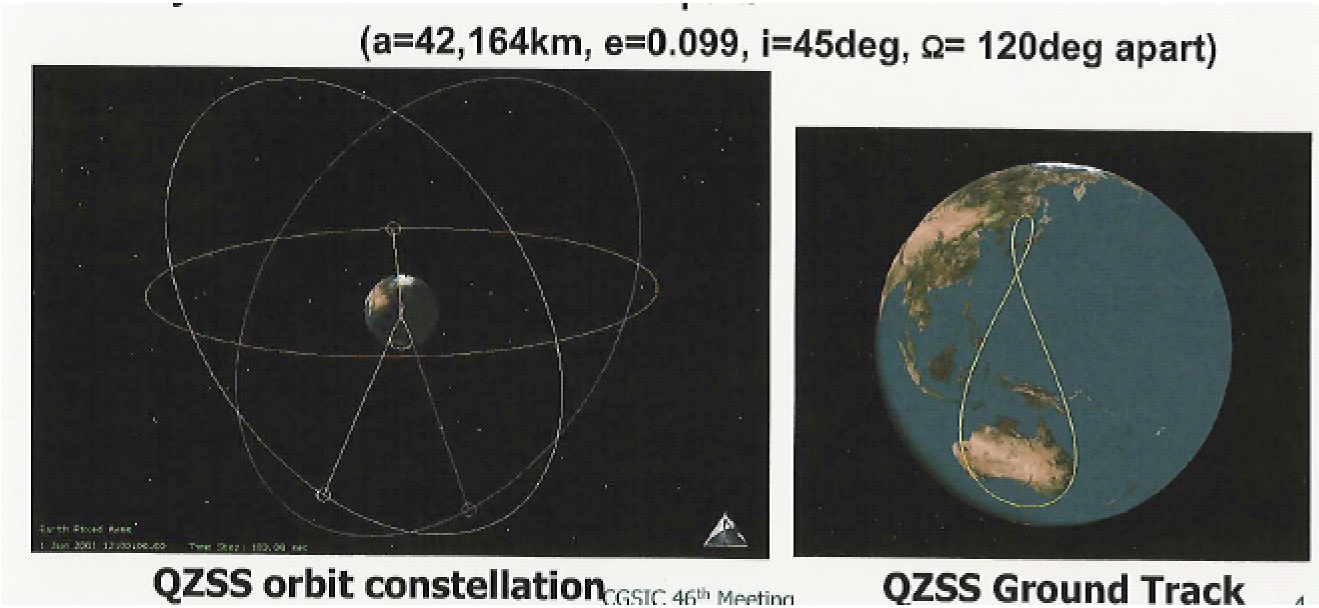
COMPASS services

- Two kinds of global services:
  - Open Service：free and open to users
    - Positioning Accuracy: 10 m
    - Timing Accuracy: 20 ns
    - Velocity Accuracy: 0.2 m/s
  - Authorized Service: ensures highly reliable use even in complex situation.

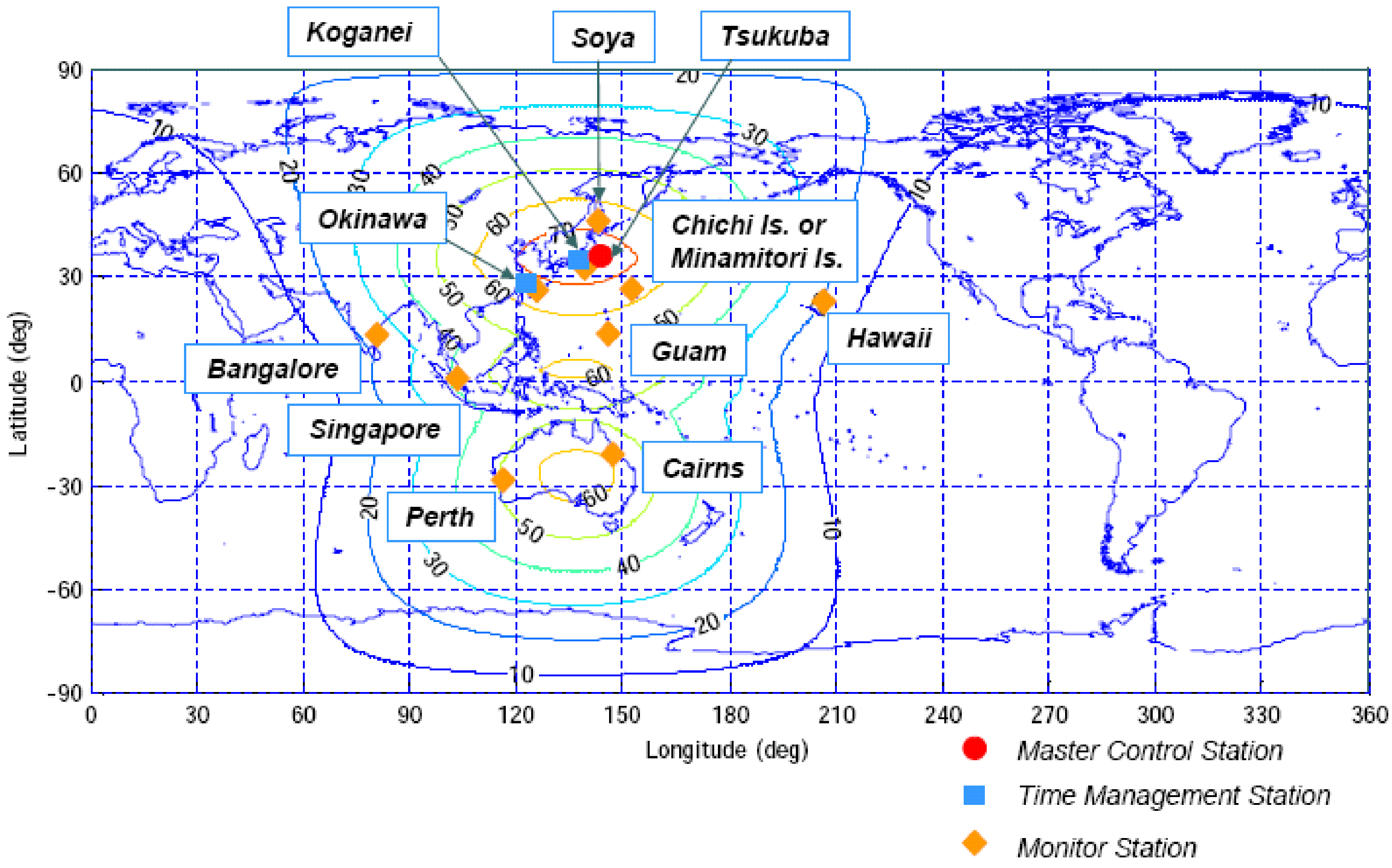
Regional satellite navigation systems

QZSS system overview

- Japan's Quasi-Zenith Satellite System
- Civil system for Asia Pacific region
- Signals on L1, L2, L5 developped in collaboration with US
- Initial objective of 3 satellites, with possibility of more extensive constellation afterwards

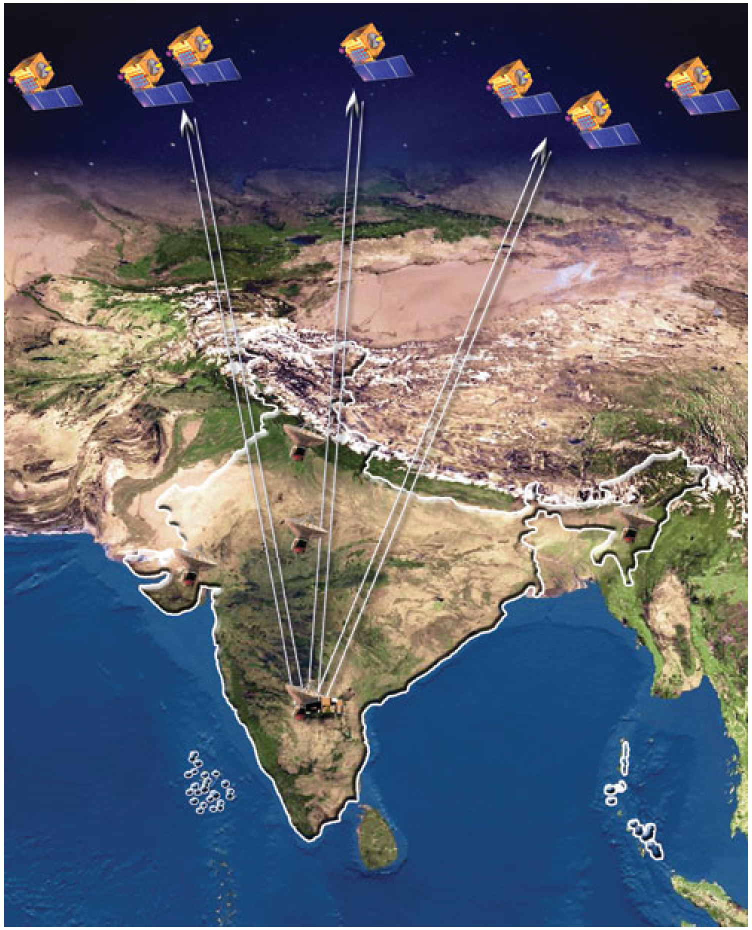


QZSS tentative ground station location



IRNSS (Indian Regional Navigational Satellite System)

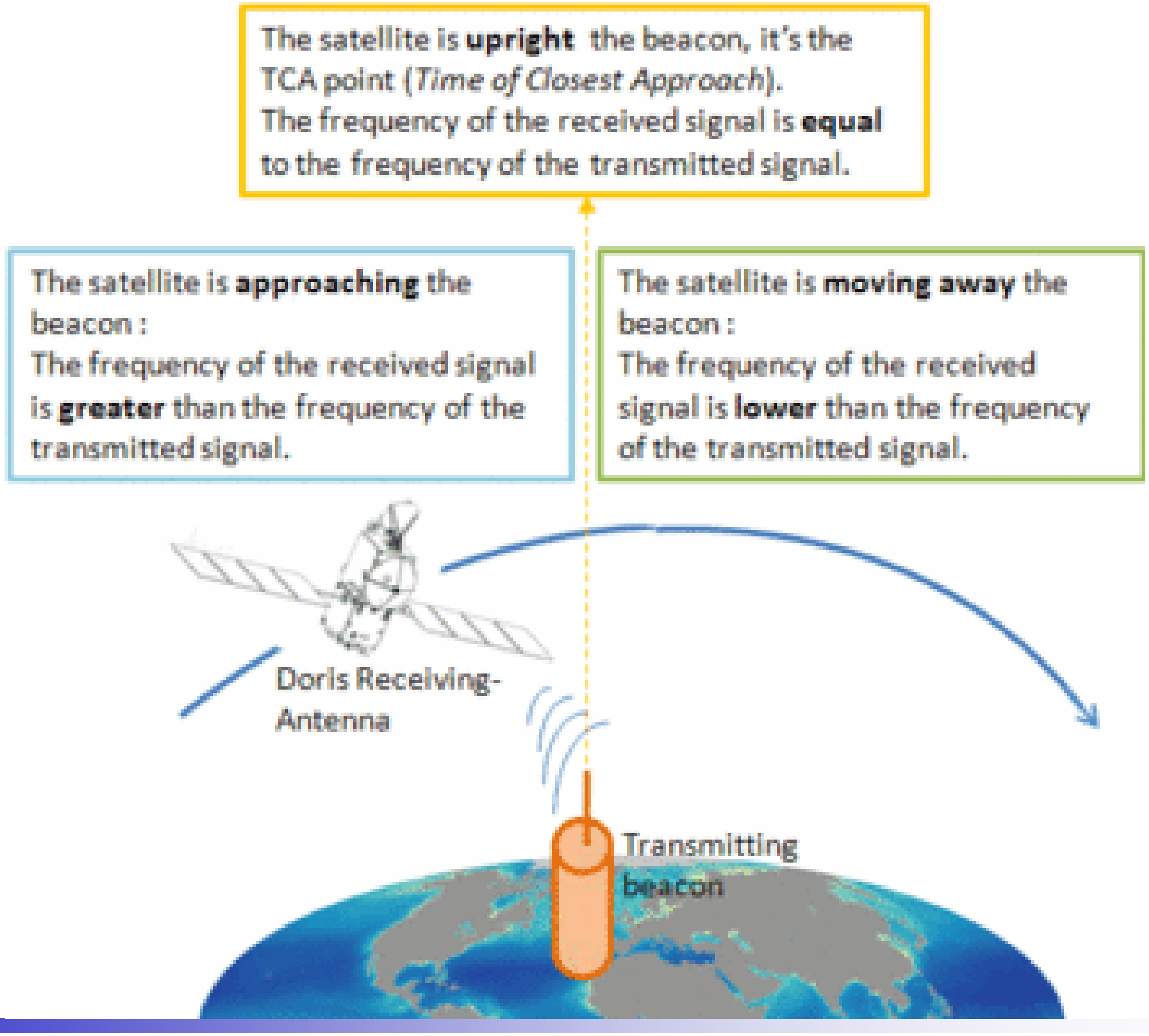
- constellation of 7 satellites into a geo-synchronous orbit, planned within next 4-5 years, India
- First satellite planned to be launched in 2009
- Ground segment: 1 master control sation + 4 monitor TT&C stations



Particular example: DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite)

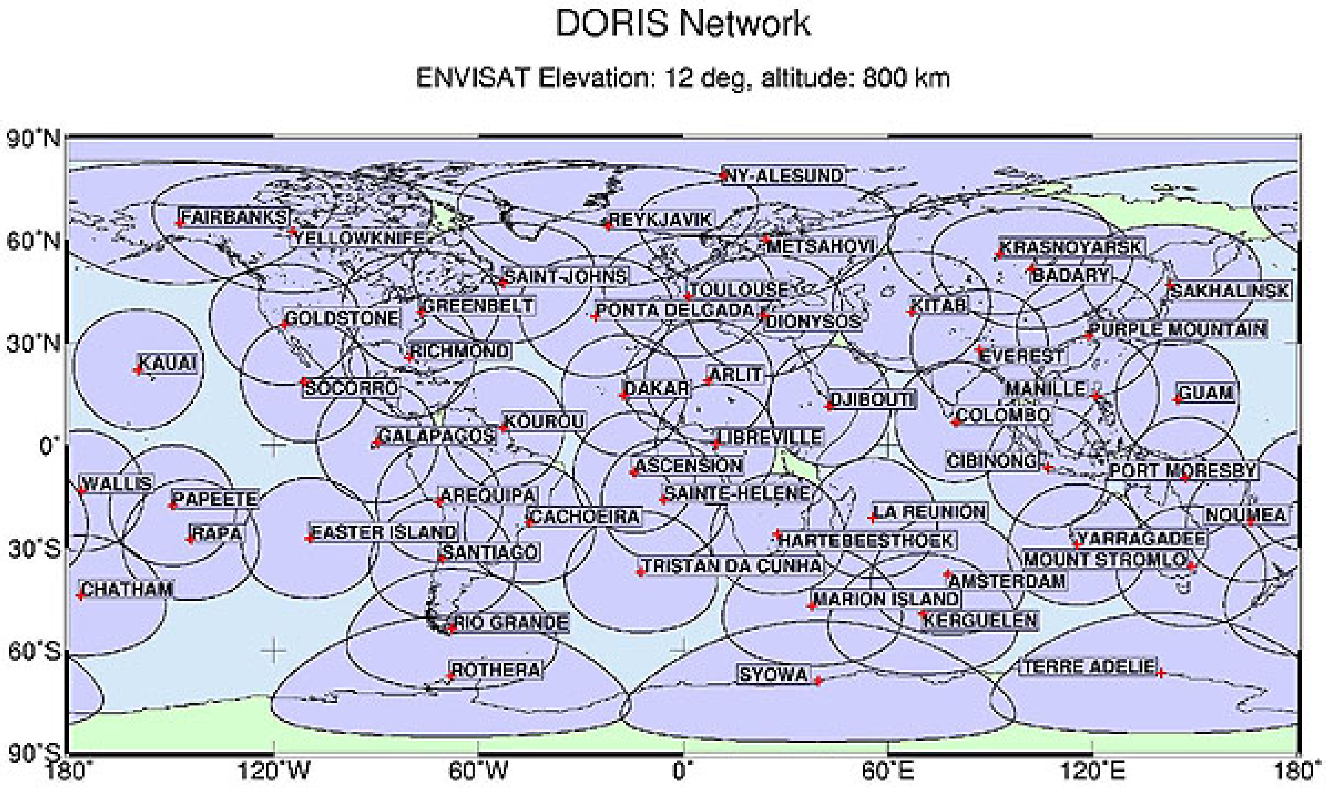
- Project initiated by CNES institute, France in collaboration with the French survey and mapping agency and the French space geodesy research centre in 1990s
- Different operational principle compared with all the other satellite navigation systems: It is based on the principle of the *Doppler effect* with a transmitting terrestrial beacons network and onboard instruments on the satellite's payload (antenna, radio receiver and oscillateur ultra-stable)
- Doppler shift measurements are taken using an S-band frequency of 2.03625 GHz, while a second VHS band signal at 401.25 MHz is used for ionospheric correction of the propagation delay.
- Applications: Solid Earth (Tectonics) & Natural Disasters (Landslides)

DORIS principle



DORIS ground segment

About 60 ground beacons placed around the globe



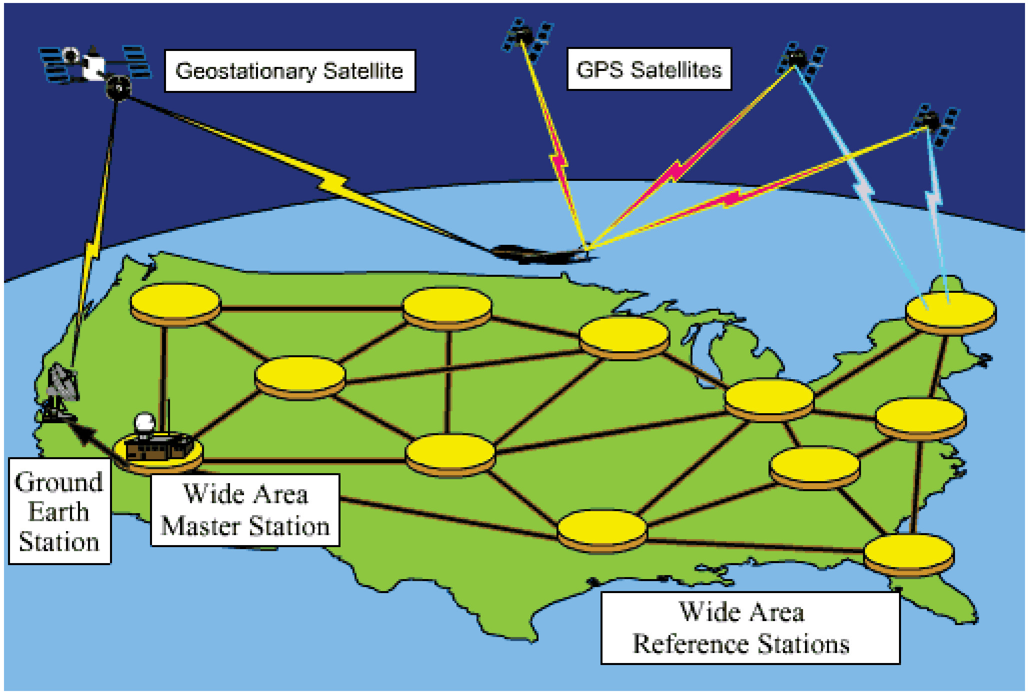
GPS augmentation

GPS augmentation: EGNOS

- European Geostationary Navigation Overlay System (EGNOS) is the precursor of Galileo and it is intended to supplement GPS and GLONASS systems
- Target accuracy is below 5 meters.
- It consists of 3 Geostationary satellites and a network of ground stations.
- EGNOS open service was declared available in early 2006 -> free of direct user charges and it supports all except safety-of-life applications.

GPS augmentation: WAAS/CWAAS

- Wide Area Augmentation System (WAAS) and Canadian Wide Area Augmentation System (CWAAS): US/Canada counterparts of EGNOS.
- It consists of Geostationary satellite(s) and a network of ground stations.



Summary & core content

- ✓ Satellite-based positioning has the advantage of global coverage (though restricted indoors and in dense urban canyons)
- ✓ Navstar GPS is one of the oldest global satellite navigation systems, and it is the only fully functioning nowadays.
- ✓ Galileo is the European satellite navigation system meant to be fully operational by 2013

Core content:

- Triangulation/multilateration principle for positioning
- Sources of error in satellite positioning
- GNSS generic system architecture