# GNSS

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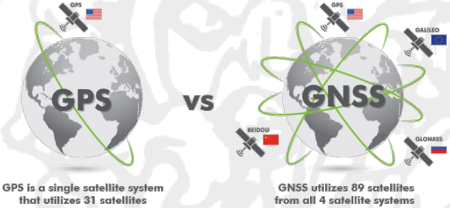
# GNSS

Global Navigation Satellite System (GNSS) is the standard generic term for satellite navigation systems. This system provides autonomous geo-spatial positioning, information about velocity and time with global coverage.

This term includes:

- **GPS**(USA)
- **GLONASS**(RU)
- **GALILEO**(EU)
- **BEIDOU**(CN)




GNSS versus the specific system

# NAVSAT(Transit)

The Transit system (also known as **NAVSAT** or Navy Navigation Satellite System (NNSS)) was the first radio navigation system based on a satellite system.

Its purpose was to provide accurate location information to the US **Polaris** submarines. It was operative between 1959 and 1996.

Born from the idea of William Guier and George Weiffenbach (prior observation of the Sputnik launch in 1957) it was composed by a 5+5 satellites system with the following characteristics:

- different polar orbits
- low and fast orbits (height:1100km, rotation period:106min)
- frequency of transmission: 150MHz-400MHz

# Global Positioning System (GPS)

The birth of the GPS is due to the **Department of Defense (DOD)** request for a service with the following characteristics:

- determination of Position, Velocity and Time
- increase of portability of the instrumentation
- availability (in terms of tolleration of failure and 24/7)
- global coverage (including the polar caps)

In the 70' the **Joint Program Office (JPO)** was created to achieve this target obtaining the GPS.

*In 1978 the first satellite of block 1 was launched.*
*In 1985 the first ones of block 2 were put into orbit.*
*In 1994 the constellation was completed with 24 satellites.*
*The first launch of the third block is from the end of 2018.*

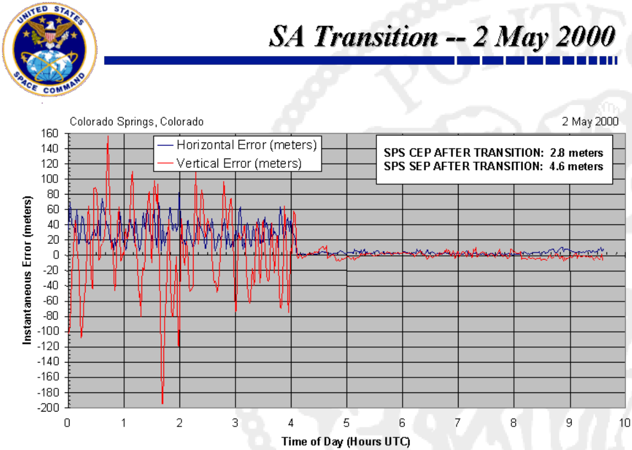
# PPS and SPS

GPS initially provided two main services:

- **Precise Positioning Service (PPS)**: exclusively for military use with maximum precision
- **Standard Positioning Service (SPS)**: available for civil use since 1994 but without guarantee of availability until 2000 (thanks to use of the Selective Availability).

**Selective Availability (SA)** was an intentional degradation of public GPS signals implemented for national security reasons.

# Selective Availability (SA)

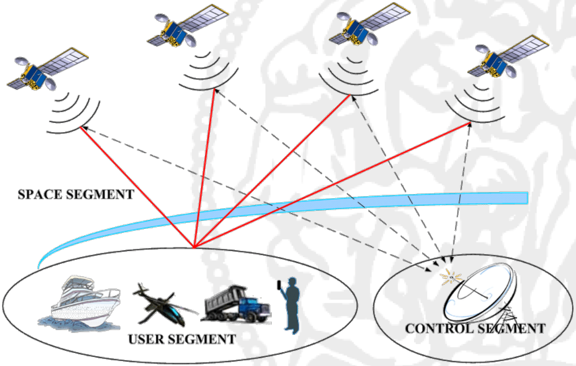



Plot of GPS navigational errors through the SA transition

# Architecture of GPS

The GPS architecture is divided into three major segments

- **space segment**
- **control segment**
- **user segment**



# Space Segment

The GPS space segment consists of a constellation of satellites transmitting radio signals to users.

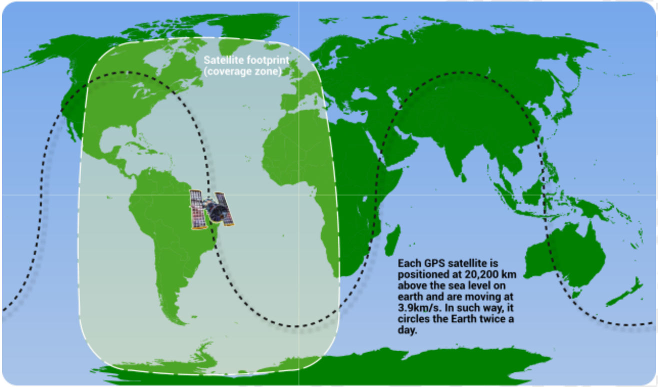
- **Procurement**
  - pre-procurement
  - procurement
  - post-procurement
- **Launch**
- **Decommissioning**
  - disposal to stable graveyard orbits
  - disposal to eccentricity build-up orbits
- **Physical satellites**

# Space Segment

The satellites in the GPS constellation are arranged into **six equally-spaced orbital planes** surrounding the Earth. Each plane contains four "slots" occupied by baseline satellites. This 24-slot arrangement ensures users can view at least four satellites from virtually any point on the planet.

The orbits are circular and with an inclination of **55 degrees** with respect to the equator and a period of approximately 12 hours (a satellite makes 2 revolutions a day around the earth).

# Space Segment



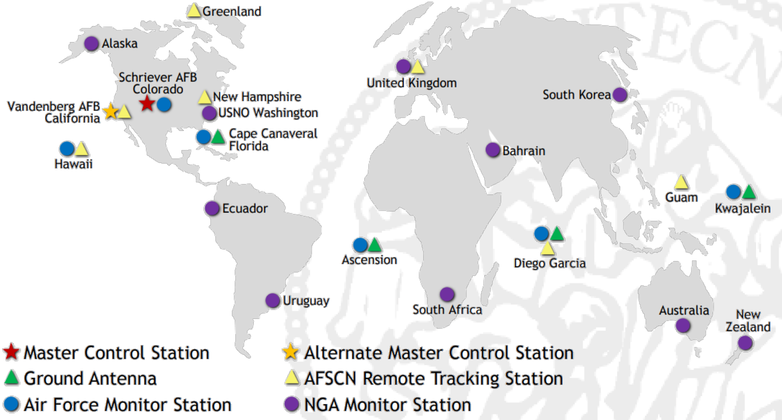

The footprint of each satellite occupying a slot in the baseline/expandable 24-slot constellation covers approximately 38% of the surface of the Earth

# Control Segment

The GPS control segment consists of a global network of **ground facilities** that track the GPS satellites, monitor their transmissions, perform analyses, and send commands and data to the constellation.

The current Operational Control Segment (OCS) includes 16 monitoring sites, a master control station, an alternate master control station and 11 command and control antennas.

# Control Segment



# User Segment

A GPS Receiver is a device capable of processing the signal of the GPS satellites and determining the user Position Velocity Time (PVT) by processing the signal broadcasted by satellites. The main uses are:

- **Civilian** (use via mobile phone, pedestrian use, ground vehicles)
- **Aviation** (GPS provides position determination for all phases of flight)
- **Navy** (underwater surveying, navigational hazard location and mapping)

# User Segment

- **Space** (from guidance systems for crewed vehicles to the management, tracking, and control of communication satellite constellations)
- **Timing** (GPS enables users to determine the time to within 100 billionths of a second, without the cost of owning and operating atomic clocks)
- **Agriculture** (farm planning, field mapping, soil sampling)
- **Geodesy**(measuring and understanding Earth's figure (geometric shape and size), orientation in space, and gravity)

# Principle of Operation

GPS operation is based on the concept of ranging and multilateration from a group or constellation of satellites in space, which act as precise reference points.

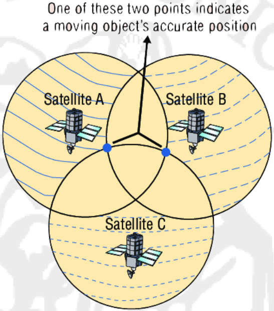
A GPS receiver measures distance from a satellite using the travel time of a radio signal. Knowing the speed at which the signal travelled, i.e. the speed of light in vacuum (299 792 458 meters per second), and the exact broadcast time, the distance travelled by the signal can be computed from the time difference of arrival.

Position estimation based on distance measurements is called trilateration when three measurements are used or multilateration when more than three measurements are used.

# Principle of Operation

Idea behind multilateration:

- Compute the distance from the satellite as $r_i = c \cdot dt_i$
- The calculated distance provides the radius of a spherical surface centered on the satellite and containing the user's location
- Repeat the same computations again
- The intersection between two spheres is a circumference
- The intersection between three spheres is two points
- One point is excluded because it is not reasonable




Trilateration

# Orbital Parameters Control

Ground stations have as one of their primary objectives tracking satellites and monitor their orbital parameters. In order to compute exactly the user's position, satellites location must be known precisely.

Ground stations compute and update each of the satellites with their own Ephemeris Data at least every day, usually once or twice a day, through a navigation message. They provide estimations 'a priori' of the future orbital elements, based on observations from the previous 8 days data and adding corrections from the last 12/24 hours.

# Orbital Parameters Control

Perturbed orbital equation takes into consideration:

- the presence of the Moon
- solar winds
- other factors

If a satellite was to be moved from its orbit, Ephemeris Data referred to if would not be adequately accurate for GPS standards. It would be temporarily marked as 'unhealthy' so that the receiver do not rely on it. Once the maneuver is over, the new Ephemeris Data can be computed and the satellite can be operative again.

# Time Reference

Time measurement is made by:

- Atomic clocks on the satellites
- Atomic clocks in ground stations
- Quartz oscillators in the receivers

Atomic clocks in GPS satellites keep time to within three nanoseconds: three-billionths of a second. Position accuracy depends on the receiver.

All GPS satellites must transmit their data signals at the exact same time, so precise synchronization is essential.

Their signals are monitored constantly and adjusted as needed. A failure of the atomic clock on one satellite would make the satellite unusable.

# Time Reference: Relativity

Why do we need to correct atomic clocks on a daily basis?

The answer is found in Einstein's Relativity.

- **Special relativity**: Moving clocks tic slower than stationary ones. This effect is known as *velocity time dilation*.
  Since Atomic clocks on satellites move faster than those on Earth, they measure $7\mu s/day$ less than those on the ground.

- **General relativity**: Clocks closer to a massive object (for example the Earth) tic slower than clocks further away (e.g. satellites), an effect known as *gravitational time dilation*.
  Because of this effect, Atomic clocks measure $45\mu s/day$ more on the satellites than those on the ground.

Combining these two effects, Atomic Clocks must be corrected by $38\mu s$ every day.

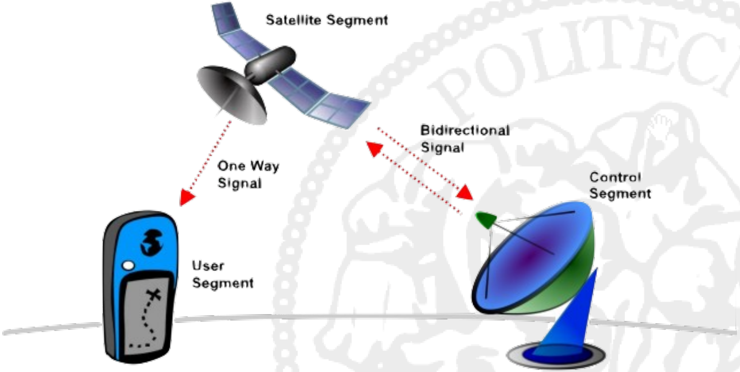
# Navigation Message

The **Navigation Message** is received by every satellite from Ground antennas and it is sent back to Earth to the users. It provides all the necessary information to allow the user to perform the positioning service.
It includes:

- Ephemeris Data
- Time parameters and clock corrections
- The constellation Almanacs
- Satellite health information
- Ionospheric parameters model

Each satellite is assigned a Pseudo Random Number (PRN).
The transmission of the entire Navigation Message takes about 12m 30s.

# Navigation Message




One way signal from satellites to receivers.
Bidirectional signal between satellites and ground antennas.

# Navigation Message: Almanacs

The **Almanac Data** allow to compute a raw estimation of all the satellites coordinates, which is needed for signal acquisition by the receiver. It is less precise than Ephemeris Data and it's uploaded with lower frequency (al least every six days) but it can be very useful for the receiver: it helps the receiver identify a region of suitable satellites to log on.

# TTFF

**Time To First Fix (TTFF)** is a measure of the time required for a GPS navigation device to acquire satellite signals and navigation data, and calculate a position solution (called a fix). It depends on the amount of information already present in the receiver.

We can identify:

**Cold start** The receiver has no Ephemeris nor Almanac Data in its memory. The TTFF is some minutes, up to 12m 30s.

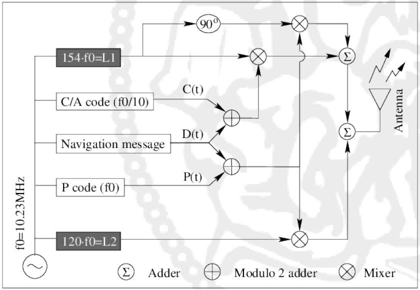
**Warm start** The receiver has Almanac Data memorized. It estimates the time within 20s and its position within 30km. The TTFF reduces up to 30s.

**Hot start** The receiver has valid time, position, Almanac, and Ephemeris data, enabling a rapid acquisition of satellite signals. The TTFF is only a few seconds.

# Transmitted Signal

List of the transmitted signals:

- L1 carrier
- L2 carrier
- PRN code:
  - Course Acquisition (C/A) code
  - Precise (P) code
- *Naviation Message* (Nav/Msg code)



# Signal Carriers

**CARRIER** Modulated sinusoidal-shaped signal which allows to transmit information data throughout space

**MODULATION** Variation of the carrier's wave shape by means of the signal which contains information to be transmitted (*modulation signal*)

**L1 (1575.42 MHz)** : Both C/A and P codes, as well as the Nav/Msg signal are modulated on this carrier

**L2 (1227.60 MHz)** : On this carrier just P code and Nav/Msg signal are modulated

$$L_1(t) = a_1 P(t) D(t) cos(f_1 t) + a_1 C(t) D(t) sin(f_1 t)$$

$$L_2(t) = a_2 P(t) D(t) cos(f_2 t)$$

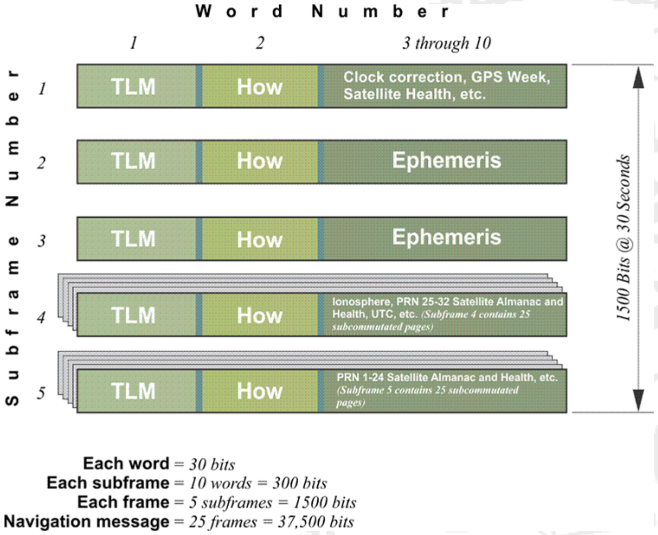
# PRN Codes

| Code | C/A | P |
|---|---|---|
| Generation rate | 1.023 MHz | 10.23 MHz |
| Accuracy [1] | $\pm 2\,m$ @ 95 % | - |
| Encryption | No | Yes |
| Code length [bits] | 1023 | $6.1871 \cdot 10^{12}$ |
| Time between repetition | 1 ms | 1 week |
| Modulation carrier(s) | L1 | L1, L2 |

**NB:** Due to the synchronization of C/A and P codes, receiving the entire P code package is not necessary. A quicker connection to the sole C/A signal is performed instead.

[1] Referred User Range Error (URE) as defined by specifications. Effective accuracy might vary upon various factors

# Navigation Message



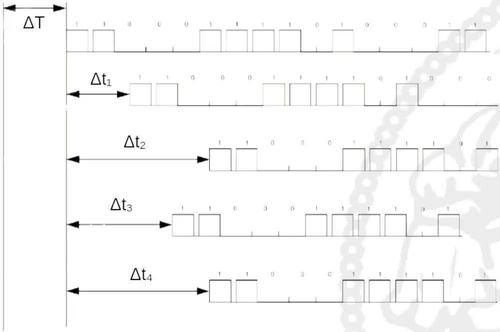
# Trilateration Process

1. The receiver connects to each satellite (whose PRN codes are known)
2. The receiver gets the data package including:
   - Time of transmission
   - Satellite's ephemerides
   - Satellite's position
3. The receiver produces a C/A code's replica
4. *dt* is calculated as the difference in time between signal transmission and signal reception
5. Hypothesis:
   - The signal is transmitted through air at the speed of light in vacuum
   - No time shift between satellite and receiver's time

   True range is defined as:

$$r_i = c \cdot \Delta t_i$$

# Pseudoranges




If satellite's time is not in sync with the receiver's time, the observable becomes the *pseudorange* [2]

Therefore it is introduced another unknown: clock's error $\Delta T$

**NB:** 4 satellites are needed in order to perform a correct multilateration

[2] e.g. usually quartz oscillator are used in receivers: they are less accurate then atomic clocks, but they are more portable

# Calculation of final position

Position is given by the solution of the following non-linear system:

$$\begin{cases} r_1 = c(\Delta t_1 + \Delta T) = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} \\ r_2 = c(\Delta t_2 + \Delta T) = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} \\ r_3 = c(\Delta t_3 + \Delta T) = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} \\ r_4 = c(\Delta t_4 + \Delta T) = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} \end{cases}$$

- Known parameters (from ephemerides and current time, obtained using satellite's time and a recursive algorithm to estimate $\Delta T$):

  $x_1, x_2, x_3, x_4, y_1, y_2, y_3, y_4, z_1, z_2, z_3, z_4$
- Observables: $\Delta t_1, \Delta t_2, \Delta t_3, \Delta t_4$
- Unknowns $x_u, y_u, z_u, \Delta T$

# Galileo

**Galileo** is a global navigation satellite system, created by the European Union through the European Space Agency (ESA), operated by the European Union Agency for the Space Programme, headquartered in Prague **Czech Republic**, with two ground operations centres in Fucino, **Italy**, and Oberpfaffenhofen, **Germany**.

Unlike the GLONASS and GPS, which were developed during the cold war mainly for **military** and later civil purposes, Galielo was developed only for **civil** purposes.

# Galileo

One of the aims of Galileo is to provide an independent high-precision positioning system so that European nations do not have to rely on the US GPS, or the Russian GLONASS systems, which could be disabled or degraded by their operators at any time. Civil infrastructure, including aircraft navigation and landing, should not rely solely upon a system with this vulnerability.

**Roadmap:**

- **development phase: 2002-2005**
- **deployment phase: 2006-2007**
- **exploitation phase: from 2008**

# Galileo

**Main features:**

- constellation of 30 satellites
- 24,000 km of altitude
- 3 orbital planes,
- 56° inclined orbit with respect to the equator (MEO constellation, Medium Earth Orbit) equally spaced satellites on each orbit

There are two tipes of service:

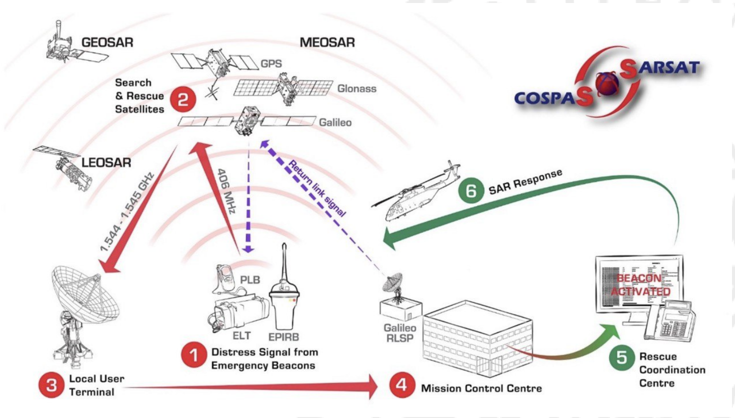
- A basic use (lower-precision) of Galileo services that is free and open to everyone.
- A fully encrypted higher-precision service that is available for free to government-authorized users.

# Search and Rescue (SAR) - Galileo Service

**Galileo provides a global search and rescue (SAR):**
Like Russia's Glonass, and the United States' Global Positioning System (GPS) satellites, Galileo satellites are equipped with a transponder which relays 406 MHz distress frequency signals from emergency beacons by a Forward Link Service to the Rescue coordination centre, which will then initiate a rescue operation.

After receipt of an emergency beacon signal, the Galileo SAR system provides a signal, the Return Link Message, to the emergency beacon, informing the person in distress that the activated beacon has been detected and help is on the way.

# Search and Rescue (SAR) - Galileo Service



# BeiDou

**BeiDou is a Chinese satellite navigation system.**
The original idea of a Chinese satellite navigation system was conceived by Chen Fangyun and his colleagues in 1980. The risk of denied access to GPS, including an alleged case in 1996 during the Third Taiwan Strait Crisis, gave impetus to the creation of BeiDou. According to the China National Space Administration, the development of the system would be carried out in **three steps:**

- **2000 - 2003:** experimental BeiDou navigation system consisting of four satellites
- **By 2012:** regional BeiDou navigation system covering China and neighboring regions
- **By 2020:** global BeiDou navigation system

# BeiDou 1

BeiDou-1 was an experimental regional navigation system, which consisted of **four satellites** (three working satellites and one backup satellite);

Unlike the American GPS, Russian GLONASS, and European Galileo systems, which use medium Earth orbit satellites, **BeiDou-1 used satellites in geostationary orbit.**
This means that the system does not require a large constellation of satellites, but it also limits the coverage to areas on Earth where the satellites are visible.

# BeiDou 1

- The first satellite, BeiDou-1A, was launched on 31 October 2000.
- The second satellite, BeiDou-1B, was successfully launched on 21 December 2000.
- The last operational satellite of the constellation, BeiDou-1C, was launched on 25 May 2003

The area that can be served is from longitude 70°E to 140°E and from latitude 5°N to 55°N.

# BeiDou 2

BeiDou-2 is not an extension to the older BeiDou-1, but rather supersedes it outright.

This new system is a constellation of **35 satellites**, which include 5 geostationary orbit satellites for backward compatibility with BeiDou-1, and 30 non-geostationary satellites (27 in medium Earth orbit and 3 in inclined geosynchronous orbit), that offer complete coverage of the globe.

# BeiDou 2

Similar to the other global navigation satellite systems, there are two levels of positioning service: open (public) and restricted (military).

The free civilian service has a 10-metre location-tracking accuracy, synchronizes clocks with an accuracy of 10 nanoseconds, and measures speeds to within 0.2 m/s. The restricted military service has a location accuracy of 10 centimeters.

The BeiDou-2 system began offering services for the Asia-Pacific region in December 2012. At this time, the system could provide positioning data between longitude 55°E to 180°E and from latitude 55°S to 55°N

# BeiDou 1 vs BeiDou 2

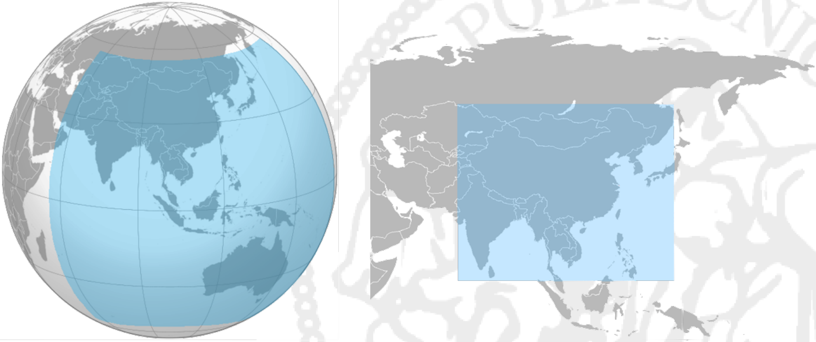


Table: *difference between the two systems*

# BeiDou 3

On 23 June 2020, the final BeiDou satellite was successfully launched, the launch of the 55th satellite in the Beidou family.

The third iteration of the Beidou Navigation Satellite System promises to provide global coverage for timing and navigation, offering an alternative to Russia's GLONASS and the European Galileo positioning system, as well as the US's GPS.

# Failure of the System

Last year, 9 clocks of the 18 Galileo satellites now in orbit have stopped operating.

Three are traditional rubidium devices; six are the more precise hydrogen maser instruments that were designed to give Galileo superior performance to the American GPS network.

Galileo was declared up and running in December. However, it is still short of the number of satellites considered to represent a fully functioning constellation, and a decision must now be made about whether to suspend the launch of further spacecraft while the issue is investigated. However, waiting until finding the solution means that if more clocks fail the capability of Galileo will reduce.

# Credit where credit is due

The present material has been prepared as part of the contribution to the *Flipped Class-innovative didactic* initiative during academic year 2021/2022 by the following students:

- Lara D'Agostino
- Sara Di Lucia
- Marco Hanna
- Lorenzo Pontello

# List of Acronyms

| | |
|---|---|
| **C/A** | Course Acquisition |
| **DOD** | Department of Defense |
| **GNSS** | Global Navigation Satellite System |
| **GPS** | Global Positioning System |
| **JPO** | Joint Program Office |
| **NNSS** | Navy Navigation Satellite System |
| **OCS** | Operational Control Segment |
| **P** | Precise |
| **PPS** | Precise Positioning Service |
| **PRN** | Pseudo Random Number |
| **PVT** | Position Velocity Time |
| **SA** | Selective Availability |
| **SPS** | Standard Positioning Service |
| **TTFF** | Time To First Fix |
| **URE** | User Range Error |