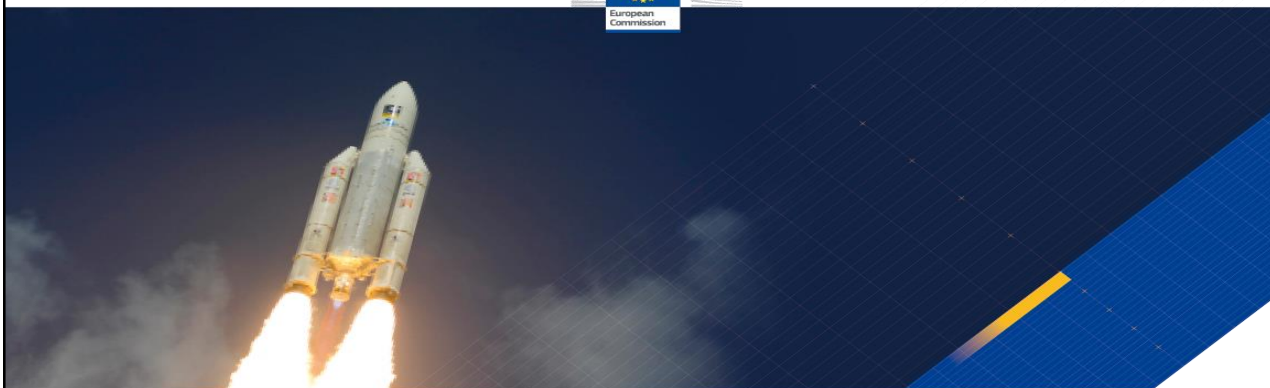

EGNSS CAPACITATION COURSE FOR UNAM

Part 1. Fundamentals of GNSS systems

Prepared by Ramón Martínez, Miguel A. Salas. ETSIT-UPM. 2022.

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Part 1. Fundamentals of GNSS systems

1. Operation of GNSS systems and applications
2. GNSS positioning basics
   - GNSS Observables
   - Range-based positioning
   - Pseudorange positioning
3. GNSS error sources
4. GNSS solution. Performance indicators
5. GNSS signals and spectrum
6. GNSS vulnerabilities
7. Orbits used in GNSS systems
8. Classification and description of satellite navigation systems
   - Global (GNSS)
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9. Position computing strategies in GNSS
10. Annexes
    - Spatial reference systems
    - Time reference systems

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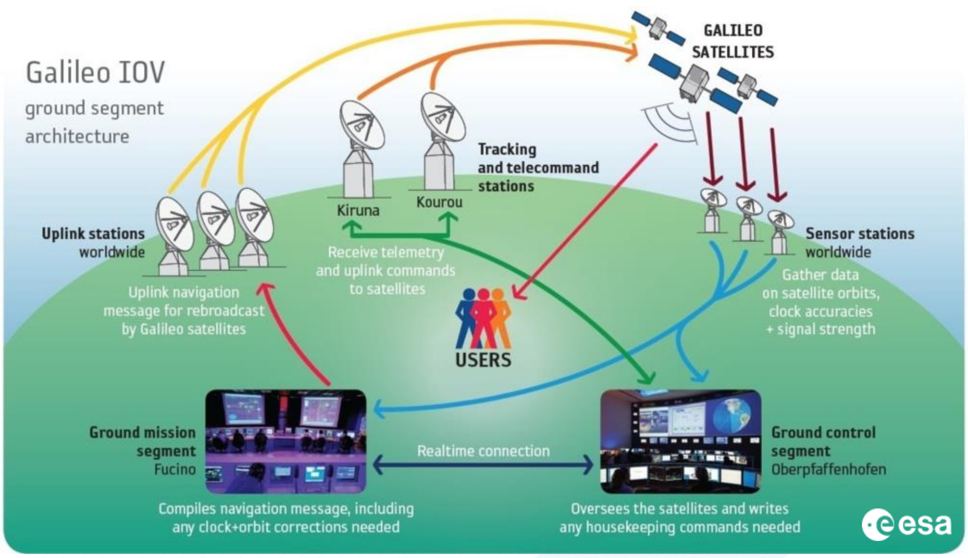
Part 1. Fundamentals of GNSS systems

Sources used to prepare the material

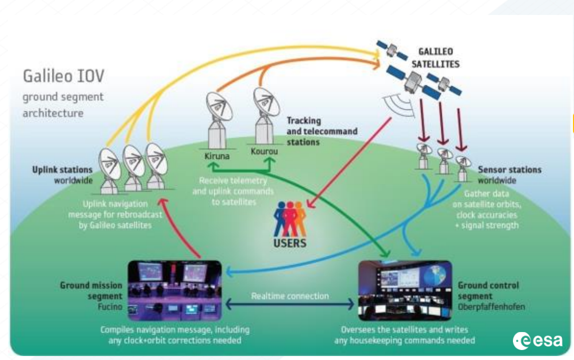
- ESA NAVIPEDIA
- Reference documents for GNSS systems (SIS ICD, SDD)
- EUSPA User and market technology reports
- J. Sanz, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data Processing Book. Vol 1: Fundamentals and algorithms, 2013.
- Peter J.G. Teunissen, Oliver Montenbruck, Eds., *Handbook of Global Navigation Satellite Systems*, Springer, 2017.
- Teaching material used in Master in Telecommunication Engineering of UPM
  - R. Martínez, M. Salas, Satellite communications course
  - R. Martínez, M. Salas, Communications systems course
- ANR017 GNSS Antenna Selection, v. 1.1., Würth Elektronik.
- Kai Borre, Dennis M. Akos, Nicolaj Bertelsen, Peter Rinder Søren, Holdt Jensen, *A Software-Defined GPS and Galileo Receiver A Single-Frequency Approach*, Springer, 2007.
- Additional materials used are included in the slides of the presentation.

General operation of GNSS positioning



GNSS. System architecture

- Un sistema GNSS está formado por **3 segmentos**:
  - **Segmento espacio**: constelación de satélites que generan las señales y los mensajes de navegación
  - **Segmento de control**: conjunto de estaciones terrenas que aseguran la operación del sistema GNSS
    - Monitorizan el estado de la constelación
    - Predicen las efemérides y evolución del reloj de los satélites
    - Mantienen el tiempo GNSS
    - Actualizan los mensajes de navegación
  - **Segmento de usuario**: receptores GNSS que determinan los observables a partir de las señales recibidas, y resuelven las ecuaciones de navegación para calcular la coordenadas del receptor y una estimación precisa del tiempo



GNSS Applications

GNSS MARKET SEGMENTS

- Consumer Solutions
- Road Transportation and Automotive
- Manned Aviation
- Maritime
- Rail
- Agriculture
- Geomatics
- Critical Infrastructures

EMERGING APPLICATIONS

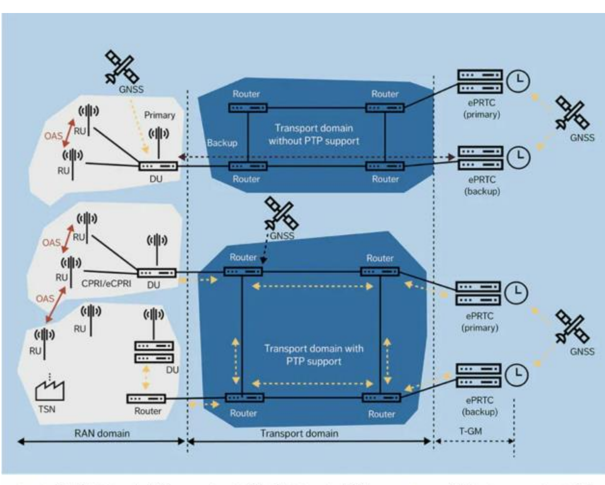
- Advanced timing services
- Emergency warning services
- Safety-critical and liability-critical transport
- Internet of Things
- Autonomous cars
- Drones and robots
- Precision agriculture
- Surveying
- Mining (open-pit mining)
- Aviation

FUTURE APPLICATIONS

- Common 3D Digital Map Concept
- Smartphones
- Navigation maps
- Augmented reality
- Autonomous Robotics
- Sports tracking

Integration of GNSS with other systems

Synchronizaton in 5G networks (Ericsson)



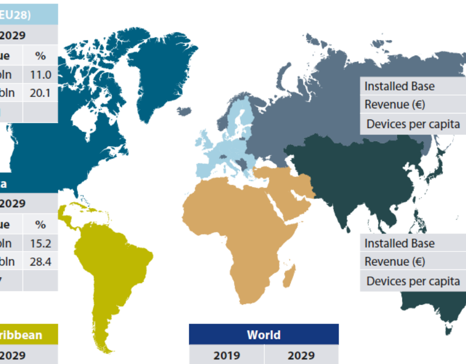
Integration with Earth Observation missions (Copernicus Program)

- **Copernicus (European Union's Earth Observation Programme)**: provides frequent and global images of land and its evolution (e.g., land fill and usage, urban areas, change detection)
- **EGNSS**: precise guidance to specific areas, location geo-tagging
- Synergies in:
  - Disaster management
  - Precision farming
  - Natural resources management
  - Smart mobility
  - …

GNSS Market

European Union (EU28)				
	2019		2029	
	Value	%	Value	%
Installed Base	0.7 bln	11.0	1.0 bln	11.0
Revenue (€)	38.4 bln	25.5	65.3 bln	20.1
Devices per capita	1.4		2.1	

Russia and Non-EU 28 (Non-EU28 Europe)				
	2019		2029	
	Value	%	Value	%
Installed Base	0.3 bln	4.0	0.3 bln	3.5
Revenue (€)	9.7 bln	6.4	16.3 bln	5.0
Devices per capita	1.1		1.5	



North America				
	2019		2029	
	Value	%	Value	%
Installed Base	1.0 bln	15.9	1.5 bln	15.2
Revenue (€)	40.3 bln	26.7	92.2 bln	28.4
Devices per capita	2.0		2.7	

Asia-Pacific				
	2019		2029	
	Value	%	Value	%
Installed Base	3.4 bln	53.2	5.1 bln	53.5
Revenue (€)	46.0 bln	30.5	106.0 bln	32.7
Devices per capita	0.8		1.1	

South America + Caribbean				
	2019		2029	
	Value	%	Value	%
Installed Base	0.6 bln	9.7	0.9 bln	9.3
Revenue (€)	8.1 bln	5.4	13.2 bln	4.1
Devices per capita	1.2		1.6	

World		
	2019	2029
	Value	Value
Installed Base	6.4 bln	9.5 bln
Revenue (€)	150.7 bln	324.4 bln
Devices per capita	0.8	1.1

Middle East + Africa				
	2019		2029	
	Value	%	Value	%
Installed Base	0.4 bln	6.3	0.7 bln	7.5
Revenue (€)	8.2 bln	5.4	31.4 bln	9.7
Devices per capita	0.2		0.4	

Source: GNSS Market Report, EUSPA, 2019.

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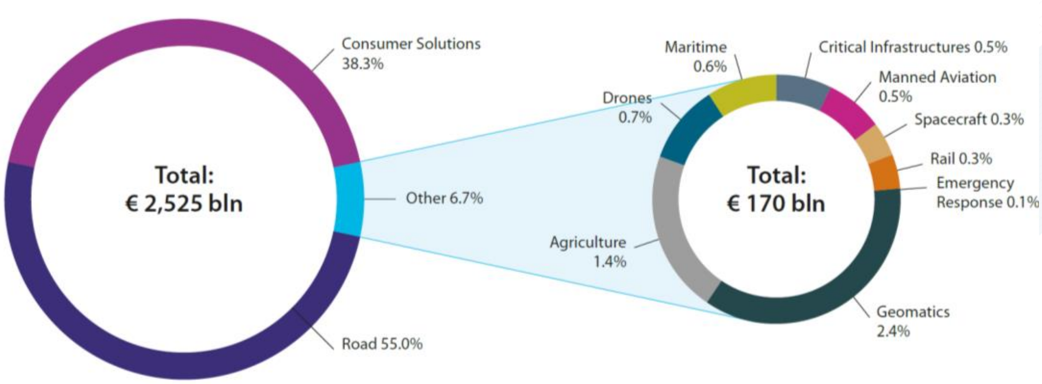
GNSS Market

2019: €150 bln to €325 bln in 2029 with a CAGR of 8%.

Cumulative Revenue 2019-2029 by segment



Source: GNSS Market Report, EUSPA, 2019.

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Part 1. Fundamentals of GNSS systems

GNSS. Positioning principles and basic observables

- The positioning principle is based on solving an elemental geometrical problem (*intersection of spheres*) involving the distances (*ranges*) of a user (receiver) to a set of at least four GNSS satellites with known coordinates.
- The *basic* observable in a GNSS system is the time required for a signal to travel from the satellite (transmitter) to the receiver. This travelling time, multiplied by the speed of light, provides a measure of the apparent distance (*pseudorange*) between them.
- The observables used to calculate the position, velocity or clock offset of the receiver are obtained from 3 observables that can be computed from the received signal transmitted by the GNSS satellites

Pseudorange | **Carrier-phase** | **Doppler-shift**

GNSS. Positioning principles and basic observables

Geometrical interpretation

- Each range defines a sphere with the satellite in its center
- To resolve 4 unknown parameters (x, y, z of the receiver, and ΔT as clock offset) and calculate the position, the measurement of ranges to four different satellites is required
- Receiver clock offset (ΔT): the 3 spheres do not intersect in a single point. Hence ΔT constitutes a new variable to be determined

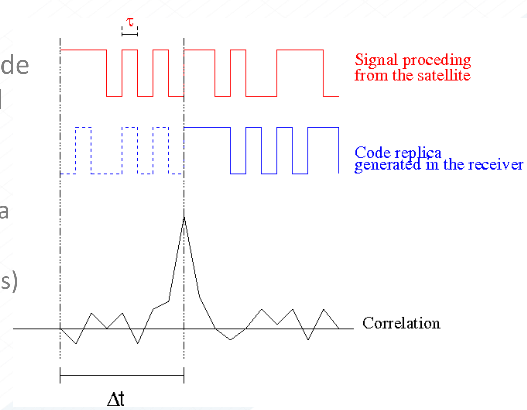
Source: EGNOS ESSP

GNSS observables

- GNSS signals enable the measurement of 3 observables: pseudorango, fase de la portadora y desviación Doppler
- **Pseudorange** (*pseudorango*): distancia satélite-estación medida a partir del tiempo de propagación de la señal desde el centro de fase de la antena satelital asumiendo que no hubiera errores en los relojes

$$D = c\Delta t$$

  - Se obtiene correlando la señal recibida con una réplica local del código del satélite
  - La precisión es reducida (en el rango de los decímetros)
  - Si los relojes del satélite y el receptor estuvieran sincronizados, el pseudorango sería la distancia real entre ambos



Source: Navipedia

GNSS observables

- **Carrier phase** (*fase de la portadora*): medida de la distancia aparente satélite-estación, que incluye ambigüedades (múltiplos de la longitud de onda)
  - Se mide mezclando la señal recibida con una réplica local a la frecuencia portadora nominal
  - Dos órdenes de magnitud más precisa que el pseudorango
- **Doppler** (*desviación Doppler*): la desviación en la frecuencia portadora recibida indica la variación de la distancia estación-satélite a lo largo del tiempo (*range-rate*)
  - Informa de la velocidad relativa o *range-rate* entre el satélite y el receptor
  - Afectado por el error en la frecuencia del receptor

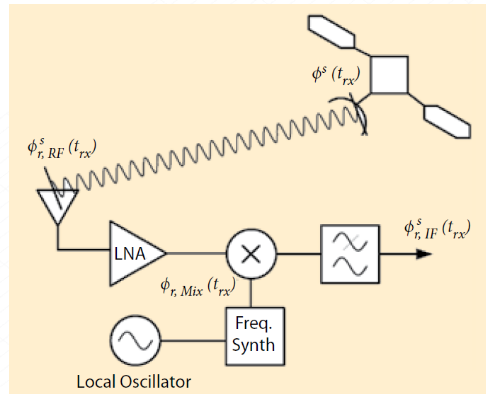
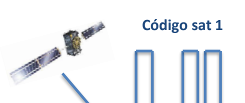


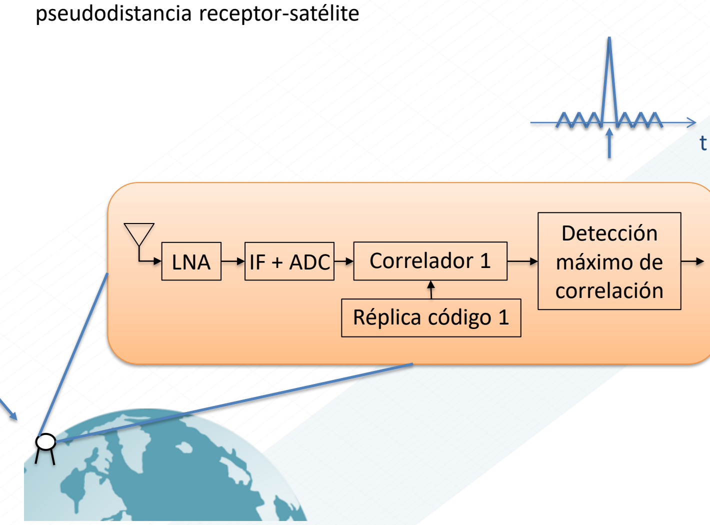
FIGURE 1 Signal phase from transmission through downconversion to intermediate frequency. At each point the signal is assumed to be a sinusoid, the phase of which is indicated in text in the figure.

Source: Adapted from InsideGNSS.

Code based positioning (SPS)

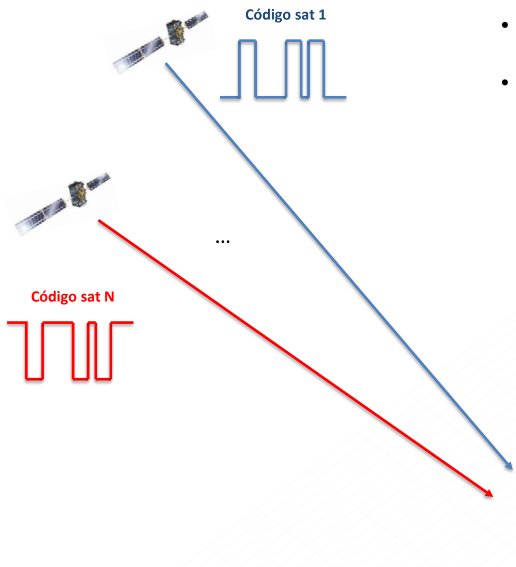


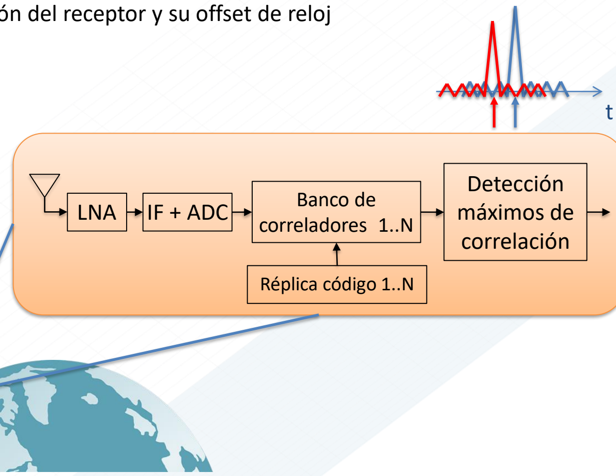
- El receptor busca el inicio de la señal transmitida por el satélite a través de un proceso de correlación
- Esta marca de tiempo informa sobre la pseudodistancia receptor-satélite



Code based positioning (SPS)

- El receptor busca el inicio de las señales transmitidas por los satélites visibles a través de un proceso de correlación
- Las marcas de tiempo donde se alcanza el máximo de correlación informan de las pseudodistancias receptor-satélites
- Con un número suficiente de satélites puede obtenerse la posición del receptor y su offset de reloj





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Range-based positioning (1)

- La medida básica realizada por un receptor GNSS es el tiempo que tarda la señal en recorrer la distancia satélite-receptor (τ_r^s)
- La distancia al satélite en el instante t, $\rho_r^s(t)$, se obtiene multiplicando por la velocidad de propagación de la luz en el vacío c

$$\rho_r^s(t) = c\tau_r^s$$

- **<u>Condiciones ideales</u>**: si los relojes de satélite y receptor están sincronizados, y en ausencia de errores producidos por ionosfera y troposfera, sin ruido de medida, entonces:

$$\rho_r^s(t) = \|\boldsymbol{r}_r(t) - \boldsymbol{r}^s(t)\| =$$
$$= \sqrt{(x_r(t) - x^s(t))^2 + (y_r(t) - y^s(t))^2 + (z_r(t) - z^s(t))^2}$$

- Donde
  - $\boldsymbol{r}^s = (x^s, y^s, z^s)^T$: coordenadas del satélite (**conocida**)
  - $\boldsymbol{r}_r = (x_r, y_r, z_r)^T$: coordenadas del receptor (**incógnita**)

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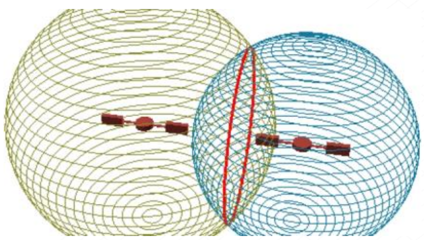
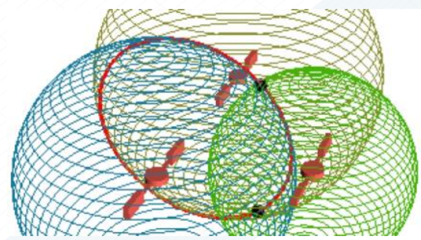
Range-based positioning (2)

- Con **1** satélite, la posición del receptor se encuentra en una esfera de radio ρ_r^1
- Con **2** satélites, la posición del receptor está en el círculo resultante de la intersección de las dos esferas de radios ρ_r^1 y ρ_r^2
- Con **3** satélites, la posición del receptor está en uno de los dos puntos resultantes de la intersección de las tres esferas de radios ρ_r^1, ρ_r^2 y ρ_r^3
- La posición del receptor se estima con tres medidas descartando el punto más alejado de la superficie terrestre





Source: James Simat

Range-based positioning (3)

- La posición del receptor $(x_r(t), y_r(t), z_r(t))$ debe cumplir simultáneamente el siguiente conjunto de ecuaciones:

$$\rho_r^1(t) = \|\mathbf{r}_r(t) - \mathbf{r}^1(t)\| = \sqrt{(x_r(t) - x^1(t))^2 + (y_r(t) - y^1(t))^2 + (z_r(t) - z^1(t))^2}$$
$$\rho_r^2(t) = \|\mathbf{r}_r(t) - \mathbf{r}^2(t)\| = \sqrt{(x_r(t) - x^2(t))^2 + (y_r(t) - y^2(t))^2 + (z_r(t) - z^2(t))^2}$$
$$\rho_r^3(t) = \|\mathbf{r}_r(t) - \mathbf{r}^3(t)\| = \sqrt{(x_r(t) - x^3(t))^2 + (y_r(t) - y^3(t))^2 + (z_r(t) - z^3(t))^2}$$

- La resolución se realiza linearizando el problema e iterando.
- En notación matricial, se pueden expresar las ecuaciones de rango como $\boldsymbol{p} = [\rho_r^1, \rho_r^2, \rho_r^3]^T$ y:

$$\boldsymbol{p} = \boldsymbol{p_0} + A\Delta\boldsymbol{x}$$

- Donde $\boldsymbol{p_0}$ es la solución calculada a partir de unas coordenadas del satélite $(x^i, y^i, z^i), i = 1, 2, 3$ y una estimación inicial de la posición del receptor $\boldsymbol{x}_0 = (x_r(0), y_r(0), z_r(0))^T = (x_{r,0}, y_{r,0}, z_{r,0})^T$

Range-based positioning (4)

- Además $\boldsymbol{A}$ es la matriz de diseño (3×3):

$$\boldsymbol{A} = \begin{pmatrix} \frac{\partial \rho_r^1}{\partial x_r} & \frac{\partial \rho_r^1}{\partial y_r} & \frac{\partial \rho_r^1}{\partial z_r} \\ \frac{\partial \rho_r^2}{\partial x_r} & \frac{\partial \rho_r^2}{\partial y_r} & \frac{\partial \rho_r^2}{\partial z_r} \\ \frac{\partial \rho_r^3}{\partial x_r} & \frac{\partial \rho_r^3}{\partial y_r} & \frac{\partial \rho_r^3}{\partial z_r} \end{pmatrix} \quad , \quad \frac{\partial \rho_r^1}{\partial x_r} = \frac{x_{r,0} - x^i}{\rho_{t,0}^i}, (i = 1,2,3)$$

- Y $\Delta \boldsymbol{x}$ representa la variación del vector de coordenadas del receptor que debe ser estimado:

$$\Delta \boldsymbol{x} = \boldsymbol{x} - \boldsymbol{x_0}$$

- Resolviendo para obtener Δx se obtiene:

$$\Delta \boldsymbol{x} = \boldsymbol{A}^{-1}(\boldsymbol{p} - \boldsymbol{p_0}) = \boldsymbol{A}^{-1}\Delta \boldsymbol{p} \quad \rightarrow \quad \boldsymbol{x} = \boldsymbol{x_0} + \Delta \boldsymbol{x}$$

- El número de iteraciones para obtener $\boldsymbol{x}$ depende de la diferencia entre las medidas $\boldsymbol{p}$ y la estimación inicial de los pseudorangos $\boldsymbol{p_0}$

Pseudorange positioning (1)

- No puede asumirse que los relojes de satélite y receptor GNSS no están sincronizados
- Por otro lado, los relojes de los satélites están sincronizados entre sí usando un tiempo de sistema, que asegura un error inferior a 1 mseg
- Por ello, las medidas de distancia del receptor que tienen un error de tiempo, por lo que se denominan **pseudorangos**:

$$p_r^s = \rho_r^s + c(dt_r - dt^s)$$

- Donde:
  - p_r^s: pseudorango entre el satélite y el receptor
  - ρ_r^s: distancia (rango) entre el satélite y el receptor
  - c: velocidad de la luz en el vació
  - dt_r: offset del reloj del receptor respecto del sistema de tiempo GNSS
  - dt^s: offset del reloj del satélite respecto del sistema de tiempo GNSS
- Un error en los relojes de 1 mseg supondría un error de posición de 300 km

Pseudorange positioning (2)

- Error en el reloj de los satélite (dt^s):
  - El operador GNSS monitoriza los relojes a bordo y determinan offsets y derivas respecto del tiempo de sistema
  - En lugar de enviar correcciones al propio reloj, se transmiten al satélite como parte del mensaje de navegación que se difunde
  - El receptor GNSS lee esta información y la usa para corregir el término dt^s
- Error de reloj en el receptor (dt_r):
  - Imposibilita que las esferas de los tres satélites se intersecten en un punto
  - La zona de incertidumbre depende de la posición relativa de los satélites
  - Por tanto, dt_r se introduce como un cuarto parámetro a estimar en la ecuación de los pseudorangos:

$$p_r^s = \rho_r^s + cdt_r$$

Pseudorange positioning (3)

- Necesitamos, por ello, 4 pseudorangos simultáneos para obtener las 3 coordenadas del receptor y el offset del reloj del receptor
- Considerando que el vector de incógnitas es $\boldsymbol{x} = (x_r, y_r, z_r, dt_r)$, la matriz de diseño $\boldsymbol{A}$ (4×4) es:

$$\boldsymbol{A} = \begin{pmatrix} \frac{\partial \rho_r^1}{\partial x_r} & \frac{\partial \rho_r^1}{\partial y_r} & \frac{\partial \rho_r^1}{\partial z_r} & 1 \\ \frac{\partial \rho_r^2}{\partial x_r} & \frac{\partial \rho_r^2}{\partial y_r} & \frac{\partial \rho_r^2}{\partial z_r} & 1 \\ \frac{\partial \rho_r^3}{\partial x_r} & \frac{\partial \rho_r^3}{\partial y_r} & \frac{\partial \rho_r^3}{\partial z_r} & 1 \\ \frac{\partial \rho_r^3}{\partial x_r} & \frac{\partial \rho_r^3}{\partial x_r} & \frac{\partial \rho_r^3}{\partial x_r} & 1 \end{pmatrix} \quad , \quad \frac{\partial \rho_r^1}{\partial x_r} = \frac{x_{r,0} - x^i}{\rho_{t,0}^i}, (i = 1,2,3,4)$$

$$\Delta \boldsymbol{x} = \boldsymbol{x} - \boldsymbol{x_0}$$

$$\Delta \boldsymbol{x} = \boldsymbol{A}^{-1}(\boldsymbol{p} - \boldsymbol{p_0}) = \boldsymbol{A}^{-1}\Delta \boldsymbol{p} \quad \rightarrow \quad \boldsymbol{x} = \boldsymbol{x_0} + \Delta \boldsymbol{x}$$

Pseudorange positioning (4)

- Si se dispone de señales de más de 4 satélites, deben usarse la señales de los m satélites disponibles para encontrar las coordenadas del receptor y offset del reloj para hacer frente a otros errores residuales o difíciles de modelar (como los atmosféricos)
- Se requiere un procedimiento de resolución de tipo ***non-linear least squares***:

$$\Delta \boldsymbol{x} = (\boldsymbol{A}^{\intercal}\boldsymbol{W}\boldsymbol{A})^{-1}\boldsymbol{A}^{\intercal}\boldsymbol{W}\Delta \boldsymbol{p}$$

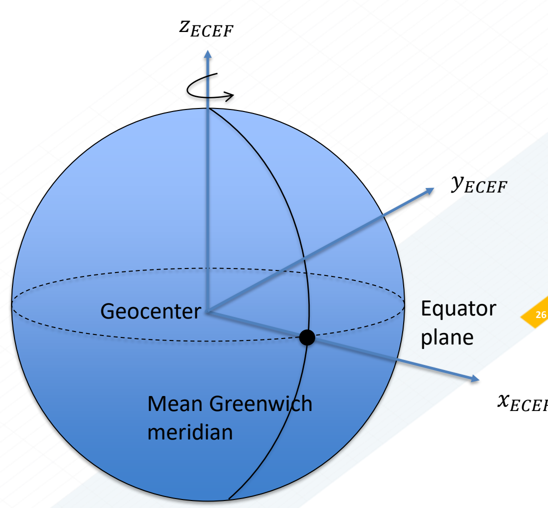
  – $\boldsymbol{A}$: Matriz de tamaño $m \times 4$
  – $\boldsymbol{W}$: matriz de ponderación que refleja la incertidumbre de las observaciones y las osibes correlaciones que pudiera haber entre ellas. Se puede modelar a partir de la matriz de covarianza de los errores de los pseudorangos $\boldsymbol{Q}_{pp}$:

$$\boldsymbol{W} = \boldsymbol{Q}_{pp}^{-1}$$

- La solución con más de 4 satélites debe realizarse de forma iterativa
- El procesado de las medidas puede hacerse en tiempo real o se pueden almacenar para postprocesado en ordenador

Sistemas de coordenadas. ECEF

- Las coordenadas cartesianas del satélite y receptor deben expresarse en un sistema de referencia
- Se usan sistemas de referencia celestial o terrestre
- Como sistema de referencia terrestre se usa el ECEF (Earth-Centered, Earth Fixed):
  – Origen: centro de la Tierra
  – Eje z: eje de rotación terrestre
  – Eje x: une el centro de la tierra con la intersección del plano equatorial y el mean Greenwich meridian



Ecuaciones de observación de GNSS. Pseudorango

- Si incorporamos todas las fuentes de error en la ecuación de pseudorango, **la ecuación de observación del pseudorango** puede expresarse como:

$$p_r^s = \rho_r^s + c(dt_r - dt^s) + T_r^s + I_r^s + e_r^s$$

  - p_r^s: pseudorango entre el satélite y el receptor
  - ρ_r^s: distancia (rango) entre el satélite y el receptor
  - c: velocidad de la luz en el vació
  - dt_r: offset del reloj del receptor respecto del sistema de tiempo GNSS
  - dt^s: offset del reloj del satélite respecto del sistema de tiempo GNSS
  - T_r^s: Retardo de propagación en la troposfera
  - I_r^s: Retardo de propagación en la ionosfera
  - e_r^s: Errores debido a multitrayecto, ruido en el receptor y otros efectos (efectos relativistas, etc.)

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Ecuaciones de observación de GNSS. Carrier-phase

- Si incorporamos todas las fuentes de error en la ecuación de observación, **la ecuación de observación de la fase de la portadora** puede expresarse como:

$$\varphi_r^s = \rho_r^s + c(dt_r - dt^s) + T_r^s - I_r^s + \lambda M_r^s + \epsilon_r^s$$

  - p_r^s: pseudorango entre el satélite y el receptor
  - ρ_r^s: distancia (rango) entre el satélite y el receptor
  - c: velocidad de la luz en el vació
  - dt_r: offset del reloj del receptor respecto del sistema de tiempo GNSS
  - dt^s: offset del reloj del satélite respecto del sistema de tiempo GNSS
  - T_r^s: Retardo de propagación en la troposfera
  - I_r^s: Retardo de propagación en la ionosfera
  - $M_r^s = N_r^s + \delta_r - \delta^s$: suma de la ambigüedad de la fase de la portadora en ciclos (N_r^s) y los errores instrumentales de receptor y satélite medido en ciclos ($\delta_r - \delta^s$)
  - λ: longitud de onda de la portadora
  - ϵ_r^s: Errores de fase debido a multitrayecto, ruido en el receptor y otros efectos

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10. Annexes
   - Spatial reference systems
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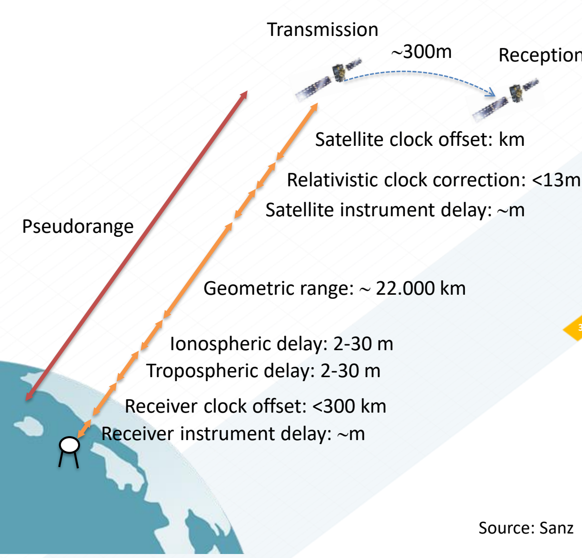
GNSS error sources

- There are diverse error sources that affect GNSS signal and the ranging accuracy
- Main effects are located on:
  - System (clock offsets, satellite ephemeris)
  - Atmosphere (ionosphere, troposphere)
  - Signal quality and level (multipath, blockage)
- These sources can be modelled to correct the errors in order to improve accuracy



Source: Sanz

GNSS error sources. Satellite clock and ephemeris

- **Clock errors**: appear when the satellite clock suffers a fault that leads to changes in the timing of the transmitted signal
  - Clock stability
  - Relativistic effects
- **Ephemeris errors**: occur when the navigation mesage contains wrong information of the satellite orbit (for example, if the ephemeris info is not updated after a satellite maneouver)
- Produce pseudorange errors
- Mitigation in GNSS:
  - Clock: downloading accurate information on the clock to the control segment to
  - Ephemeris: uploading precise ephemeris obtained from a ground station network and reducing the time to update navigation message
- Both errors can be corrected using Precise Point Positioning (PPP)

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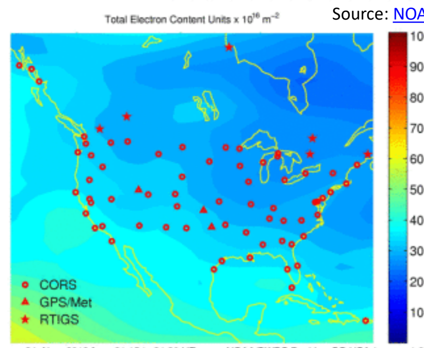
GNSS error sources. Atmospheric effects. Ionosphere

- **Ionosphere**: 3D distribution of electrons between 100 and 1000 km
- It is a dispersive media that produces refraction of the GNSS signals
- Total Electron Content (TEC) density changes along the day and depends on the Sun cycle
- Mitigation in GNSS:
  - SF receivers: rx applies a prediction model to compensate the error (Models: Klobuchar, NeQuikG)
  - DF receivers: correction up to 99.9% as refraction depends on the square inverse of the frequency

Source: NOAA



- Ionospheric delay can be approximated by:

$$I = \frac{40.3 \cdot TEC}{f^2}$$

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GNSS error sources. Atmospheric effects. Troposphere

- **Troposphere**: layer at an altitude of 60 km
- Delay depends on temperature, pressure, humidiy and location of trasmitter and receiver
- Signa is refracted in the troposphere introducing and additional delay (lower than ionospheric delay)
- Non-dispersive media (effects do not depend on frequency)
- Mitigation in GNSS: use models (Sastamoinen model, Hopfield model, TropGrid model (ESA)) and/or to estimate delay from empirical data

- Tropospheric delay (Collins' model):

$$T(E) = (T_{z,dry} + T_{z,wet})M(E)$$

  - E: elevation ($E > 5\ deg$)
  - $T_{z,dry}$: Hydrostatic component delay is caused by the dry gases
  - $T_{z,wet}$: Wet component delay caused by the water vapour and condensed water in form of clouds (it depends on weather)
  - $M(E)$: obliquity factor

$$M(E) = \frac{1.001}{\sqrt{0.002001 + sin^2(E)}}$$

Source: Navipedia

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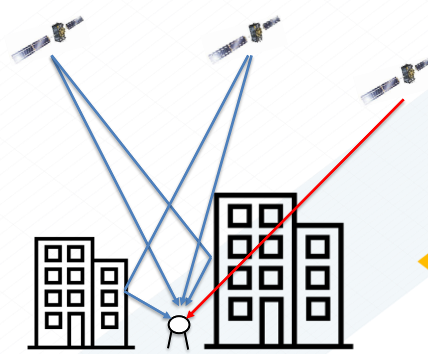
GNSS error sources. Multipath and blockage

- **Multipath**: different copies of the signal transmitted from the satellite reaches the receiver
- These copies are combined in the receiver and the quality of the signal is worsened
- Echoes comes from reflection in objects in the surrounding of the receive antenna
- **Blockage**: a neighbour object blocks the signal
- Blockage reduces the received signal power compromising the detection of the satellite in the receiver
- Both effects reduce the positioning accuracy
- Mitigation in GNSS: use antennas with very low gain at elevations close to horizon and signal processing techniques



Multipath and blockage in urban environment

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GNSS error sources. Other error sources

- Receiver noise:
  - Due to the noise introduced by system components such as the antenna, cables, and amplifiers, and signal quantization noise
  - It cannot be avoided completely
  - Affects the signal processing process required to decode the navigation message
- Instrumental delay: produced by cables, antennas and filters used in the satellite and in the receiver
  - Affect both code and carrier measurements
- Variation of the antenna phase center (APC) with angles (elevation and azimuth) and frequency
  - APC does not coincide with the physical center of the antenna
  - Critical when the highest precisión is required (PPP)
- Intentional error sources such as interferences and jamming affect system performances

Part 1. Fundamentals of GNSS systems

Precisión de las soluciones de posición

- La precisión de las coordenadas del receptor y offset de reloj (Δx) depende de la matriz de covarianza de la solución obtenida Q_{xx}

$$Q_{xx} = \left[(A^{\top}WA)^{-1}A^{\top}W\right]Q_{xx}\left[(A^{\top}WA)^{-1}A^{\top}W\right]^{\top} = \left(A^{\top}Q_{pp}^{-1}A\right)^{-1}$$

- La diagonal de Q_{xx} representa las coordenadas y offset del reloj obtenidos
- El resto de elementos de Q_{xx} indican el nivel de correlación entre dichas variables
- La ecuación anterior permite evaluar el impacto sobre algún parámetros de:
  - Un determinado diseño (matriz A)
  - Una medida (matriz Q_{pp})
- Por ejemplo, nos permite responder a:
  - ¿Cuál es el efecto de la configuración satelital en la los elementos de la matriz Q_{xx}?
  - ¿Cómo se propagan los modelos de errores según la configuración de los satélites?
  - ¿Cuál es la tolerancia de un modelo de error para obtener una precisión?

Precisión de las soluciones de posición. UERE (User Equivalent Range Error)

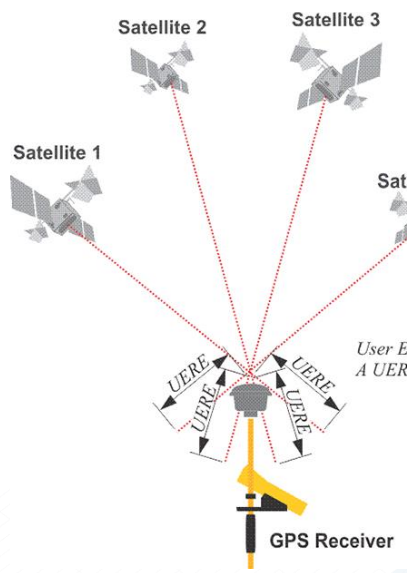
- Si asumimos que las medidas y os erres residuales están incorrelados (es decir, $Q_{pp} = \sigma^2 I_m$, siendo I_m la matriz identidad de orden m), entonces:

$$Q_{xx} = \sigma^2(A^{\top}A)^{-1}$$

- Si se combinan las fuentes de error en los relojes y efemérides de los satélites, errores atmosféricos, ruido en el receptor y los multitrayectos, obtenemos el **UERE** (User Equivalent Range Error), que podemos usar para caracterizar σ.
- El UERE se divide en dos partes:
  - **SISRE** (Signal-In-Space Range Error): errores relacionados con los segmentos de control y satélites (órbitas en el mensaje de navegación, relojes)
  - **UEE** (User Equipmente Error): asociado al receptor y entorno

$$UERE = \sqrt{SISRE^2 + UEE^2}$$

Precisión de las soluciones de posición. UERE (User Equivalent Range Error)



User Equivalent Range Error (UERE)
A UERE is the biases expressed as a range

Source: PSU

Curso de capacitación en EGNSS para UNAM. Ramón Martínez, Miguel A. Salas, ETSIT-UPM. 2022. v1.0

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Precisión de las soluciones de posición. UERE budget

- El error budget muestra la contribución de cada fuente de error al UERE
- El UEE final tiene una gran dependencia con:
  - Tipo de receptor (receptores duales pueden corregir error ionosférico)
  - Antena (puede mitigar el efecto del multitrayecto)
  - Figura de ruido del receptor
  - Elevación receptor-satélite

UERE error budget in GNSS

Error source	Contribution 1σ (m)
SISRE	
Broadcast satellite orbit	0.2-1.0
Broadcast satellite clock	0.3-1.9
Broadcast group delays	0.0-0.2
UEE	
Unmodeled ionospheric delay	0-5
Unmodeled tropospheric delay	0.2
Multipath	0.2-1
Receiver noise	0.1-1
UERE	0.5-6m

$$UERE = \sqrt{SISRE^2 + UEE^2}$$

$$\sigma^2_{UERE} = \sigma^2_{clk} + \sigma^2_{eph} + \sigma^2_{iono} + \sigma^2_{tropo} + \sigma^2_{multipath} + \sigma^2_{noise}$$

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Precisión de las soluciones de posición. DOP (Dilution of Precision)

- Se puede extraer una medida de la precisión de la solución $\boldsymbol{\sigma_G}$ a partir de la varianza de los parámetros estimados:

$$\boldsymbol{\sigma_G} = \sqrt{\boldsymbol{\sigma_E^2} + \boldsymbol{\sigma_N^2} + \boldsymbol{\sigma_U^2} + \boldsymbol{\sigma_{dt}^2}} = \boldsymbol{\sigma} tr\{(\boldsymbol{A}^{\top}\boldsymbol{A})^{-1}\}$$

  - $\boldsymbol{\sigma_E^2}$: varianza del error de la componente Este de la posición
  - $\boldsymbol{\sigma_N^2}$: varianza del error de la componente Norte de la posición
  - $\boldsymbol{\sigma_U^2}$: varianza del error de la componente de altura de la posición
  - $\boldsymbol{\sigma_{dt}^2}$: varianza del error del offset de reloj
- Estas varianzas se pueden calcular a partir de las coordenadas geocéntricas ECEF
- Los elementos de la matriz $\boldsymbol{A}^{\top}\boldsymbol{A}$ son función de la geometría satélite-receptor
- Como la traza de $(\boldsymbol{A}^{\top}\boldsymbol{A})^{-1}$ es mayor que 1, amplifica $\boldsymbol{\sigma}$, por lo que aumenta el error o disminuye la precisión
- $\boldsymbol{\sigma_G}$ sólo depende de la geometría, no de las medidas

Precisión de las soluciones de posición. GDOP (Geometric Dilution of Precision)

- De la GDOP ($\boldsymbol{\sigma_G}$), que incluye información de posición y offset de reloj, se pueden extraer otras medidas de DOP
- Position Dilution of Precision (PDOP): precisión de posición

$$\boldsymbol{PDOP} = \sqrt{\boldsymbol{\sigma_E^2} + \boldsymbol{\sigma_N^2} + \boldsymbol{\sigma_U^2}}$$

- Horizontal Dilution of Precision (HDOP): precisión en el plano horizontal

$$\boldsymbol{HDOP} = \sqrt{\boldsymbol{\sigma_E^2} + \boldsymbol{\sigma_N^2}}$$

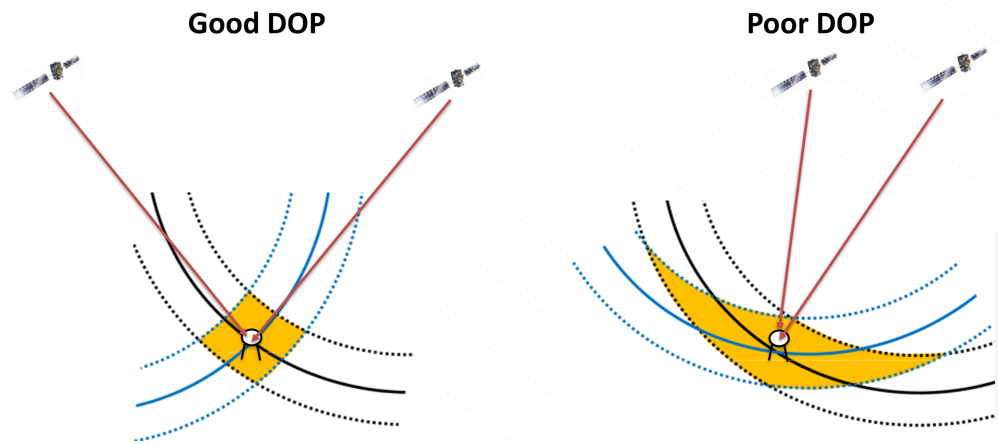
- Vertical Dilution of Precision (VDOP): precisión en la altura

$$\boldsymbol{VDOP} = \sqrt{\boldsymbol{\sigma_U^2}}$$

- Time Dilution of Precision (TDOP): precisión temporal

$$\boldsymbol{TDOP} = \sqrt{\boldsymbol{\sigma_t^2}}$$

Precisión de las soluciones de posición. GDOP (Geometric Dilution of Precision)



El error debido a la geometría depende de la posición relativa de los satélites y el usuario.

Source: Adapted from Navipedia

Precisión de las soluciones de posición. Error total

- La expresión usada para *aproximar* el error total cometido en el cálculo de la posición viene dada por:

$$\boldsymbol{Error = DOP \times UERE}$$

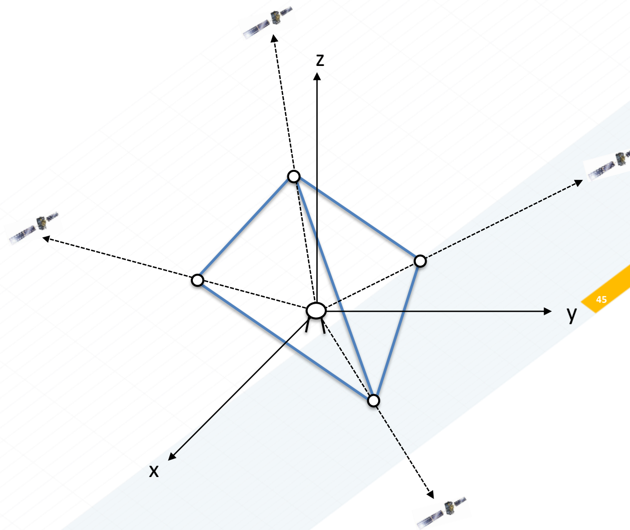
- **DOP**: puede reducirse aumentando el número de satélites visibles para elegir los que proporcionan una geometría óptima
  - Valor práctico de DOP: 2 (idealmente, 1)
- **UERE**: puede reducirse con mejores receptores, algoritmos y modelos para estimar las fuentes de error

Ubicación óptima de 4 satélites para minimizar GDOP

- Para minimizar el GDOP con 4 satélites, deben situarse en los vectores unitarios de un tetraedro de volumen máximo
- 3 satélites espaciados 120 grados y situados en un plano perpendicular al cuarto satélite

- En una situación práctica con una elevación mínima de 5 grados, quedaría:

Satélite	1	2	3	4
Elevación (º)	5	5	5	90
Acimut (º)	0	120	240	0



Ubicación óptima de 4 satélites para minimizar GDOP. Ejemplo

- En una situación práctica con una elevación mínima de 5 grados, quedaría:

Satélite	1	2	3	4
Elevación (º)	5	5	5	90
Acimut (º)	0	120	240	0

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0.996 & 0.087 & 1 \\ 0.863 & -0.498 & 0.087 & 1 \\ -0.863 & -0.498 & 0.087 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \rightarrow (\boldsymbol{A}^{\mathsf{T}}\boldsymbol{A})^{-1} = \begin{bmatrix} 0.672 & 0 & 0 & 0 \\ 0 & 0.672 & 0.087 & 0 \\ 0 & 0 & 1.6 & -0.505 \\ 0 & 0 & -0.505 & 0.409 \end{bmatrix} \longrightarrow$$

GDOP = 1.83
PDOP = 1.72
TDOP = 0.64
HDOP = 1.16
VDOP = 1.26

- Si σ_{UERE} = 7m (SPS):
  - Error vertical (2σ): 17.64 m
  - Precisión horizontal (2σ): 16.24 m
  - Precisión en tiempo (2σ): 2 × TDOP × σ_{UERE} /c = 30 ns

GNSS performance evaluation

The four parameters used to characterize GNSS performance are based on the RNP (Required Navigation Performance) specification are:

- **Accuracy**: The accuracy of an estimated or measured position of a craft (vehicle, aircraft, or vessel) at a given time is the degree of conformance of that position with the true position, velocity and/or time of the craft. Since accuracy is a statistical measure of performance, a statement of navigation system accuracy is meaningless unless it includes a statement of the uncertainty in position that applies.
- **Availability**: The availability of a navigation system is the percentage of time that the services of the system are usable by the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.
- **Continuity**: The continuity of a system is the ability of the total system (comprising all elements necessary to maintain craft position within the defined area) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.
- **Integrity**: Integrity is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.

Source: Navipedia

GNSS performance. Accuracy

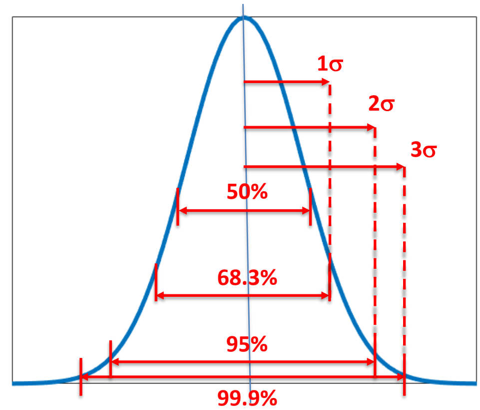
- Def.- Degree of conformance of that position with the true position, velocity and/or time of the craft. Since accuracy is a *statistical measure of performance*, a statement of navigation system accuracy is meaningless unless it includes a statement of the uncertainty in position that applies.
- Accuracy measures:
  - **x Percentile** (x% or x-th): Means that x% of the positions calculated have an error lower or equal to the accuracy value. Typical used values are 50%, 67%, 75% and 95%. *Having an accuracy of 5m (95%) means that in 95% of the time the positioning error will be equal or below 5m*.
  - **Circular Error Probable** (CEP): Percentile 50%.
  - **Root Mean Square Error** (rms): The square root of the average of the squared error.
  - **x sigma**: 1 sigma corresponds to one standard deviation and x sigma corresponds to x times 1 sigma.
  - **Mean Error**: Average error
  - **Standard Deviation**: Standard deviation of the error.

Source: Navipedia

GNSS performance. Accuracy

- SIS user range errors (UREs) in GNSS can be modelled as a zero-mean normal distributon with a standard deviation represented by the broadcast user range accuracy (URA)
- Under the previous model, we can define probabiities associated with rms and σ-probabilites
- Navigation solution and error budgets are valid under the hypothesis of errors:
  - Statistically independent for different SVs
  - Error modeled as random Gaussian variables with zero mean

Zero-mean Gaussian (normal) distribution



Source: Adapted from Povero

GNSS performance. Availability

- Def.- Percentage of time that the services of the system are usable by the navigator.
- Availability is an indication of the ability of the system to provide usable service within the specified coverage area.
- Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use.
- It is a function of:
  - Physical characteristics of the environment (e.g. obstacles that might mask part of all of the satellites in the sky)
  - Technical capabilities of the transmitter facilities
  - Constellation configuration and its visibility at user location

Source: Navipedia

GNSS performance. Continuity

- Def.- Probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.
- Continuity of a system is the ability of the total system (comprising all elements necessary to maintain craft position within the defined area) to perform its function without interruption during the intended operation
- The continuity is usually measured as the probability that the system performance is kept under the operational requirements during a certain amount of time.
- Therefore, common continuity measurements are:
  - %/h: Probability that the operational performance is kept over a one hour period.
  - %/15s: Probability that the operational performance is kept over a fifteen seconds period.

Source: Navipedia

GNSS performance. Continuity

- There are different types of failures that have an impact on continuity:
  - **Hard Failures**: cessation of GNSS signal transmission, not predictable
    - Long-term: irrecoverable loss of the signal transmission (a new satellite shall be launched)
    - Short-term: temporary loss of signal (switching to a redundant system)
  - **Wear-Out Failures**: predictable of schedulable. Characteristic of the satellite End-of-Life (EOL) operating phase
  - **Soft Failures**: GNSS signal is available but the satellite or control segment transmits an alert, being the signal unavailable to users (not predictable)
  - **Satellite O&M Activities**: due to operation and management activities. They can be planned in advance reducing the loss of continuity

Source: Navipedia

GNSS performance. Integrity

- Def.- Measure of the trust that can be placed in the correctness of the information supplied by a navigation system.
- Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation
- Integrity parameters:
  - **Alert Limit** (AL): The alert limit for a given parameter measurement is the error tolerance not to be exceeded without issuing an alert.
  - **Time to Alert** (TTA): The maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment enunciates the alert.
  - **Integrity Risk**: Probability that, at any moment, the position error exceeds the Alert Limit.
  - **Protection Level** (PL): Statistical bound error computed so as to guarantee that the probability of the absolute position error exceeding said number is smaller than or equal to the target integrity risk.

Source: Navipedia

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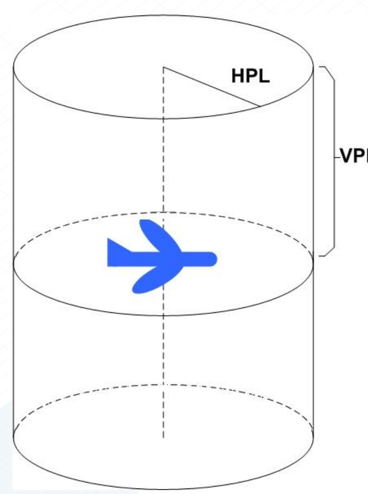
GNSS performance. Integrity. Protection level

- During normal operations it is not possible to know the position error of an aircraft
- Thus, a statistical bound to position error called protection level needs to be computed in order to be able to measure the risk that the alert limit is surpassed
- Hence, the system is not declared unavailable when the alert limit is exceeded by the actual position error, but by the protection level (as then the risk for position error to exceed the alert limit would be above the target integrity risk).
- **A horizontal (respectively vertical) protection level is a statistical bound of the horizontal (respectively vertical) position error computed so as to guarantee that the probability of the absolute horizontal (respectively vertical) position error exceeding said number is smaller than or equal to the target integrity risk.**



Source: Navipedia

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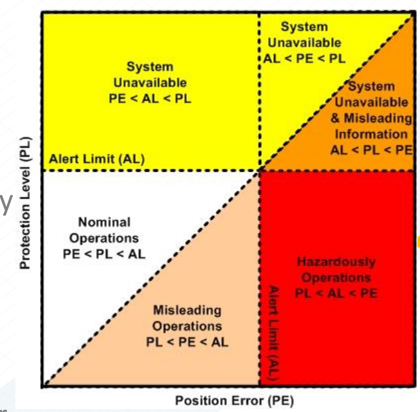
GNSS performance. Integrity. Stanford Diagram

- An integrity failure is an integrity event that lasts for longer than the TTA and with no alarm raised within the TTA.
- The Stanford diagram actually accounts for integrity events and not for integrity failures, but allows to distinguish between two types of integrity events: misleading information (or MI) events and hazardously misleading information (or HMI) events:
  - A **misleading information** (MI) event occurs when, being the system declared available, the position error exceeds the protection level but not the alert limit.
  - A **hazardously misleading information** (HMI) event occurs when, being the system declared available, the position error exceeds the alert limit.



Source: Navipedia

Part 1. Fundamentals of GNSS systems

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GNSS signal components

The structure of GNSS signals comprises three main components:

- **Carrier** – sinusoidal electromagnetic waves generated by an oscillator synchronized with an atomic clock on every satellite. Carrier frequencies are chosen in the range 1100-1600 MHz and are used to transmit information (through modulation with spreading codes and data component, when present), and for carrier phase ranging.
- **Spreading codes** – seemingly random binary sequences, that can be reproduced in a deterministic manner by intended receivers. They are mainly used to spread the signal spectrum for increased strength, immunity to interference and authorization of the signal usability for public, military, commercial or other services. Codes are typically generated at 1-10 MHz. After de-spreading the signal in the correlator, the GNSS receiver is able to perform synchronization over time and code phase ranging.
- **Data component** – low-frequency data streams (e.g. 125 Hz for Galileo I/NAV) containing navigation information: primarily satellite clock and ephemeris data (CED) but also ionospheric correction models, service parameters, integrity and authentication indicators, and other data. Some signals (named 'pilot') are not modulated with data for improved tracking performance.

Source: GNSS User Tech Report 2020, EUSPA.

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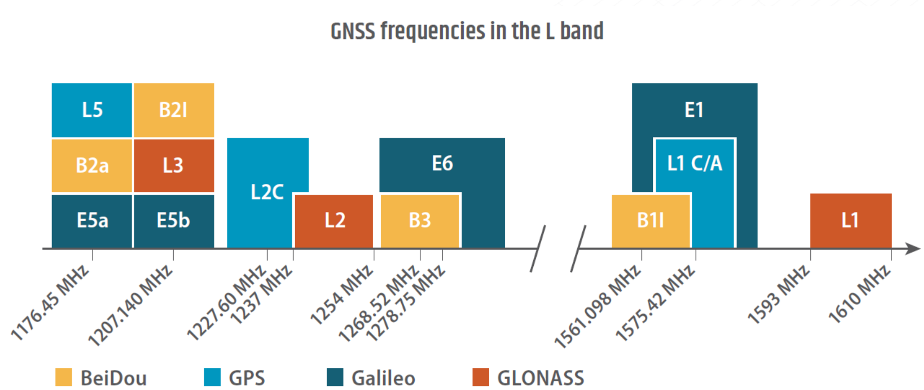
GNSS frequencies

- The use of several frequencies provides advantages such as improved accuracy, interference robustness, compensation of ionosphere errors, use of carrier-phase algorithms (PPP, RTK, PPP-RTK) and interoperability with modernized SBAS systems



Source: GNSS User Tech Report 2020, EUSPA.

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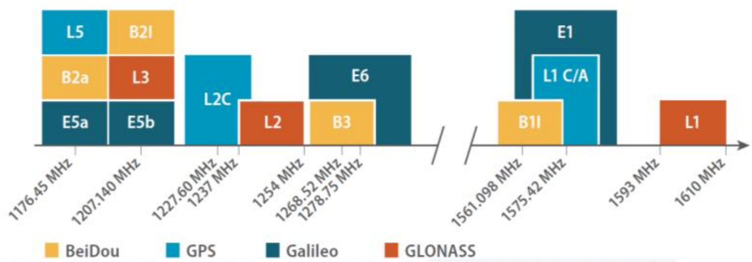
GNSS frequencies

- Two common frequency ranges are used:
  - L5/E5/B2/L3 signals in the lower L Band (1164-1215 MHz)
  - L1/E1/B1 signals in the upper L Band (1559-1610 MHz)
- Allocated worldwide to GNSS on a primary basis and are shared with aeronautical radio navigation service (ARNS) systems
- Radio-frequency compatibility between GNSS systems under the '1 dB criterion'

GNSS frequencies in the L band



Source: GNSS User Tech Report 2020, EUSPA.

GNSS frequencies

- **Dual-frequency receivers** offer significant advantages over single-frequency receivers in terms of achievable accuracy, but also in terms of improved resistance to interference (owing to frequency diversity). Historically, dual-frequency use has been limited for many years to professional or governmental users and to expensive L1 + L2 receivers. The advent of four full GNSS constellations that provide high quality open signals in the E5 frequency band has been a game changer, and has triggered widespread availability of E1 + E5 dual frequency chipsets for the mass market.
- **E5** brings a wealth of advantages: being supported by all GNSS and modernised SBAS, these signals will be broadcast on more satellites than any other frequency. Furthermore, this frequency band is shared with the Aeronautical Radio Navigation Service (ARNS) and therefore subject to increased regulatory protection (similar to L1/E1) and suitable for safety critical applications. In addition, signals on E5 benefit from a high chipping rate and of a higher received power than E1/L1 or L2.
- In terms of compatible PVT strategies, dual (or more) frequency processing brings even more significant advantages. Despite the theoretical single frequency compatibility of all processing methods listed in the table on the left, **in practice dual frequency is the minimum requirement for carrier phase-based algorithms** (RTK, PPP-RTK and PPP).
- Triple frequency can further improve the performance of the carrier phase ambiguity resolution algorithms along three characteristics: the maximum separation from a reference station (for RTK and Network RTK), the reliability of the solution, and the time required to obtain and validate this solution. However currently only high accuracy, professional grade receivers have adopted triple or even quadruple frequency processing.

Source: GNSS User Tech Report 2020, EUSPA.

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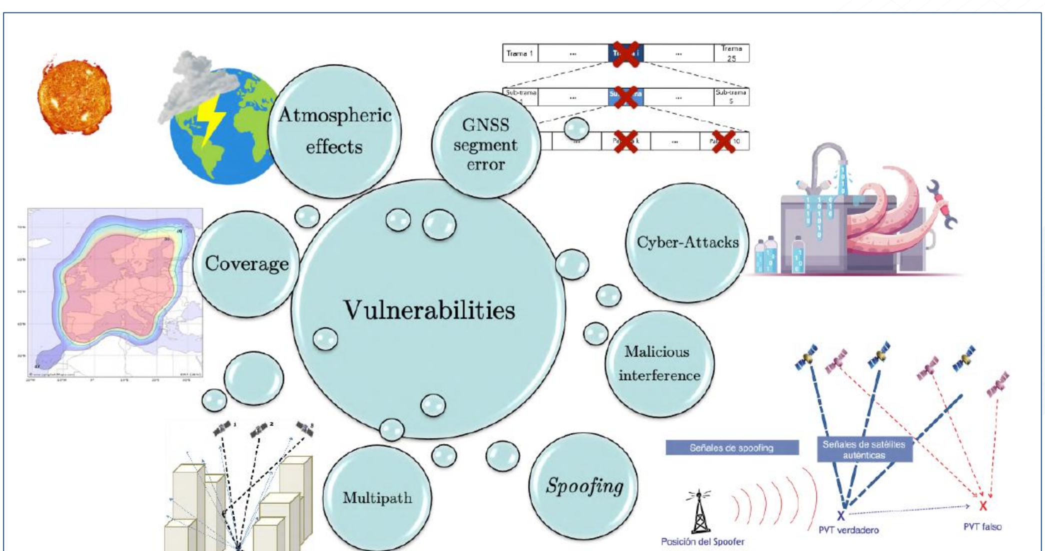
GNSS vulnerabilities



Source: Diego Carmena, ETSIT-UPM

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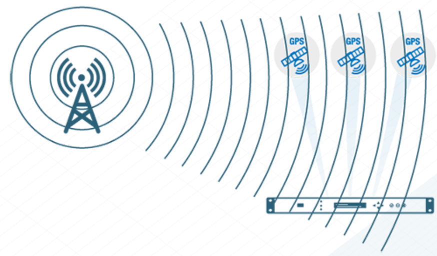
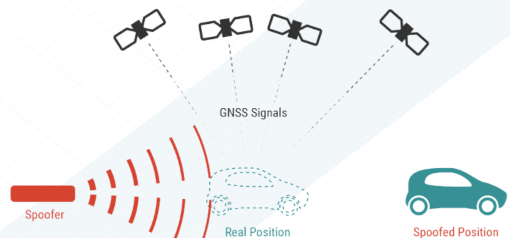
GNSS vulnerabilities. Jamming and spoofing

- Received GNSS signals are weak and suffers from different types of interferences
- **Jamming**: intentional interference in the same GNSS band transmitted to overpower GNSS signals (leads to denial of service)
- **Spoofing**: structured interference signal that resembes closely to a GNSS signals and can be considered as authentic for a GNSS receiver (leads to errors in the position)
- **Meaconing**: retransmission of recorded GNSS signals with a higher power than the original

Jamming (Bodet Time)



Spoofing (DROTEK)



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Part 1. Fundamentals of GNSS systems

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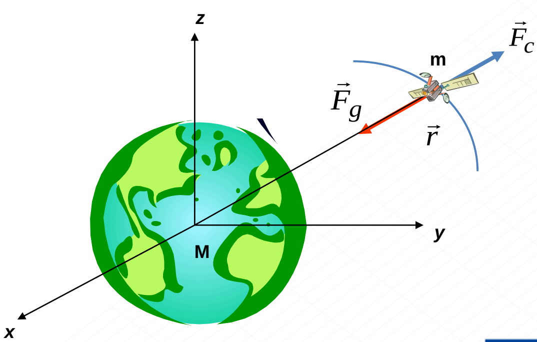
Orbits. Derivation of Kepler Law's

- Kepler's Laws can be derived from Newton's Laws of Motion and Law of Universal Gravitation under the following hypothesis:
  - Earth and satellite are point masses
  - Only gravitation forces are considered
  - Two-body problem



$$\vec{F}_g = G\frac{Mm}{r^2}(-\hat{r})$$

$$\vec{F}_c = m\vec{a} = m\frac{d^2\vec{r}}{dt^2}$$

$$\vec{F}_g = \vec{F}_c \Rightarrow \frac{d^2\vec{r}}{dt^2} + \hat{r}\frac{k}{r^2} = 0$$

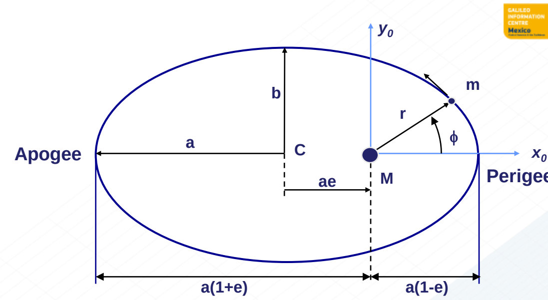
$$k = GM \sim 3.99 \times 14^{14}\ \frac{m^3}{s^2}\ (Kepler\ constant)$$

Source: Martínez

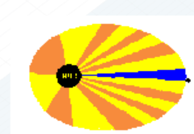
Orbits. Kepler's Laws

1. Satellite orbit is located in a plane orthogonal to $\vec{r}$ and $\vec{v}$ that includes the center of mass of the Earth and are elliptical with the Earth in one of its focus.

$$r = \frac{a(1-e^2)}{1+e\cos\varphi} \qquad v = \sqrt{k\left(\frac{2}{r}-\frac{1}{a}\right)}$$



2. Equal areas are swept out in equal times by the vector joining a satellite and the Earth center $\vec{r}$.



3. The ratio of the square of the period of revolution and the cube of the orbit semimajor axis is a constant.

$$T = 2\pi\frac{a^{3/2}}{k^{1/2}}$$

Source: Martínez

Orbits. Period and velocity of artificial satellites

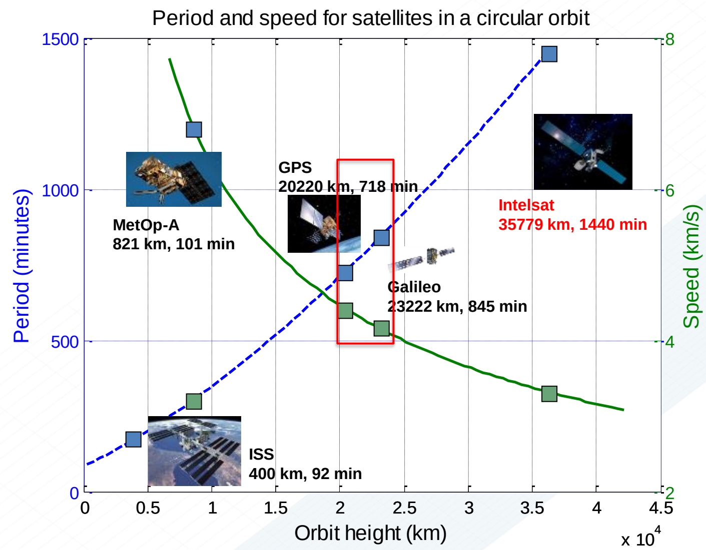
Orbital period:

$$T = \sqrt{\frac{4\pi^2 a^3}{\mu}}$$

Orbital velocity:

$$v = \sqrt{k\left(\frac{2}{r} - \frac{1}{a}\right)}$$

$$v(circular) = \sqrt{\frac{k}{a}}$$

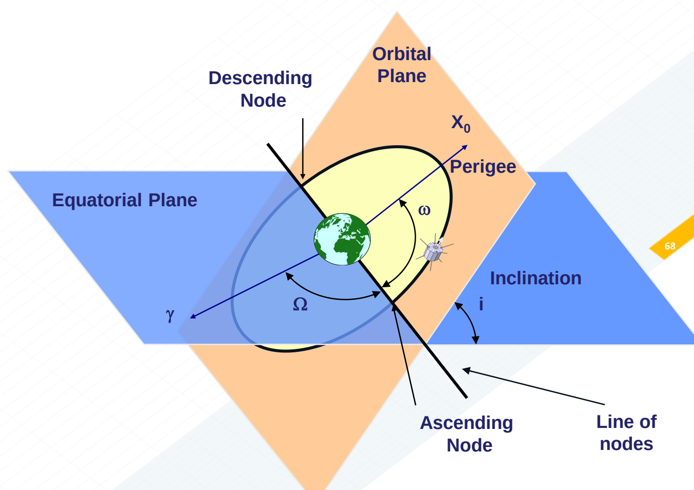


Source: Martínez

Orbits. Orbit ephemeris

- The solution to describe the satellite orbit $\vec{r}(t)$ can be specified using 6 parameters called the satellite ***ephemeris***.

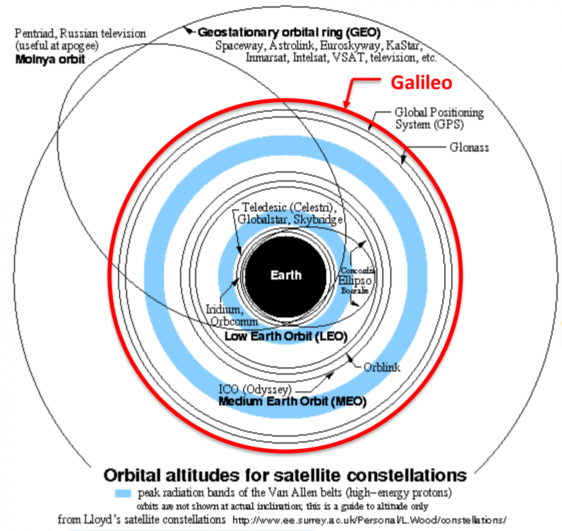
1) Eccentricity (e)
2) Semimajor axis (a)
3) Right Ascension of Ascending Node or RAAN (Ω)
4) Inclination (i)
5) Argument of perigee (ω)
6) Time of Perigee (t_p) or Mean Anomaly (M)



Source: Martínez

Satellite artificial orbits

- Satellite orbits can be classified according to the satellite altitude:
- **LEO** (Low Earth Orbit):
  - 300<h<1500 km
  - Communications, EO, scientific
- **MEO** (Medium Earth Orbit):
  - h~10.000 km and 20.000<h<25000 km
  - Communications and GNSS
- **GEO** (Geostationary Earth Orbit):
  - h=36.000 km
  - Communications and weather forecast
- **HEO** (Highly Elliptical Earth Orbit):



Source: adapted from Lloyd Wood

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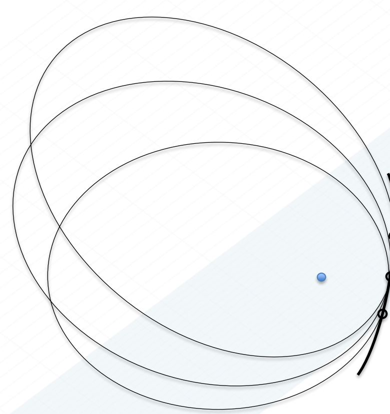
Orbits. Orbital perturbations

- In the absence of the hypothesis of Kepler's laws, satellite orbits are disturbed due to:
  - Earth is not a point mass
  - Earth mass is not uniformly distributed
  - Presence of thrid bodies (Sun, Moon)
  - Radiation pressure
  - Atmospheric drag
- In the presence of perturbations, the satellite orbit can be modelled as an ellipse with constantly changing parameters
- Thus, the perturbed satellite orbit is modelled with an *oscullating ellipse* as:

$$\{\vec{r}(t),\dot{\vec{r}}(t)\} \leftrightarrow \{a(t),e(t),i(t),\omega(t),\Omega(t),M(t)\}$$



Source: adapted from Teunissen

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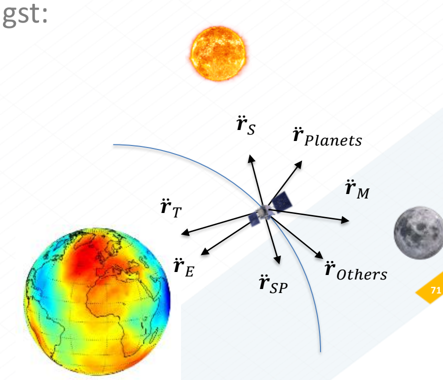
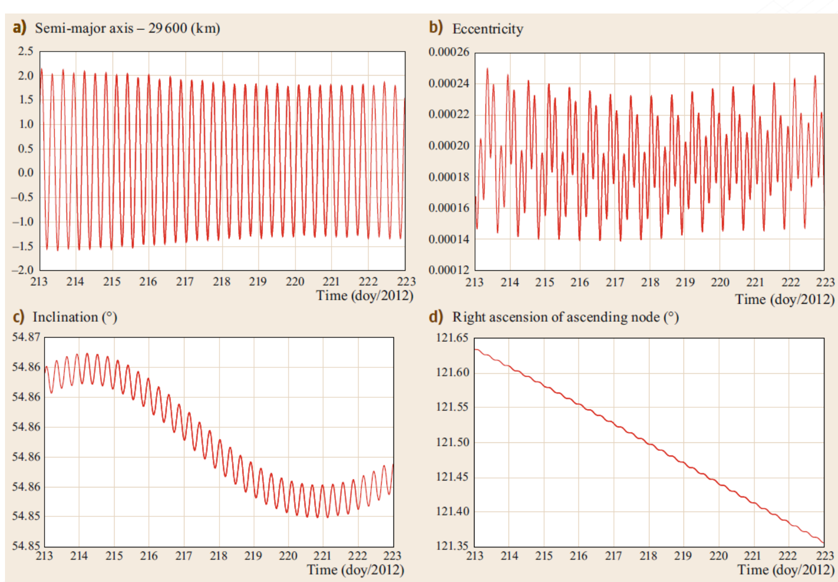
Orbits. Perturbations at GNSS altitudes

- MEO orbits are selected for GNSS as a trade-off amongst:
  - Perturbations
  - Visibility from Earth
  - Launch cost
  - Number of satellites to provide global service
- Potential effects on acceleration (after 2 orbits):
  - Earth's oblateness ($\ddot{r}_E$): few km
  - Sun and Moon attraction ($\ddot{r}_S$ and $\ddot{r}_M$): 100's of meters
  - Higher armonics in geopotential: <100 m
  - Albedo, tides ($\ddot{r}_T$), planets effects ($\ddot{r}_{Planets}$) are negligible
- Solar radiation pressure ($\ddot{r}_{SP}$, non-potential):
  - Difficult modelling as it depends on the satellite structure, materials, optical surface, and altitude
  - Effect < 100m



Source: adapted from Sanz

Orbits. Example of osculating elements



Source: Teunissen

Orbis. Visibility

- Satelite orbits shall provide the largest elevation to satellites from ground to allow for better link conditions
- Proper inclination angles of the orbital planes shall be used

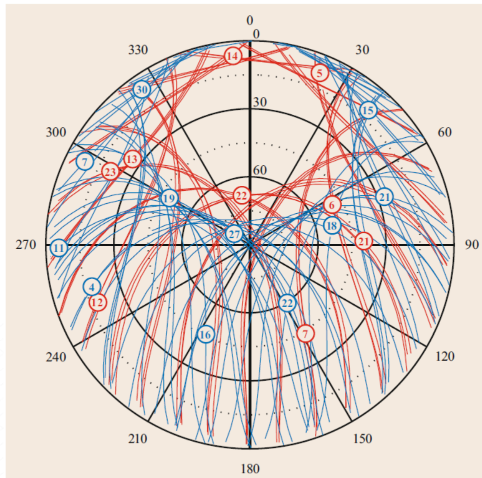
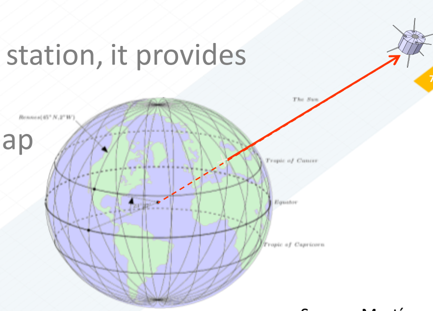


Fig. 3.8 Azimuth and elevation of GPS and GLONASS satellites for an observer in Munich ($\varphi = 48.8°$N) over a 24 h period on 1st April 2015. At the midnight epoch a total of 11 GPS satellites and 9 GLONASS satellites were visible above a 5° elevation threshold

Source: Teunissen

Orbits. Ground tracks

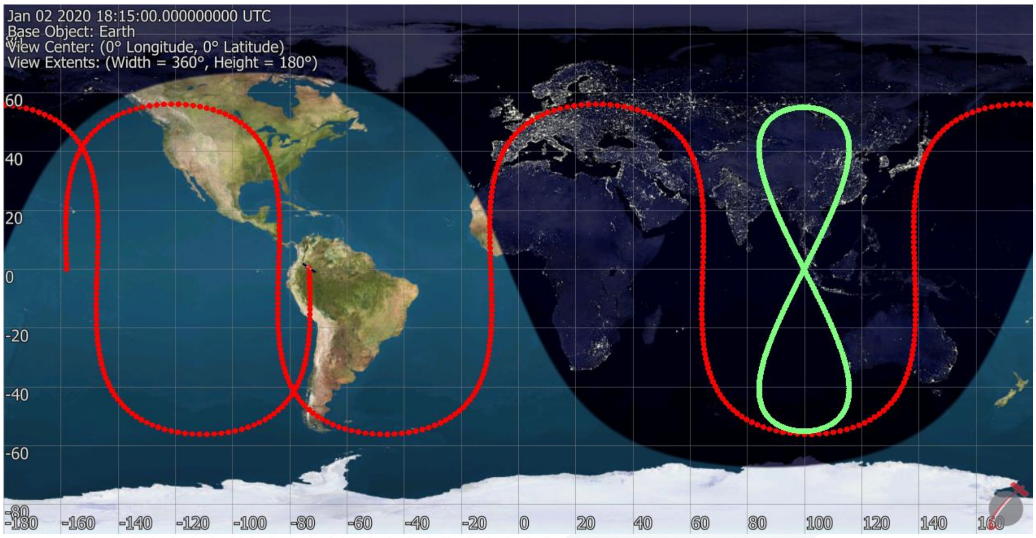
- **Subsatellite point** is the intersection of the line between the satellite and the Earth center with the Earth surface
- **Satellite ground track** is the representation of the subsatellite point as it moves in the orbit
  - It gives information of orbit parameters (inclination, eccentricity) and revisit times
  - In conjunction with the field of view of the ground station, it provides information of visibility
- Satellite ground track is usually represented in a 2D map



Source: Martínez

Orbits. Ground tracks

MEO IGSO



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Part 1. Fundamentals of GNSS systems

1. Operation of GNSS systems and applications
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   - GNSS Observables
   - Range-based positioning
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5. **GNSS signals and spectrum**
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    - Time reference systems

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Classification of satellite based navigation systems

Global systems (GNSS)

- Operate worldwide with **global service** constellations with satellites transmitting signals that GNSS receivers use to determine their location
- Current systems:
  - GPS
  - Galileo
  - Glonass
  - Beidou

Regional systems (RNSS)

- Provide GNSS service in a given **regional area** with a lower number of satellites in GEO, IGSO and HEO ver the service area
- Can be designed to complement GNSS
- Current systems:
  - NavIC (India)
  - QZSS (Japan)

Satellite-Based Augmentation Systems (SBAS)

- Improve the performance (reliability and accuracy) of GNSS by correcting signal measurement errors and by providing information about the accuracy, integrity, continuity and availability of its signals
- Current systems:
- EGNOS (EU)
- WAAS (US)
- GAGAN (India)
- MSAS (Japan)
- SDCM (Russia)
- BDSBAS (China)
- KASS (South Korea)
- A-SBAS (African and Indian Ocean)
- SPAN: AUS & NZ

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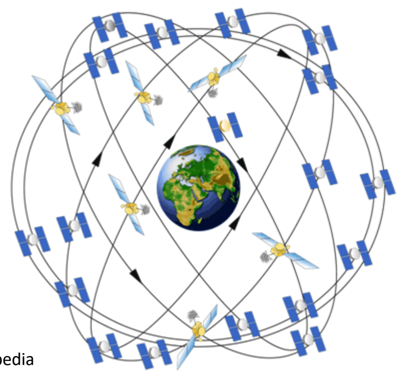
GPS (Global Positioning System)

Global GNSS owned and operated by United States of America.

Space Segment

- Walker-delta, **24**/3/1, i=56 deg, 20180 km (11h58m04s), expandable



Source: Navipedia

Ground segment

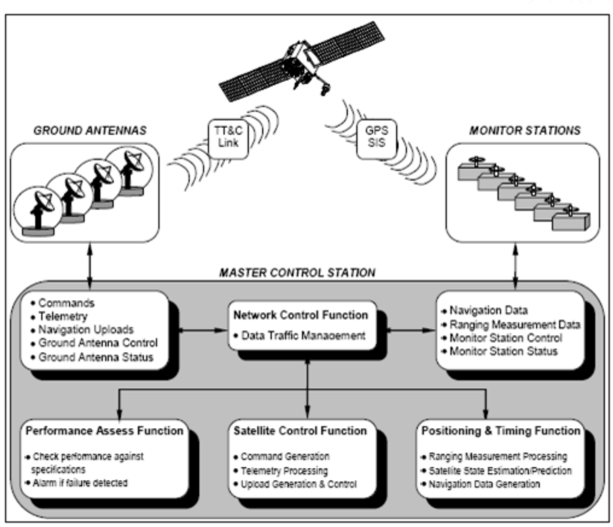
- Master Control Station (MCS)
- Alternate Master Control Station
- Network of ground antennas (GAs)
- Network of globally-distributed monitor stations (MSs)

Source: Navipedia

GPS (Global Positioning System)

Global GNSS owned and operated by United States of America.

Architecture



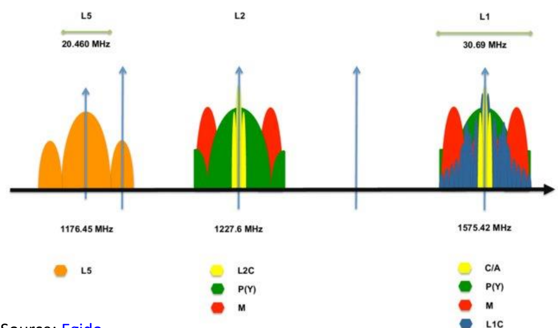
Source: Navipedia

GPS (Global Positioning System)

Global GNSS owned and operated by United States of America.

Signals

- L1 (1575.42 MHz)
- L2 (1227.60 MHz)
- L5 (1176.45 MHz)



Source: Egido

Services

- **Standard Positioning Service** (SPS): positioning and timing service for civilian users, with declared 95% performances of 12 m for horizontal and 22 m for vertical
- **Precise Positioning Service** (PPS): positioning and timing service provided by way of authorized access to ranging signals broadcast at the GPS L1 and L2 frequencies (1-2 m, 95% for horizontal and vertical)

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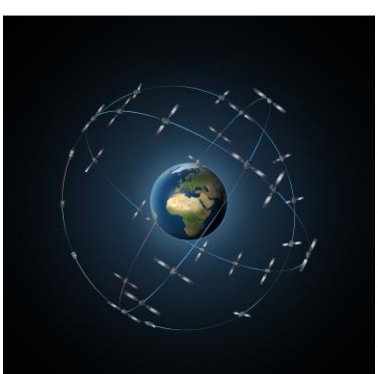
Galileo

Global GNSS owned and operated by European Union.

Space Segment

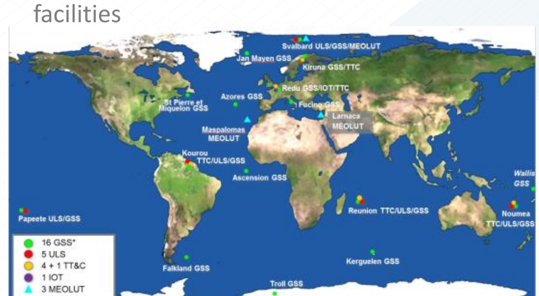
- 24+ MEO satellites (23222 km, 56º, 14h05 min) – Walker 24/3/1



Source: ESA

Ground segment

- Galileo Sensor Stations (GSS)
- Galileo Uplink Stations (ULS)
- TT&C stations
- Mission control centres and complementary facilities



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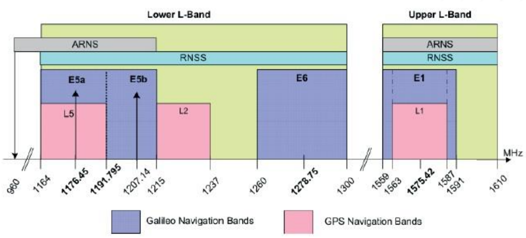
Galileo

Global GNSS owned and operated by European Union.

Signals

- E1: 1575.42 GHz
- E6: 1278.75 MHz
- E5: 1191.795 MHz
- E5a: 1176.450 MHz
- E5b: 1207.140 MHz



Source: https://galileognss.eu/

Services

- **Open Service** (OS): positioning and timing services (horizontal accuracy at 95% for a DF receiver are 4 m (8 m for vertical accuracy), with an availability of the service of 99.5%))
- **High Accuracy Service** (HAS): encrypted, includes added value services to OS though and additional signal in a different frequency band
- **Public Regulated Service** (PRS): restricted to government-authorised users, for sensitive applications that require a high level of service continuity
- **Search and Rescue Service** (SAR): Europe's contribution to COSPAS-SARSAT, picking up from emergency beacons

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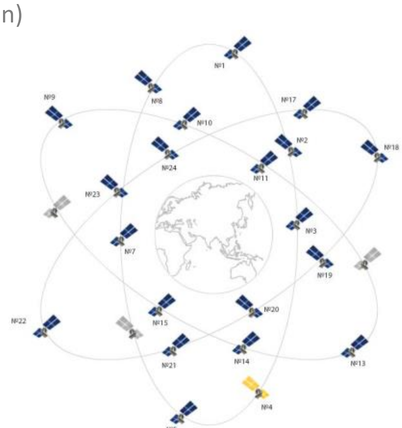
GLONASS

Global GNSS owned and operated by Russian Federation.

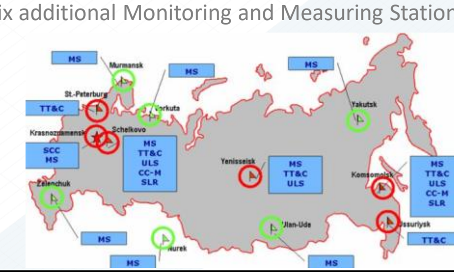
Space Segment

- 24+ MEO satellites (19.100 km, 64.8º, 11h15 min)



Ground segment

- A System Control Centre at Krasnoznamensk
- A network of five TT&C centers
- The Central Clock situated in Schelkovo (near Moscow)
- Three Upload Stations
- Two Laser Ranging Stations (SLR)
- A network of four Monitoring and Measuring Stations
- Six additional Monitoring and Measuring Stations



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GLONASS

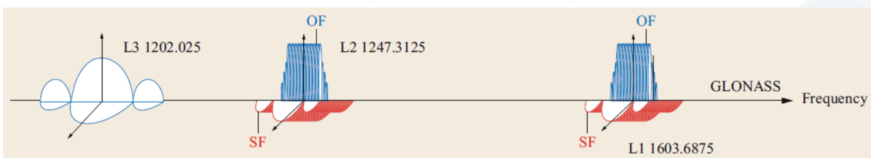
Global GNSS owned and operated by Russian Federation.

Signals

- L1: ~1602 MHz (FDMA (20 MHz) and CDMA)
- L2: ~1246 MHz (FDMA (20 MHz) and CDMA)
- L3: 1202.025 MHz (CDMA)

Services

- Standard Positioning Service (SPS): unencrypted open service for users worldwide
- Precise Positioning Service (PPS): encrypted for the use of authorized users only



Source: Teunissen.

Service type: O: open, S: authorized special

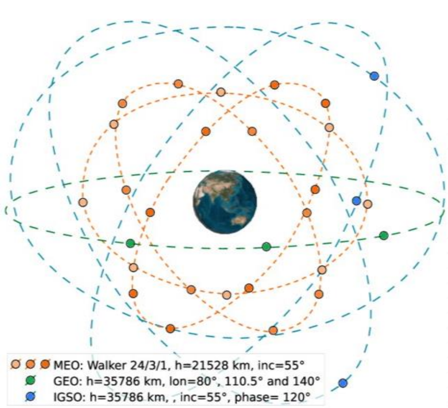
Modulation type: F: FDMA, C: CDMA

BeiDou (BDS) (formerly, Compass)

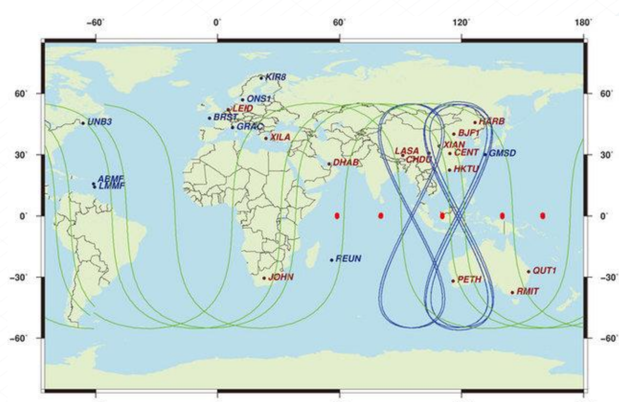
Global GNSS owned and operated by People's Republic of China.

Space Segment

- 35 satellites (27 MEO, 3 IGSO, 5 GEO)



Ground tracks



BeiDou (BDS) (formerly, Compass)

Global GNSS owned and operated by People's Republic of China.

Ground Segment

- Master Control Station: responsible for satellite constellation control and processing the measurements received by the Monitor Stations to generate the navigation message
- Upload Stations: responsible for uploading the orbital corrections and the navigation message to BeiDou satellites
- Monitor Stations: collect BeiDou data for all the satellites in view from their locations.
- National BeiDou Ground Based Augmentation System (BDGBAS)
- A nation-wide reference station network

Source: Shen, 2016.

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BeiDou (BDS) (formerly, Compass)

Global GNSS owned and operated by People's Republic of China.

Signals

Signal	Modulation	Access	Bandwidth	Central frequency	Satellites
B1	BPSK	CDMA	4.096 MHz	1561.098 MHz	
B1C (OS)	BOC/QMBOC	CDMA	32.736 MHz	1575.42 MHz	MEO, IGSO
B2a	BPSK	CDMA	20.46 MHz	1176.45 MHz	
B3 (OS)	BPSK	CDMA	20.46 MHz	1268.52 MHz	MEO, IGSO, GEO

Source: Navipedia

Services

- Global services
  - **Open service** (similar to GPS and Galileo, 10m)
  - **Authorized service**
- Regional services:
  - **Wide area differential services** (1m, supported by 30 station broadcasting GEO corrections)
  - **Short message service**

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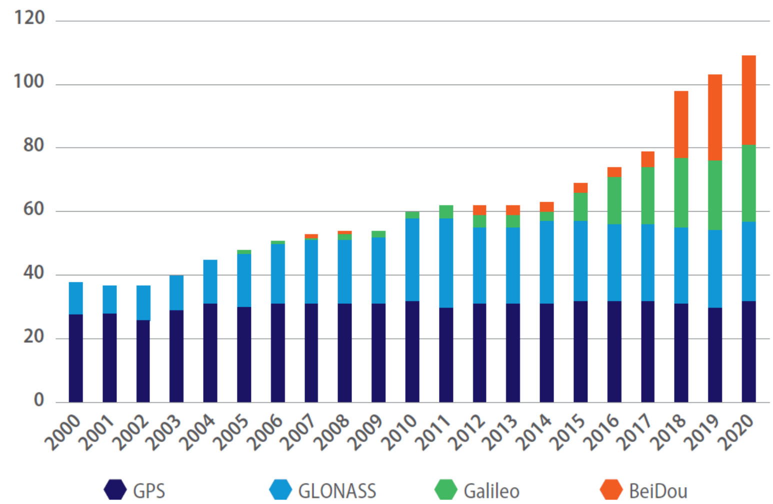
GNSS. Operational MEO satellites



* Excluding test satellites. Reporting global coverage only (Medium Earth Orbit).

Source: GNSS User Tech Report 2020, EUSPA.

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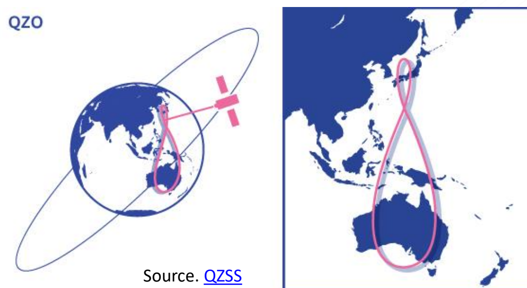
Regional systems. QZSS (Quasi-Zenith Satellite Systems)

Regional GNSS owned and operated by NC and Mitsubishi Electric Corporation under Quasi-Zenith Satellite System Service Co., Ltd.

Space Segment

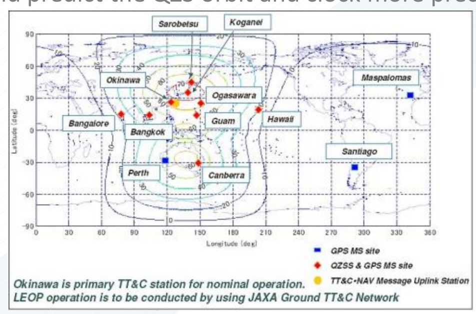
- 3-Quasi-zenith orbits (QZO), elliptical GSO + 1 GEO (127 E)
- QZO: Inclination: 43+/-4 degrees
- QZO: Longitude: 135 +/-5 deg E
- Allows adequate elevation from Japan locations



Source. QZSS

Ground segment

- Master Control Station (MCS)
- Monitoring Station (MS)
- Tracking and Control Stations (TCS),
- 10 MSC around Japan and overseas to estimate and predict the QZS orbit and clock more precisely



Source: Jaxa

Regional systems. QZSS (Quasi-Zenith Satellite Systems)

Regional GNSS owned and operated by NC and Mitsubishi Electric Corporation under Quasi-Zenith Satellite System Service Co., Ltd.

Signals

- L1C/A, L1C, L1S, L1Sb: 1575.42 MHz
- L2C: 1227.60 MHz
- L5, L5S: 1176.45 MHz
- L6 (LEX): 1278.75 MHz
- S-band: 2 GHz band

Services

- Complements GPS
- Satellite Positioning, Navigation and Timing Service (PNT)
- Sub-meter Level Augmentation Service (SLAS)
- Centimeter Level Augmentation Service (CLAS)
- Positioning Technology Verification Service
- QZSS Safety Confirmation Service (Q-ANPI)
- Public Regulated Service
- SBAS Transmission Service

Regional systems. QZSS (Quasi-Zenith Satellite Systems)

Regional GNSS owned and operated by NC and Mitsubishi Electric Corporation under Quasi-Zenith Satellite System Service Co., Ltd.

Signal name	QSZ-1	QSZ-2, QSZ-3 and QSZ-4		Transmission service	Center frequency
	Block IQ	Block IIQ	Block IIG		
	Quasi zenith satellite orbit (QZO)	Quasi zenith satellite orbit (QZO)	Geostationary orbit (GEO)		
	One satellite	Two satellites	One satellite		
L1C/A	◎	◎	◎	Satellite Positioning, Navigation and Timing Service (PNT)	1575.42 MHz
L1C	◎	◎	◎	Satellite Positioning, Navigation and Timing Service (PNT)	
L1S	◎	◎	◎	Sub-meter Level Augmentation Service (SLAS)	
				Satellite Report for Disaster and Crisis Management (DC Report)	
L1Sb	-	-	◎ Around 2020	SBAS Transmission Service	
L2C	◎	◎	◎	Satellite Positioning, Navigation and Timing Service (PNT)	1227.60 MHz
L5	◎	◎	◎	Satellite Positioning, Navigation and Timing Service (PNT)	1176.45 MHz
L5S	-	◎	◎	Positioning Technology Verification Service	
L6 (LEX)	◎	◎	◎	Centimeter Level Augmentation Service (CLAS)	1278.75 MHz
S-band	-	-	◎	QZSS Safety Confirmation Service	2 GHz band

Source: Navipedia

Regional systems. NavIC (Navigation with Indian Constellation) (formerly, IRNSS)

Regional GNSS owned and operated by the Government of India.

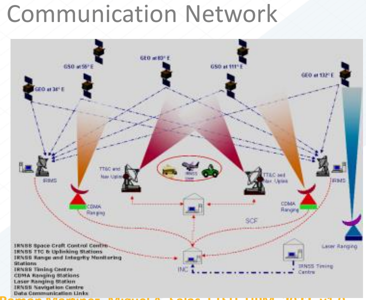
Space Segment

- 7 satellites (3 GEO at 32.5, 83 and 131.5 E, 4 IGSO crossing at 55 and 111.75 E)
- IGSO inclination: 29 deg

Source: ISRO

Ground Segment

- ISRO Navigation Centre
- IRNSS Spacecraft Control Facility
- IRNSS Range and Integrity Monitoring Stations
- IRNSS Network Timing Centre
- IRNSS CDMA Ranging Stations
- Laser Ranging Stations
- Data Communication Network



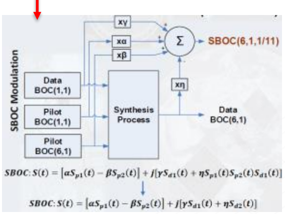
Source: ISRO

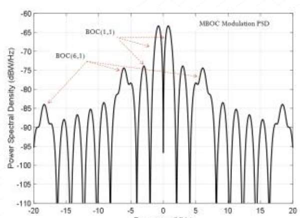
Regional systems. NavIC (Navigation with Indian Constellation) (formerly, IRNSS)

Regional GNSS owned and operated by the Government of India.

Signals

Signal	Carrier Frequency	Bandwidth	Modulation
L5	1176.45 MHz	24 MHz (1164.45 -1188.45 MHz)	BPSK
S	2492.028 MHz	16.5 MHz (2483.778 - 2500.278 MHz)	
L1	1575.42 MHz	1563.42-1587.42 MHz	SBOC (MBOC PSD)





[Upadhyay, 21]

Services

- Standard Positioning Service (SPS): provided to all the users
- Restricted Service (RS): encrypted service provided only to the authorised users
- Messaging service: to users in the Indian region through IRNSS-1A

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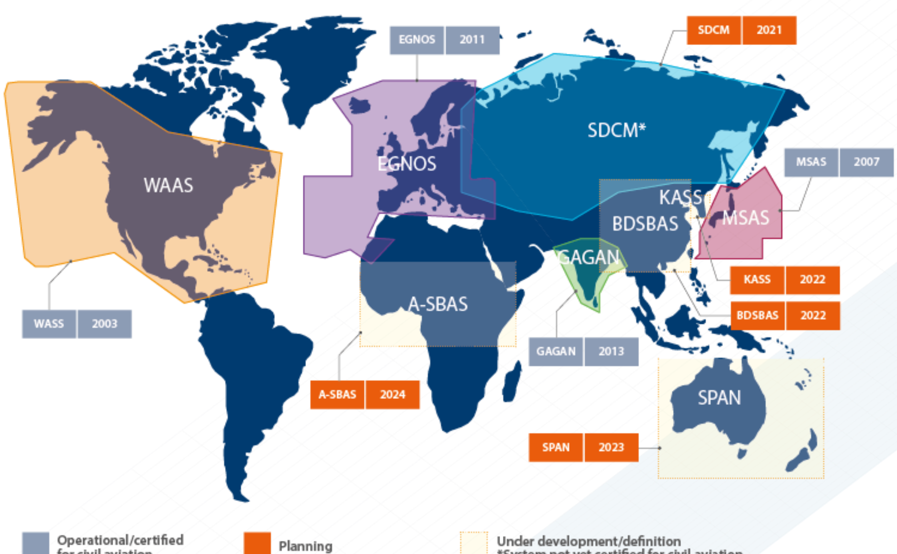
Satellite-Based Augmentation Systems (SBAS)

- Los sistemas aumentados tres servicios complementarios a los usuarios de GNSS:
  - Monitoreo de la integridad en tiempo real para mejorar la seguridad (GIC: GNSS/Ground Integrity Channel)
  - **Correcciones** diferenciales en un área amplia para mejorar la precisión (WAD: Wide Area Differential)
  - Una función de ranging transmitiendo una señal L1 o E1 desde un satélite GEO para mejorar disponibilidad y continuidad
- El uso de los sistemas SBAS se da en: aviación, agricultura, marítimo, ferrocarril, servicios basados en localización, aplicaciones de tiempo y sincronización, topografía y cartografía
- Los sistemas SBAS operativos en la actualidad son:
  - EGNOS
  - MTSAT (Japan)
  - GAGAN (India)
  - QZSS (componente de aumentación)

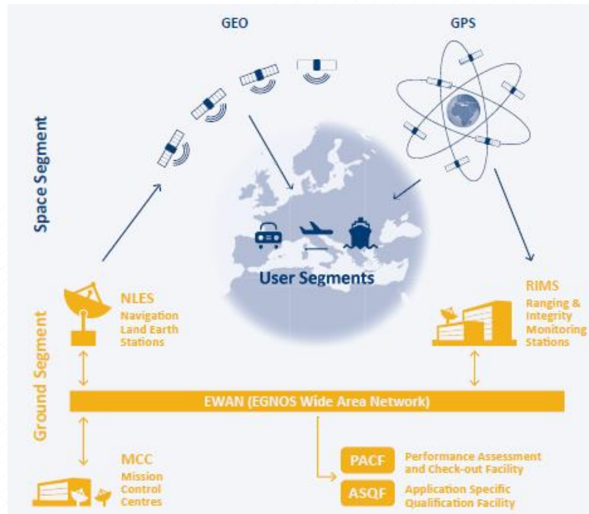
Satellite-Based Augmentation Systems (SBAS)



Source: EUSPA

Satellite-Based Augmentation Systems (SBAS). Arquitectura

- **Segmento espacial**:
  - Satélites GEO con una carga útil SBAS
- **Segmento terreno de control**:
  - Estaciones de referencia (sensing)
  - Centros maestros
  - Estaciones de uplink
- **Segmento usuario**: los receptores capaces de demodular y procesar las señales SBAS



Source: EDAS v2.2

GNSS Interoperablity

- *"Interoperability refers to the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system"* (ICG or International Committee on Global Navigation Satellite Systems)
- In the GNSS context, interoperability should be understood as the capability for user equipment to exploit available navigation signals of different GNSS and to produce a combined solution which generally exhibits performance benefits (e.g. better accuracy, higher availability) with respect to the standalone system solution.
- Interoperability shall be considered at System Level (*capability of all GNSS systems to provide the same solution standalone*) and at Signal Level (next slide)

Source: Navipedia

GNSS Interoperablity at signal level

- For GNSS, signal interoperability considers the following factors
- **Reference Frames**: Two GNSS are said to be interoperable from a reference frame perspective if the difference between frames is below the target accuracy. E.g GPS uses WGS84 and Galileo uses GTRF, with a difference within 3 cm
- **Time Reference**: GPS Time and Galileo System Time (GST) are expected to be within the nanoseconds order of magnitude. the required parameters to transform the GST time to UTC as part of the Galileo navigation messages. The Galileo System provides the “Galileo to GPS Time Offset” (GGTO) as part of the navigation messages.
- Use of the **same carrier frequency**: it has high impact on receiver complexity and cost (e.g. number of bandpass filters)
- **Signals In Space**: design of the modulation, signal structure or selection of the codes that require only “software modifications” at the receiver

Source: Navipedia

GNSS Interoperablity. Performance of multiconstellation receivers

- A multi-constellation receiver can access signals from several constellations: e.g. GPS, Galileo, GLONASS and BeiDou
- Having a larger number of satellites in the field of view of the satellite outperforms single GNSS receivers in the following terms:
  - Reduced signal acquisition time
  - Improved position and time accuracy
  - Reduction of problems caused by obstructions such as buildings and foliage or multipath
  - Improved spatial distribution of visible satellites, resulting in improved dilution of precision (DOP)
  - Improved robustness, as independent systems are harder to spoof than a single one
- To determine position in a single GNSS mode, a receiver must track at least four satellites.
- In multi-constellation mode, the receiver must track five satellites, at least one of which must be from a satellite in the other constellation, so the receiver can determine the time offset between constellations.
- As of 2020, 76% of receivers are multiconstellation (GNSS User Tech Report)

Source: NOVATEL

Overall view of GNSS, RNSS and SBAS

System	GPS	Galileo	GLONASS	BeiDou	NavIC	QZSS	EGNOS
Owner and Operator	USA	EU	Russian Fed.	China	India	Japan	EU
Orbital altitude	20180 km	23222 km	19130 km	21528 km (MEO) 36000 km (IGSO, GEO)	36000 km (GEO, IGSO)	QZO (a=42164 km)	36000 km (GEO)
Orbital period	11h58m	14h5m	11h16m	12h38m	23h56	23h56	23h56
Orbital inclination	55 deg	56 deg	64.8 deg	55 deg	27 deg (IGSO)	43 deg (IGSO)	0 deg
Number of satellites	24+	24+	24+	35	7	3+	(2021)
Services	SPS / PPS	OS / HAS / PRS / SAR	SP / HP	OS / AS (global) WADS / PRS (regional)	SPS / RS	PNT / SLAS / CLAS / PTVS / Q-ANPI / PRS / DC-Report / SBAS	OS / EDAS / SoL
Frequency	1575.42 MHz (L1) 1227.6 MHz (L2) 1176.45 MHz (L5)	1575.42 GHz (E1) 1278.75 MHz (E6) 1191.795 MHz (E5) 1176.450 MHz (E5a) 1207.140 MHz (E5b)	~1602 MHz (~L1) ~1246 MHz (~L2)	1561.098 MHz (B1) 1589.742 MHz (B1-2) 1207.14 MHz (B2) 1268.52 MHz (B3)	1176.45 MHz (L5) 2492.028 MHz (S)	1575.42 MHz (L1) 1227.60 MHz (L2) 1176.45 MHz (L5) 1278.75 MHz (L6) 2 GHz band (S)	1575.42 MHz (L1) 1176.45 MHz (L5) (EGNOS v3)
Signal format	CDMA	CDMA	FDMA	CDMA	CDMA	CDMA	CDMA
Reference frame	WGS84	GTRF	PZ-90	CGCS 2000	WGS84	JGS	ENT
Time reference	GPST	GST	UTC(SU)	BTC	IRNSS System time	QZSSRT	ETRF
Service area	Global	Global	Global	Global	India + 1500km	East Asia, Oceania	Regional
Initial service	Dec 1993	>2016	Sept 1993	Dec 2012			
Status	Operational	Operational	Operational	Operational			Operational

Source: Geospatialworld

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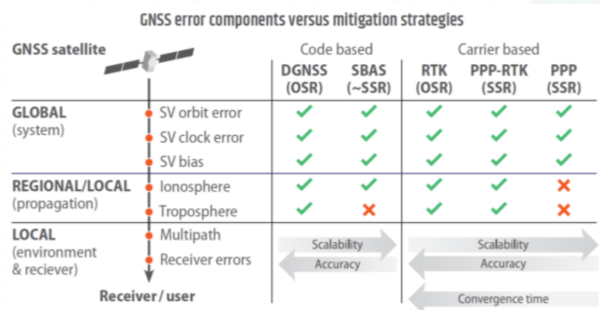
GNSS. Position computing strategies

- GNSS errors are usually reduced via two modelling methods:
  - **Observation Space Representation** (OSR) provides a single compound ranging correction as observed in a nearby (real or virtual) reference station
  - In the **State Space Representation** (SSR) method, the various error sources are estimated separately by a network of continuously operating reference stations (CORS) before being sent to the receiver.
- Depending on the error sources that are compensated, different GNSS position computation strategies can be used



Source: GNSS User Tech Report 2020, EUSPA.

GNSS. Position computing strategies

SPP: Single Point Positioning

PPP: Precise Point Positioning

RTK: Real Time Kinematic

DGNSS: Differential GNSS

SBAS: Satellite-Based Augmentation System

SF: Single Frequency

DF: Dual Frequency

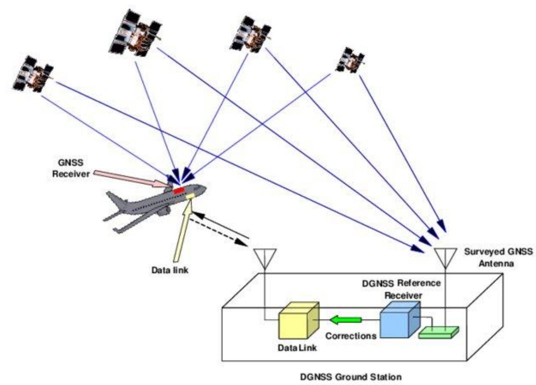
TF: Triple Frequency

Method *	SPP	DGNSS	SBAS	RTK	PPP-RTK	PPP
Observable	Code	Code	Code	Carrier	Carrier	Code/Carrier
Positioning	Absolute (in the GNSS reference frame)	Relative	Relative	Relative	Absolute (in the tracking network reference frame)	Absolute (in the tracking network reference frame)
Comm Link	No	Yes	Yes (GNSS like)	Yes	Yes	Yes
Single Frequency (SF) Dual Frequency (DF) Triple Frequency (TF)	SF or DF	SF	SF current DF planned	Mostly DF	(SF) DF or TF	(SF) DF or TF
Time To First Fix (TTFF)	Rx TTFF	As SPP + time to receive corrections	As DGNSS	As DGNSS + time to resolve ambiguities	Faster than PPP, but slower than RTK	As RTK, but time to estimate ambiguities significantly higher (more unknowns)
Accuracy Horizontal	5-10 m DF 15-30 m SF	< 1 m to < 5 m	< 1 m	1 cm + 1 ppm baseline	< 10 cm	< 10 cm to < 1 m
Coverage	Worldwide	Up to 100s Km	Up to 1000s Km	Up to 10s Km	Regional	Worldwide

Source: GNSS User Tech Report 2020, EUSPA.

GNSS. Position computing strategies. DGNSS

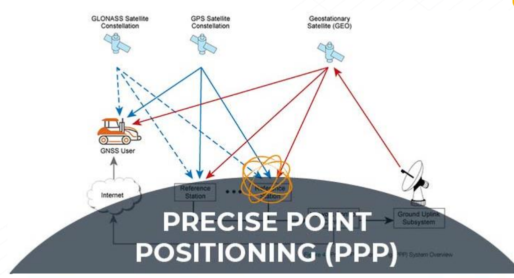
- DGNSS consists in the determination of the GNSS position for an accurately-surveyed position known as reference station
- Given that the position of the reference station is accurately known, the deviation of the measured position to the actual position and more importantly the corrections to the measured pseudoranges to each of the individual satellites can be calculated.
- These corrections can thereby be used for the correction of the measured positions of other GNSS user receivers.
- No integrity is provided

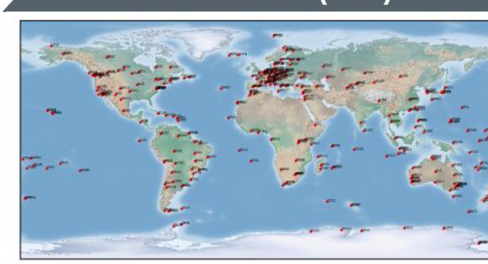


Source: Sabatini, 2017.

GNSS. Position computing strategies. PPP

- PPP is a signal augmentation technique that removes GNSS system using a single reciver
- PPP relies on GNSS satellite ia satellite or Internet clock and orbit corrections provided by a network of global Continuously Operating Reference Stations (CORS)
- After calculation of the corrections, they are transmitted to the user via satelie or the Internet
- Convergence times of 5 to 30 minutes are required to resolve local biases (atospheric conditions, multipath and satellite geometry)

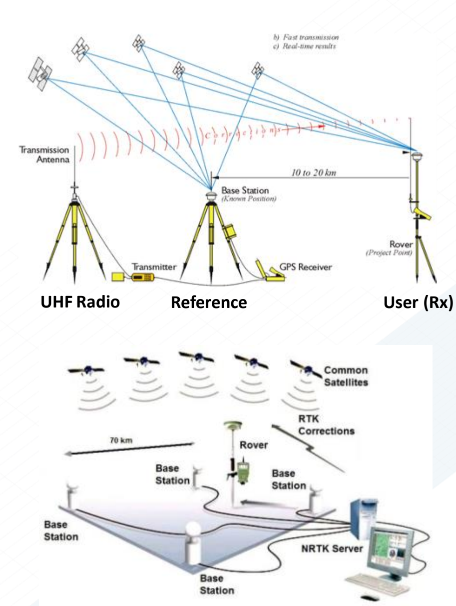




IGS network. Galileo stations
Stations providing GNSS observation data
Source: IGS

GNSS. Position computing strategies. RTK

- RTK is based on the use of carrier measurement and the transmissin of corrctions from a base station (with a location precisely known)
- An RTK base station covers service areas of 30 to 50 km and requires a ral-time communication channelto connect the base station and the receiver
- In Network RTK, corrections are provided for a network of base stations, and the receiver uses the closest base station



RTK (top) and NRTK (bottom)

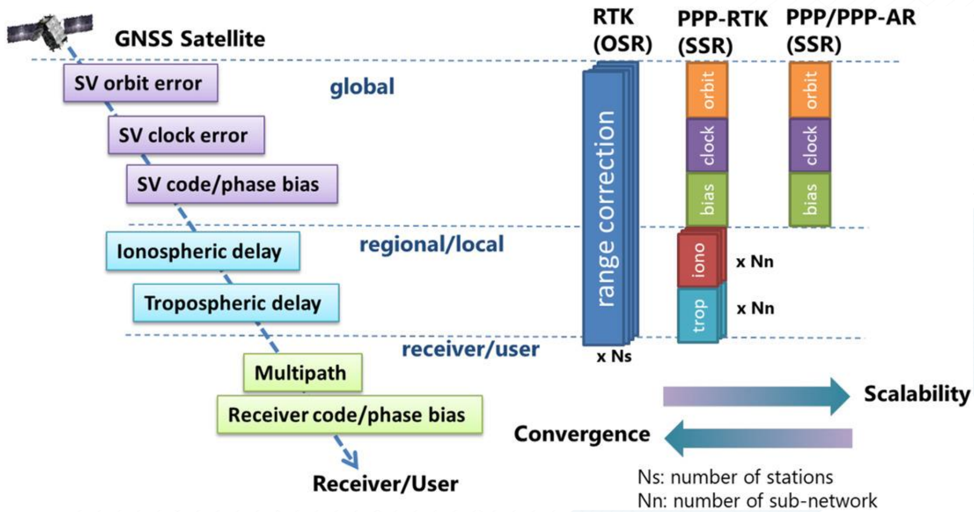
Source: Choy, RMIT University.

GNSS. Position computing strategies. PPP-RTK

- PPP-RTK: augments PPP estimations with precise undifferenced atmospheric corrections and satellite clock corrections from a network of CORS, so that instantaneous ambiguity fixing is achievable for users within the network, these resolved integer ambiguities lead to shorter convergence times
- PPP-RTK uses a map of atmospheric errors generated by a network of CORS, the quality of this map determines the ambiguity resolution capability of the service. This map is most accurate at the location of each CORS (where the data is generated) and as the distance between the rover and the CORS increases the quality of the map degrades, leading to longer convergence times.

Source: PPP-RTK market and tech. report, EUSPA

GNSS. Position computing strategies. PPP, RTK and PPP-RTK



Source: PPP-RTK market and tech. report, EUSPA

GNSS. Position computing strategies. PPP, RTK and PPP-RTK

Solution	Features	Benefits	Drawbacks
PPP	State-space Global No integer nature of ambiguity, i.e. dm accuracy	Has no local ground infrastructure requirements Global	Long convergence times Lower accuracy
RTK	Observation space Local/Regional Integer nature of ambiguity, i.e. cm accuracy	High accuracy (2cm) Near-instant convergence times	Highly reliant upon local ground infrastructure Short range of transmissions
PPP-RTK	State space Local/Regional Integer nature Cm accuracy	Fast convergence times High accuracy Lower density CORS network than NRTK Degrades to standard PPP	Reliant upon local ground infrastructure

Source: PPP-RTK market and tech. report, EUSPA

GNSS system times

- Los sistemas GNSS se basan en el cálculo del tiempo de propagación de las señales transmitidas por los satélites hasta el receptor
- Requieren, por tanto, el uso de relojes precisos y estándares para medir y referenciar el tiempo
- Cada sistema GNSS tiene su propio tiempo de sistema (*system time*)
- Todos están basados en el TAI (International Atomic Time), definido como:

"The TAI second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Cesium 133 atom"

- El TAI se mide combinando las señales de más de 400 relojes atómicos de alta precisión distribuidos por todo el mundo para mantener el "SI second" lo más preciso posible

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GNSS system times

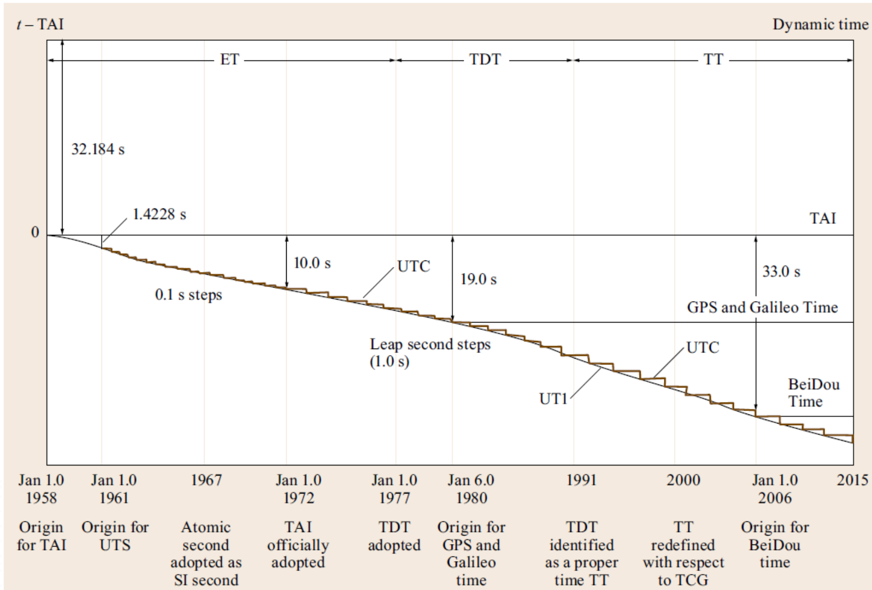
Todos los sistemas GNSS tiene diferentes sistemas de tiempo, con diferentes offsets y orígenes respecto del TAI.

t(GPS) = TAI – 19s

T(GLONASS) = UTC + 3h

t(Galileo) = TAI – 19s

t(BeiDou) = TAI – 33s



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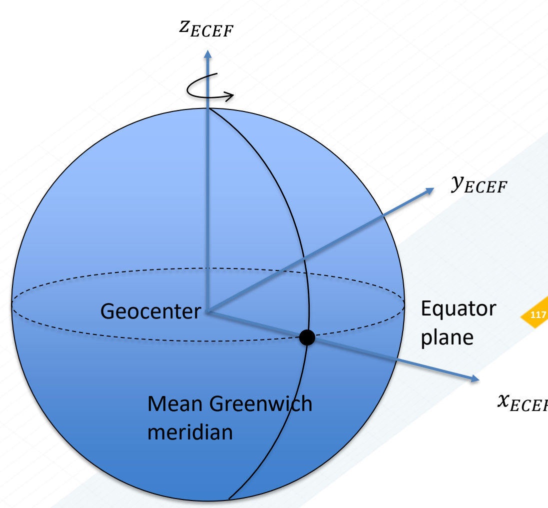
Sistemas de coordenadas. ECEF

- Las coordenadas cartesianas del satélite y receptor deben expresarse en un sistema de referencia
- Se usan sistemas de referencia celestial o terrestre
- Como sistema de referencia terrestre se usa el ECEF (Earth-Centered, Earth Fixed):
  - Origen: centro de la Tierra
  - Eje z: eje de rotación terrestre
  - Eje x: une el centro de la tierra con la intersección del plano ecuatorial y el meridiano de Greenwich promedio



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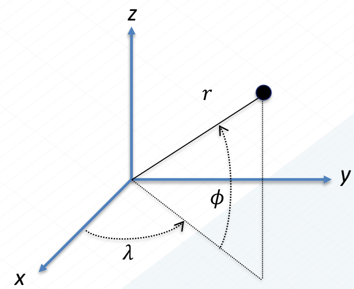
Spatial reference systems

- Para establecer las coordenadas de un punto es necesario definir un sistema de coordenadas con:
  - Origen
  - Orientación
  - Escala
- Por ellos, es necesario definir:
  1) Sistema de coordenadas para fijar objetos en el universo que no tenga rotación en el tiempo
  2) Sistema de coordenadas referenciado a Tierra para relacionar objetos en tierra y satélites orbitando alrededor

- Sistemas de coordenadas cartesianos y esféricos (coord. esféricas lat(ϕ), lon(λ))



$$x = r\cos\phi\cos\lambda$$
$$y = r\cos\phi\sin\lambda$$
$$z = r\sin\phi$$

$$r = \sqrt{x^2 + y^2 + z^2}$$
$$\lambda = \tan^{-1}\left(\frac{y}{x}\right)$$
$$\phi = \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right)$$

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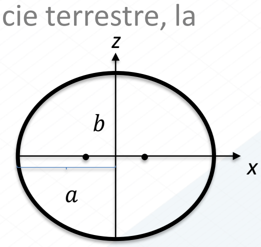
Elipsoides de referencia

- Para establecer las coordenadas geodéticas respecto de la superficie terrestre, la Tierra se modela como un elipsoide de revolución
- Sus parámetros son:
  - Semieje mayor a y semieje menor b
  - Flattening (achatamiento): $f = \frac{a-b}{a}$
- Los elipsoides de referencia se basan en medidas geodéticas, incluyendo satélites, o en modelos del potencial gravitatorio terrestre
- El elipsoide adoptado internacionalmente es el GRS80:
  - $a = 6\,378\,137\ m$
  - $f = \frac{1}{298.257222101}$
- Cada sistema GNSS tiene su propio elipsoide de referencia para situar un punto respecto de la superficie terrestre



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Relación entre coordenadas cartesianas y coordenadas geodéticas

De coordenadas cartesianas a geodéticas (elipsoide):

$x = (N + h)\, cos\varphi\, cos\lambda$

$y = (N + h)\, cos\varphi\, sin\lambda$

$z = \left((1 - e^2)N + h\right) sin\varphi$

De coordenadas geodéticas (elipsoide) a cartesianas:

$\lambda = tan^{-1}\left(\frac{y}{x}\right)$

Mediante un proceso iterativo, se obtiene h y φ

Valores iniciales:

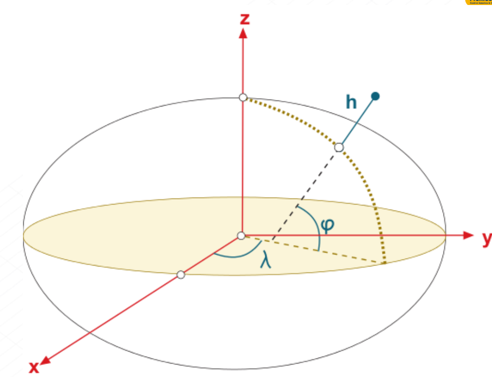
$$\varphi(0) = tan^{-1}\left(\frac{z}{(1-e^2)p}\right), p = \sqrt{x^2 + y^2}$$

Iteraciones ($i = 1, \ldots$):

$$N(i) = \frac{a}{\sqrt{1+e^2 sin^2\varphi(i-1)}}$$

$$h(i) = \frac{p}{cos\varphi(i-1)} - N(i)$$

$$\varphi(i) = tan^{-1}\left(\frac{z}{\left(1-e^2\frac{N(i)}{N(i)+h(i)}\right)p}\right)$$

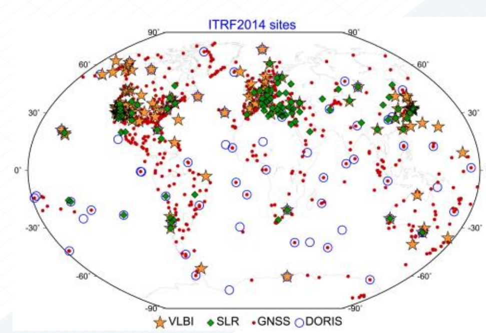


Coordenadas geodéticas:

- Latitud geodética (φ)
- Longitud geodética o esférica (λ)
- Altura geodética (h)
- N : radio de cobertura del elipsoide en la dirección perpendicular al plano elíptico meridiano

Sistemas de referencia terrestres usados en GNSS

- Cada sistema GNSS debe adoptar un sistema de referencia para posicionar receptores, estaciones y satélites
  - GPS: WGS84
  - Galileo: GRTF
  - Glonass: PZ90
  - Beidou: CGCS 2000
- Los diferentes sistemas deberían estar alineados con el ITRF (International Terrestrial Reference Frame)
  - Representa la capa de referencia más básica para los datos espaciales del planeta Tierra
  - Su red es lo suficientemente densa como para establecer y desarrollar marcos a escala regional y nacional
  - Estándar global para todas las actividades que requieren datos de posición
- Existen sucesivas versiones del ITRF que se van actualizando de acuerdo con las variaciones de los parámetros que lo conforman
- El ITRF se actualiza según los datos recogidos en una red de estaciones GNSS, VLBI, SLR y DORIS distribuidas en todo el mundo



Source: Altamimi

Reference frames in GNSS

WGS84 (GPS)

Ellipsoid		
Semi-major axis of the ellipse	a	$6\,378\,137.0\ m$
Flattening factor	f	$1/298.257223563$
Earth angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}\ rad/s$
Gravitational constant	μ	$3\,986\,004.418 \cdot 10^{8}\ m^3/s^2$
Speed of light in vacuum	c	$2.99792458 \cdot 10^{8}\ m/s$

PZ90 (Glonass)

Ellipsoid		
Semi-major axis of the ellipse	a	$6\,378\,136.0\ m$
Flattening factor	f	$1/298.257839303$
Earth angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}\ rad/s$
Gravitational constant	μ	$3\,986\,004.4 \cdot 10^{8}\ m^3/s^2$
Speed of light in a vacuum	c	$2.99792458 \cdot 10^{8}\ m/s$
Second zonal harmonic coefficient	J_2^0	$1\,082\,625.75 \cdot 10^{-9}$

Source: Navipedia