GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

ECE 514E– RADAR & SATELLITE ENGINEERING

Tuesday, 23 September 2025

WHAT IS GNSS

Global Navigation Satellite System (GNSS) is a satellite-based system that provides geographic positioning anywhere on Earth.

MAJOR GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

Global Navigation Satellite System (GNSS) includes:

1. **Global Position System (GPS)** - USA
2. **Galileo** - European
3. **Global Navigation Satellite System (GLONASS)** – Russian
4. **Beidou Navigation Satellite System (BDS)** - Chinese

GLOBAL POSITIONING SYSTEM (GPS)

- The **Global Positioning System (GPS),** originally Navstar GPS, is a satellite-based radio-navigation system owned by the United States government and operated by the United States Air Force.
- The GPS project was launched by the U.S. Department of Defence in 1973 for use by the United States military.
- It was allowed for civilian use in the 1980s and became fully operational in 1995.
- USA can selectively deny access to the system, as happened to the Indian military in 1999 during the Kargil War, or degrade the service at any time.
- As a result, a number of countries have developed or are in the process of setting up other global or regional navigation systems.

WHY CIVILLIANS WERE ALLOWED TO USE GPS?

- In 1983, the Soviet interceptor aircraft shot down the Korean civilian airliner that strayed into prohibited airspace because of navigational errors, killing all 269 people on board.

- Thereafter, U.S. President Ronald Reagan announced that GPS would be made available for civilian uses once it was completed

Further Reading:

The Plane Crash That Gave Americans GPS - The Atlantic

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SOME GPS SATELLITES

NAME	NORAD	INT'CODE	LAUNCH DATE	STATUS
NAVSTAR 62 (USA 201)	32711	2008-012A	2008-03-15	IN ORBIT
NAVSTAR 61 (USA 199)	32384	2007-062A	2007-12-20	IN ORBIT
NAVSTAR 60 (USA 196)	32260	2007-047A	2007-10-17	IN ORBIT
NAVSTAR 59 (USA 192)	29601	2006-052A	2006-11-17	IN ORBIT
NAVSTAR 58 (USA 190)	29486	2006-042A	2006-09-25	IN ORBIT
NAVSTAR 57 (USA 183)	28874	2005-038A	2005-09-26	IN ORBIT
NAVSTAR 63 (USA 203)	34661	2009-014A	2009-03-24	IN ORBIT
NAVSTAR 37 (USA 117)	23833	1996-019A	1996-03-28	IN ORBIT
NAVSTAR 56 (USA 180)	28474	2004-045A	2004-11-06	IN ORBIT
NAVSTAR 46 (USA 145)	25933	1999-055A	1999-10-07	IN ORBIT
NAVSTAR 51 (USA 166)	27663	2003-005A	2003-01-29	IN ORBIT
NAVSTAR 36 (USA 100)	23027	1994-016A	1994-03-10	IN ORBIT
NAVSTAR 55 (USA 178)	28361	2004-023A	2004-06-23	IN ORBIT
NAVSTAR 24 (USA 79)	21890	1992-009A	1992-02-23	IN ORBIT
NAVSTAR 50 (USA 156)	26690	2001-004A	2001-01-30	IN ORBIT
NAVSTAR 35 (USA 96)	22877	1993-068A	1993-10-26	IN ORBIT
NAVSTAR 54 (USA 177)	28190	2004-009A	2004-03-20	IN ORBIT
NAVSTAR 23 (USA 71)	21552	1991-047A	1991-07-04	IN ORBIT
NAVSTAR 44 (USA 135)	25030	1997-067A	1997-11-06	IN ORBIT
NAVSTAR 49 (USA 154)	26605	2000-071A	2000-11-10	IN ORBIT

GLOBAL NAVIGATION SATELLITE SYSTEM (GLONASS)

1. **Development of GLONASS** began in the Soviet Union in 1976.
2. **Beginning 1982**, numerous rocket launches added satellites to the system until the constellation was completed in 1995.
3. **In 2001,** under Vladimir Putin's presidency, the restoration of the system was made a top government priority and funding was substantially increased after a decline in capacity during the late 1990s.
4. In October 2011, the full orbital constellation of 24 satellites was restored, enabling full global coverage.
5. GLONASS is the most expensive program of the Russian Federal Space Agency, consuming a third of its budget.
6. The GLONASS satellites' designs have undergone several upgrades, with the latest version being GLONASS-K2, scheduled to enter service in early 2018.

Further Reading:

About GLONASS (glonass-iac.ru)

SOME GLONASS SATELLITES

NAME	NORAD	INT'CODE	LAUNCH DATE	STATUS
COSMOS 2443 (GLONASS)	33379	2008-046B	2008-09-25	**IN ORBIT**
COSMOS 2425 (GLONASS)	29670	2006-062A	2006-12-25	**IN ORBIT**
COSMOS 2434 (GLONASS)	32393	2007-065A	2007-12-25	**IN ORBIT**
COSMOS 2411 (GLONASS)	28509	2004-053B	2004-12-26	**IN ORBIT**
COSMOS 2447 (GLONASS)	33466	2008-067A	2008-12-25	**IN ORBIT**
COSMOS 2426 (GLONASS)	29671	2006-062B	2006-12-25	**IN ORBIT**
COSMOS 2436 (GLONASS)	32395	2007-065C	2007-12-25	**IN ORBIT**
COSMOS 2449 (GLONASS)	33467	2008-067B	2008-12-25	**IN ORBIT**
COSMOS 2424 (GLONASS)	29672	2006-062C	2006-12-25	**IN ORBIT**
COSMOS 2435 (GLONASS)	32394	2007-065B	2007-12-25	**IN ORBIT**
COSMOS 2448 (GLONASS)	33468	2008-067C	2008-12-25	**IN ORBIT**
COSMOS 2431 (GLONASS)	32277	2007-052C	2007-10-26	**IN ORBIT**
COSMOS 2403 (GLONASS)	28114	2003-056C	2003-12-10	**IN ORBIT**
COSMOS 2444 (GLONASS)	33380	2008-046C	2008-09-25	**IN ORBIT**
COSMOS 2418 (GLONASS)	28916	2005-050B	2005-12-25	**IN ORBIT**
COSMOS 2433 (GLONASS)	32275	2007-052A	2007-10-26	**IN ORBIT**
COSMOS 2404 (GLONASS)	28112	2003-056A	2003-12-10	**IN ORBIT**
COSMOS 2442 (GLONASS)	33378	2008-046A	2008-09-25	**IN ORBIT**
COSMOS 2419 (GLONASS)	28915	2005-050A	2005-12-25	**IN ORBIT**
COSMOS 2432 (GLONASS)	32276	2007-052B	2007-10-26	**IN ORBIT**

GALILEO GNSS

1. **In 1999**, the different concepts of the three main contributors of ESA (Germany, France and Italy) for Galileo were compared and reduced to one by a joint team of engineers from all three countries.

2. The first stage of the Galileo programme was agreed upon officially on **26 May 2003** by the European Union and the European Space Agency.

3. The system is intended primarily for civilian use, unlike the more military-orientated systems of the United States (GPS), Russia (GLONASS), and China (Beidou).

4. The European system will only be subject to shutdown for military purposes in extreme circumstances.
5. It will be available at its full precision to both civil and military users.
6. The countries that contribute most to the Galileo Project are Germany and Italy.

SOME GALILEO SATELLITES

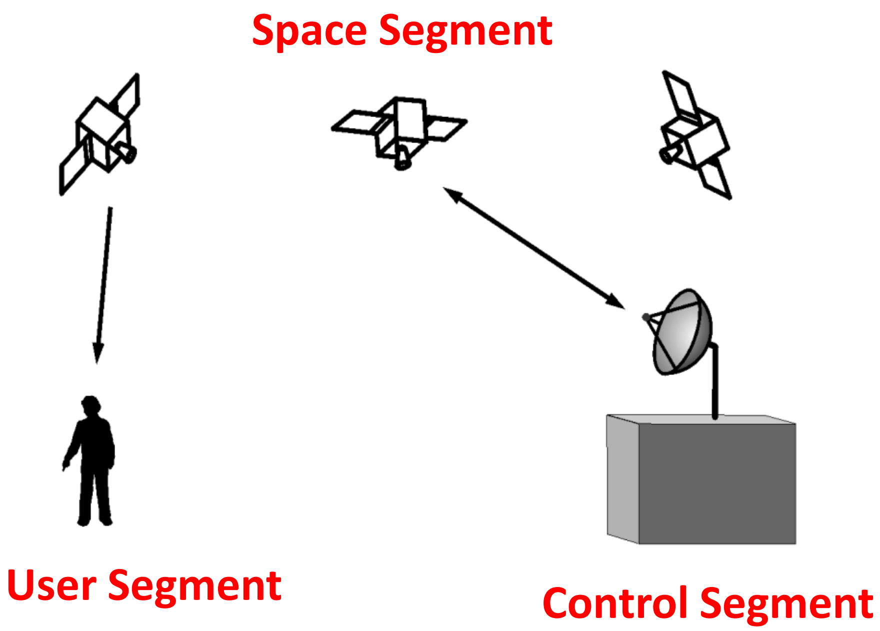
NAME	NORAD ID	INTL'CODE	LAUNCH DATE	STATUS
GALILEO-PFM	37846	2011-060A	2011-10-21	IN ORBIT
GALILEO 15 (267)	41859	2016-069A	2016-11-17	IN ORBIT
GALILEO 9 (205)	40889	2015-045A	2015-09-11	IN ORBIT
GALILEO-FM2	37847	2011-060B	2011-10-21	IN ORBIT
GALILEO 18 (26E)	41862	2016-069D	2016-11-17	IN ORBIT
GALILEO 10 (206)	40890	2015-045B	2015-09-11	IN ORBIT
GALILEO	20298	1989-084B	1989-10-18	DECAYED
GALILEO 20 (2C6)	43056	2017-079B	2017-12-12	IN ORBIT
GALILEO 14 (26B)	41549	2016-030A	2016-05-24	IN ORBIT
GALILEO 6 (262)	40129	2014-050B	2014-08-22	IN ORBIT
GALILEO 21 (2C7)	43057	2017-079C	2017-12-12	IN ORBIT
GALILEO 13 (26A)	41550	2016-030B	2016-05-24	IN ORBIT
GALILEO 5 (261)	40128	2014-050A	2014-08-22	IN ORBIT
GALILEO 19 (2C5)	43055	2017-079A	2017-12-12	IN ORBIT
GALILEO-FM3	38857	2012-055A	2012-10-12	IN ORBIT
GALILEO 17 (26D)	41861	2016-069C	2016-11-17	IN ORBIT
GALILEO 12 (269)	41174	2015-079A	2015-12-17	IN ORBIT
GALILEO 22 (2C8)	43058	2017-079D	2017-12-12	IN ORBIT
GALILEO-FM4	38858	2012-055B	2012-10-12	IN ORBIT

FEATURES OF NAVIGATION SATELLITES

1. Each satellite is equipped with devices that are used for navigation and other special tasks.
2. The satellite receives, stores, and processes transmitted information from a ground control centre.
3. To identify each satellite, the satellites have various identification systems such as
   a) the launched sequence number,
   b) the orbital position number,
   c) the system specific name.

COMPONENTS OF THE GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

- The GNSS consists of 3 main segments:
  1. **Space Segment:** the constellation of satellites
  2. **Control Segment:** operation and monitoring of the GNSSS System
  3. **User Segment:** all GNSSS receivers and processing software
- Sometimes a 4th segment is added, i.e
  - **Ground Segment:** permanent civilian networks of reference sites, associated analyses and archives



GNSS CONTROL SEGMENT

1. GNSS control segment is responsible for controlling the whole system including
   a) the deployment and maintenance of the system,
   b) tracking of the satellites in their orbits and the clock parameters
   c) upload of the data
   d) monitoring of auxiliary data
   e) data encryption
   f) service protection against unauthorized users.
2. Tracking stations located around the world coordinate the activities for controlling and monitoring the system using bidirectional communication between these stations and GNSS satellites

GNSS USER SEGMENT

- GNSS User segment consists of passive receivers able to decode received signals from satellites.
- Using these receivers is not associated with any fees.
- Civilians are not allowed to access GNSS military signals.
- Therefore, besides the special receivers designed for military applications, there is a diversity of GNSS receivers available on the market today.

WHAT IS GPS?

1. **The Global Position (ing) System (GPS)** is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations.
2. A GPS receiver uses signals from the satellites within the constellation as reference points to calculate positions accurate to a few meters.

GPS SIGNALS

1. **GPS satellites** transmit low power radio signals on multiple frequencies.
2. L1 and L2 were the basic carrier frequencies that contain the navigation signals, while L5 was added in the year 2021.
   a) **The L1 frequency is 1575.42 MHz (10.23 x 154):** It has two parts: the Coarse/Acquisition Code (C/A) and the Precision Code (P-code). The P-code was in the first decade reserved for military use, while the C/A was open to the public.
   b) **L2 frequency is 1227.6 (10.23 x 120) MHz:** The lower frequency allows the signal to penetrate better through obstacles such as cloud cover, trees, and buildings
   c) **L5 frequency is 1176 (10.23 x 115) MHz**
3. A receiver can identify the signals because each GPS satellite transmits a unique code using spread spectrum technology.

GENERATION OF GPS SIGNALS

1. Each GPS satellite transmits data on three frequencies, L1 (1,575.42 Mhz) and L2 (1,227.60 MHz) and L5(1,176 MHz).
2. The atomic clocks aboard the satellite produces the fundamental L-band frequency, 10.23 Mhz.
3. The carrier frequencies are generated by multiplying the fundamental frequency by 154, 120 and 115, respectively.
4. Two pseudorandom noise (PRN) codes, along with:
   a) Satellite ephemerides (satellite coordinates),
   b) Ionospheric modeling coefficients,
   c) Status information
   d) System time
   e) Satellite clock corrections

   are superimposed onto the carrier frequencies, L1, L2 and L5.

1. The measured travel times of the signals from the satellites to the receivers are used to compute the ranges (distance of each satellite from a receiver).

THE IONOSPHERE (RECAP)

1. The ionosphere is the ionized part of the Earth's upper atmosphere, located at altitudes from about 50 to 1000 km.
2. Major factors influencing the processes in the ionosphere:
   a) ultraviolet and X-ray radiation of the Sun,
   b) cosmic rays passing through the Earth's atmosphere
   c) the Earth's magnetic field
3. Ionization occurs mainly due to the solar activity, therefore there is a strong dependence of the ionospheric properties on position and time depending on
   a) Longitude, latitude and altitude above the Earth's surface,
   b) Day and night
   c) Time of a year
   d) Solar activity cycle phase

THE IONOSPHERE (RECAP)

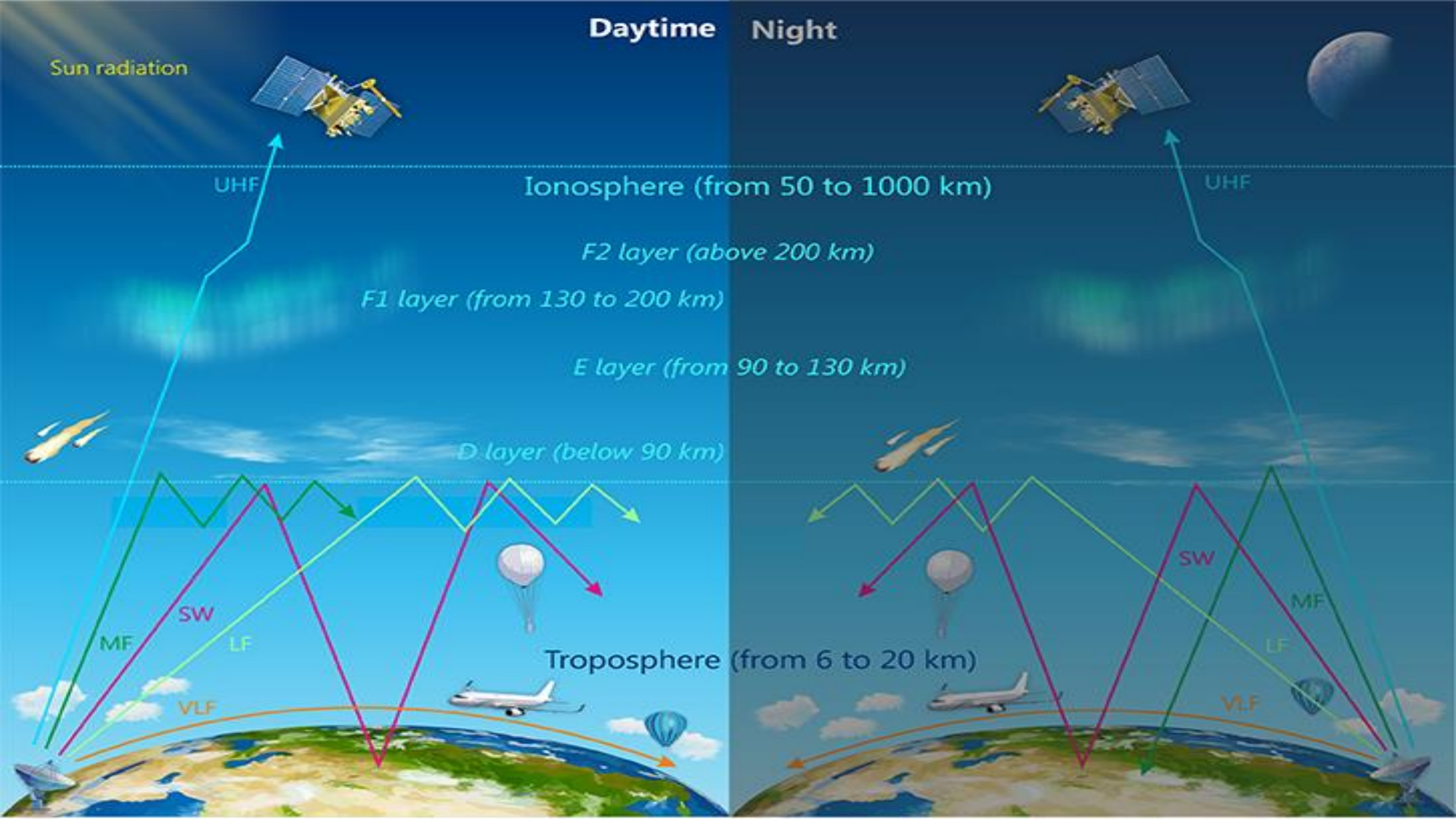
1. The state of ionosphere is described by several parameters including:
   a) Electron content in the ionosphere,
   b) Ionic composition, ionic and electron temperatures
   c) Particles velocity, etc.

2. The Ionosphere is widely studied because it affects radio wave propagation especially in MF (300 KHz – 3 MHz) and HF(3 MHz – 30 MHz) bands.

3. For global navigation satellite systems (GNSS), the key parameter is the **electron content in the ionosphere**, since it directly affects the radio waves propagation and causes an ionospheric delay in range measurements.

RECAP: IONOSPHERE LAYERS

1. Depending on the height and electron content distribution, the ionosphere is conventionally divided into layers:
    1. D (below 90 km)
    2. E (from 90 to 130 km)
    3. F1 (from 130 to 200 km)
    4. F2 (above 200 km).
2. The maximum ion and electron concentration is located in F2 layer at 250 – 450 km height.



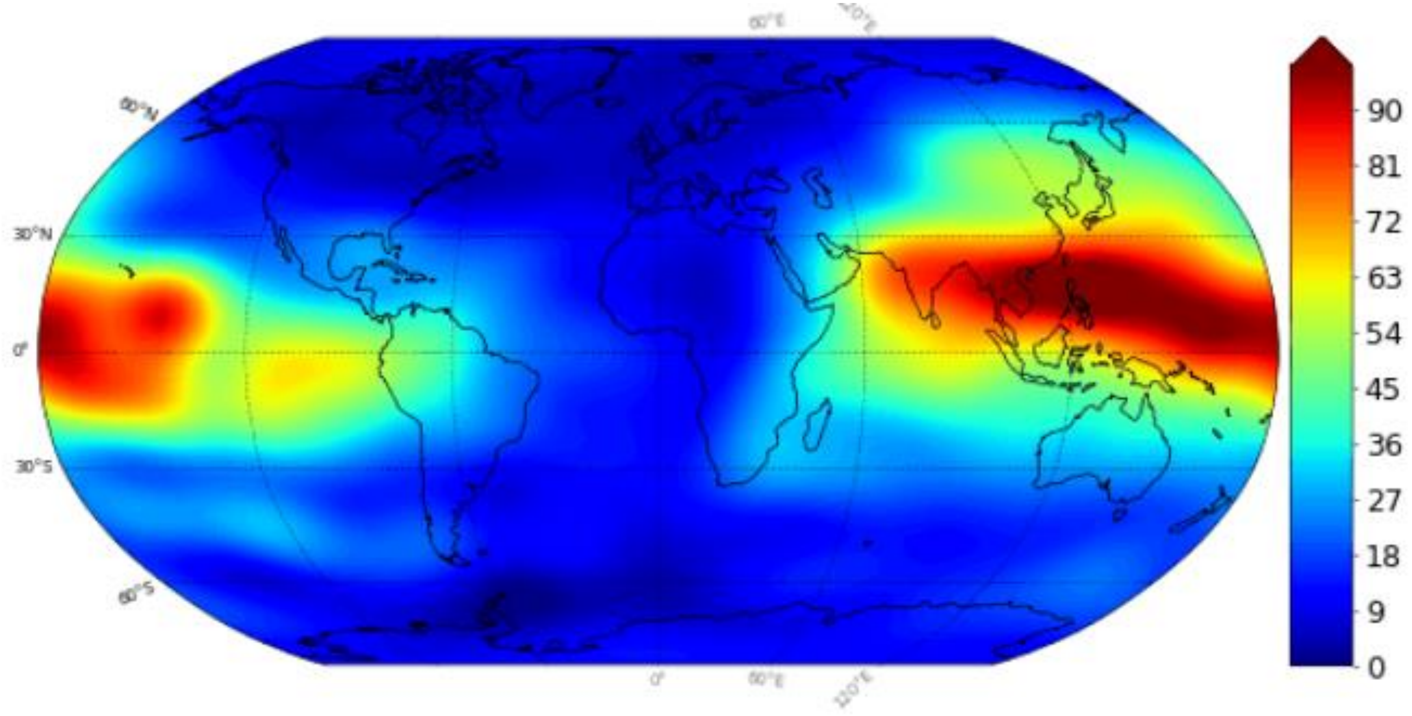
Daytime
Night
Sun radiation
UHF
Ionosphere (from 50 to 1000 km)
UHF
F2 layer (above 200 km)
F1 layer (from 130 to 200 km)
E layer (from 90 to 130 km)
D layer (below 90 km)
SW
MF
LF
SW
MF
LF
Troposphere (from 6 to 20 km)
VLF
VLF

IONOSPHERIC MODELS

1. Existing ionospheric models as applied for GNSS can be conventionally divided into two groups, i.e **Complex physical ionospheric) and (ii) Single-layer ionospheric models.**
   1. **Complex physical ionospheric models:** Based on physical laws of magnetic hydrodynamics and kinetic equations. They describe physical processes in the ionosphere, evaluate a variety of indicators and their spatial distribution. Uses the following:
      a) GNSS measurements
      b) Global ionosondes network
      c) Powerful incoherent scattering radars
      d) Satellite probes
      e) Individual measurements from various space vehicles.
   2. **Single-layer ionospheric models:** based on the assumption that all free electrons of the ionosphere are located in an infinitely thin layer at a certain height above the Earth's surface. The layer's height is selected from 350 to 450 km.

Further Reading: About the Earth's ionosphere (glonass-iac.ru)

IONOSPHERIC MAPS

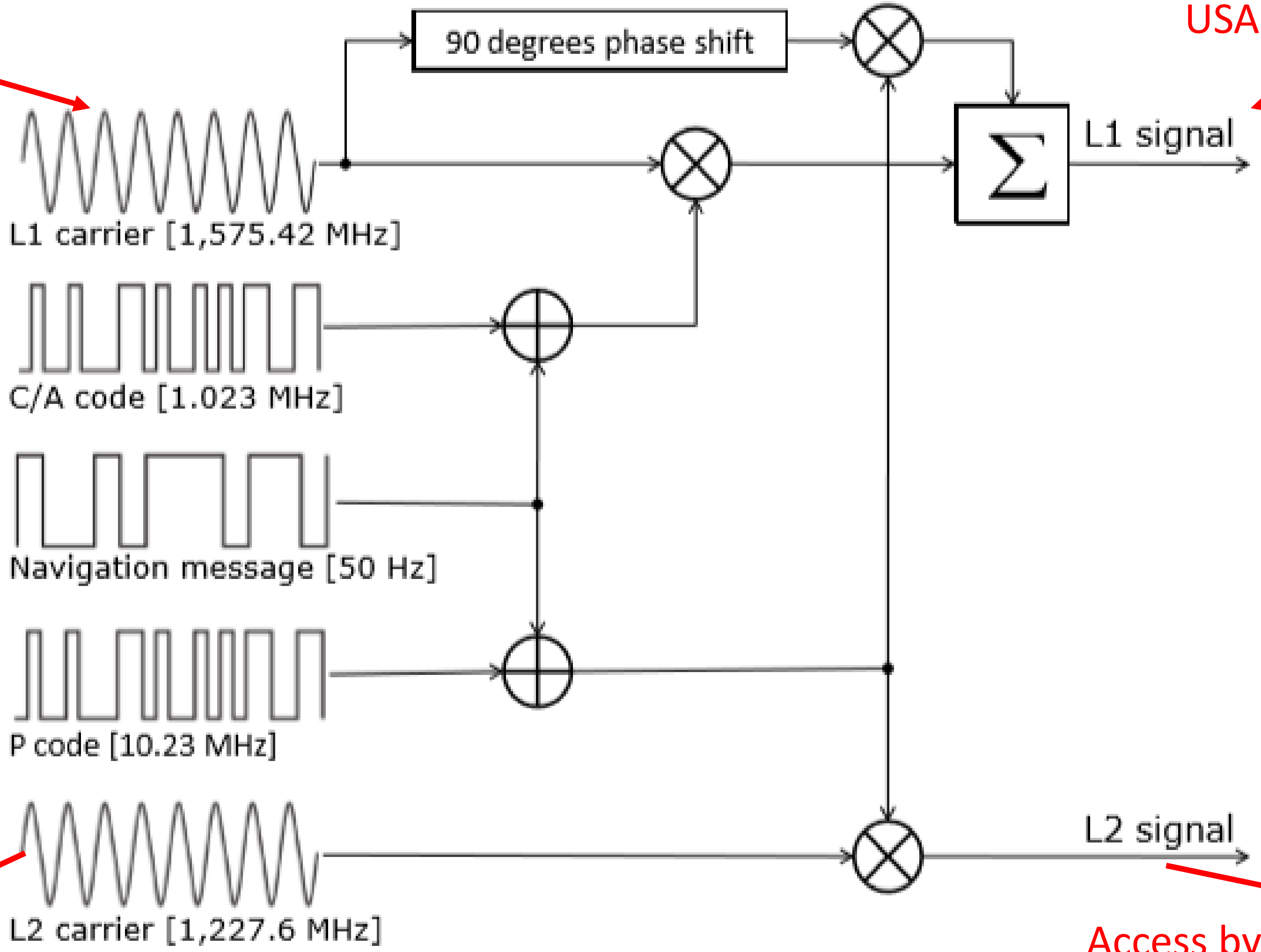


Further Reading:
Ionospheric maps (glonass-iac.ru)

GPS PILOT SIGNALS & CODES

Generated by 10.23 MHz x 154

Access by civilians and USA military



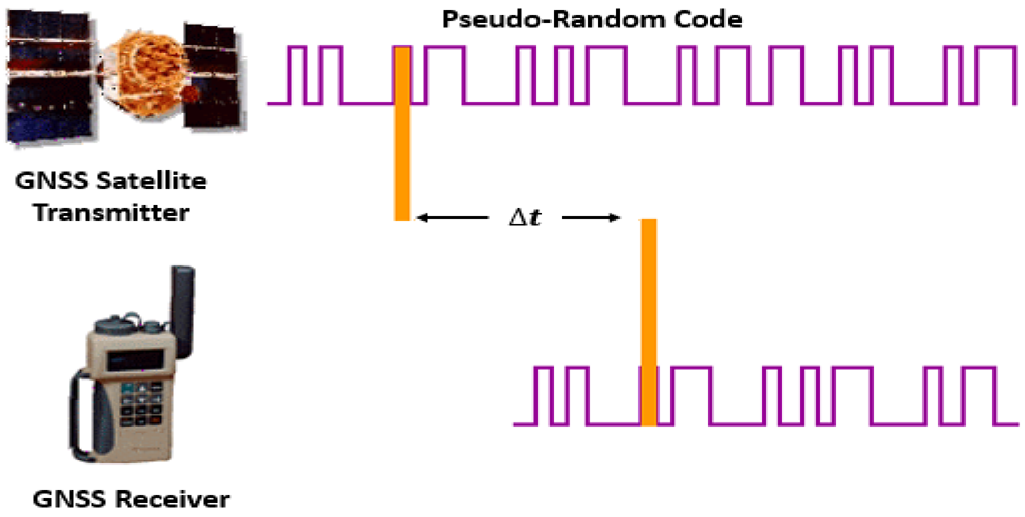
Generated by 10.23 MHz x 120

Access by USA government and military Only

SATELLITE RANGING

1. GNSS receivers calculate range from satellites much like the DME which we studied in radar engineering

$$\boldsymbol{R = c\Delta t}$$

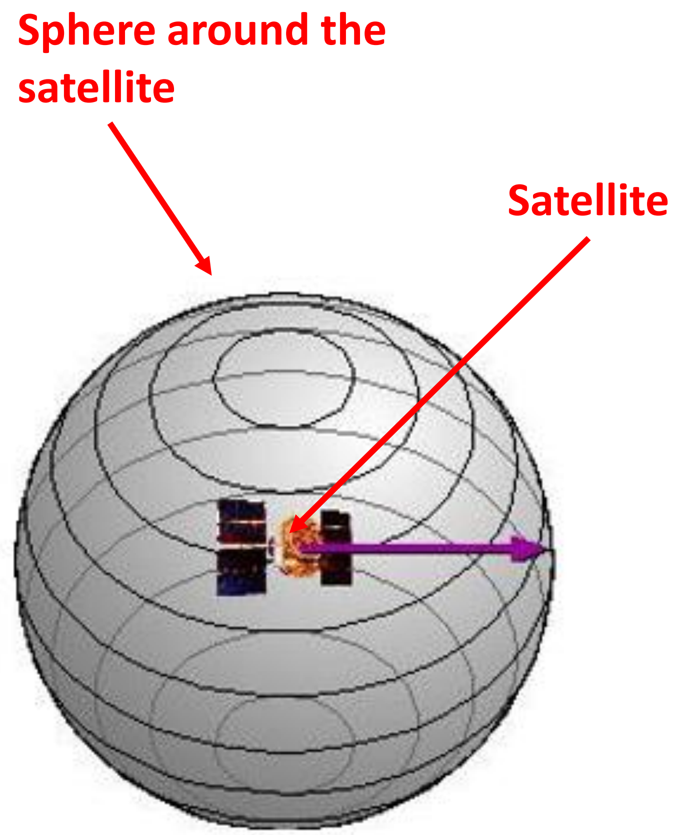


1. GNSS satellites are equipped with extremely accurate atomic clocks, so the timing of transmissions is always known.
2. GNSS receivers contain cheaper clocks, which tend to be sources of measurement error.

SATELLITE POSITIONING (1)

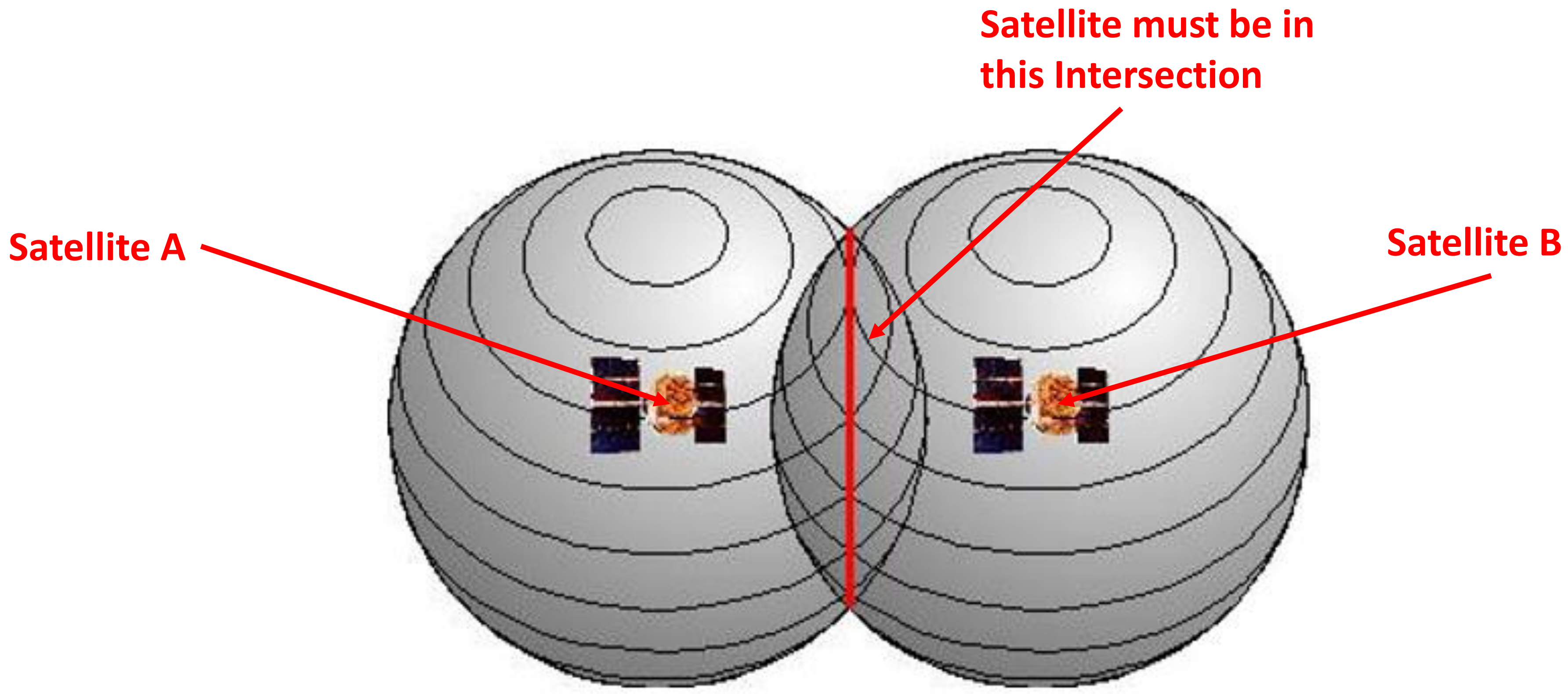
- The GPS constellation is configured so that a minimum of four satellites is always "in view" everywhere on Earth.

- If only one satellite signal was available to a receiver, the set of possible positions would include the entire range sphere surrounding the satellite.



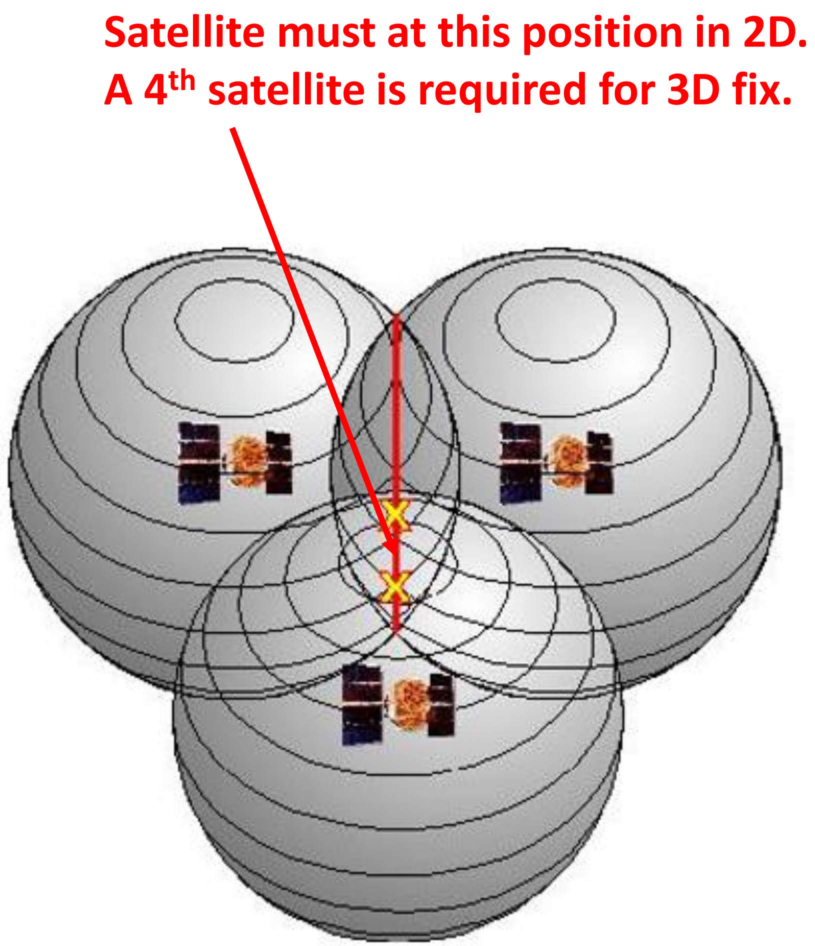
SATELLITE POSITIONING (2)

- If two satellites are in the GNSS, a receiver can tell that its position is somewhere along a circle formed by the intersection of two spherical ranges shown below.



SATELLITE POSITIONING (3)

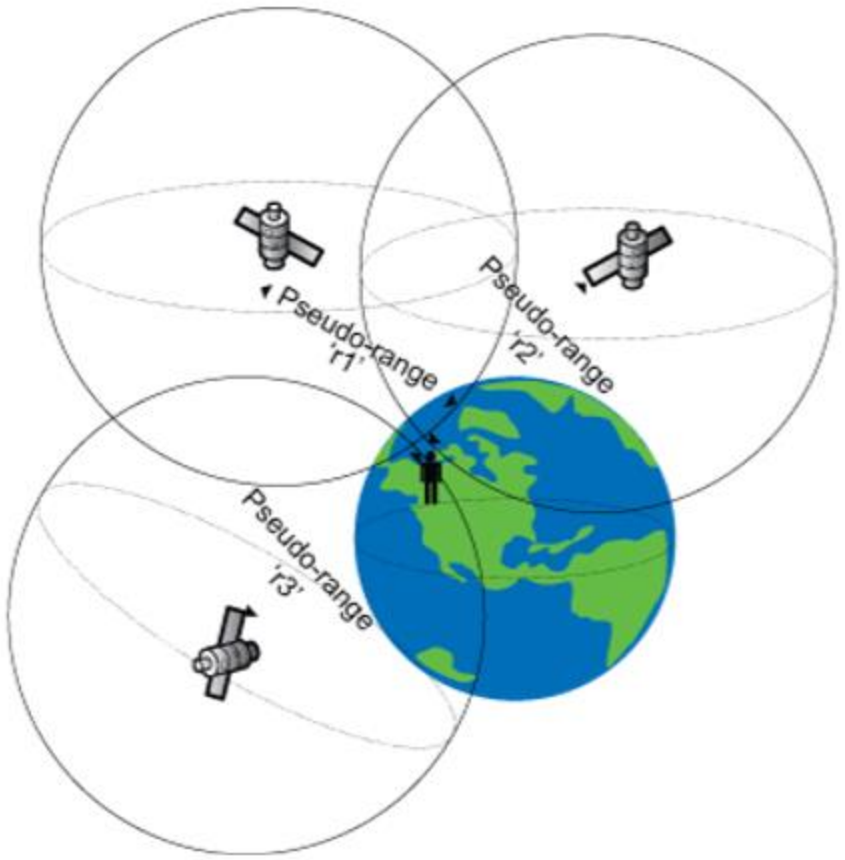
- If distances from **three GNSS** satellites are known, the receiver's position must be one of two points at the intersection of three spherical ranges.
- Three satellites are required for a two-dimensional (horizontal) fix.
- Four ranges are needed for a three-dimensional fix (horizontal and vertical).



HOW GNSS COMPUTES THE POSITION

- Three satellites are used to triangulate a position (longitude, latitude).

- A fourth satellite needs to be in line of sight to calculate height.



CONTENTS OF A GPS SIGNAL

1. A GPS signal contains a pseudorandom code, **ephemeris data** and **almanac data**.
   a) **Pseudorandom code** identifies the satellite that is transmitting information.
   b) **Ephemeris data** contains information about the status of the satellite (healthy or unhealthy), current date and time.
   c) **Almanac data** informs the receiver the coordinates of the satellite over a specified interval.

GENERAL DEFINITIONS

Ephemeris: A table or data file giving the calculated positions of a celestial object at regular intervals throughout a period.

Almanac: An annual calendar containing important dates and statistical information such as astronomical data

GPS SPACE SEGMENT

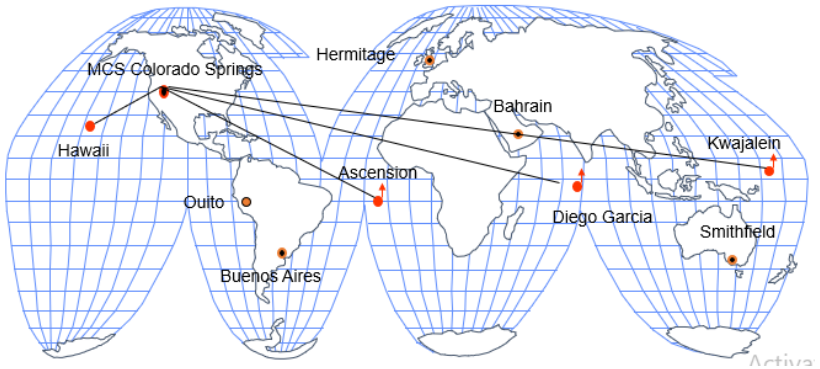
1. The space segment of GPS system consists of 24 active satellites in MEO at a median altitude of 20,200km above the earth.
2. The satellites are spaced in orbits to ensure that at any point of time there are usually a minimum 6 satellites in the receiver view.
3. Currently there are 31 operational GPS satellites plus 3 to 4 parked satellites that can be reactivated when it is needed

GPS SPACE SEGMENT - SUMMARY

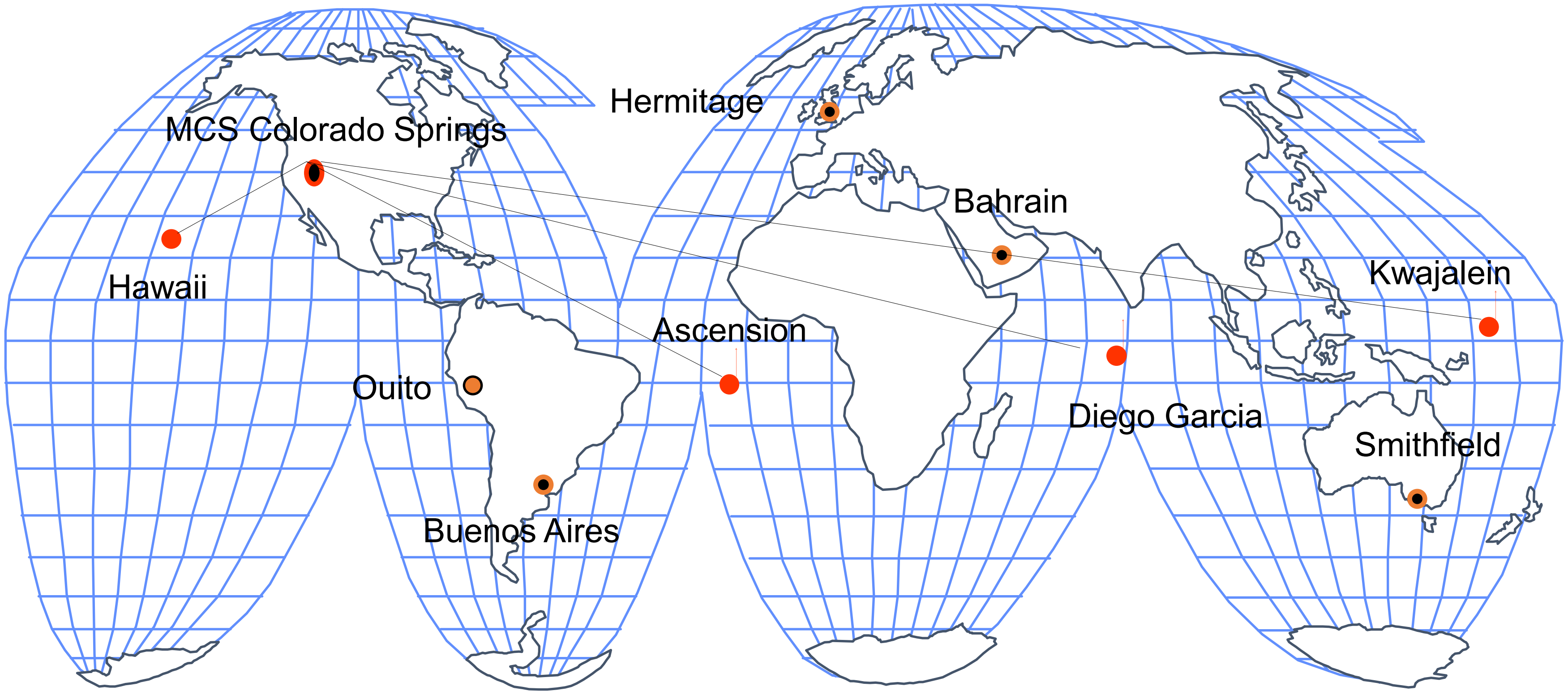
- **The space segments nominally consists of 24 satellites, currently:**
  - 28 (24+4 spares) active GPS satellites (26 Block II, 2 Block IIR)
  - Constellation design: at least 4 satellites in view from any location at any time to allow navigation (solution for 3 position + 1 station clock unknowns)
  - “Right Time, Right Place, Any Time, Any Place”
- **GPS Orbit characteristics:**
  - Semi-Major Axis (Radius): 26,600 km
  - Orbital Period : 11 h 58 min
  - Orbit Inclination: 55 degrees
  - Number of Orbit Planes: 6 (60 degree spacing)
  - Number of Satellites: 24 (4 spares)
  - Approximate Mass: 815 kg,
  - Life span 7.5 year
  - Data Rate (message): 50 bit/sec
  - PRN (Pseudo-Random Noise) Codes: Satellite-dependent Codes
  - Transmit, Frequencies L-Band L1: 1,575.42 MHz
    L2: 1,227.60 MHz
  - L5: 1,176 MHz

GPS CONTROL SEGMENT

- **GPS control segment** consists of a network of monitoring stations that are responsible for satellites' tracking, monitoring, and maintenance.
- **The master control station** is located in the state of Colorado, does the following:
    1. gets data from each of the monitoring stations, which are distributed around the world,
    2. determines both the data to be uploaded and the ground stations that will transmit this control data to the satellites.



GPS CONTROL SEGMENT (1)



US Airforce Tracking Sites

US Airforce Upload Sites

US NIMA Tracking Sites

MCS – Master Control Station

GPS USER SEGMENT

- The user segment consists of handset radio receivers that receive signals from GPS satellites available in the view.

- There are billions of receivers in use today including receivers in smart phones.

CLASS DISCUSSION

- Why factors led to setting the height of the GPS satellites at around 20,000 kms? Why not LEO or lower portions of MEO?

- The higher altitude, the more satellite footprint. With a 'constellation' of 30 active satellites, you can use the system pretty much anywhere on Earth.
- Satellites in higher orbits are not affected by the earth's gravitation forces and atmospheric drag. Hence, they require less orbital adjustments and have longer lifespan.
- However, higher orbits reduces the accuracy

- Lower orbits would need more satellites for global coverage
- Satellites in lower orbits are affected more by gravity and atmospheric drag hence require orbital adjustments and therefore have shorter lifespan.