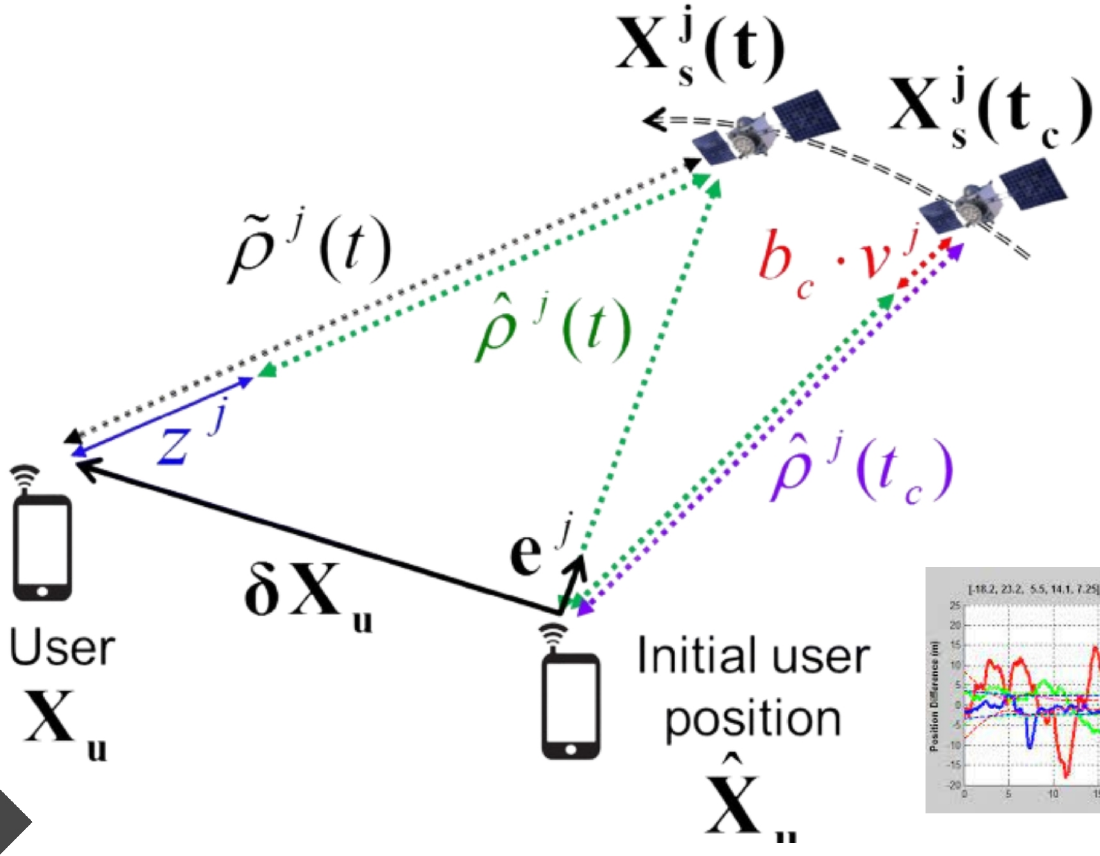
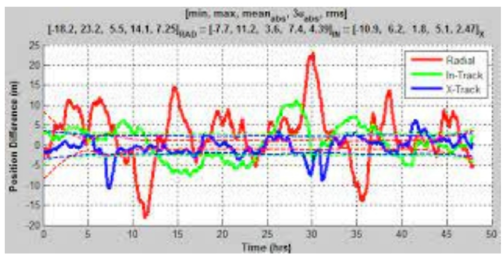
BSc Surveying Sciences
Year II Semester II
Department of Surveying & Geodesy
Faculty of Geomatics
Sabaragamuwa University of Sri Lanka 70140 Belihuloya

COURSE MATERIAL :

ADVANCED CONCEPTS OF GNSS





Curricula Enrichment delivered through the Application of Location-based Services to Intelligent Transport Systems (LBS2ITS)

Erasmus+

Co-funded by the Erasmus+ Programme of the European Union

SG 32211 – Advanced Concepts of GNSS

Course/Teaching material

Contents

Module Overview

This course is intended for students who have completed the theory and hands-on experience with fundamentals in GNSS, and who are looking advance knowledge on GNSS measurements, error sources and mitigation. In addition, this course aims to explore the theoretical concepts related with location-based services (LBS).

Learning Outcomes and Academic Skills

By the end of the course, students should be able to:

- Explain the mathematical models of GNSS measurements and error sources
- Explain the precise positioning with carrier phase and integer ambiguity resolution
- Perform Precise Point Positioning (PPP) technique through applying correction models
- Differentiate and apply free and open source software for GNSS data processing
- Explain the methods and use of mobile devices for indoor positioning

Assessment

Individual course work	40 %
Reports/Presentations	30 %
Individual course work	30 %

Teaching Organization

TEACHING ACTIVITY	*SEMESTER WORKLOAD (HOURS)*
lectures	23 hours
exercises / assignments	4 hours
final examination	2 hours
other (specify):	
Preparation - Student Centred Learning activities	23 hours
Lab Practical activities	20 hours
Self-Learning (Library & Internet)	24 hours
Field reports and presentations	4 hours
total number of hours	100 hours

1.0 GNSS Measurements and Error Sources

What is Global Navigation Satellite Systems (GNSS)?

Global navigation satellite system (GNSS) is a general term describing any satellite constellation that provides positioning, navigation, and timing (PNT) services on a global or regional basis. GNSS provides global coverage. Examples of GNSS include Europe's Galileo, the USA's NAVSTAR Global Positioning System (GPS), Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and China's BeiDou Navigation Satellite System.

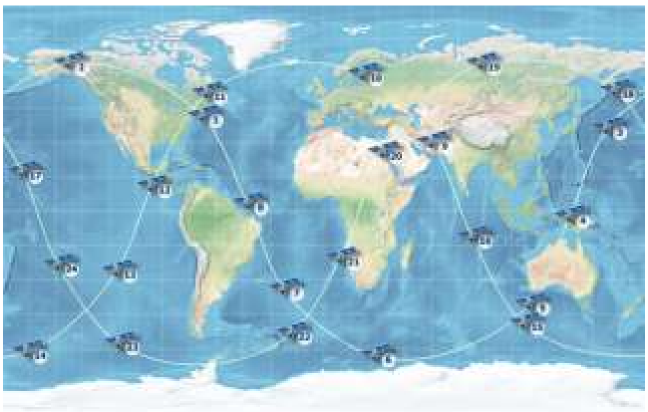
Performance of GNSS based on four (04) criteria:

1. Accuracy: the difference between a receiver's measured and real position, speed or time;
2. Integrity: a system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm;
3. Continuity: a system's ability to function without interruption;
4. Availability: the percentage of time a signal fulfils the above accuracy, integrity and continuity criteria.

GLONASS

Operated by the Russian Federation. The operational system consists of 24+ satellites.

https://glonass-iac.ru/en/about_glonass/

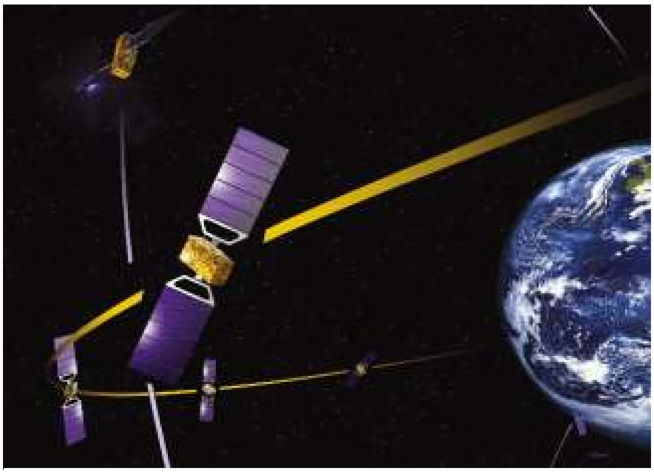


GLONASS capability enhancement:

Capabilities	**Glonass**	**Glonass-M**	**Glonass-K**	**Glonass-K2**
Time of Deployment	1982-2005	2003-2016	2011-2018	2017+
Status	Decommissioned	In use	Design maturation based on in-orbit validation	In development
Nominal Orbit Parameters	Circular Altitude - 19,100 km Inclination - 64,8° Period - 11 h 15 min 44 sec			
Number of Satellites in the Constellation (Used for Navigation)	24			
Number of Orbital Planes	3			
Number of Satellites in a Plane	8			
Launchers		Soyuz-2.1b, Proton-M		
Design Lifetime, years	3.5	7	10	10
Open Access Signals (for FDMA Signals Center Frequency Values are Provided)	L1OF (1602 MHz)	L1OF (1602 MHz) L2OF (1246 MHz) L3OC (1202 MHz) for SVs 755+	L1OF (1602 MHz) L2OF (1246 MHz) L3OC (1202 MHz) L2OC (1248 MHz) for SVs 17L+	L1OF (1602 MHz) L2OF (1246 MHz) L1OC (1600 MHz) L2OC (1248 MHz) L3OC (1202

Galileo

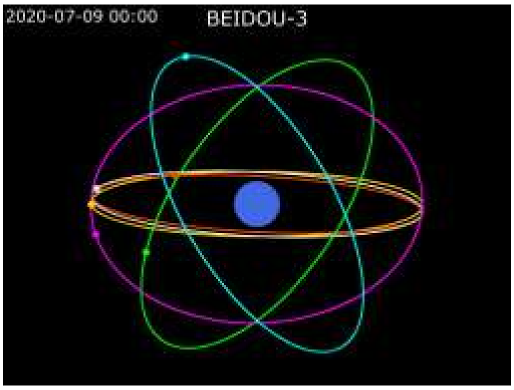
Galileo is a global GNSS owned and operated by the European Union. The EU declared the start of Galileo Initial Services in 2016 and planned to complete the system of 24+ satellites by 2020 (currently 30 satellites). Galileo is interoperable with GPS and Glonass.



https://www.esa.int/Applications/Satellite_navigation/Galileo/Galileo_satellites

BeiDou Navigation Satellite System (BDS)

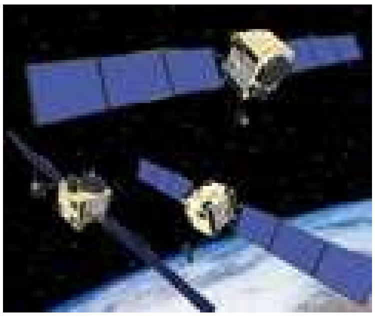
BeiDou, or BDS, is now a global GNSS owned and operated by the People's Republic of China. BDS was previously called Compass. Expanded the system to provide global coverage with 35 satellites by 2020. BDS-3 (BeiDou-3) was commissioned in August 2020. Currently 42 operational satellites. With BDS-3, full global coverage for PNT, offered an alternative to Russia's **GLONASS**, the European **Galileo**, and the US's **GPS**.

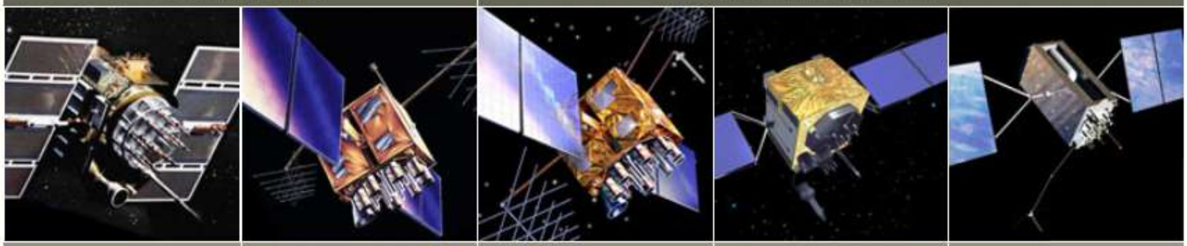


http://en.beidou.gov.cn/

Global Positioning System (GPS)

The Global Positioning System (GPS) is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services. This system consists of three segments: the space segment, the control segment, and the user segment. The U.S. Air Force develops, maintains, and operates the space and control segments.





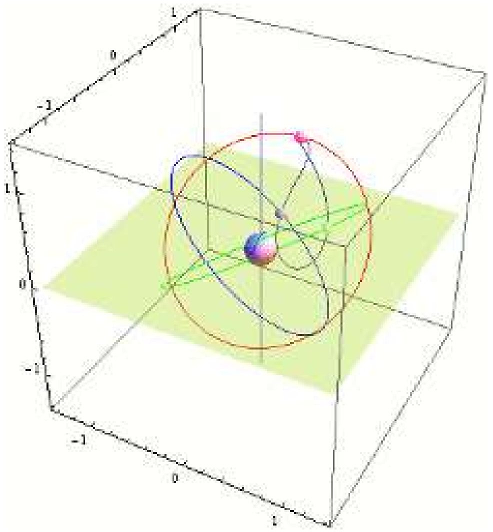
LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	6 operational	7 operational	12 operational	6 operational
▪ Coarse Acquisition (C/A) code on L1 frequency for civil users ▪ Precise P(Y) code on L1 & L2 frequencies for military users ▪ 7.5-year design lifespan ▪ Launched in 1990-1997 ▪ Last one decommissioned in 2019	▪ C/A code on L1 ▪ P(Y) code on L1 & L2 ▪ On-board clock monitoring ▪ 7.5-year design lifespan ▪ Launched in 1997-2004	▪ All legacy signals ▪ 2nd civil signal on L2 (L2C) *LEARN MORE* ➡ ▪ New military M code signals for enhanced jam resistance ▪ Flexible power levels for military signals ▪ 7.5-year design lifespan ▪ Launched in 2005-2009	▪ All Block IIR-M signals ▪ 3rd civil signal on L5 frequency (L5) *LEARN MORE* ➡ ▪ Advanced atomic clocks ▪ Improved accuracy, signal strength, and quality ▪ 12-year design lifespan ▪ Launched in 2010-2016	▪ All Block IIF signals ▪ 4th civil signal on L1 (L1C) *LEARN MORE* ➡ ▪ Enhanced signal reliability, accuracy, and integrity ▪ No Selective Availability *LEARN MORE* ➡ ▪ 15-year design lifespan ▪ IIIF: laser reflectors; search & rescue payload ▪ First launch in 2018

https://www.gps.gov/

Other GNSS

Regional and Satellite based augmentation systems (SBAS) are also considered as GNSS

Quasi-Zenith Satellite System (QZSS)



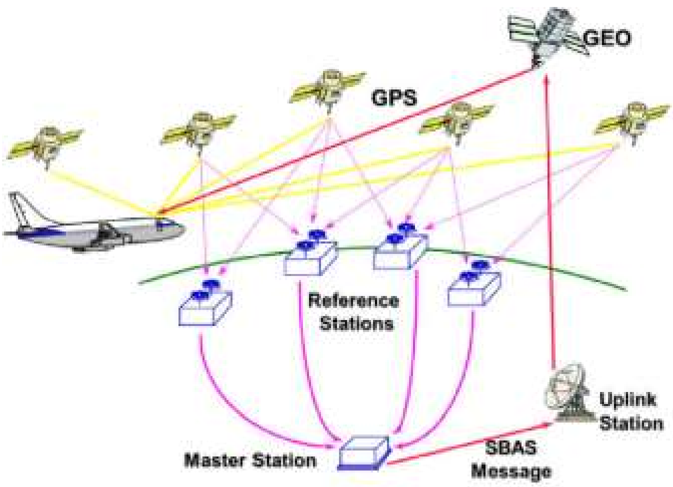
QZSS is a regional GNSS owned by the Government of Japan and operated by QZS System Service Inc. (QSS). QZSS complements GPS to improve coverage in East Asia and Oceania. Japan declared the official start of QZSS services in 2018 with 5 operational satellites, and plans to expand the constellation to 7 satellites by 2025 for autonomous capability

https://qzss.go.jp/en/

Indian Regional Navigation Satellite System (IRNSS) / Navigation Indian Constellation (NavIC)

IRNSS is a regional GNSS owned and operated by the Government of India. IRNSS is an autonomous system designed to cover the Indian region and 1500 km around the Indian mainland. The system consists of 8 satellites. In 2016, India renamed IRNSS as the Navigation Indian Constellation (NavIC, meaning "sailor" or "navigator").

Satellite-based Augmentation (SBAS) Systems

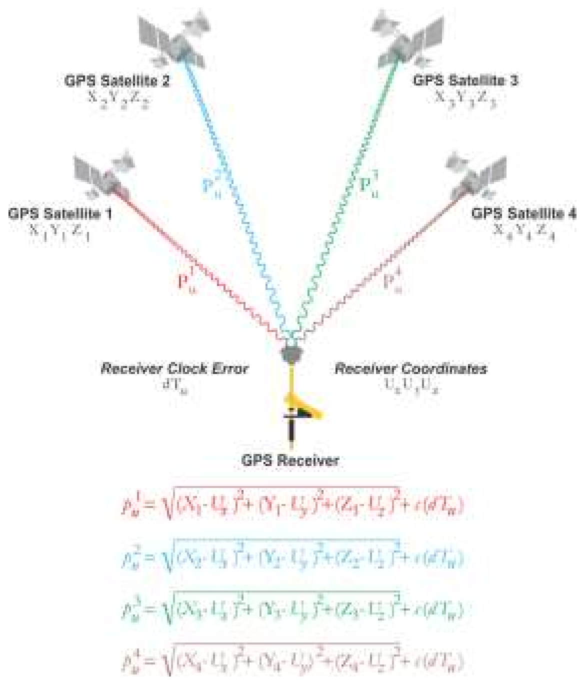


A satellite-based augmentation system is any system that aids GNSS by providing accuracy, integrity, availability, or any other improvement to positioning, navigation, and timing that is not inherently part of GNSS itself.

1.1 Code and Carrier Measurement Models

GNSS is Based on trilateration. It determines position by measuring distances to points at known coordinates. Trilateration requires 3 ranges to 3 known points. GPS point positioning requires 4 "Pseudoranges" to 4 satellites.

The satellite navigation observables are ranges which are deduced from measured time or phase differences. They are based on a comparison between received signals and receiver-generated signals. Satellite navigation uses the "one-way concept" where two clocks are involved, namely one in the **satellite** and the other in the **receiver** The ranges are biased by satellite and receiver clock errors and, consequently, they are denoted as **Pseudoranges**



Pseudorange = (time difference) × (speed of light)

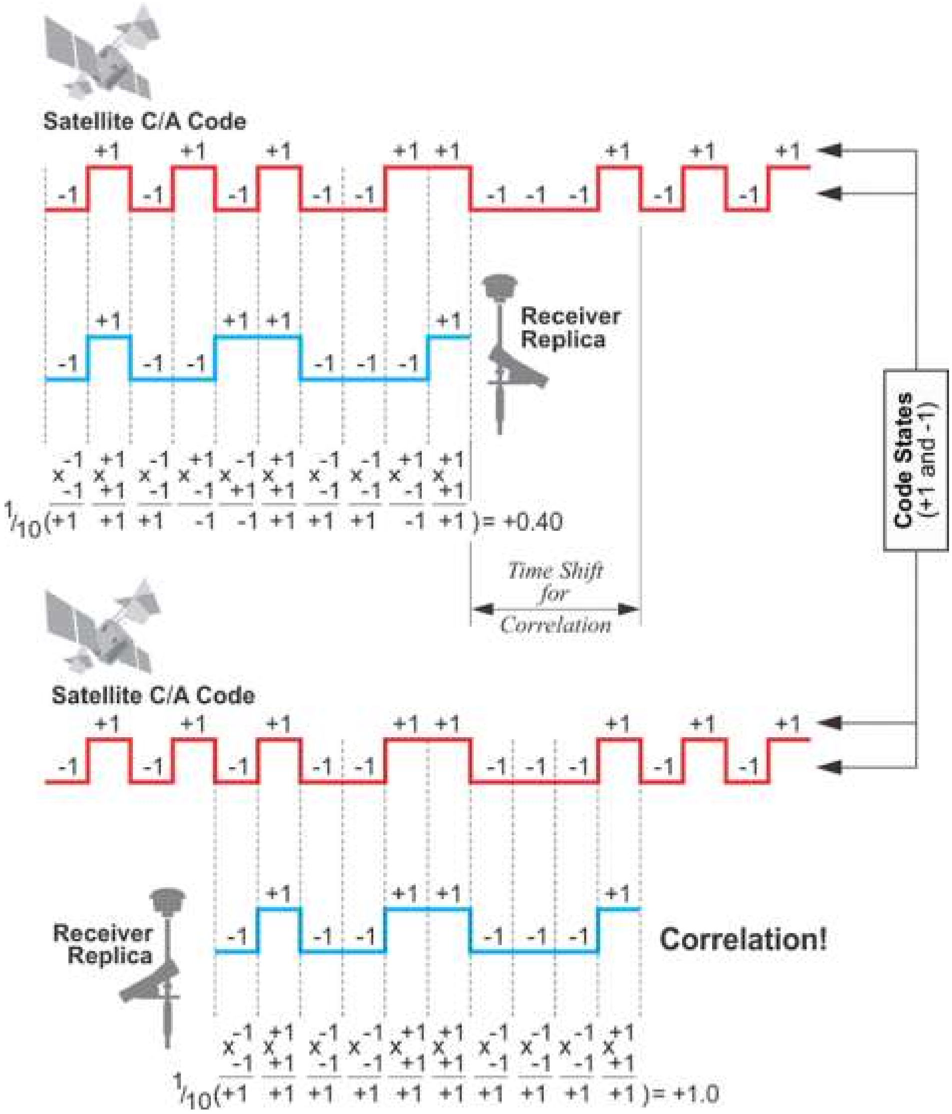
How do we know the position of the satellites?

"Navigation Message," which can be read by the user's GPS receivers. It includes orbit parameters (broadcast ephemeris) from which the receiver can compute satellite coordinates (X,Y,Z) which are Cartesian coordinates in a geocentric system, known as WGS-84. Algorithm which transforms the orbit parameters into WGS-84 satellite coordinates at any specified time is called the "Ephemeris Algorithm".

GPS signal transmission and reception

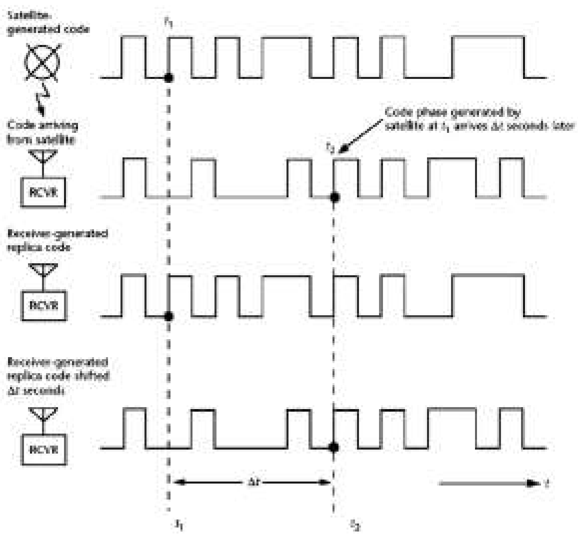
Signals are boosted by an amplifier. Antenna of satellite radiate the signal into space in the form of electromagnetic waves. The GPS signal starts in the satellite as a voltage which oscillates at the fundamental clock frequency of 10.23 MHz and then separately multiplied in frequency by the integers 154, 120 and 115, to create the L1 , L2 and L5 carrier waves. GPS signals modulated into the carrier waves (L1, L2 and L5) which are random binary codes (C/A, P, M, navigation message, etc.) called **Pseudo Random Noise codes (PRN codes).**

Signal transmit at very close to the speed of light in a vacuum, and signal then enters the receiver and measures it using a process known as "autocorrelation."



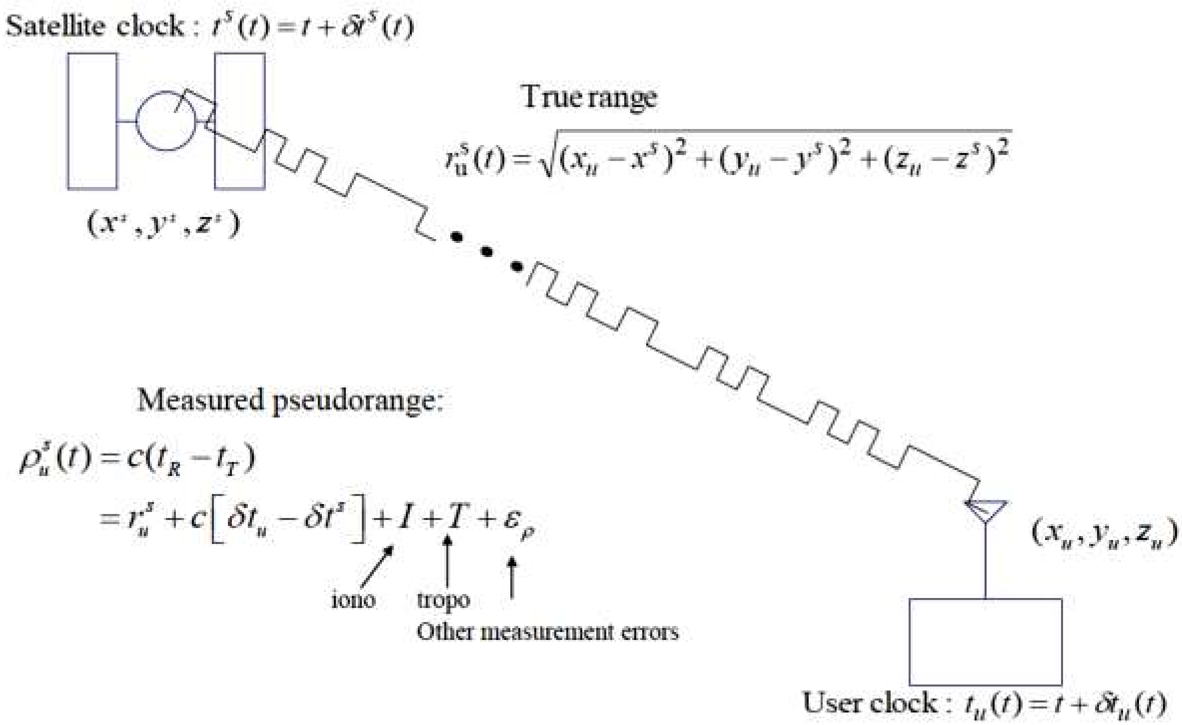
Autocorrelation process

Code (Pseudorange) Measurements



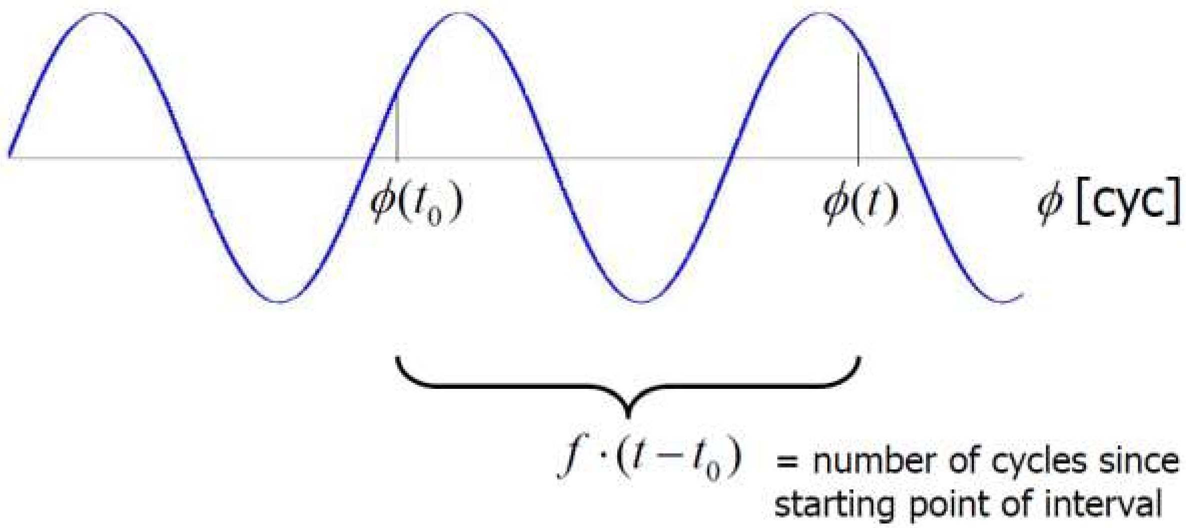
- **With a perfect user clock, signal transit time can be multiplied by the speed of light to yield a range measurement**
- **With an imperfect user clock, measured transit time for each satellite's signals are biased by a common user clock error – measurements are referred to as *pseudorange.***

Code (Pseudorange) Measurement model



Carrier Phase measurements

"Phase," "Frequency" and "Clock Time"

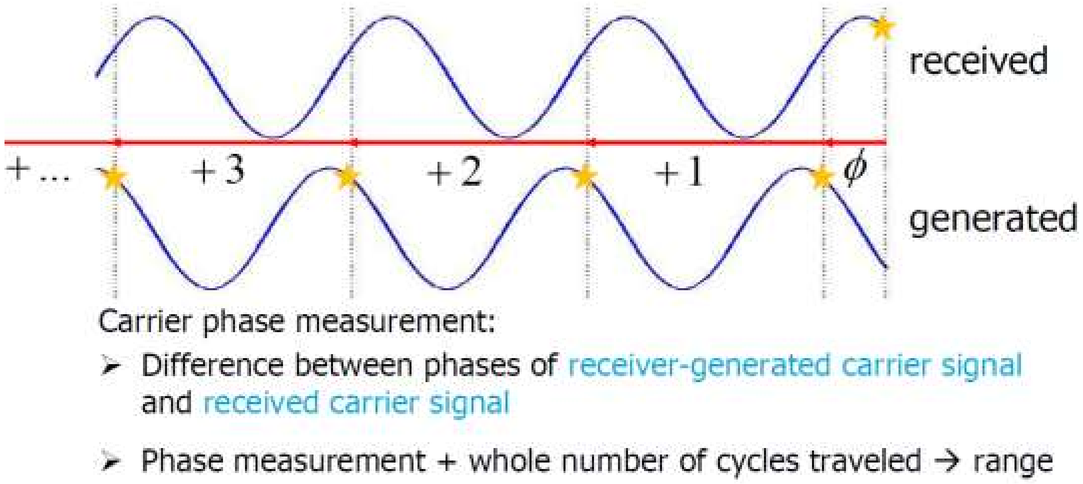


Carrier Phase:

$$\phi(t) = \phi(t_0) + f \cdot (t - t_0)$$

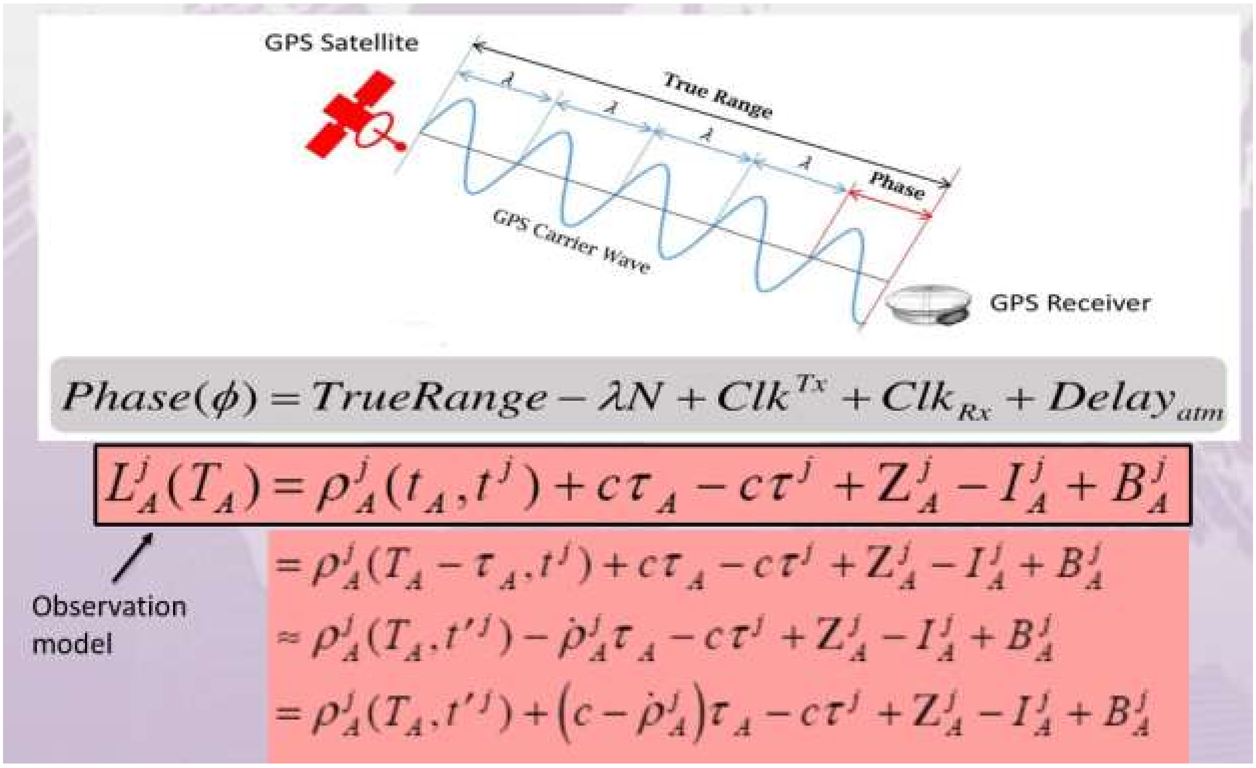
Phase Ambiguity

Only record the fractional phase of the first measurement. Integer number of cycles, N, is unknown



$$\Phi + N = \varphi_R - \varphi_G$$

Observation Model



How can phase be used to measure distance?

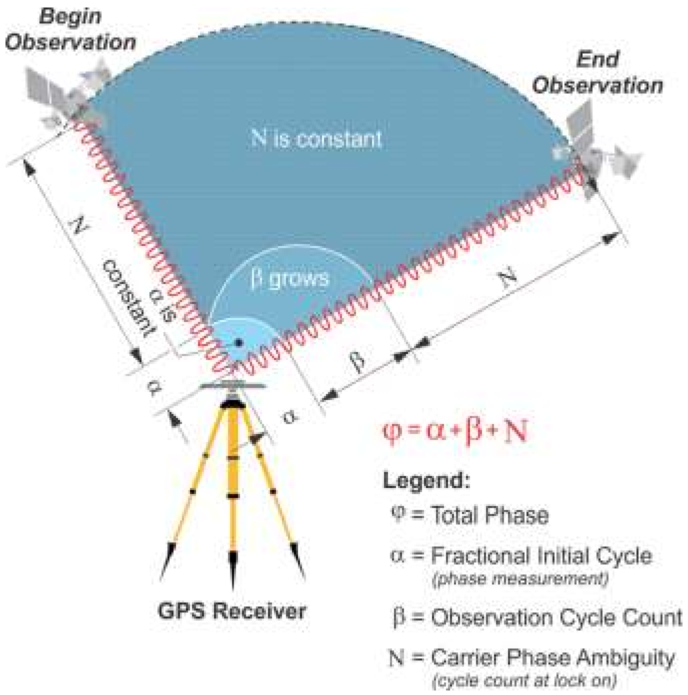
Phase link to clock time and then develop phase as the pseudorange model

Components of the Carrier Phase Observable

Three parts:

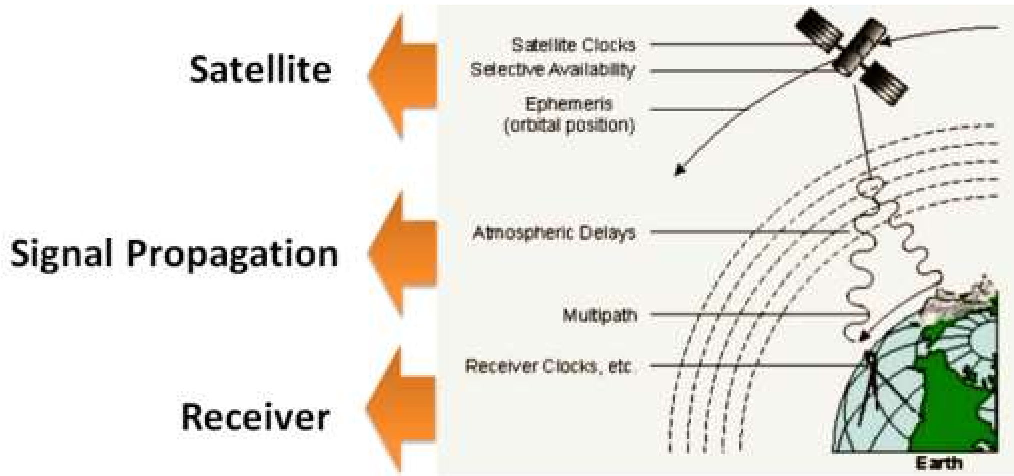
The fractional initial phase and integer cycle ambiguity N at the first instant of the lock-on do not change during the session (if no cycle slips)

The number of full phase cycles grows from the moment of lock on until the end of the observation (as the satellite moves from one place to another



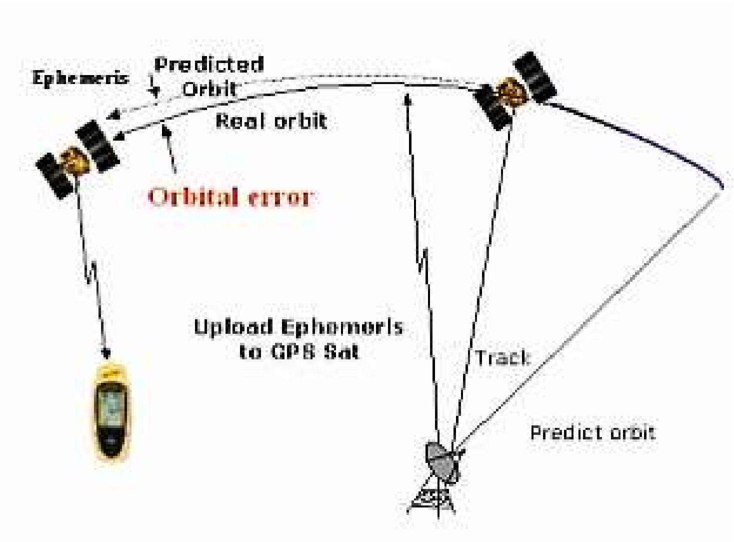
1.2 Measurement errors and modeling

GPS measurements are affected by random and systematic errors which affects the accuracy of measurements



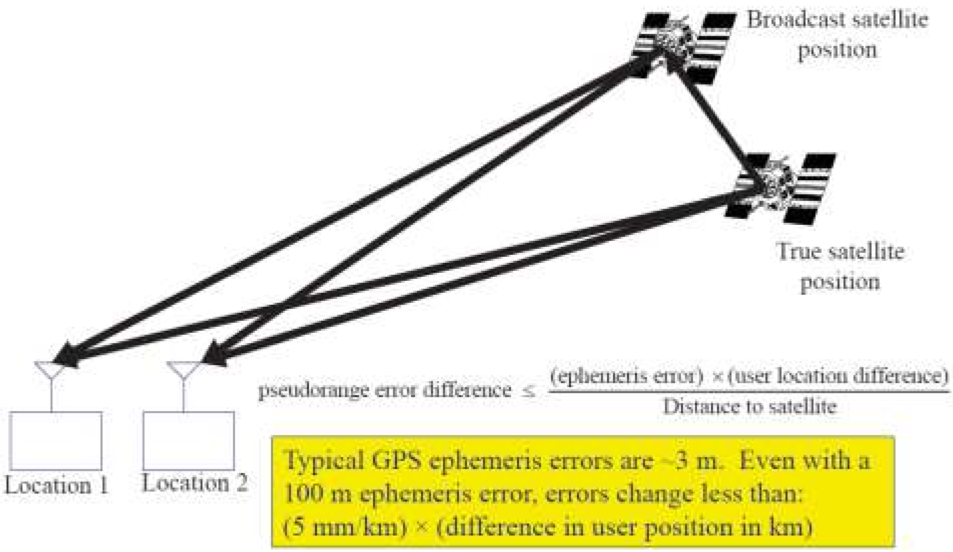
Ephemeris or Orbital error

Ephemeris errors are differences between true satellite position (real orbit) and position computed using GNSS navigation message (predicted orbit)



Estimate ephemeris (orbital) error:

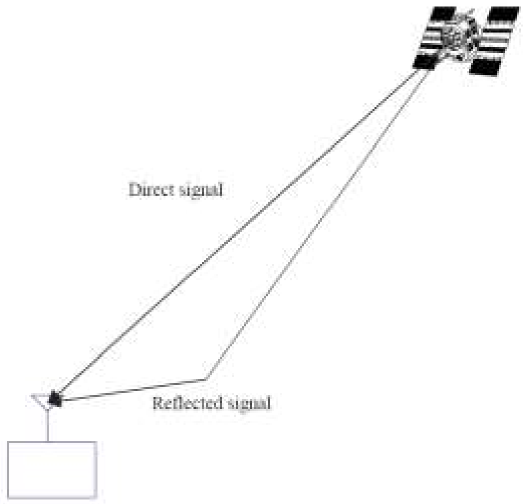
$$\frac{\text{Satellite Position Error}}{\text{Range Satellite}} = \frac{\text{Baseline Error}}{\text{Baseline Length}}$$

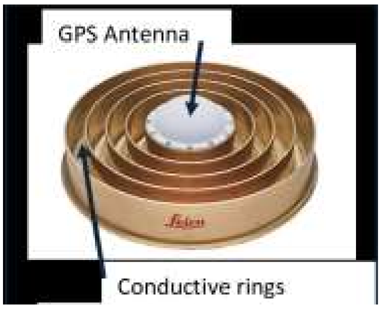


Satellite and Receiver Clock Errors

Can be removed through differencing between the receivers. Also, by applying the satellite clock correction in the navigation message. In contrast, GPS receivers use inexpensive crystal clocks, so the receiver clock error is much larger than the satellite clock error. Can be removed through differencing between the satellites or treating as an additional unknown parameter in the estimation process

Multipath

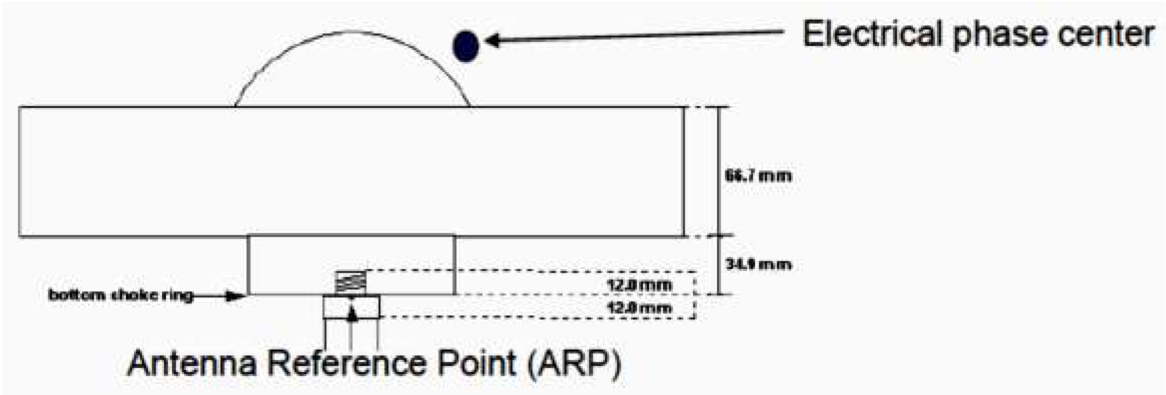




The best way to eliminate this error is to construct the observation site with no reflecting surfaces. Another option is to use a choke ring antenna

Antenna Phase Center Variation

Antenna phase center varies depending on elevation, azimuth of GPS satellite and signal intensity, and antenna type. This results range error. The error is in the order of few *cm* depending on antenna type.



Receiver Measurement Noise

This results from the limitations of receiver's electronics and a good GPS system should have a minimum noise level.

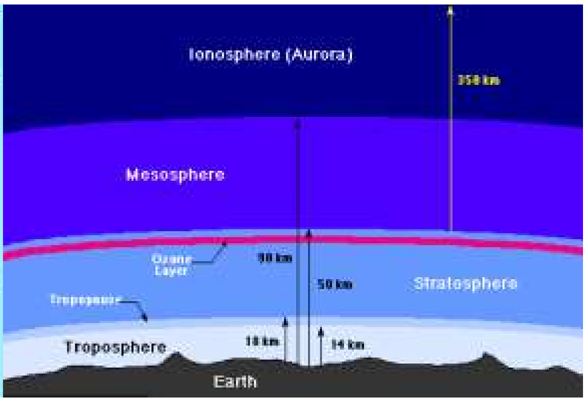
1.3 Signal Propagation errors and modeling

Subdivision of the Atmosphere

With respect to signal propagation a subdivision into ***troposphere*** and ***ionosphere***

- Troposphere (0-40 km) – Signal propagation depends mainly on the water vapour content and on temperature
- Ionosphere (70-1000 km) – Signal propagation is mainly affected by free charged particles

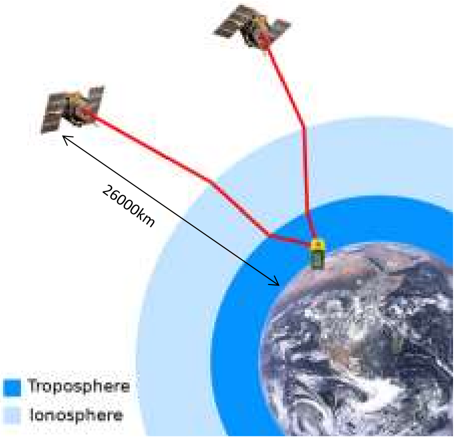
Altitude [km]	Temperature	Ionisation	Magnetic field	Propagation	Technical
100 000	Thermo - sphere	Protono - sphere	Magneto - sphere	Iono - sphere	Upper Atmo - sphere
10 000					
1 000		Iono - sphere			
100	Mesosphere				
	Stratosphere				
10	Troposphere	Neutro - sphere	Dynamo - sphere	Tropo - sphere	Lower Atmo - sphere



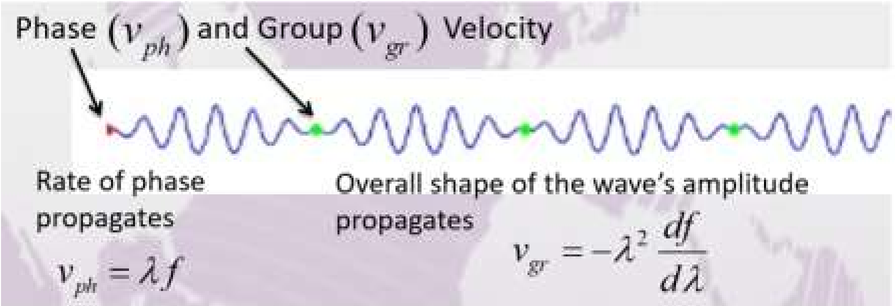
Ionosphere

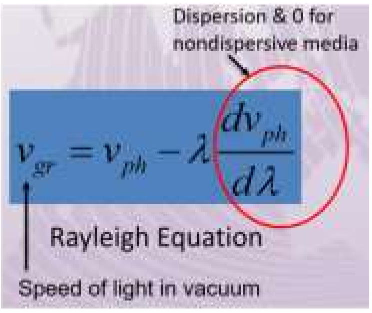
The upper part of the Earth's atmosphere (70-1000 km). There, ultraviolet and X-ray radiations coming from Sun interact with gas, molecules and atoms resulting gas ionization.

Electron density is not constant and divided into sub regions/layers vary with time. Dispersive medium (bend and change speed)



Phase and group velocity





With refractive index ,$v = \frac{c}{n}$, how the wave propagates through the medium. c is the speed of the light in a vacuum.

Modified Rayleigh Equation:

$$n_{gr} = n_{ph} + f\frac{dn_{ph}}{df}$$

Ionospheric Refraction

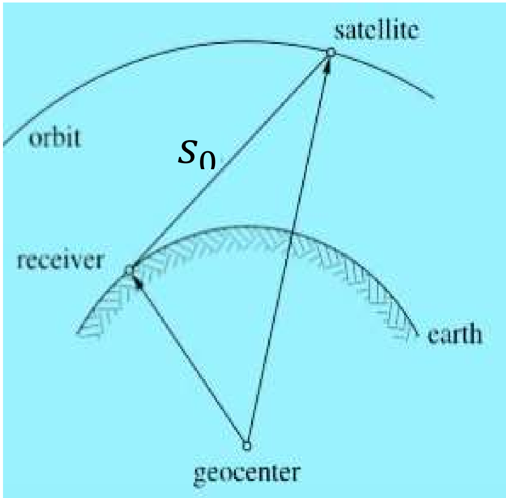
The phase refractive index

$$n_{ph} = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \frac{c_4}{f^4} + \ldots$$

The coefficients *c*2, *c*3, *c*4 depend on **electron density,** N_e (number of electrons per cubic meter). Pseudorange (measured range) = Geometric range (actual range) + Range correction (Ionospheric refraction)

$$s = s_0 + \Delta^{\text{Iono}}$$

Δ^{Iono} - Ionospheric refraction



With phase and group refractive index:

$$\Delta_{ph}^{Iono} = -\frac{40.3}{f^2}TEC \qquad \Delta_{gr}^{Iono} = \frac{40.3}{f^2}TEC$$ in meters

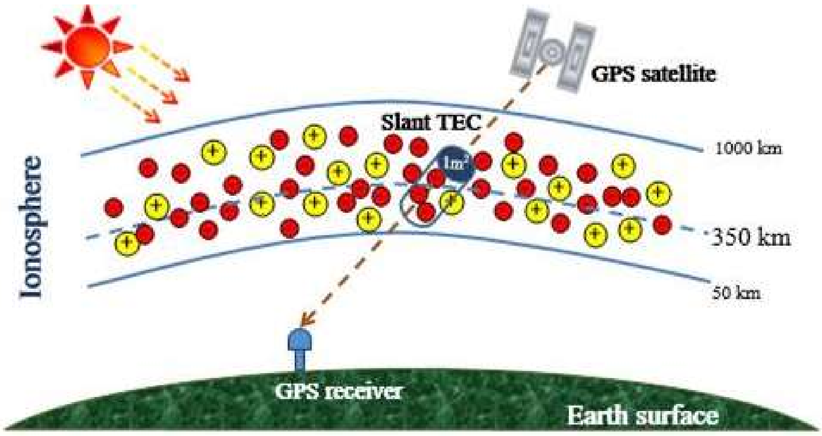
The TEC, Total Electron Content, is given in TEC units (TECU)

$$1\text{TECU} = 10^{16} \text{ electrons per } m^2$$

Ex. the delay $\Delta_{ph}^{Iono} = 0.18m$,if frequency 1.5GHz and 1 TECU

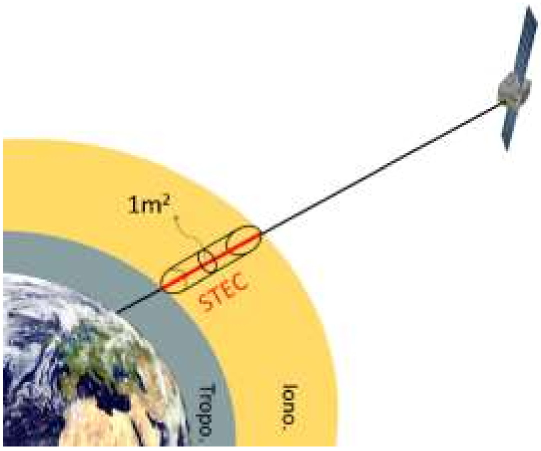
Total Electron Content (TEC)

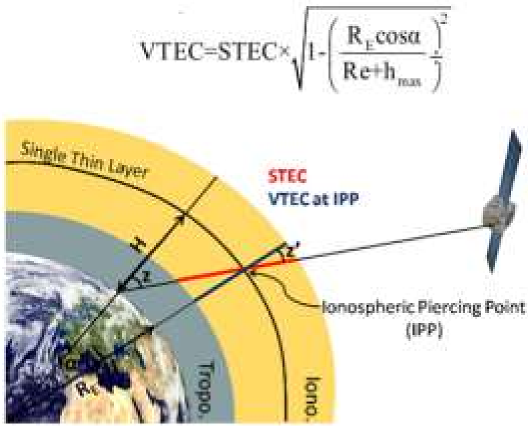
TEC is the total number of electrons integrated between two points, along a tube of one meter squared cross section



Slant & Vertical Total Electron Content (STEC & VTEC):

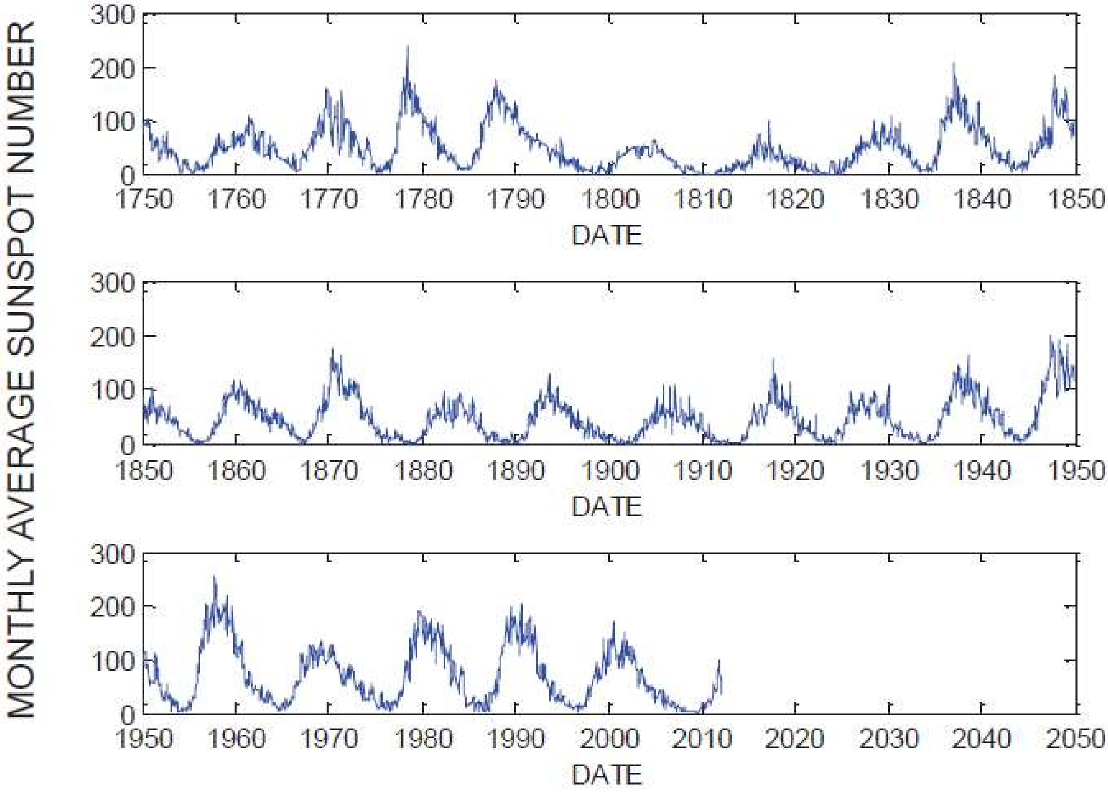
TEC calculated on the path different than zenith is STEC and local zenith is VTEC



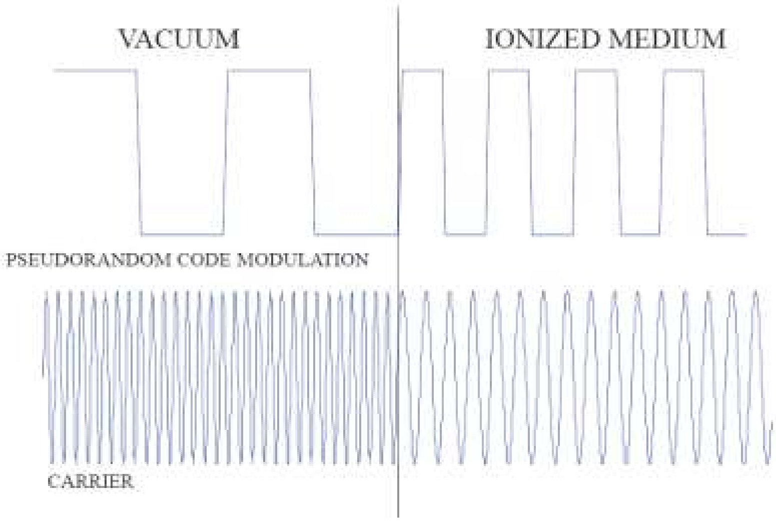


TEC depends on number of factors:

- The time of the day (max in early afternoon and min around midnight)The time of the year (higher in winter than in summer)
- The 11-year solar cycle (reach a max value approx. every 11 years)
- The Geographic location (minimum in mid latitude regions and highly irregular in polar and equatorial regions)



Ionospheric Divergence



- As the distance between the user and a GPS satellite grows:

  – the number of carrier wavelengths in between grows

  – the number of code chips in between grows

- When the number of free electrons in the ionosphere grows (with distance between the user and GPS satellite fixed):

– the number of carrier wavelengths between the user and the GPS satellite decreases (phase velocity increases)

– the number of code chips between the user and the GPS satellite increases (group velocity decreases)

- Care must be taken when aiding code pseudorange measurements with carrier phase measurements

Correcting for Ionospheric Delay Errors

- Ionospheric modelling (global and local).
- It is difficult to find a satisfying model for the TEC because of the various time-dependent influences.
- The most efficient method is the Elimination of TEC using linear combination of dual frequency measurements (L1 & L2)

Dual-frequency user:

Ionospheric delay effects are dispersive – delays are inversely proportional to carrier frequency squared

First-order ionospheric delay depends on inverse of squared frequency along the ray path

$$\Delta^{Iono} = \frac{40.3}{f^2} STEC$$

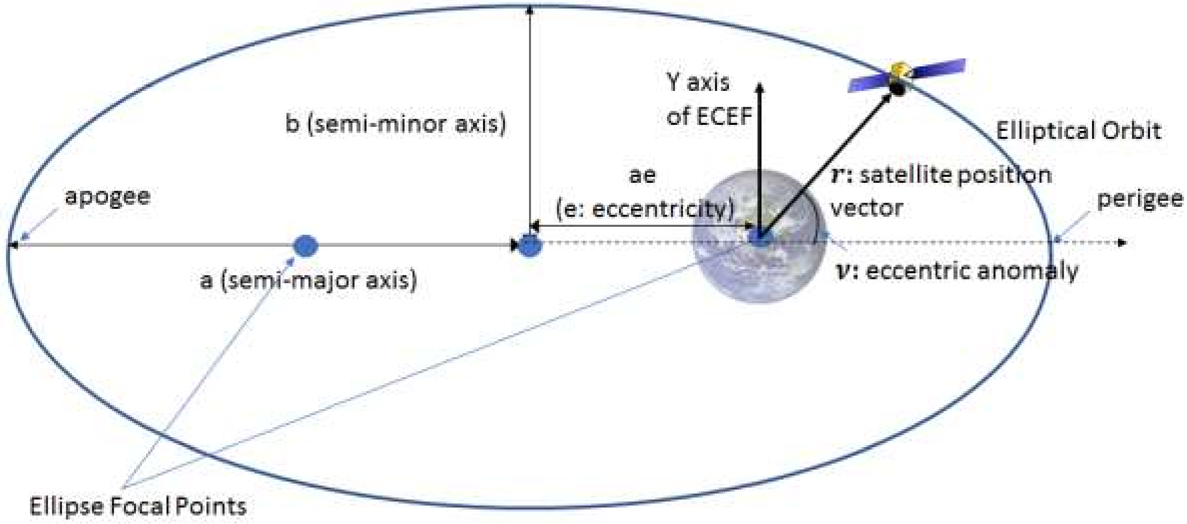
Two-frequency receivers can remove this error source (up to 99.9%) using ionosphere-free combination of pseudoranges (PC) or carriers (LC).

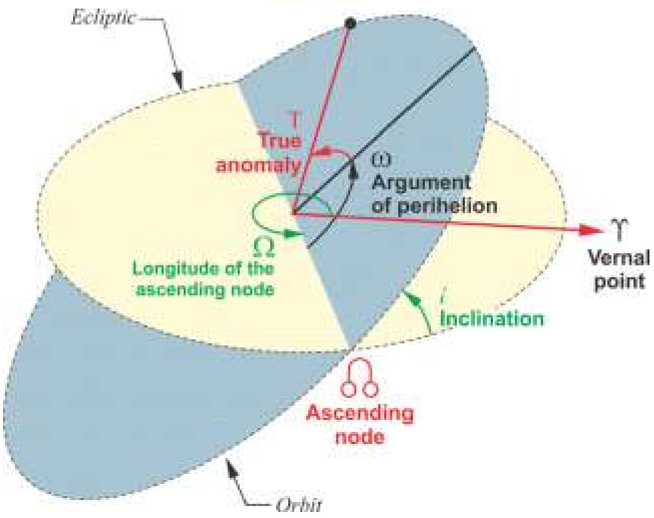
$$LC = \frac{f_1^2 L1 - f_2^2 L2}{f_1^2 - f_2^2}$$

Single-frequency user:

- Each GPS satellite broadcasts ionospheric delay model coefficients (Klobuchar model)
- Single-frequency users can remove about a 50% of the ionospheric delay using the Klobuchar model, whose parameters are broadcast in the GPS navigation message.
- 90% of time, residual range error is < 10 m
- Residual errors are highly correlated
- Model tends to either overestimate or underestimate ionospheric delay on all satellites simultaneously

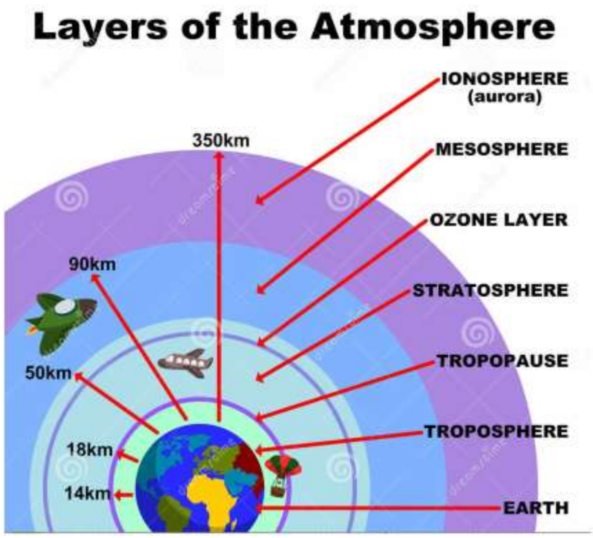
Satellite Ephemeris

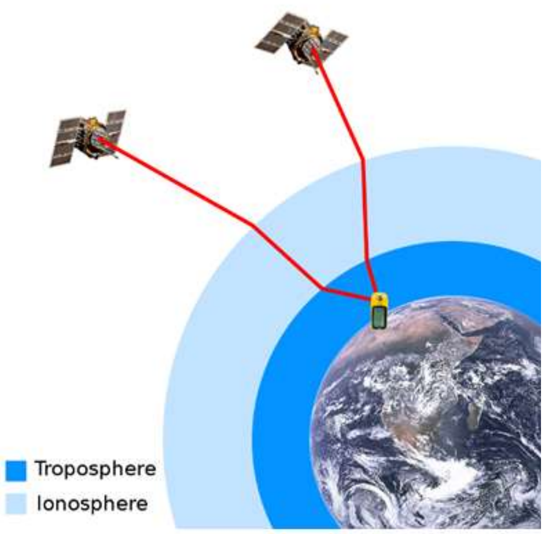




Troposphere

The lowest layer of the atmosphere next to the Earth surface (up to 40km)



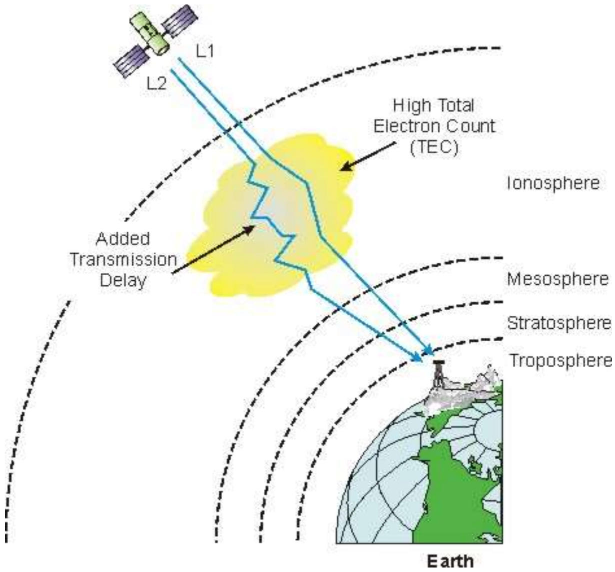


Tropospheric Delay

Tropospheric delays are a factor of atmospheric pressure, temperature and humidity.

Electrically neutral atmospheric region which means non-dispersive medium w.r.t to frequencies < 15 GHz. So, the propagation is frequency independent. It delays the GPS carrier and codes identically.

Elimination of the tropospheric refraction by dual-frequency methods is not possible

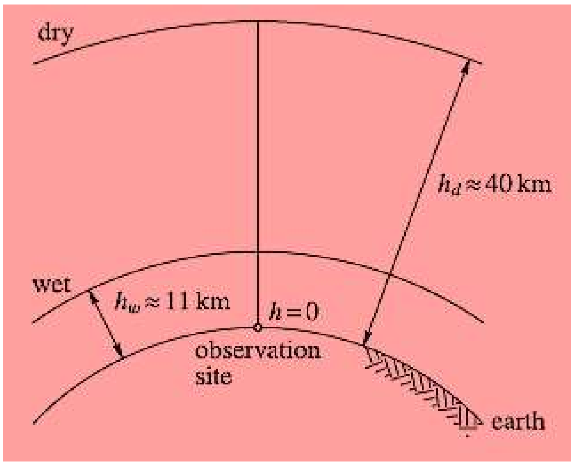


Tropospheric delays is broken into two components: Dry and Wet

Dry component results from the dry (hydrostatic) atmosphere and represents 90% of the total delay and can be predicted using mathematical models

Wet component depends on the water vapour along the GPS signal path - difficult to measure

$$N^{\text{Trop}} = N_d^{\text{Trop}} + N_w^{\text{Trop}}$$



Correcting for Tropospheric Errors

Tropospheric path delay for the elevation angle

Hopfield model

$$\Delta_d^{\text{Trop}}(E) = \frac{10^{-6}}{5} \frac{77.64}{\sin\sqrt{E^2 + 6.25}} \frac{p}{T} [40\,136 + 148.72\,(T - 273.16)]\,,$$

$$\Delta_w^{\text{Trop}}(E) = \frac{10^{-6}}{5} \frac{(-12.96\,T + 3.718 \cdot 10^5)}{\sin\sqrt{E^2 + 2.25}} \frac{e}{T^2}\,11\,000\,.$$

By measuring,

p – Atmospheric pressure in mb

T – Temperature in K

E – Elevation angle

e – Partial pressure of the water vapour in mb

Saastamoinen model

$$\Delta^{\text{Trop}} = \frac{0.002277}{\cos z}\left[p + \left(\frac{1255}{T} + 0.05\right)e - \tan^2 z\right]$$

z – zenith angle of the satellite

Saastamoinen model – Refined

$$\Delta^{\text{Trop}} = \frac{0.002277}{\cos z}\left[p + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R$$

The correction terms B, δR are interpolated from Tables

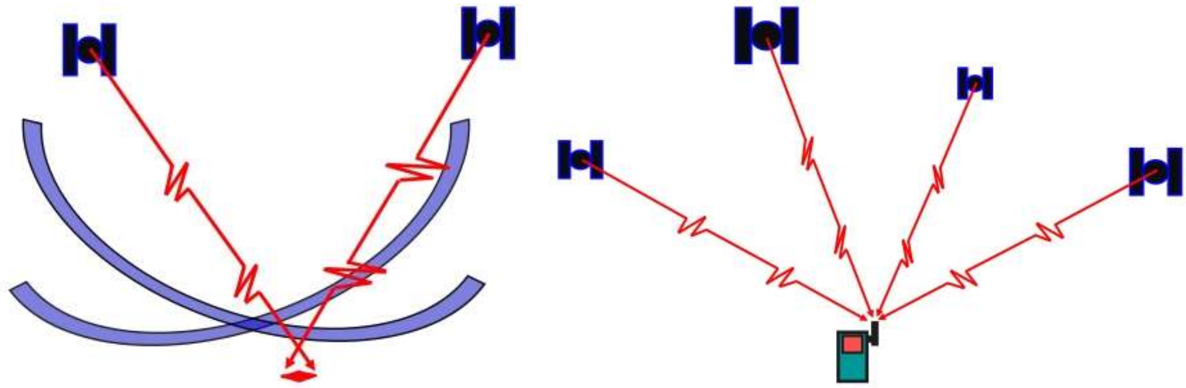
Tropospheric problems

- Many different models and approaches are available
- Difficulty in modeling the water vapour. simple use of surface measurements is not enough.
- Water vapour radiometers have been developed (measure the sky brightness temperature by radiometric microwave observations along the signal path enabling the calculation of the wet path delay
- Precise radiometers are expensive, and problems in low elevation angles
- One solution is to combine surface and radiosonde meteorological data, water vapour radiometer measurements and statistics

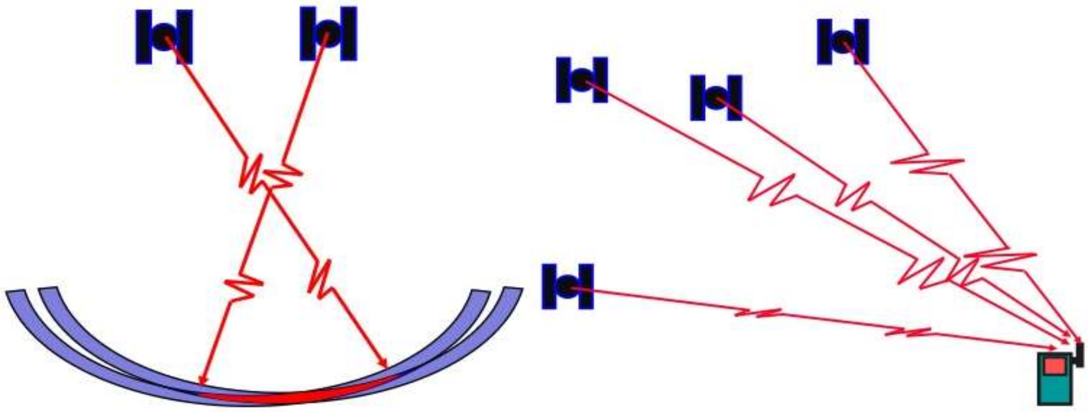
Satellite Geometry Measures

The overall positioning accuracy of GPS is measured by the combined effect of the unmodeled measurement errors and the satellite geometry. In general, the more spread out the satellites in the sky better the satellite geometry

Good



Poor



Dilution of Precision

PDOP – Position Dilution of Precision **(commonly used)**

HDOP – Horizontal Dilution of Precision

VDOP – Vertical Dilution of Precision

TDOP – Time Dilution of Precision

GDOP – Geometric Dilution of Precision

If we have (a priori) an expected value for the error in the data, σ

$$VDOP \equiv \sigma_h$$
$$HDOP \equiv \sqrt{\sigma_n^2 + \sigma_e^2}$$
$$PDOP \equiv \sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_h^2}$$
$$TDOP \equiv \sigma_\tau$$
$$GDOP \equiv \sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_h^2 + c^2\sigma_\tau^2}$$

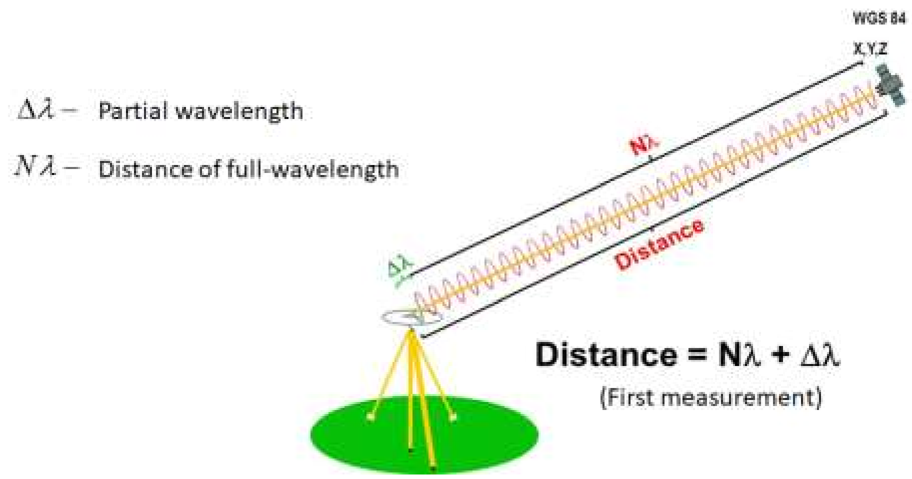
QUALITY	PDOP
Very Good	*1-3*
Good	*4-5*
Fair	*6*
Suspect	*>6*

2.0 Precise Positioning with Carrier Phase

Relative positioning require minimum of two GNSS receivers, with at least one occupying a station with known coordinates. The user position can then be estimated relative to one or multiple reference stations, using differenced carrier phase observations and a baseline or network estimation approach.

2.1 Carrier phase measurements with Integer ambiguity resolution

Distance from the satellite to the user's antenna can be expressed in terms of the number of wavelengths of the underlying signal carrying the codes.



Integer ambiguity is the uncertainty of full-number of wavelengths. Resolving the integer ambiguity allows phase measurements to be related to distance

When a receiver is turned on, the fractional part of the phase is observed and an integer counter is initialized. During signal tracking, the counter is incremented by one cycle whenever the fractional phase changes from 2π to 0.

Thus, at any given epoch, the observed accumulated phase (**Φ**) is the sum of the fractional phase (φ) and the integer counter (*n*) along with another term called the **integer ambiguity (N)** – *the number of integer cycles of the carrier that have passed between the satellite and the receiver at the time of initial acquisition*

$$\Phi = \varphi + n + N$$

Φ is the total phase, **φ** is the fractional initial cycle, **n** is the integer counter and **N** is the **ambiguity**

Since **N** is unknown, it needs to be estimated along with the 3-D receiver position in the estimator. Hence, the solution of **N** revolves around a ***"float"*** value, often close to its true integer value. To exploit the full potential of the carrier phase measurements, an additional step is required to resolve the float ambiguity estimates to its true integer value. This procedure is known as **ambiguity resolution**.

Ambiguity Resolution – Relative Positioning

Modeling process:

- Step 1: Least squares "Float" solution (Double difference carrier phase model)

$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

  - ➢ Estimate station coordinates, atmospheric delay, and carrier phase ambiguity $\nabla\Delta B_{AB}^{jk}$

- Step 2: Ambiguity resolution

  - ➢ Fix $\nabla\Delta B_{AB}^{jk}$ to nearest integer

- Step 3: Least squares "fixed" solution

$$\nabla\Delta L_{AB}^{jk} + \lambda_0 \nabla\Delta N_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk}$$

Known: ambiguity resolved carrier phase

Classical static technique

- TWO-step approach:
  - ➢ First step to estimate station coordinates and real-valued ambiguities
  - ➢ Second step to resolve initial ambiguities to integer values
    - Round real values to nearest integers
    - Use estimated errors to evaluate if resolution to integer is feasible. Ambiguities only fixed if integer value is within an appropriate confidence interval e.g. ±3σ

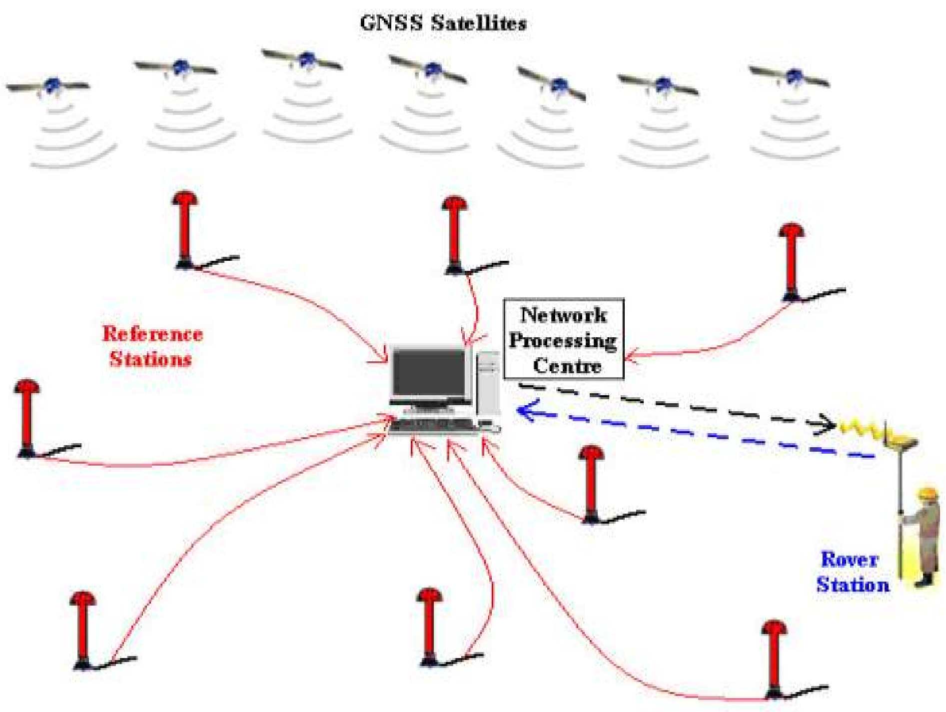
Modern techniques

Various methods for resolution of ambiguities have been developed and implemented

- Simple Rounding
- Ambiguity Function Method
- Fast Ambiguity Resolution Approach (FARA)
- Least Squares Ambiguity Search Technique
- Fast Ambiguity Search Filter (FASF)
- Least squares AMBiguity Decorrelation Adjustment (LAMBDA)

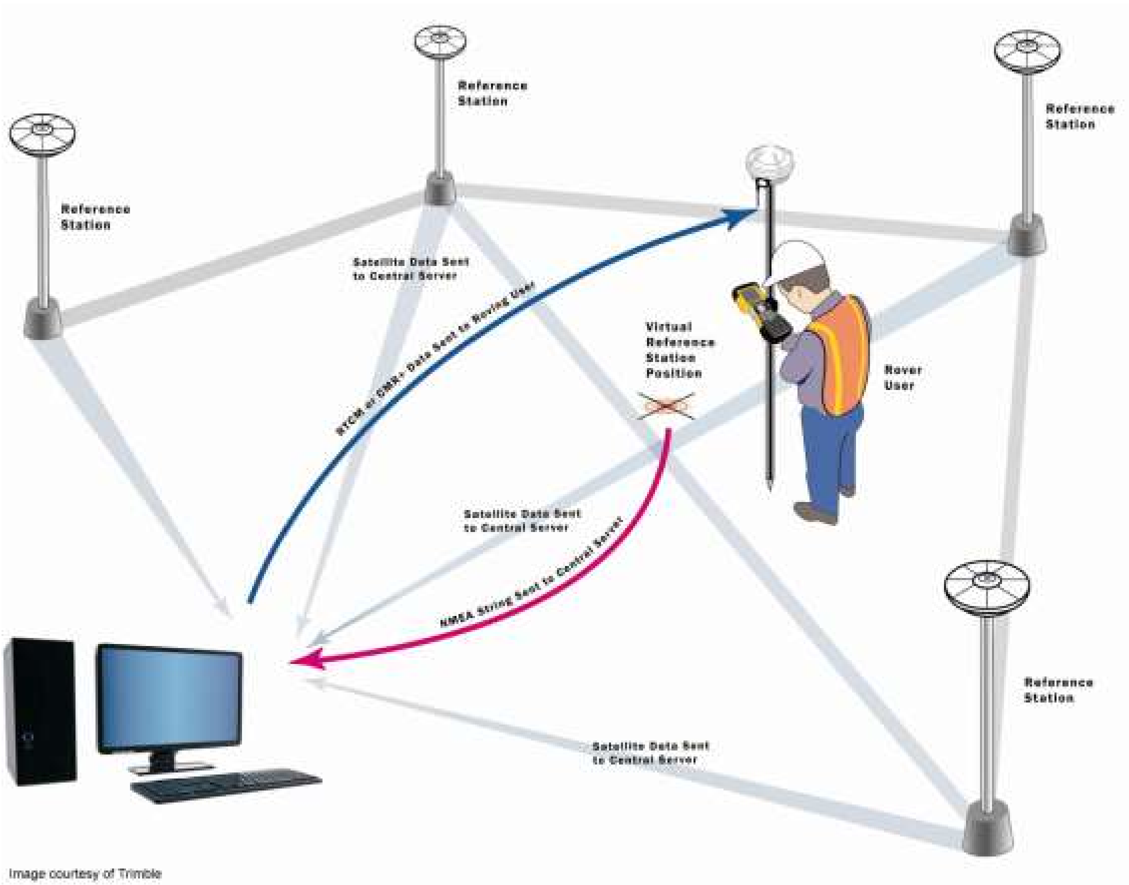
Ambiguity resolution procedure works best on **double-differenced** ambiguity terms. Double-differencing of observations mathematically eliminates the clock and equipment biases, along with satellite orbit and atmospheric errors, leaving only the intended integer nature of the ambiguities.

2.2 Network correction solutions for RTK



Several permanently established reference stations working together to optimize the management of sources of error over a larger coverage area. A special network RTK software is used to manage incoming data from the stations, generating RTK corrections and finally sending custom corrections to the users

Network RTK – VRS



VRS or virtual reference station: the control centre "simulates" a reference station near the rover. Two-way communication for the rover to report its approximate position to the control center, and reference station data is tailored for the simulated reference station. Virtual RINEX can be created from data of surrounding reference stations using the same software used for network RTK services.

Advantages and disadvantages of network RTK

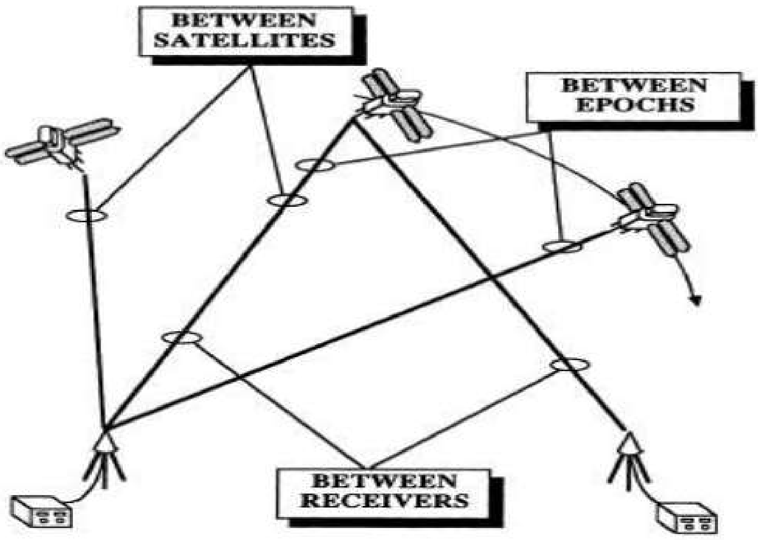
	Disadvantages
• User to have only one RTK receiver. A reference station does not need to be established or quality assured by the user • Good quality in a larger coverage area, unlike single station RTK where the measurement uncertainty increases significantly with the distance to the reference station • Measurement takes place directly in a uniform and modern reference system adapted for GNSS measurement	• Requires working mobile internet, i.e. two-way communication, between service provider and user • Lack of traceability, as the user does not have access to complete information about the calculation method

2.3 Linear combination models of observations

Both observables (carrier phases and code phases) lead to pseudoranges. It is advantage to use all observables, or their linear combinations, in the parameter estimation process.

Meaningful combinations are:

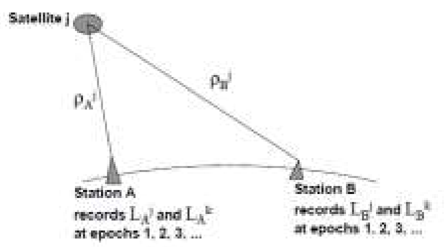
- between observations at different stations (receivers)
- between observations of different satellites
- between observations at different epochs



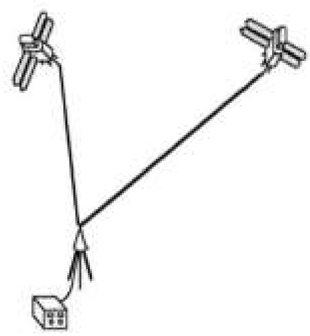
Single Differencing

Can be formed between:

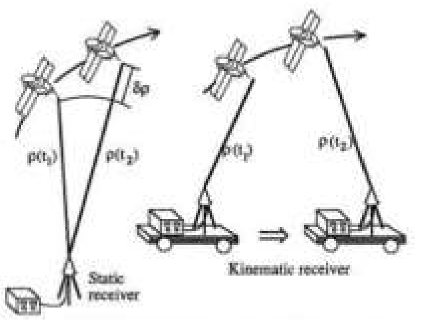
- Two receivers



- Two satellites



- Two epochs



Receiver single differences

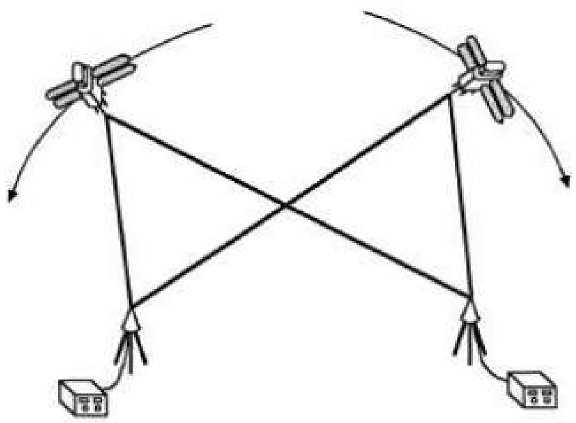
$$L_A^j = \rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$
$$L_B^j = \rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j$$

$$\begin{aligned}
\Delta L_{AB}^j &\equiv L_A^j - L_B^j \\
&= \left(\rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j\right) - \left(\rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j\right) \\
&= \left(\rho_A^j - \rho_B^j\right) + \left(c\tau_A - c\tau_B\right) - \left(c\tau^j - c\tau^j\right) + \left(Z_A^j - Z_B^j\right) - \left(I_A^j - I_B^j\right) - \left(B_A^j - B_B^j\right) \\
&= \Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j
\end{aligned}$$

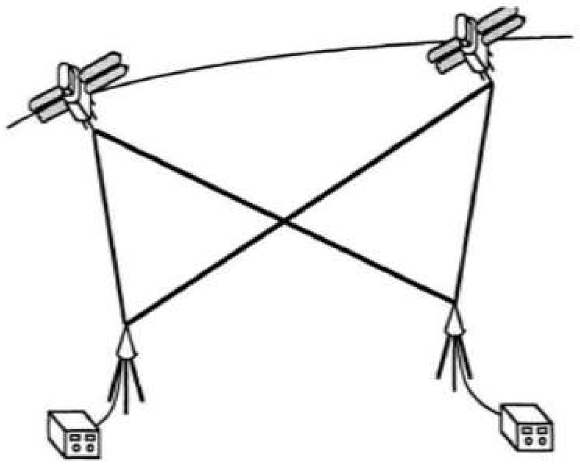
Double Differencing

Can be:

Receiver –satellite double differences



Receiver –time double differences



Two results are identical. Additional advantage is that the ambiguity is an integer

$$\begin{aligned}
\nabla\Delta B_{AB}^{jk} &= \Delta B_{AB}^j - \Delta B_{AB}^k \\
&= \left(B_A^j - B_B^j\right) - \left(B_A^k - B_B^k\right) \\
&= \lambda_0\left(\varphi_{0A} - \varphi_0{}^j - N_A^j\right) - \lambda_0\left(\varphi_{0B} - \varphi_0{}^j - N_B^j\right) - \lambda_0\left(\varphi_{0A} - \varphi_0{}^k - N_A^k\right) + \lambda_0\left(\varphi_{0B} - \varphi_0{}^k - N_B^k\right) \\
&= -\lambda_0\left(N_A^j - N_B^j - N_A^k + N_B^k\right) \\
&= -\lambda_0 \nabla\Delta N_{AB}^{jk}
\end{aligned}$$

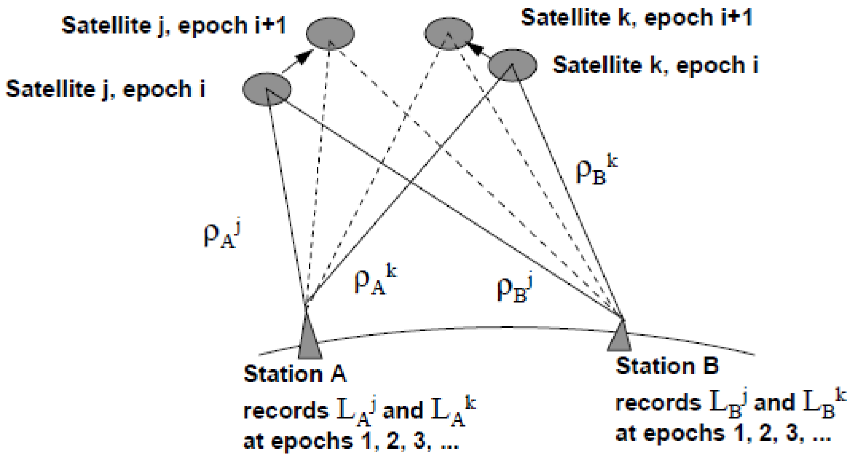
Integer

We can write the double differenced phase observation equation:

$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

Triple Differencing

To eliminate the integer ambiguity



Consider two successive epochs (*i*, *i*+1) of double differenced data from receivers *A* and *B* observing satellites *j* and *k*:

$$\nabla\Delta L_{AB}^{jk}(i) = \nabla\Delta\rho_{AB}^{jk}(i) + \nabla\Delta Z_{AB}^{jk}(i) - \nabla\Delta I_{AB}^{jk}(i) - \lambda_0 \nabla\Delta N_{AB}^{jk}$$
$$\nabla\Delta L_{AB}^{jk}(i+1) = \nabla\Delta\rho_{AB}^{jk}(i+1) + \nabla\Delta Z_{AB}^{jk}(i+1) - \nabla\Delta I_{AB}^{jk}(i+1) - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

The triple difference phase is defined as the difference between these two:

$$\begin{aligned}\delta(i,i+1)\nabla\Delta L_{AB}^{jk} &\equiv \nabla\Delta L_{AB}^{jk}(i+1) - \nabla\Delta L_{AB}^{jk}(i) \\ &= \delta(i,i+1)\nabla\Delta\rho_{AB}^{jk}(i) + \delta(i,i+1)\nabla\Delta Z_{AB}^{jk}(i) - \delta(i,i+1)\nabla\Delta I_{AB}^{jk}(i)\end{aligned}$$

Integer ambiguity is removed. Any cycle slips will appear as outliers, and can be removed by conventional techniques (statistical). Less precise and inappropriate for precise surveys.

The observation equation for triple differences is identical for code and carrier phases

2.4 Precise Point Positioning (PPP) with correction models

One of the practical constraints imposed by DGNSS is that simultaneous observations be made at reference stations. An alternative post-processing approach uses ***un-differenced dual-frequency pseudorange and carrier phase observations along with IGS precise orbit products***, for stand-alone precise geodetic point positioning (static or kinematic) with centimeter precision – **Precise Point Positioning (PPP).**

It uses all the available GNSS constellations (GPS, GLONASS, GALILEO, BEIDOU, QZSS) and combine precise satellite positions and clocks with un-differenced, dual-frequency (to remove the first order effect of the ionosphere), pseudorange and carrier-phase GNSS observables.

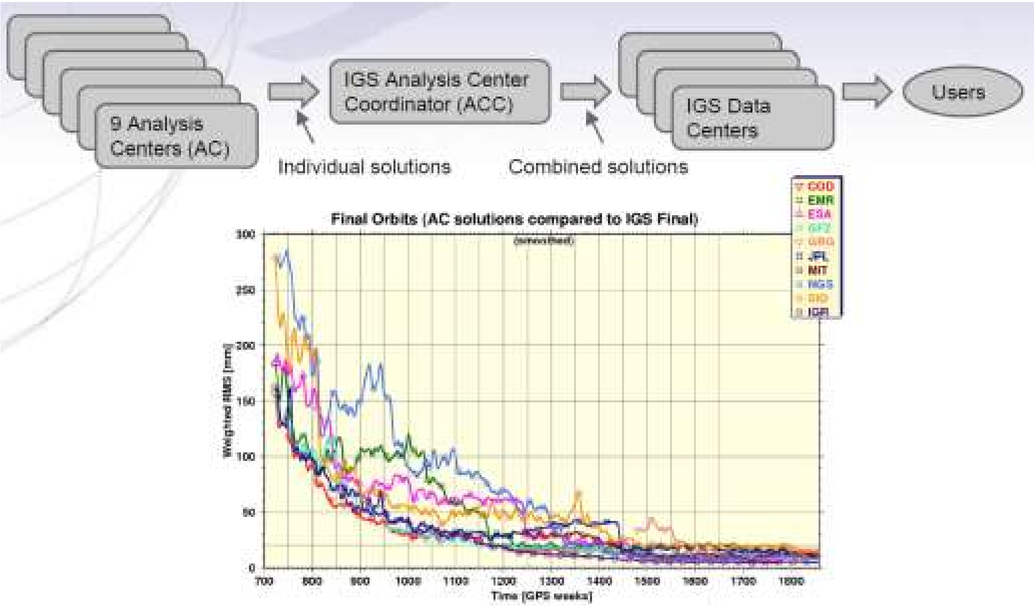
Use of a network of reference stations in order to compute precise estimates of GNSS satellites orbits and clock errors

One of the main drawbacks of PPP techniques is that they require a long convergence time to achieve the utmost performance.

PPP Benefits

- PPP involves only a single GNSS receiver and, therefore, no reference stations are needed in the vicinity of the user.
- PPP can be regarded as a global position approach because its position solutions refer to a global reference frame. As a result, PPP provides much greater positioning consistency than the differential approach in which position solutions are relative to the local base station(s)
- PPP reduces labour and equipment cost and simplifies operational logistics to field work since it eliminates the dependency on base station(s).
- PPP can support other applications beyond positioning. For example, as PPP technique estimates receiver clock and tropospheric effect parameters in addition to position coordinate parameter

IGS Analysis Centers (AC) contribute daily Ultra-rapid, Rapid and Final GPS/GLONASS orbit and clock solutions to the IGS combinations.



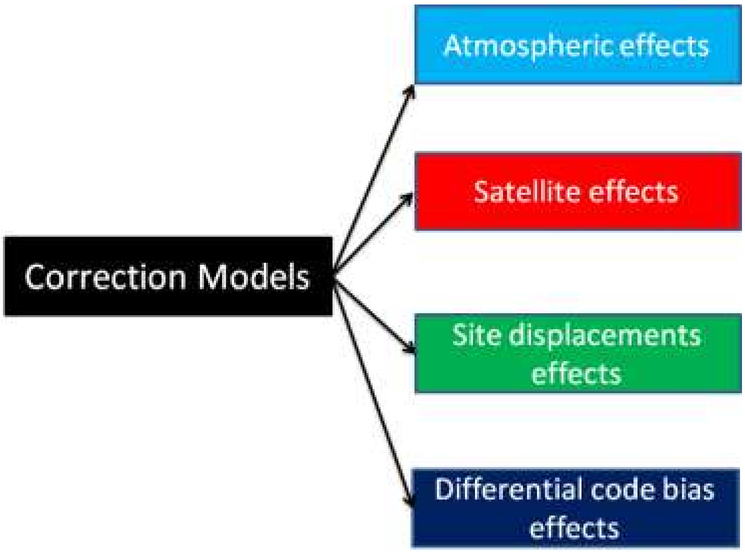
IGS Products - Ephemerids

Type		Accuracy	Latency	Updates	Sample Interval	
Broadcast	orbits	~100 cm	real time	--	daily	Broadcast Ephemeris
	Sat. clocks	~5 ns RMS ~2.5 ns SDev				
Ultra-Rapid (predicted half)	orbits	~5 cm	real time	at 03, 09, 15, 21 UTC	15 min	Precise Ephemerids
	Sat. clocks	~3 ns RMS ~1.5 ns SDev				
Ultra-Rapid (observed half)	orbits	~3 cm	3 - 9 hours	at 03, 09, 15, 21 UTC	15 min	
	Sat. clocks	~150 ps RMS ~50 ps SDev				
Rapid	orbits	~2.5 cm	17 - 41 hours	at 17 UTC daily	15 min	
	Sat. & Stn. clocks	~75 ps RMS ~25 ps SDev			5 min	
Final	orbits	~2.5 cm	12 - 18 days	every Thursday	15 min	
	Sat. & Stn. clocks	~75 ps RMS ~20 ps SDev			Sat.: 30s Stn.: 5 min	

Precise GPS Ephemeris is done by:

- Precise modelling of GPS satellites
- Precise modelling of GPS signal
- Precise modelling of GPS antenna
- Algorithms

To achieve *cm*-to-*mm* precision, PPP heavily relies on very accurate error models. For *cm* differential positioning and baselines of less than 100 km, these correction terms can be safely neglected. But significant for PPP and all precise global analyses (relative or undifferenced approaches).



Atmospheric Effects

1. Higher-order ionospheric delay effects

First-order ionospheric effect can be mitigated using the dual-frequency linear combination of ionospheric-free GNSS observables. Higher-order ionospheric effects need to be included into the PPP measurements models

2. Tropospheric delay effects

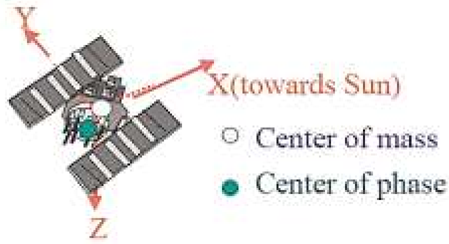
Commonly computed by means of specific mapping functions and for a given value of the Zenith Troposphere Delay (ZTD). PPP target accuracies, more complex mapping functions need to be implemented (Viena Mapping Function 1 (VMF1) (refer Boehm et al. 2006) - separately account for the hydrostatic (dry) and wet components of the ZTD

Dry component can be accurately computed from surface pressure, station latitude and height, while the wet one is estimated from the data

Satellite Effects

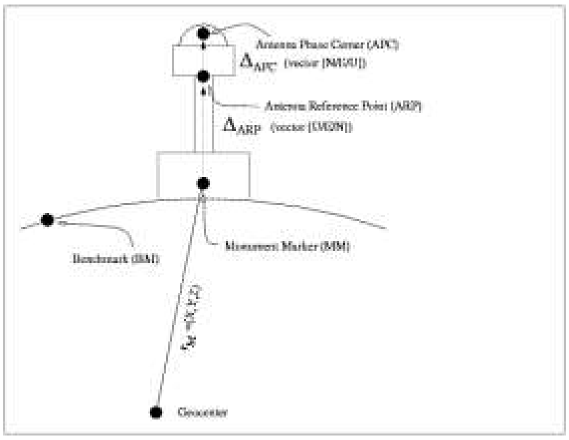
1. Satellite Antenna offsets

Separation between the satellite center of mass and the phase center of its antenna



2. Receiver Antenna Phase Center (APC)

The manufacturers provide technical information on the APC position relative to the ARP



3. Phase wind-up correction

Rotation of either receiver or satellite antenna will change the carrier-phase up to one cycle (one wavelength) – phase wind-up effect. Satellite antennas undergo slow rotations as their solar panels are being oriented towards the Sun.

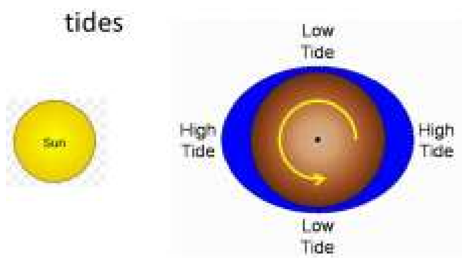
4. Site Displacements effects

Stations undergo periodic movements (real or apparent) reaching a few *dm.*

Solid earth tides:

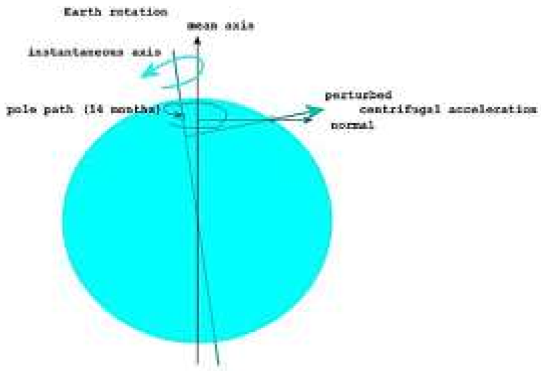
The periodic part is averaged out for static positioning over a 24-h period. The permanent part remains

The permanent and periodical tidal displacements, must be applied to be consistent with the ITRF (Tide-free)



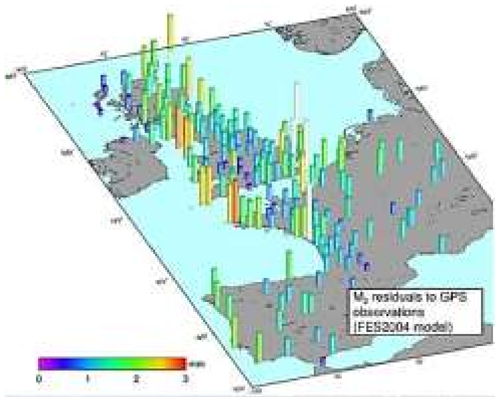
Rotational deformation due to polar motion (polar tides)

Changes of the Earth's spin axis with respect to Earth's crust, polar motion, causes periodical deformations in the Earth centrifugal potential - *cause periodical station position displacements*



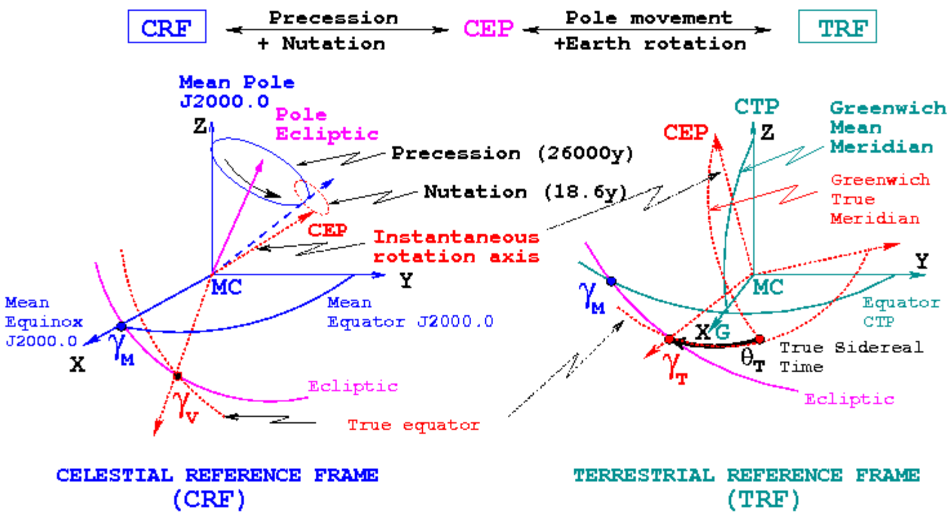
Ocean loading

Ocean loading is similar to solid Earth tides. Results from the load of the ocean tides on the underlying crust. Diurnal and semi diurnal periods



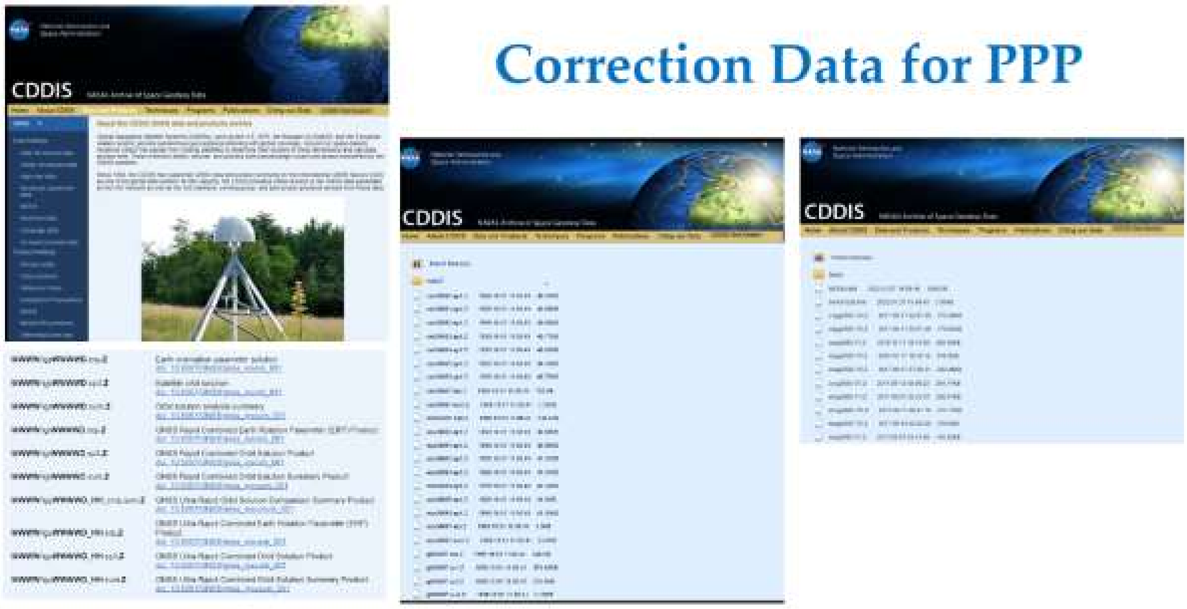
Earth rotation parameters (ERP)

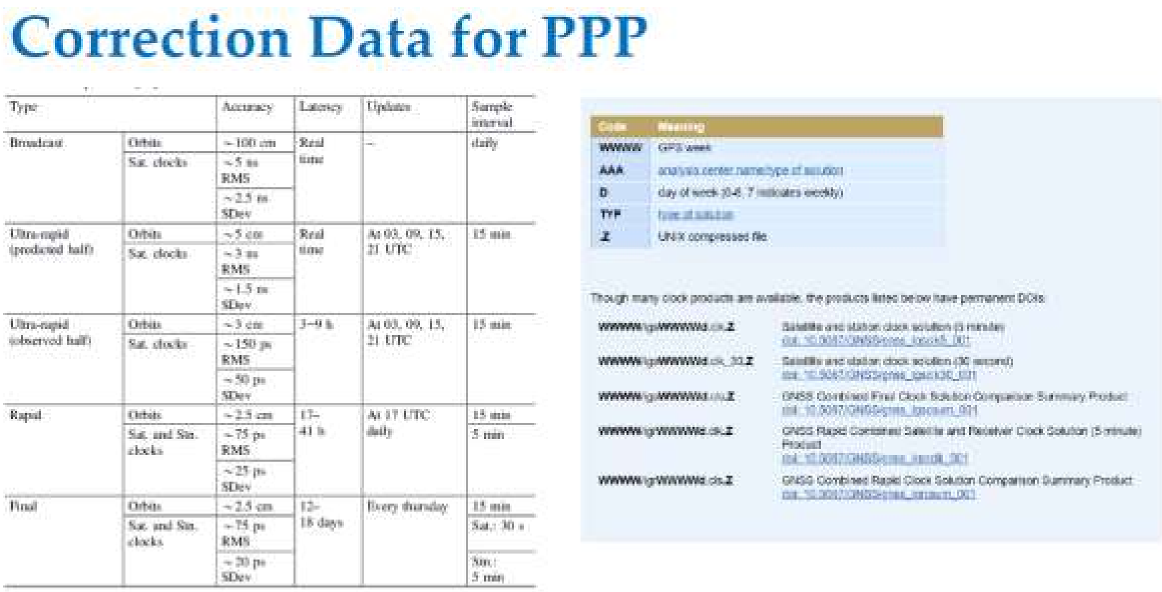
ERP facilitate accurate transformations between terrestrial and inertial reference frames that are required in global GNSS analysis



Differential code bias effects

Differential Code Biases (DCBs) are the systematic errors, or biases, between two GNSS code observations at the same or different frequencies. DCBs are required for code-based positioning of GNSS receivers, extracting ionosphere total electron content (TEC), and other applications.





Correction Data for PPP

Type		Accuracy	Latency	Updates	Sample interval
Broadcast	Orbits	~100 cm	Real time	–	daily
	Sat. clocks	~5 ns RMS			
		~2.5 ns SDev			
Ultra-rapid (predicted half)	Orbits	~5 cm	Real time	At 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~3 ns RMS			
		~1.5 ns SDev			
Ultra-rapid (observed half)	Orbits	~3 cm	3–9 h	At 03, 09, 15, 21 UTC	15 min
	Sat. clocks	~150 ps RMS			
		~50 ps SDev			
Rapid	Orbits	~2.5 cm	17–41 h	At 17 UTC daily	15 min
	Sat. and Stn. clocks	~75 ps RMS			5 min
		~25 ps SDev			
Final	Orbits	~2.5 cm	12–18 days	Every thursday	15 min
	Sat. and Stn. clocks	~75 ps RMS			Sat.: 30 s
		~20 ps SDev			Stn.: 5 min

Code	Meaning
WWWW	GPS week
AAA	analysis center name/type of solution
D	day of week (0-6, 7 indicates weekly)
TYP	type of solution
.Z	UNIX compressed file

Though many clock products are available, the products listed below have permanent DOIs:

3.0 Open source GPS

3.1 Introduction for open source GNSS

Open Source GNSS tools

- TEQC – UNAVOC
- RTKLIB
- GPSTk (GPS Toolkit)
- gLAB - ESA
- GNSS-SDR (Software Defined Receiver)
  - Open source software runs in C++
- MG - APP (Multi GNSS- Automatic Precise Processing)
- GAMIT / GLOBK (GNSS At MIT / GLOBal Kalman filter)

Online Free GNSS Tools

- **CSPRS – PPP** (Canadian Spatial Reference System PPP)
- **SCOUT Service** (Scripps Coordinate Update Tool)
  - Uses GAMIT Software
- **AUSPOS**
  - Online differential positioning software
- **Auto-GIPSY**
  - Automated mail/FTP positioning service
  - Replaced by Automatic Precise Point Positioning Service (APPS) by JPL, Nasa.
- **OPUS** (Online Positioning User Service)
  - Dual frequency services limited for USA users

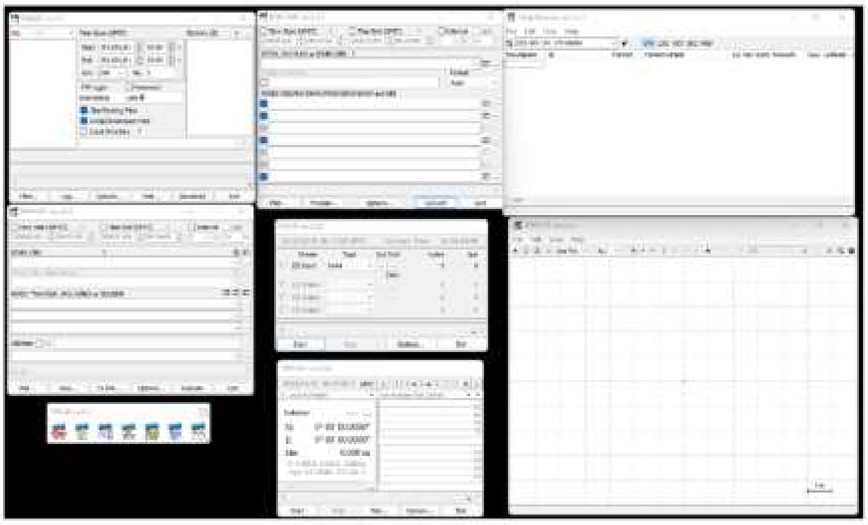
3.2 GNSS data processing with open source software (RTKLib)

RTKLIB

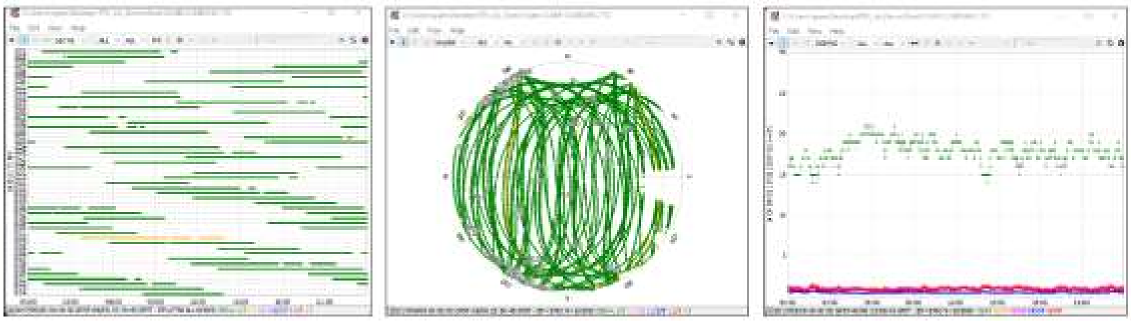
- An open source package for GNSS Positioning & Analysis
- Developed by Tokyo University of Marine Science and Technology
- Support for multi-GNSS.
- Positioning solutions for real-time and post-processing.
- Development started from 2006.
- Multi-constellation support from 2009.
- Latest version is 2.4.2 of 2013.
- Version 2.4.3 is still under development.

RTKLIB APs

- RTKNAVI : Real-time positioning
- RTKPOST : Post-processing baseline analysis
- RTKPLOT : Plot raw observation data and solutions
- RTKCONV: RTK Converter for raw receiver log

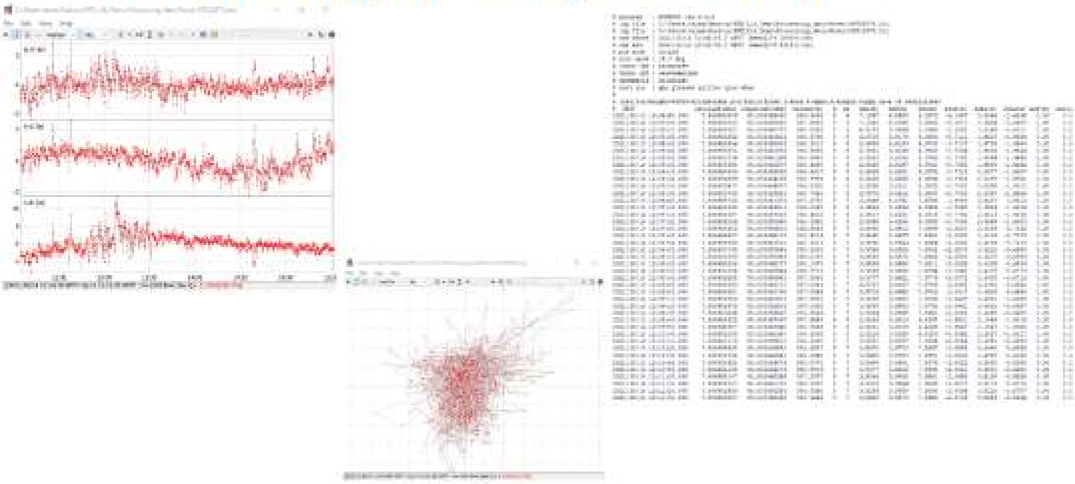


RTKPLOT

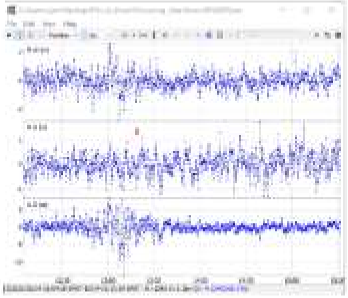


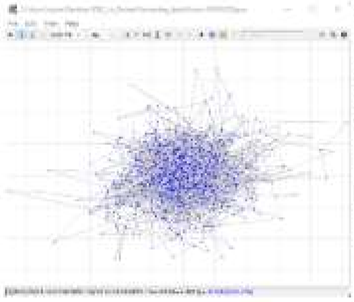
Individual satellites, Satellite constellations and signals can be selected for the plotting.

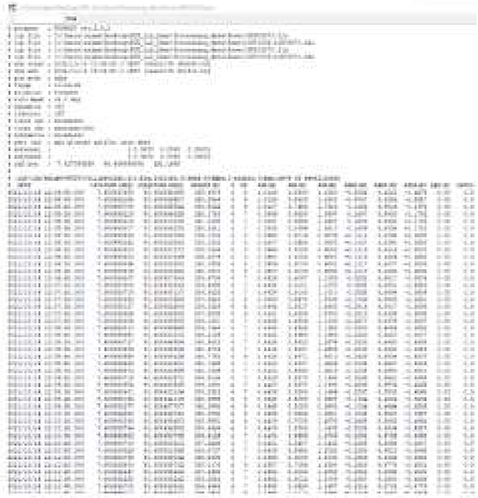
RTKLIB Output – Single solution



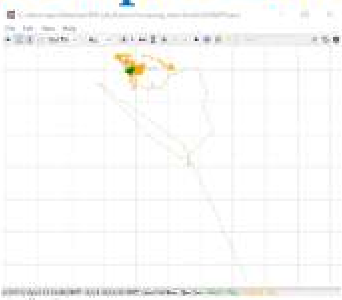
RTKLIB Output – DGPS

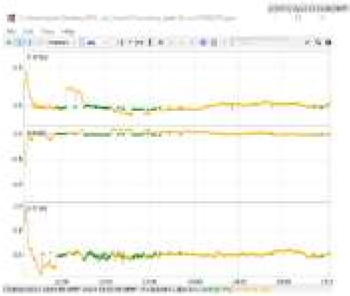


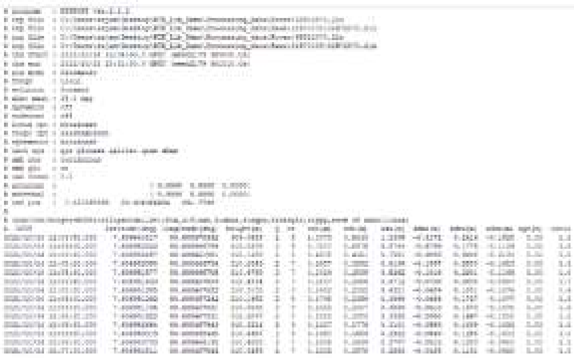




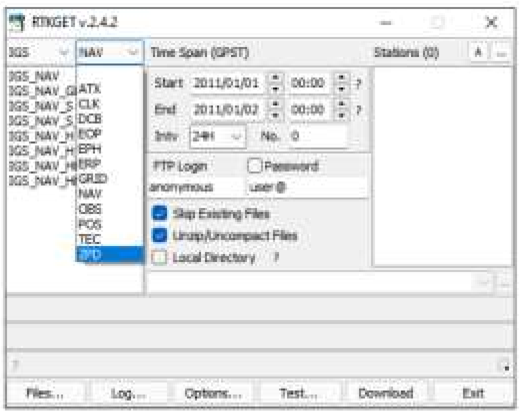
RTKLIB Output – Kinematic / Static



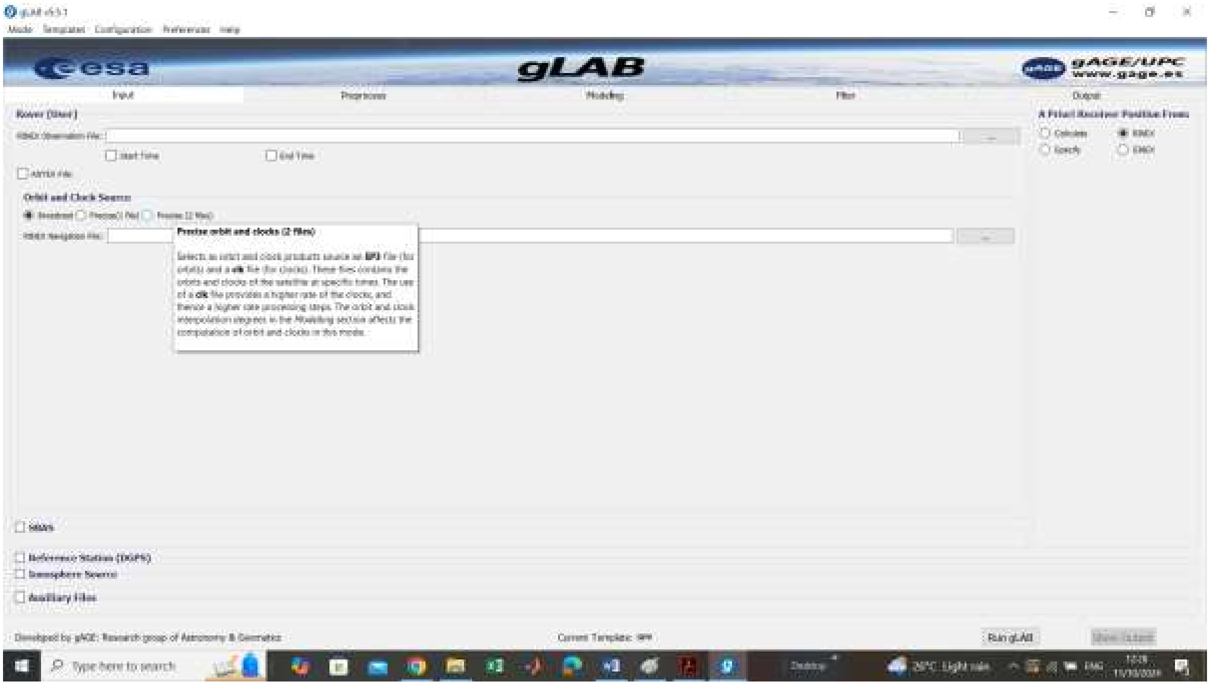


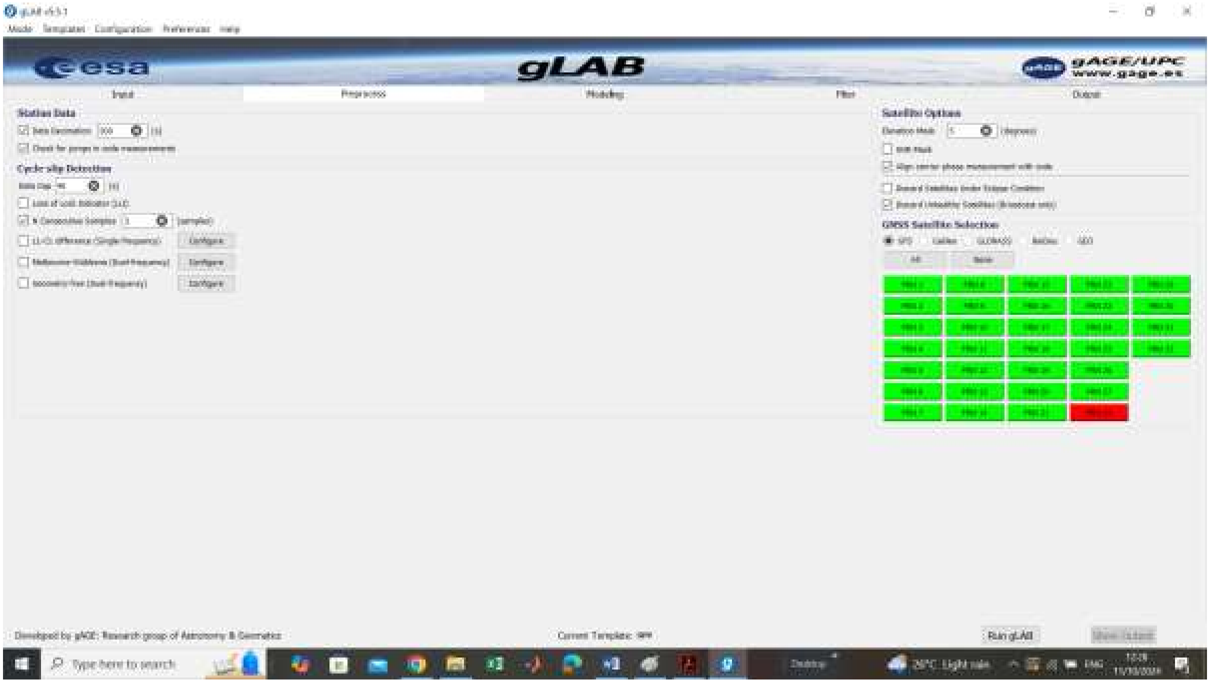


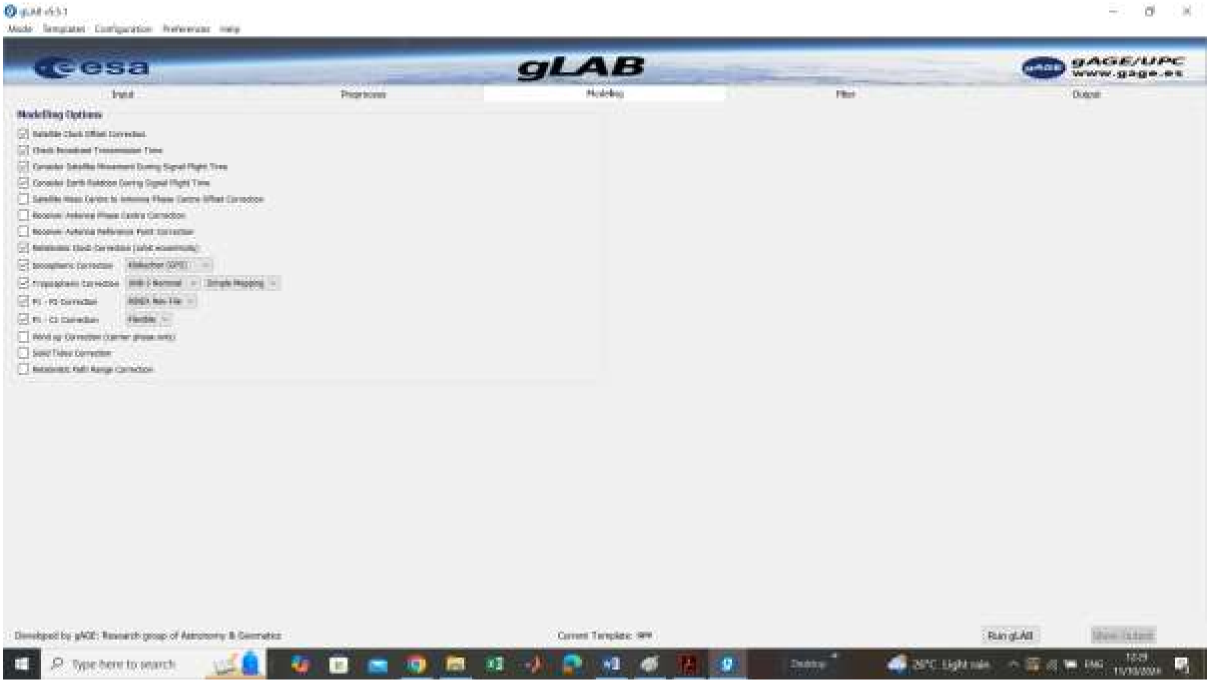
RTKGET



GNSS data processing with open source software (gLAB)




gLAB
Input
Preprocess
Modeling
Filter
Station Data
Cycle-slip Detection
Satellite Options
GNSS Satellite Selection
Run gLAB


gLAB
Input
Preprocess
Modeling
Filter
Modelling Options
Run gLAB

4.0 GPS Receivers

4.1 Signal-to-Noise Ratio (SNR) and Ranging Precision

The Signal-to-Noise Ratio (SNR) is a key parameter in GPS (Global Positioning System) that measures the strength and quality of the received satellite signal relative to background noise. It plays a crucial role in determining the precision of GPS ranging, which directly impacts the accuracy of the user's position.

SNR is typically measured in decibels (dB) and indicates how much stronger the satellite signal is compared to the noise around it. A higher SNR means a clearer signal, while a lower SNR means the signal is being significantly affected by noise. Several factors can influence the SNR in GPS:

- **Distance from the satellite**: As the signal travels farther from the satellite, it weakens, leading to a lower SNR.
- **Atmospheric conditions**: The ionosphere and troposphere can introduce noise and signal delays, affecting SNR.
- **Multipath effects**: When GPS signals reflect off buildings or other surfaces, they may reach the receiver with different path lengths and phases, reducing SNR.
- **Obstructions**: Buildings, trees, or even your body can block or degrade GPS signals, reducing SNR.
- **Receiver Electronics**

Ranging Precision

Ranging is the process of measuring the distance between a GPS receiver and a satellite. The precision of this ranging depends on how accurately the signal travel time is measured. This is where SNR comes into play.

Relationship between SNR and Ranging Precision:

- **High SNR**: When the GPS receiver has a high SNR, it can lock onto the signal with higher precision, leading to better timing accuracy and more accurate range measurements. In simple terms, with less noise, the receiver can better detect the precise arrival time of the signal.
- **Low SNR**: A lower SNR increases the noise in the signal, which introduces errors in the timing measurements. This, in turn, reduces the precision of range estimates, resulting in less accurate positioning.

Mathematical Perspective:

The **code-phase tracking error** (which affects the accuracy of ranging) can be approximated as:

$$\sigma \approx \frac{\lambda}{2\pi . SNR}$$

Where:

- σ is the standard deviation of the ranging error (precision).
- λ is the wavelength of the GPS signal.
- SNR is the signal-to-noise ratio.

As SNR increases, the ranging error decreases, improving precision.

3. Practical Implications

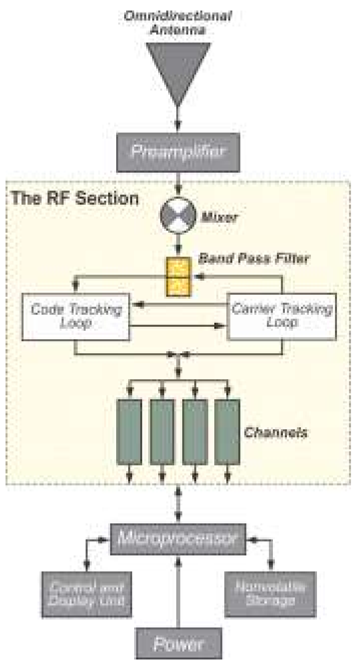
- **Good SNR (e.g., >40 dB)**: Results in a more accurate position fix, often within a few meters.
- **Poor SNR (e.g., <30 dB)**: Can lead to significant errors, sometimes causing position errors of tens of meters or even more. In extreme cases, the GPS receiver may lose the satellite signal entirely.

Mitigating Low SNR Effects:

- Using **antenna improvements** such as higher gain antennas or better placement (e.g., avoiding obstructions).
- **Dual-frequency GPS receivers** can reduce some noise caused by atmospheric conditions by comparing signals on different frequencies.
- **Averaging and filtering techniques** to smooth out noisy measurements

4.2 Signal Conditioning and Acquisition at GPS receiver

Signal conditioning is the process of preparing the incoming GPS signal for further processing, ensuring the weak signals from GPS satellites are amplified, filtered, and downconverted to a suitable format for digital processing.



Key stages in signal conditioning include:

a. Amplification (Low-Noise Amplifier - LNA)

- **Function**: The GPS signals arriving at the receiver are extremely weak, typically around -130 to -160 dBm. Therefore, the first stage in signal conditioning is amplifying the received signal without adding too much noise. This is done using a **low-noise amplifier (LNA)**.
- **LNA Characteristics**: It should have a high gain and low noise figure to maintain a good signal-to-noise ratio

(SNR) after amplification. The LNA is usually placed as close as possible to the antenna to avoid signal loss.

b. Filtering

- **Function**: GPS signals are transmitted at specific frequencies (L1, L2, L5 bands), but other signals in the environment, such as cellular or Wi-Fi signals, can interfere. Filtering is essential to remove these unwanted signals and only allow the relevant GPS signals to pass.
- **Bandpass Filters**: These are used to isolate the GPS bands (e.g., 1575.42 MHz for L1, 1227.60 MHz for L2) and reject out-of-band noise and interference.

c. Downconversion

- **Function**: The GPS signal received by the antenna is at a high radio frequency (RF). To process it digitally, it needs to be converted to a lower frequency, known as the intermediate frequency (IF), or directly down to baseband. This is done using mixers.
- **Mixing**: The high-frequency signal is mixed with a local oscillator signal to reduce its frequency, often to an IF that is easier to process digitally.

d. Analog-to-Digital Conversion (ADC)

- **Function**: After amplification and filtering, the analog GPS signal is converted into a digital signal through an ADC. The ADC must sample the signal at a high enough rate (determined by the Nyquist criterion) to capture the relevant information without aliasing.

Signal Acquisition in GPS Receivers

Signal acquisition is the process of detecting the GPS satellite signals, identifying the visible satellites, and determining the code phase and Doppler shift associated with each satellite. Acquisition is necessary for the receiver to establish the time of arrival of the signal, which is used in position calculation.

Acquisition involves two main tasks:

- **Code phase acquisition**: Finding the alignment between the satellite’s transmitted pseudorandom noise (PRN) code and the receiver's locally generated version.
- **Frequency acquisition**: Estimating the Doppler shift due to relative motion between the satellite and the receiver.

a. Correlator Process

- GPS signals use **Direct Sequence Spread Spectrum (DSSS)** modulation, where the signal is modulated by a pseudorandom code (PRN). The acquisition process is based on **correlation** between the incoming signal and a locally generated version of the PRN code.
- **Code Correlation**: The receiver generates a copy of the satellite's PRN code and slides this code over the incoming signal to find the best match. When the code aligns correctly, the correlation output is maximized, indicating the satellite's signal has been acquired.

b. Doppler Shift Estimation

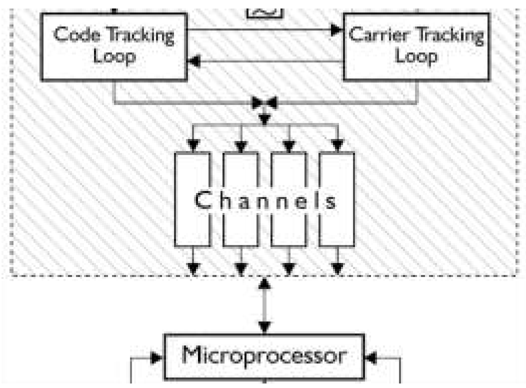
- Due to relative motion between the satellite and the receiver, there is a Doppler shift in the frequency of the received signal. GPS receivers search across a range of Doppler frequencies to find the correct frequency shift for each satellite.
- **Search Space**: The acquisition process typically involves searching over a range of possible code phases and Doppler shifts. This is done using a 2D grid (code phase vs. Doppler frequency) in the correlator.

c. Coherent and Non-coherent Acquisition

- **Coherent Acquisition**: The correlator integrates the signal over a period that is an exact multiple of the PRN code period, improving SNR.
- **Non-coherent Acquisition**: The receiver integrates over a period longer than the PRN code, but without keeping phase information, which is less efficient but useful when signal strength is very low.

4.3 Code and Carrier Tracking at GPS receiver

In GPS receivers, once the signal from a satellite has been acquired, the next critical step is **code and carrier tracking**. These processes enable the receiver to continuously follow the satellite's signal, refine the timing and Doppler estimates, and extract navigation data from the signal. Accurate code and carrier tracking are essential for precise positioning, velocity, and timing (PVT) calculations.



Code Tracking

GPS satellites transmit signals that are modulated with a unique **pseudorandom noise (PRN) code**. Code tracking ensures that the receiver remains synchronized with this PRN code as it arrives from the satellite.

The primary goals of code tracking are:

- **Maintain code alignment**: Ensure the locally generated PRN code aligns with the incoming satellite signal.

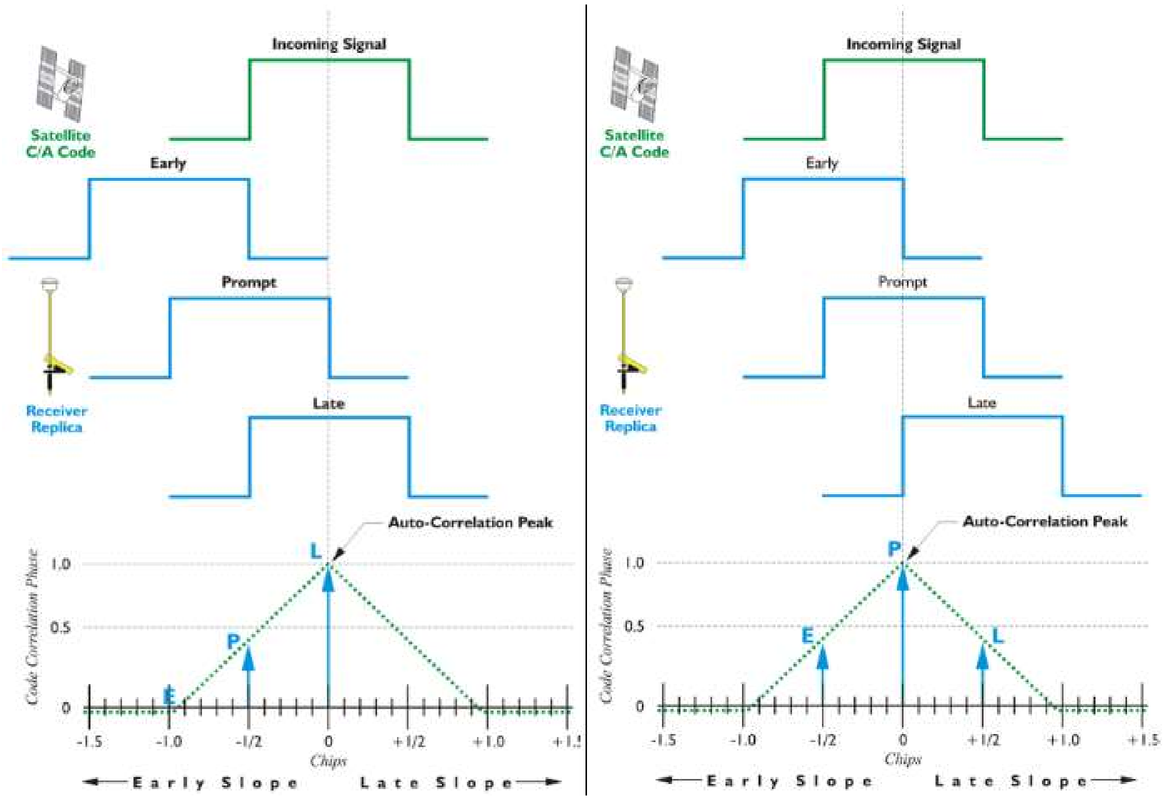
- **Measure signal delay (pseudorange)**: Accurately measure the time delay between transmission and reception, which is used to compute the pseudorange (the apparent distance between the satellite and the receiver).

Code Tracking Loop: Delay Lock Loop (DLL)

The most common method for code tracking in GPS receivers is the **Delay Lock Loop (DLL)**. The DLL keeps the locally generated PRN code in phase with the received satellite signal.

- **Early, Prompt, and Late Correlators**: The DLL generates three versions of the locally generated PRN code:
    1. **Early**: Slightly ahead of the received code.
    2. **Prompt**: Ideally aligned with the received code.
    3. **Late**: Slightly behind the received code.

    The receiver correlates the received signal with each of these codes. The goal is to adjust the timing so that the **prompt correlator** produces the maximum correlation, meaning the local code is in sync with the satellite code.



Carrier Tracking

In addition to the code, GPS signals are modulated on a **carrier wave** (typically at L1 = 1575.42 MHz, L2 = 1227.60 MHz, and L5 = 1176.45 MHz). Carrier tracking is used to:

- **Measure Doppler shift**: Due to relative motion between the satellite and receiver, the received carrier frequency is shifted. Tracking this shift allows the receiver to estimate its velocity relative to the satellite.
- **Refine pseudorange measurements**: Since the carrier wave has a much shorter wavelength than the PRN code, carrier tracking can provide much finer measurement precision.

a. Carrier Tracking Loop: Phase Lock Loop (PLL)

The carrier signal is tracked using a **Phase Lock Loop (PLL)**. The PLL keeps the locally generated carrier wave aligned with the received carrier.

- **Carrier Phase**: The PLL tracks the **phase difference** between the received carrier wave and the locally generated one. This phase difference is proportional to the Doppler shift introduced by the relative motion of the satellite and receiver.
- **Error Signal**: The phase difference between the incoming carrier and the local carrier is used to generate an **error signal**. If the local carrier is lagging behind or ahead, the loop adjusts the local oscillator to reduce this error.
- **Tracking Loop**: The error signal is fed into a loop filter, which adjusts the frequency and phase of the local oscillator to maintain phase alignment with the incoming signal. This allows the receiver to continuously track the carrier frequency and phase.

b. Carrier Doppler Shift

The Doppler shift (the difference between the received carrier frequency and the expected carrier frequency) is directly proportional to the relative velocity between the satellite and receiver. This shift can be used to estimate the receiver's velocity along the line of sight to the satellite.

c. Carrier Smoothing

Because the carrier phase is tracked much more precisely than the code phase (due to the shorter wavelength of the carrier), GPS receivers often use **carrier phase smoothing** to improve the accuracy of pseudorange measurements. By combining code and carrier tracking information, the receiver can reduce the noise in the range estimates.

Cycle Slips in Carrier Tracking

In the context of GPS, a **cycle slip** is a sudden jump in the phase of the carrier signal being tracked. This occurs when the receiver momentarily loses lock on the carrier due to signal blockage, interference, or poor signal quality.

- **Detection and Correction**: Receivers use specialized algorithms to detect cycle slips by comparing successive carrier phase measurements. If a cycle slip is detected, the receiver attempts to correct it by adjusting the tracking loop.

Integration of Code and Carrier Tracking

Both code and carrier tracking loops operate simultaneously and continuously in GPS receivers. The code tracking loop provides pseudorange measurements, while the carrier tracking loop provides Doppler shift and precise phase information. These measurements are combined to:

- **Compute position**: The pseudorange and Doppler data from multiple satellites are used in a process called **trilateration** to compute the receiver's 3D position.
- **Estimate velocity**: Doppler shift information from the carrier tracking loop is used to estimate the receiver's velocity relative to each satellite

5.0 Location-based Services (LBS)

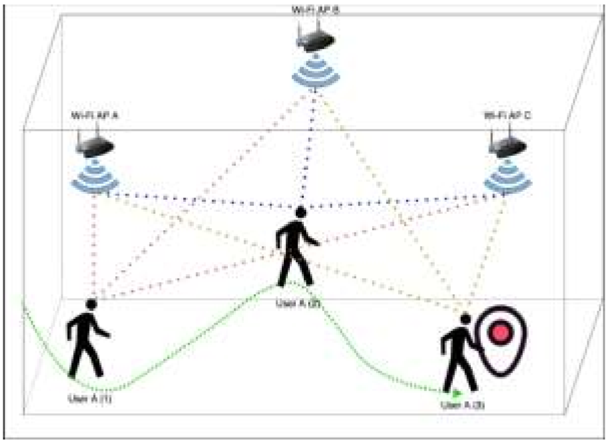
5.1 Overview of Geo-location techniques

Geo-location techniques refer to methods used to determine the geographic location of a device, person, or object on Earth. These techniques can vary in terms of accuracy, cost, and availability, and are used in a wide range of applications, from navigation to location-based services in mobile apps. An overview of the main geo-location techniques are:

1. Global Positioning System (GPS)

GPS is a satellite-based navigation system. Devices equipped with a GPS receiver can triangulate their location using signals from at least four of the 30+ GPS satellites orbiting the Earth. Each satellite transmits a signal containing the satellite's location and the exact time the signal was transmitted.

2. Wi-Fi Positioning System (WPS)

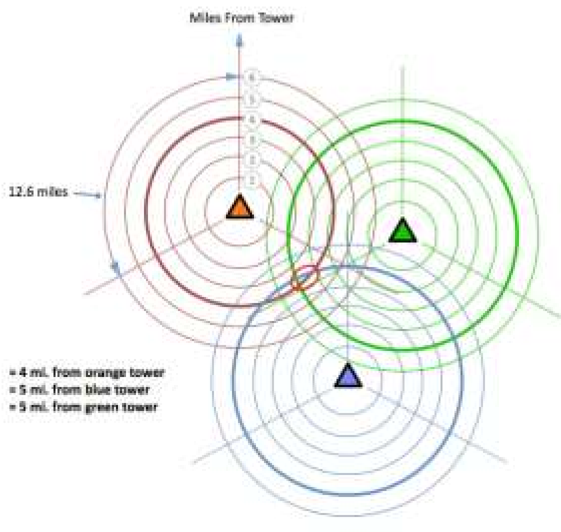


Wi-Fi positioning determines location by analyzing the signal strength and MAC addresses of nearby Wi-Fi access points. By referencing a database of known Wi-Fi hotspots and their locations, the system can estimate the device's position.

Accuracy: 10-50 meters in urban areas where Wi-Fi access points are dense. Accuracy decreases in rural areas.

Applications: Indoor positioning, location-based services for smartphones, and augmented reality (AR) applications.

3. Cellular Triangulation

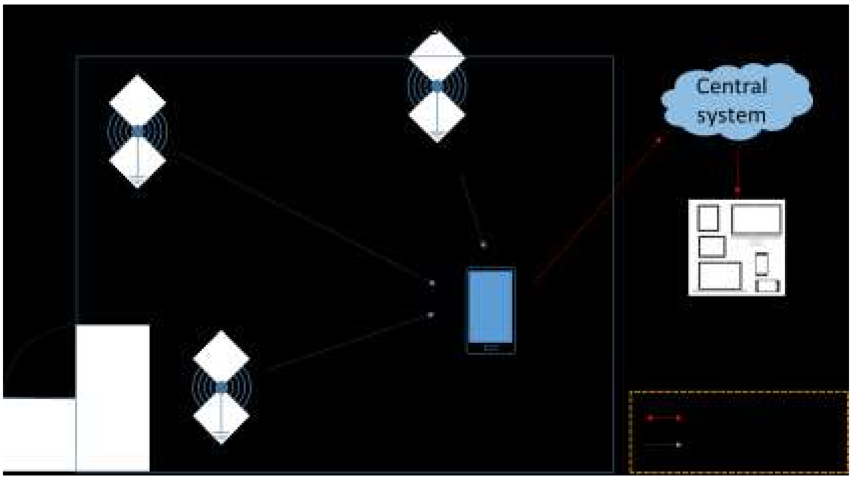


Cellular triangulation determines location by analyzing signal strengths from multiple cell towers. By measuring the time it takes for signals to travel between the cell towers and the device, the location can be triangulated.

Accuracy: 50-200 meters, depending on the density of cell towers.

Applications: Emergency services (e.g., 911 calls), location-based services in areas without GPS coverage.

4. Bluetooth Beaconing



Bluetooth beacons are low-energy transmitters that emit Bluetooth signals to nearby devices. The location is estimated based on proximity to beacons, with signal strength indicating distance.

Accuracy: 1-5 meters.

Applications: Indoor navigation, proximity marketing, asset tracking, and smart home automation.

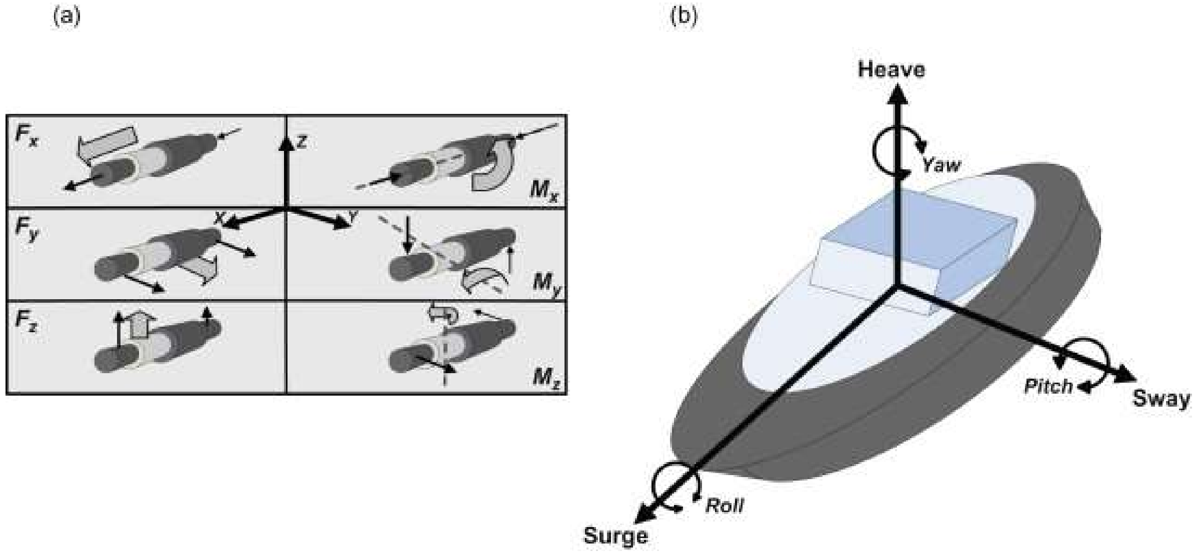
5. IP Address-Based Location

An IP address is linked to the Internet Service Provider (ISP) and can provide a rough estimate of location based on the provider's location data and the region the IP is assigned to.

Accuracy: Broad—ranges from a few kilometers to hundreds of kilometers, depending on the ISP.

Applications: Online advertising, content localization, website analytics, and regional restrictions (geo-blocking).

6. Inertial Navigation Systems (INS)

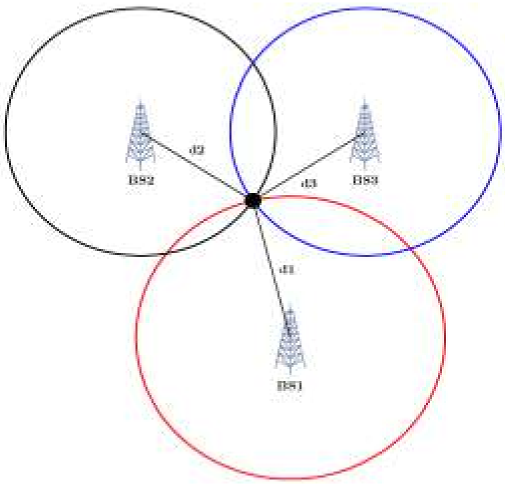


Inertial navigation systems use accelerometers and gyroscopes to calculate a device's position based on its velocity, direction, and the time elapsed since the last known position. This technique is useful when GPS signals are weak or unavailable.

Accuracy: High short-term accuracy but suffers from drift over time, causing increasing errors without external calibration.

Applications: Aviation, underwater navigation, and autonomous vehicle navigation.

7. Geolocation by Radio Frequency (RF) Signal

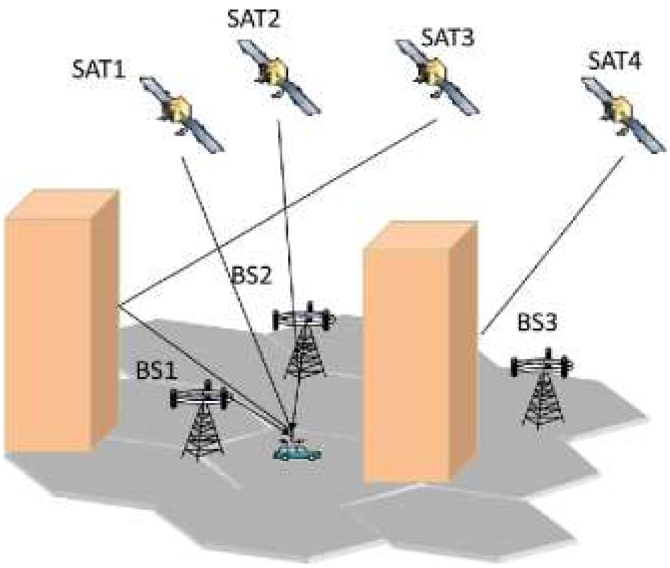


RF signals can be used to determine location through signal time-of-flight measurements, signal strength, or by using a network of RF receivers to triangulate the signal source.

Accuracy: Highly variable, ranging from 10-100 meters depending on the technology and environment.

Applications: IoT device tracking, surveillance, and military applications.

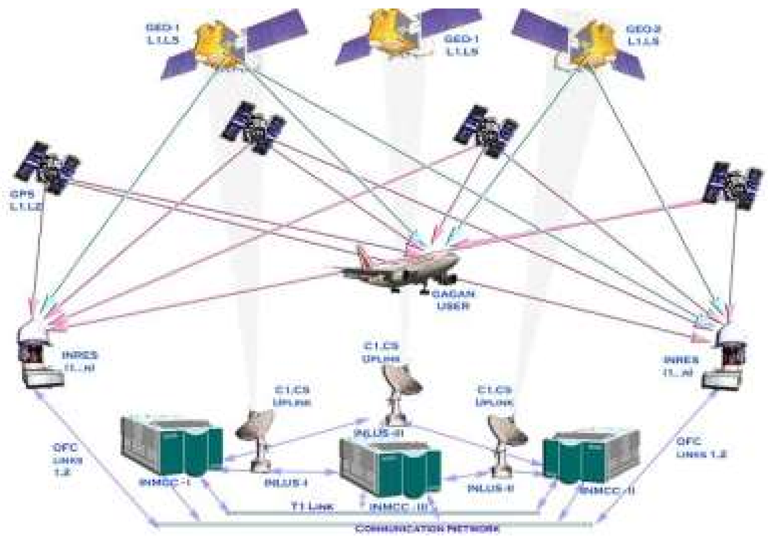
8. Hybrid Positioning Systems



Hybrid positioning combines multiple techniques, such as GPS, Wi-Fi, Bluetooth, and cellular triangulation, to improve location accuracy and reliability. The device may switch between methods depending on signal strength or availability.

Accuracy: Can be very accurate, within 1-10 meters, by combining multiple sources of data.
Applications: High-precision applications like autonomous driving, indoor-outdoor navigation, and advanced location-based services.

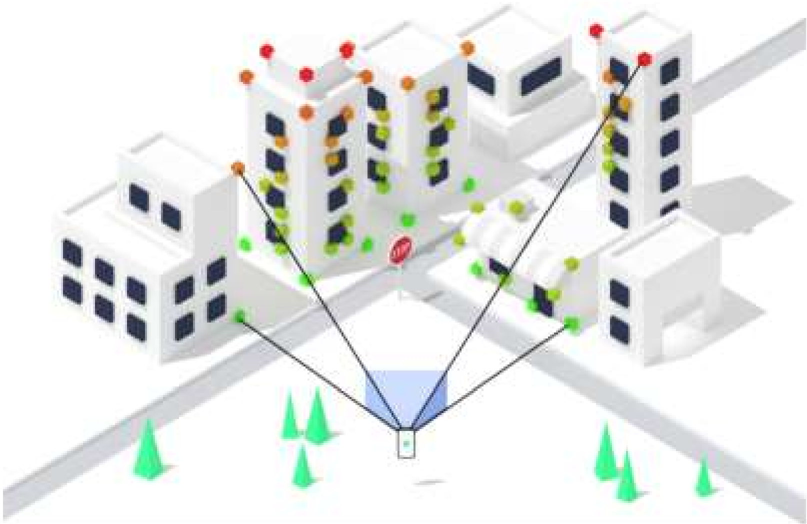
9. Satellite-Based Augmentation Systems (SBAS)



SBAS improves the accuracy of GPS by using additional satellite data to correct GPS signal errors caused by atmospheric disturbances. SBAS is common in aviation to ensure safety during landing and take-off.
Accuracy:Sub-meter accuracy.

Applications: Aviation, agriculture, and surveying.

10. Visual Positioning Systems (VPS)

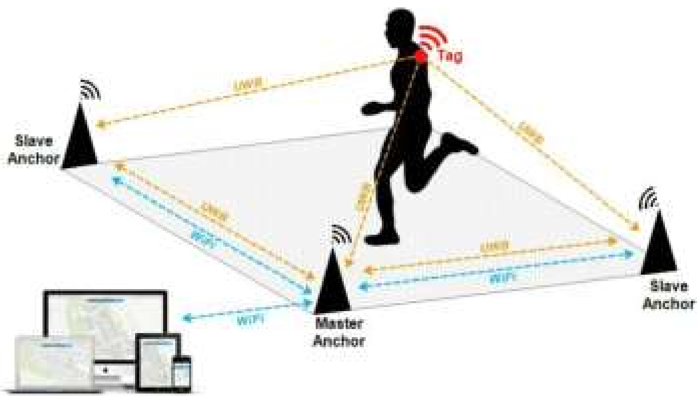


VPS uses computer vision and machine learning to analyze images or video feeds of the environment to determine location. This can involve matching features in the environment (e.g., landmarks) with known data from a location database.
Accuracy: Can be very accurate, especially in well-mapped areas, with potential sub-meter precision.
Applications: Augmented reality (AR), autonomous robots, and indoor navigation.

5.2 Indoor positioning

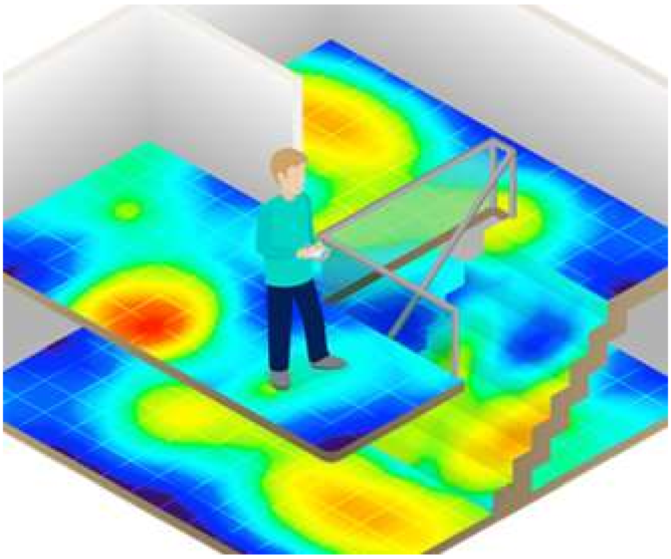
Indoor positioning systems (IPS) are specialized geolocation solutions that provide accurate positioning within enclosed spaces where traditional GPS signals are weak or unavailable. These systems are increasingly used in various applications, such as indoor navigation, asset tracking, and personalized services. Above is an overview of key indoor positioning technologies and their characteristics. In addition following techniques are also used:

11. Ultra-Wideband (UWB) Positioning



UWB uses very short radio pulses across a wide frequency spectrum. It measures the time it takes for signals to travel between a tag and multiple anchors, allowing for precise distance calculation through Time of Flight (ToF).
Accuracy: 10–30 cm.
Applications: High-precision tracking of equipment or people (e.g., hospitals, warehouses, sports tracking).
Challenges: Higher infrastructure cost and limited range (10–50 meters).

12. Magnetic Field Mapping



Indoor environments have unique magnetic field patterns due to structural elements like steel and concrete. A device measures the local magnetic field and compares it with a pre-mapped fingerprint database to estimate location.

Accuracy: 1–2 meters.
Applications: Indoor navigation in malls, airports, or large offices.
Challenges: Requires extensive pre-mapping of the environment, and magnetic interference can affect accuracy.

Comparison of Indoor Positioning Technologies

Technology	Accuracy	Range	Cost	Best Use Cases
Wi-Fi	5–15 meters	Up to 50 m	Low	Indoor navigation, analytics
BLE Beacons	1–5 meters	10–30 m	Moderate	Proximity marketing, navigation
UWB	10–30 cm	10–50 m	High	Asset tracking, sports, robotics
RFID (Active)	<1 meter	Up to 100 m	Moderate	Inventory, access control
Magnetic Mapping	1–2 meters	Varies	Low to moderate	Indoor navigation
INS	Varies	Unlimited	Low	Robotics, pedestrian tracking
VPS	<1 meter	Varies	High	AR apps, indoor navigation
Ultrasound	5–10 cm	<10 m	High	Precision tracking (medical)

Applications of Indoor Positioning Systems

Retail and Malls:
Indoor navigation to help customers find stores.
Proximity marketing with BLE beacons to deliver targeted ads.

Hospitals:
Tracking medical equipment and staff.
Indoor navigation for patients and visitors.

Airports and Train Stations:
Wayfinding for passengers.
Location-based alerts for gate changes or boarding calls.

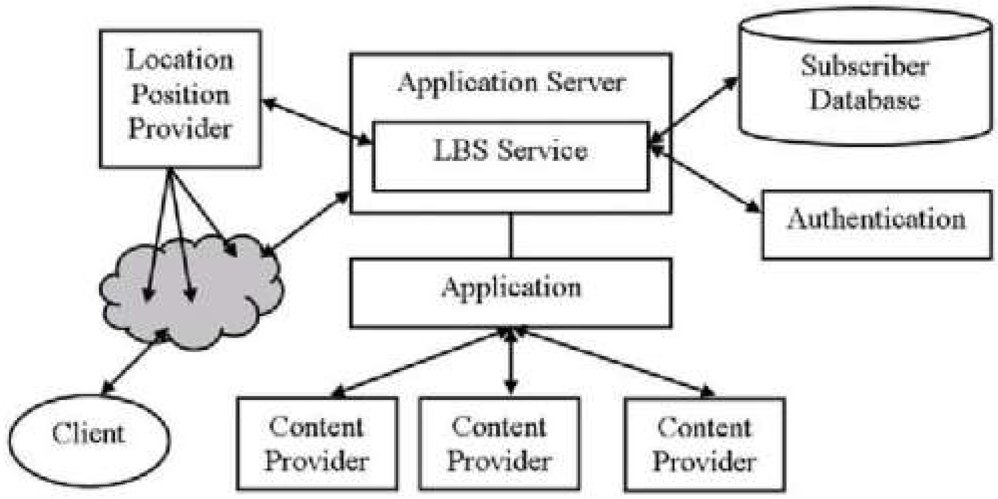
Warehouses and Manufacturing:
Real-time tracking of inventory and equipment.
Route optimization for autonomous vehicles.

Museums and Exhibitions:
Delivering contextual information based on visitor location.
Enabling interactive experiences with AR.

Smart Buildings:
Automating lighting and climate control based on occupants' positions.
Enhancing security with location-based access control.

5.3 LBS Architecture

Location-Based Services (LBS) architecture involves various components that work together to deliver location-based functionalities. LBS systems use geographic data to provide personalized, context-aware services to users through mobile devices or other systems. This architecture supports applications such as navigation, geofencing, asset tracking, proximity marketing, and emergency services.



Workflow of a Typical LBS System

Location Acquisition:
The user's device collects its location using GPS, Wi-Fi, or other methods.

Request Transmission:
The device sends a request (e.g., for nearby restaurants) along with its current coordinates to the LBS server via the communication network.

Processing at the LBS Server:
The server queries the GIS database for nearby points of interest (POIs) and processes the request. If needed, the LBS server interacts with third-party content providers (e.g., restaurant listings).

Response Transmission:
The LBS server sends the relevant data (e.g., a list of restaurants) back to the user's device.

Rendering on the Client Device:
The user's device displays the results on a map or as a list. The application may also trigger additional actions, such as sending push notifications or generating navigation routes.

5.4 Integration with GISs

The integration of Location-Based Services (LBS) with Geographic Information Systems (GIS) plays a crucial role in providing real-time, context-aware location services. GIS provides the spatial data infrastructure, such as maps, geocoding, and spatial analysis, while LBS delivers real-time location tracking, personalized notifications, and routing based on user or asset positions. This combination enables enhanced services in navigation, asset management, emergency response, and smart city applications

Key Components in LBS-GIS Integration

LBS Components:

Positioning System: Determines the real-time location of users or assets (via GPS, Wi-Fi, Bluetooth, etc.).

LBS Server: Processes location data and manages services like geofencing, routing, and alerts.

Communication Network: Connects the user's device, LBS server, and GIS components.

Application Layer: User-facing apps like maps, ride-hailing apps, or emergency dispatch systems.

GIS Components:

Spatial Database: Stores geospatial data such as maps, road networks, building footprints, and Points of Interest (POIs).

Geocoding and Reverse Geocoding Services: Converts addresses into geographic coordinates (latitude, longitude) and vice versa.

Map Rendering Engine: Provides visualization of geographic data on maps.

Spatial Analysis Tools: Supports routing, proximity analysis, and location-based queries (e.g., finding the shortest path).