Satellite Positioning

GE-703

GPS Observables, System Biases and Improvement Techniques

Dinesh Mani Bhandari
RS&GIS | Mechatronics Engineer
Email: dinesh.bhandari@pasc.tu.edu.np

TU Institute of Engineering (IOE)
पश्चिमाञ्चल क्याम्पस
PASHCHIMANCHAL CAMPUS

Contents - I

GPS Observables:

1. Code Pseudoranges
2. Carrier Phase
3. Doppler Frequency

System Biases and Errors:

1. Multipath
2. Timing and Orbital Biases
3. Troposphere
4. Ionosphere

GPS Errors and System Bias

There are various errors resulting from various sources which affects satellite ranging and hence affects GPS performance.

Errors in range measurements create a range of uncertainty around the GPS position.

The sum of all systematic errors or biases contributing to the measurement error is referred to as range bias.

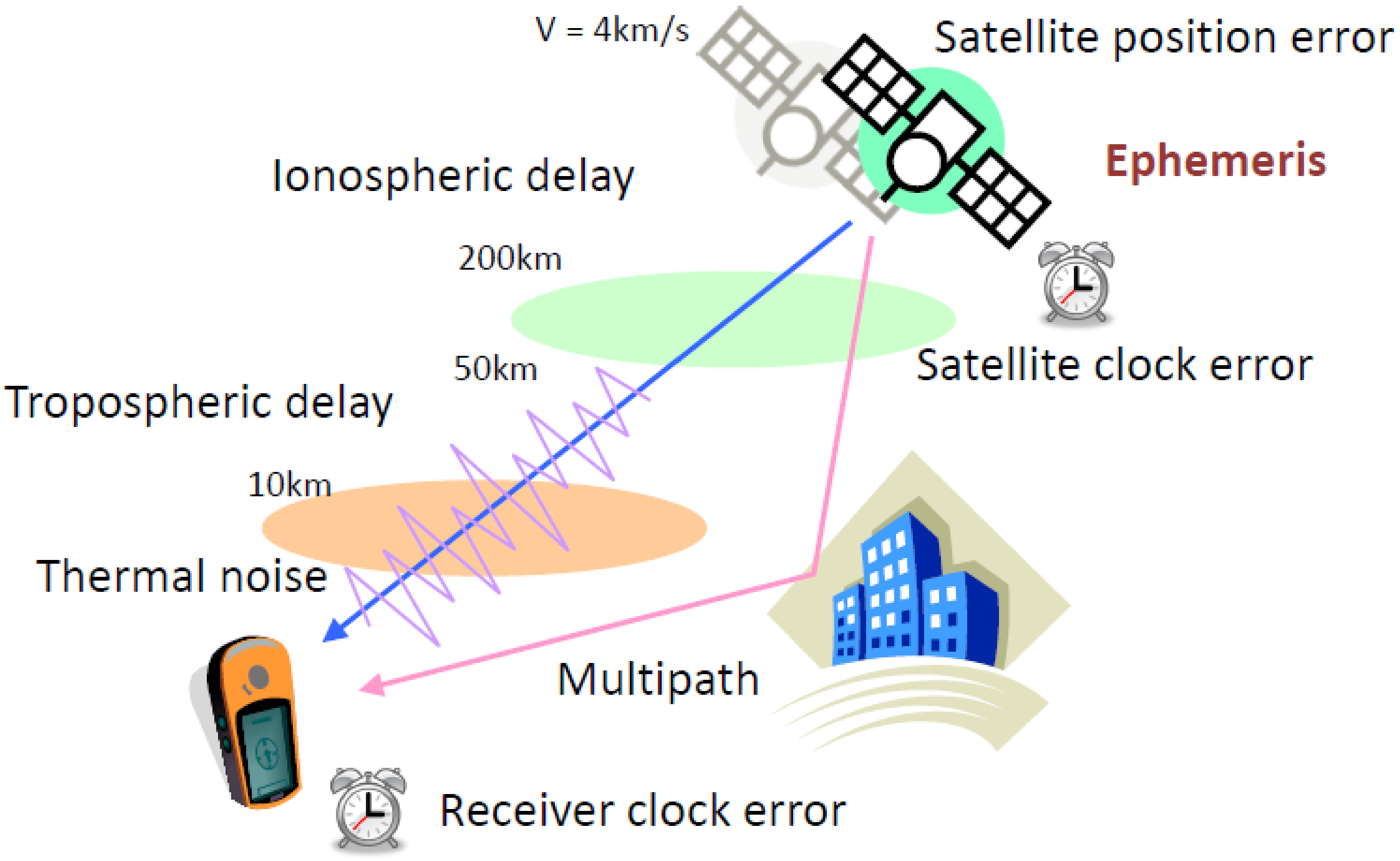
The observed GPS range, without removal of biases, is referred to as a biased range or pseudo-range.

GPS errors can arise from inaccuracies in estimate of satellite position and satellite clock and electronic inaccuracies, tropospheric and ionospheric effect along signal propagation path, , atmospheric absorption, receiver noise generated through signal processing errors, signal multipath effect etc.

GPS Errors and System Bias

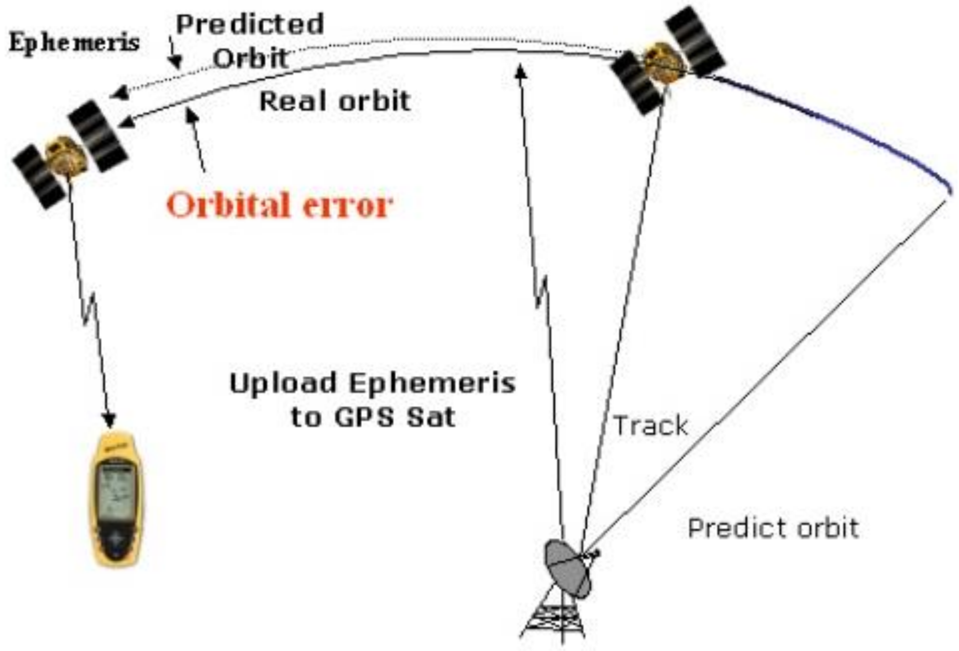
The GPS errors are associated with absolute GPS positioning mode are:

i. Ephemeris errors and orbit perturbations
ii. Clock stability
iii. Ionospheric delays
iv. Multi-path
~~v. Selective availability~~
vi. Anti spoofing
vii. Receiver noise



Ephemeris Error & Orbit Perturbations

- Satellite ephemeris errors are errors in the prediction of a satellite position.
- Ephemeris errors are satellite dependent and very difficult to correct and compensate while modelling the orbit of a satellite because many forces acting on the predicted orbit of a satellite are difficult to measure directly.
- Ephemeris errors produce equal error shifts in the calculated absolute point positions.
- Main force acting on GNSS satellites is Earth's central gravitational force, but there are many other significant perturbations.
  - Non sphericity of the Earth's gravitational potential
  - Third body effect
    - Direct attraction of Moon and Sun
- Solar radiation pressure
  - Impact on the satellite surfaces of photons emitted by the Sun



Clock Stability

- A time offset is the difference between the time recorded by the satellite clock and that recorded by the receiver.
- Range errors observed by the user as a result of the time offset between the satellite and receiver clock have a linear relationship and can be approximated by the following relation.

$$R_E = T_0 \times c$$

where R_E is the user equivalent range error (UERE); T_0 the time offset c the speed of light.

Example for the calculation of user equivalent range error:

When time offset $T_0 = 1.5$ µsec (1.5×10^{-6})

$$c = 29{,}97{,}92{,}458 \text{ m/sec}$$

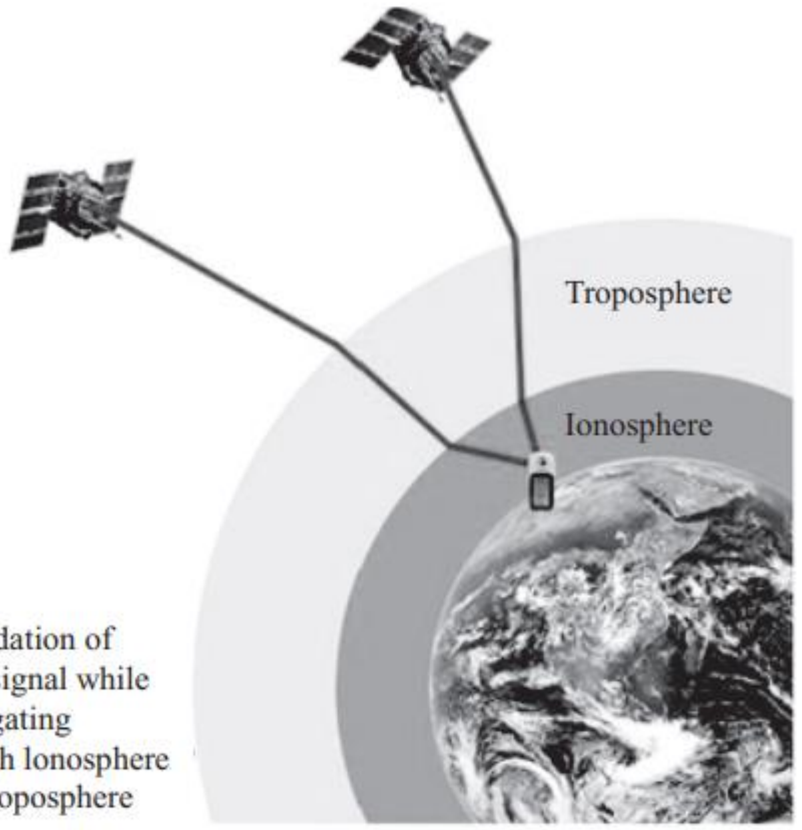
$$R_E = 1.5 \times 10^{-6} \times 299792458 = 450 \text{ m} = \text{user equivalent range error}$$

Satellite and Receiver Clock Errors

- GPS receivers use ordinary quartz crystal oscillators, to keep the cost of GPS receivers at an economical level.
- In absolute positioning, the receiver clock off set has to be estimated as an unknown parameter in the navigation solution which estimates the receiver position and receiver clock at the same time.
- The receiver clock off set can be estimated within 1 µs or better. The limit in the accuracy results from the effects of measurement noise and the atmospheric impact on the GPS signal.
- A standard model ionospheric and tropospheric correction has to be applied or in the case where dual Frequency GPS receivers are used the ionospheric free combination can be employed.

Ionospheric Delays

- GPS signals are electromagnetic signals and as such are nonlinearly dispersed and refracted when transmitted through a highly charged environment like the ionosphere.
- Dispersion and refraction of the GPS signal is referred to as the ionospheric range effect because it results in an error in the GPS range value.
- Also, as the satellite signal passes through the ionosphere, it is slowed down because the medium is denser compared with outer space.
- These delays can introduce an error in the range calculation as the velocity of the radio signals from the satellite is affected. The ionospheric range effects are frequency dependent and are not constant.



Degradation of radio signal while propogating through Ionosphere and Troposphere

Ionospheric Delays

- There are several factors that influence the number of delays caused by the ionosphere:
- Satellite Elevation and Satellite Geometry
  - The longer the signal is in the ionosphere, the greater the ionospheric effect.
- Density of Ionosphere
  - At night, there are very little ionospheric influences and during day-time the light and heat from the sun increases the effect of the ionosphere and slows down the signal.
- Resolution of Ionospheric Delay
  - Resolution of ionospheric delays can be accomplished by using a dual frequency GPS receiver.
  - The time delay for a higher frequency carrier wave is less than it is for a lower frequency wave due to the dispersive nature of the ionosphere.

Troposphere Delays

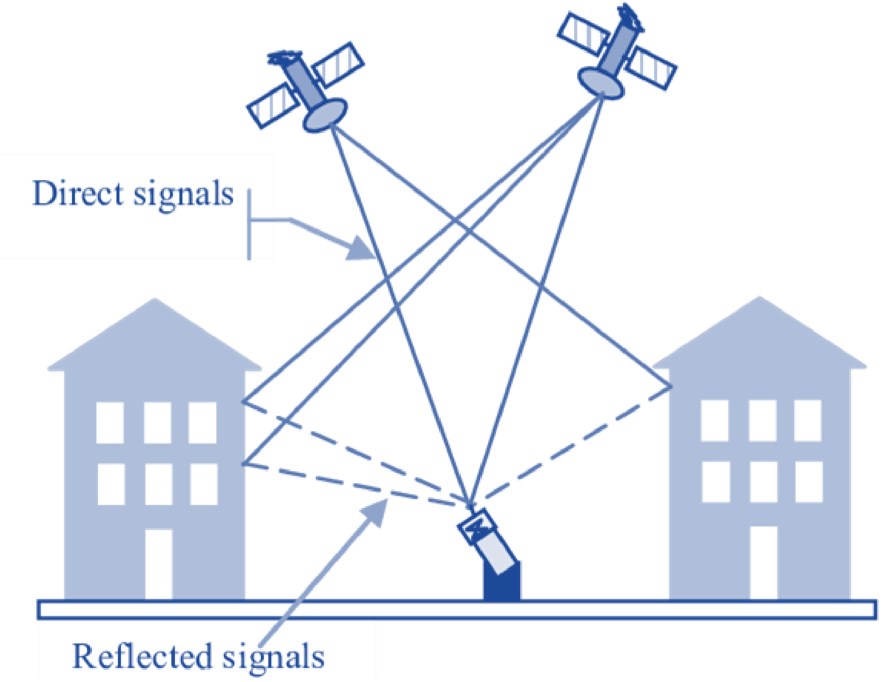
- The tropospheric delay adds a slight distance to the range the receiver measures between itself and the satellite.

- The delay caused by the troposphere is maximum when the satellite is close to horizon and minimum when the satellite is at zenith.

- Modelling the troposphere is one among the technique used to reduce the bias in GPS data processing and it can be up to 95% effective.

Signal Multipath

- Signal Multipath is an error affecting positioning that occurs when the signal arrives at the receiver from more than one path due to reflection of signals.
- This occurs when the GPS receiver is positioned close to large reflecting surfaces such as a lake, a big rock, a building or other manmade structures.
- Reflected signals increases the travel time of the signal, thereby causing errors.
- Multipath error is different for different frequencies. It affects the phase measurements, as well as the code measurements.
- Rejections of Multipath signals are necessary for only high accuracy measurements.



Anti-Spoofing

Spoofing: An act to make the receiver lock on a false signal and then slowly take away pull to the desired path such that sufficient time passes prior to the detection

- Similar to bring a magnet near the compass to change the North Direction as required

- Anti-spoofing (AS) of the GPS system is designed for an anti potential spoofer (or jammer).

Spoof: Provide false information as if it were true

Jamming and Interference	Spoofing
Intentional and Non-Intentional	Intentional
Can be Detected	**Difficult to Detect**
Denial of Service	**Available of Service but Lead to False Position Data**
Many Solutions Exist	No Effective Solution for Existing Signals
Many Research and Studies	Fewer Research and Studies

Receiver Noise

- How precisely a GPS receiver can measure the pseudo-range and carrier phase largely depends on how much noise accompanies the signals in the receiver's tracking loops.
- The more the noise, the worse the performance of the receiver is.
- This noise either comes from the receiver electronics itself or is picked up by the receiver's antenna.
- Receiver noise includes a variety of errors associated with the ability of the GPS receiver to measure a finite time difference. These include signal processing, clock/signal synchronization and correlation methods, receiver resolution, signal-to-noise ratio, etc.

GPS Errors Budget

- The positioning accuracy depends on the magnitude of error in the individual pseudorange measurement.

Typical contributions of errors are usually presented as the GPS error budget.

User Equivalent Range Error (UERE)

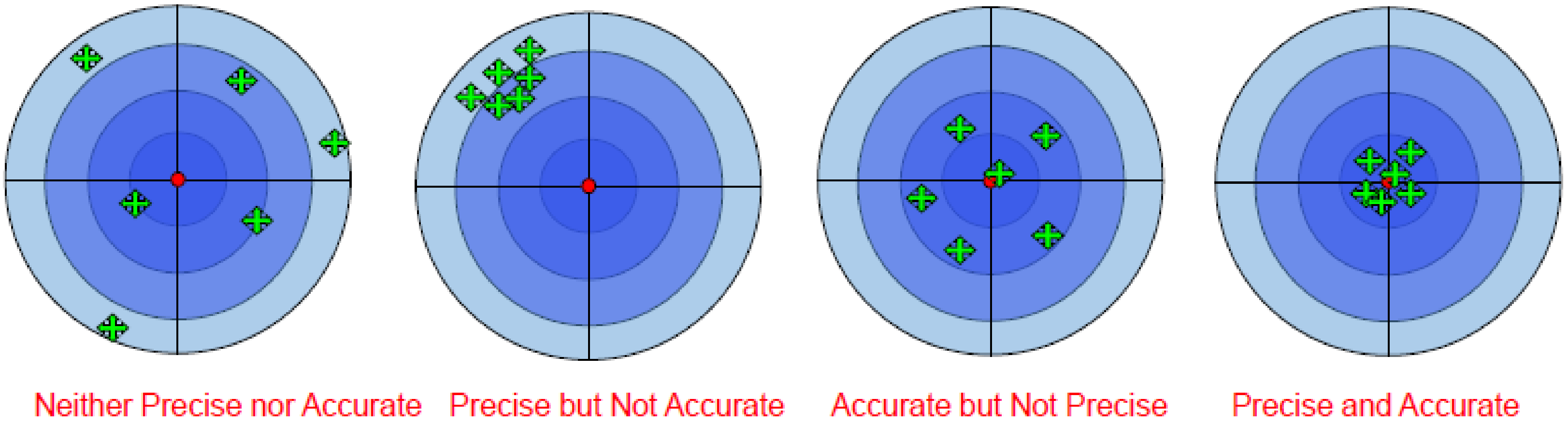
$$UERE = \sqrt{3^2 + 3^2 + 4^2 + 0.7^2 + 1.4^2 + 0.8^2} = 6.09$$

Error Type	Error (meters)	Segment
Ephemeris	3.0	Signal-In-Space
Clock	3.0	Signal-In-Space
Ionosphere	4.0	Atmosphere
Troposphere	0.7	Atmosphere
Multipath	1.4	Receiver
Receiver	0.8	Receiver
UERE	**6.09**	

Driver, Ted (2011). The GPS Error Budget
http://thenogspot.blogspot.in/p/gps-error-budget.html

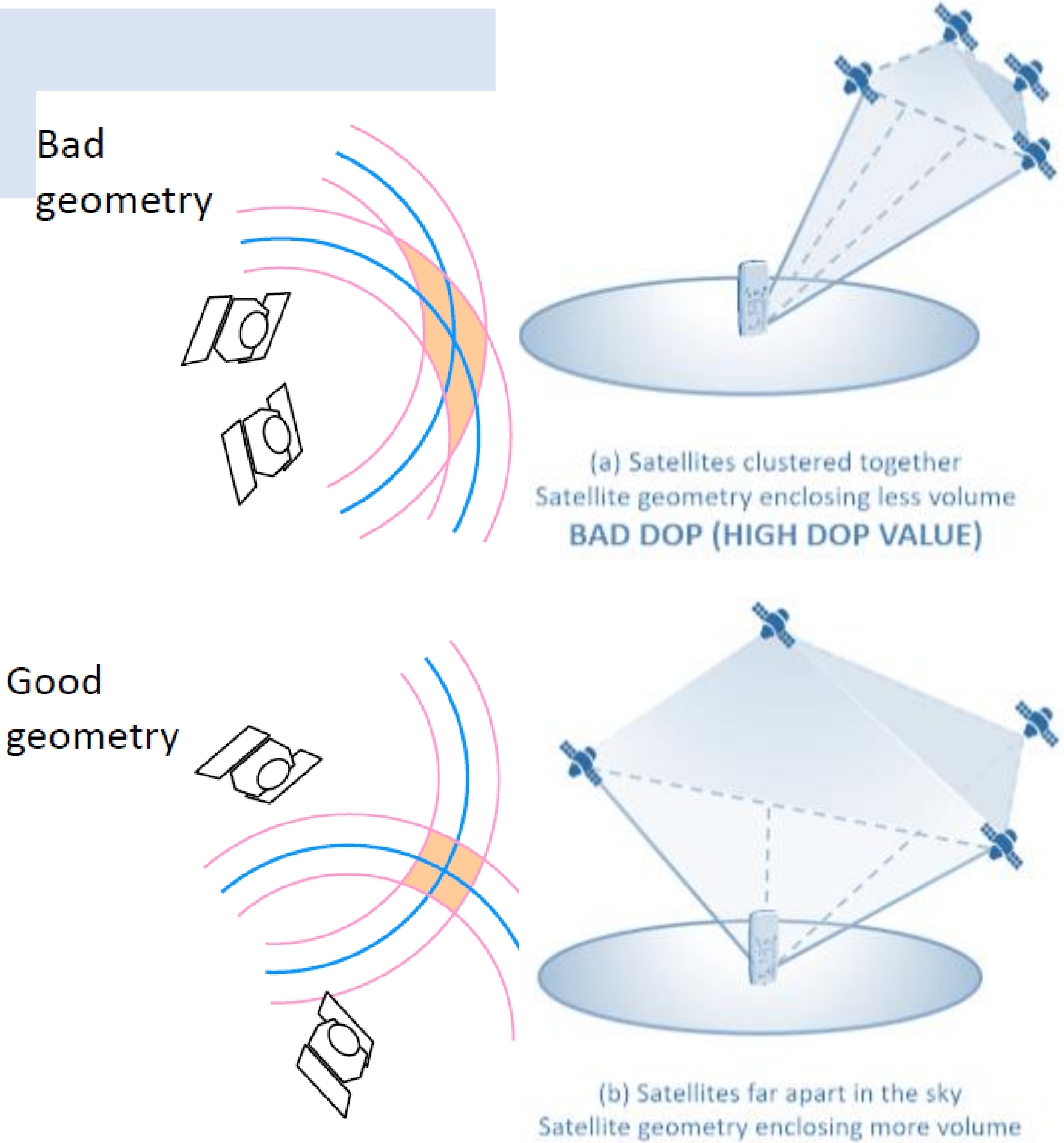
Accuracy vs Precision

- Accuracy
  - Capable of providing a correct measurement
  - Measurement is compared with true value
  - Affected by systematic error
- Precision
  - Capable of providing repeatable and reliable measurement
  - Statistical analysis of measurement provides the precision
  - Measure of random error
  - Systematic error has no effect



Dilution of Precision

- The geometry of satellites in the sky at the time of the GPS survey has a significant impact on positional accuracy.
- Errors contributed by bad satellite geometry called Dilution of Precision or DOP can *amplify* UERE leading to a decrease in positional accuracy.
- When satellites are far apart in the sky, a large tetrahedron (or polyhedron) volume is created minimizing the area of positioning uncertainty which leads to good DOP (Small DOP values).
- On the other hand, when visible satellites are clumped together in one part of the sky, the polyhedron volume is less which leads to bad DOP (Large DOP values).



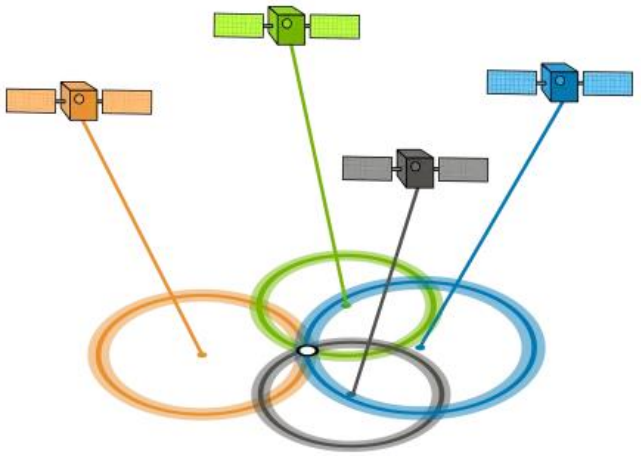
(a) Satellites clustered together
Satellite geometry enclosing less volume
BAD DOP (HIGH DOP VALUE)

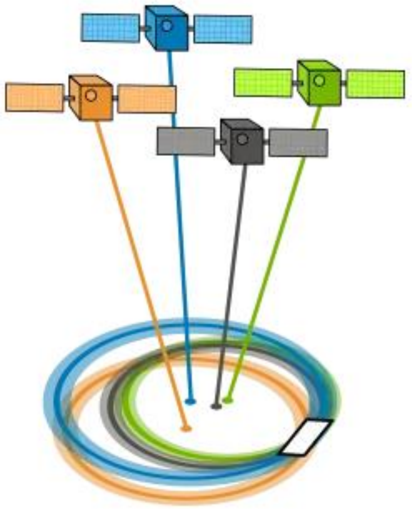
(b) Satellites far apart in the sky
Satellite geometry enclosing more volume
GOOD DOP (LOW DOP VALUE)

Dilution of Precision

Limits of DOP that should be considered while GPS observation

DOP Value Calculated by the Receiver	Normal Rating	Explanation on the Rating
<1	Ideal and best	Best possible confidence level to be used for applications which require highest precision
1–2	Excellent	At excellent confidence level, positional measurements are considered accurate and the accuracy level is good enough to meet most of the sensitive applications
2–5	Good	This level is appropriate for making positional measurements reliable for navigation and for large scale mapping
5–10	Moderate	Positional Measurements may be used but a more open view of sky is recommended
10–20	Fair	Represents a low confidential level. Position information should be discarded or shall be used for a very rough estimate of position.
>20	Poor	Position Measurements are in accurate as much as 300m and should not be adopted for any purpose.





The ideal arrangement (of the minimum four satellites) is one satellite directly overhead, three others equally spaced near the horizon.

GPS Observables / Measurements

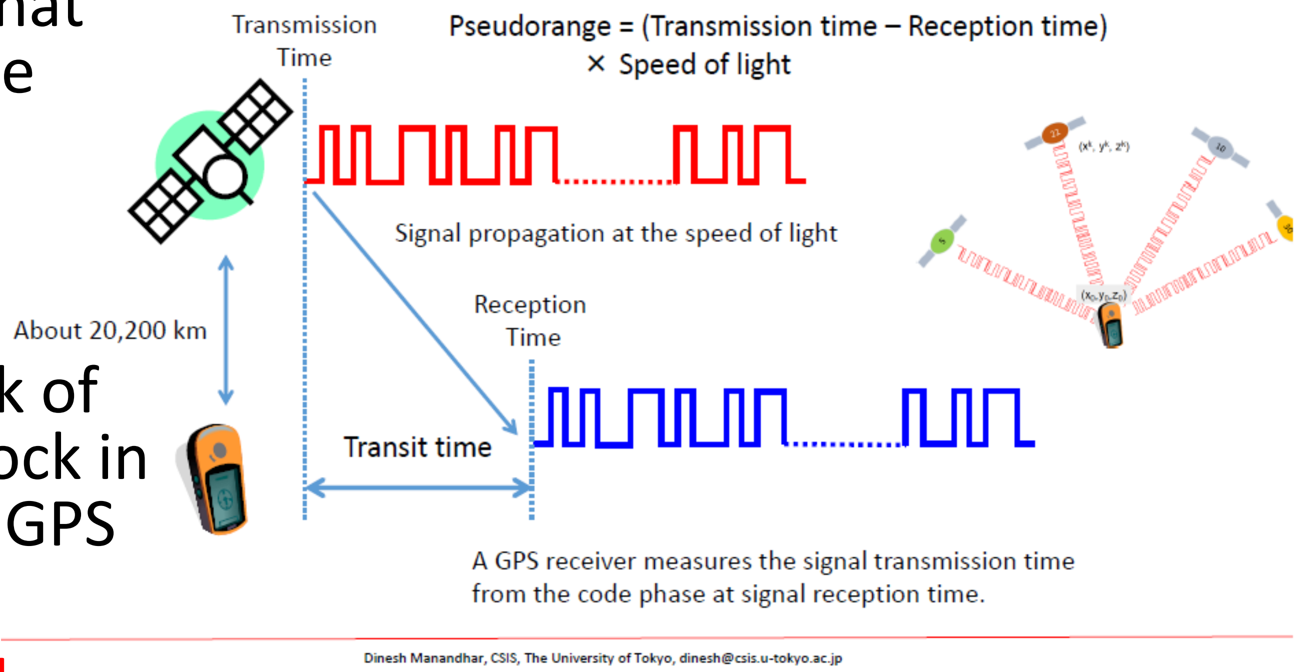
While tracking a satellite signal, a GPS receiver monitors three parameters:

pseudo-ranges, carrier phase, and Doppler.

- Code pseudo-ranges for autonomous and less precise/accurate positioning
- Carrier phase observables for more precise/accurate positioning.
- Doppler measurement reflects the rate of change of the carrier phase.

GPS Observables: Pseudorange

- The GPS receiver measures the distance (pseudorange) between the satellite and the antenna by measuring the time that the signal takes to propagate from the satellite to the receiver.
- The pseudorange is this time offset multiplied by the speed of light.
- The pseudorange is biased by the lack of time synchronization between the clock in the GPS satellite and the clock in the GPS receiver.
- Other bias effects include the ionosphere and troposphere delay, multipath and receiver noise.

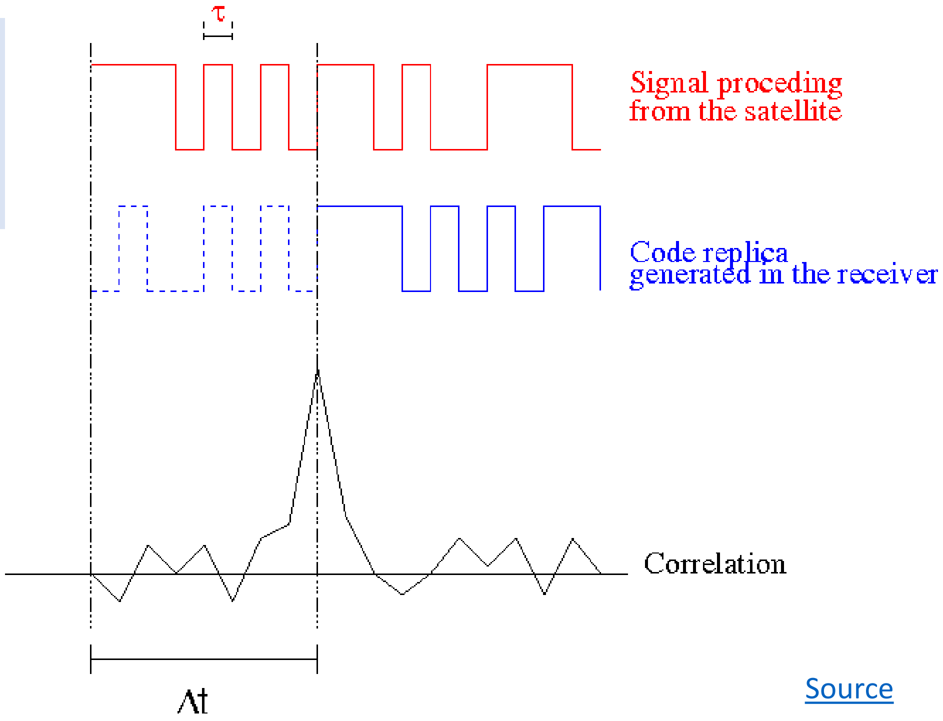


GPS Observables: Pseudorange

The pseudo-range is calculated by cross-correlating the pseudo-random noise code received from the satellite and with a replica generated by the receiver.

- The basic pseudo-range equation is given by

$$p = \rho + \mathrm{d}\rho + c(\mathrm{d}t - \mathrm{d}T) + d_{\mathrm{ion}} + d_{\mathrm{trop}} + \varepsilon_{\mathrm{mp}} + \varepsilon_{\mathrm{p}}$$



Source

where p is the pseudo-range measurement,

ρ the true range between receiver's antenna and the satellite's antenna at the time of signal transmission,

$\mathrm{d}\rho$ satellite orbital errors,

c the speed of light,

$\mathrm{d}t$ the satellite clock offset from GPS time,

dT the receiver clock offset from GPS time,

d_{ion} the ionospheric propagation delay on pseudo-range,

d_{trop} the tropospheric propagation delay on pseudo-range,

$\varepsilon_{\mathrm{mp}}$ the multipath on pseudo-range,

ε_{p} the receiver noise, and

$$P = \rho + c(\mathrm{d}t - \mathrm{d}T) + d_{\mathrm{ion}} + d_{\mathrm{trop}} + \varepsilon$$

where ε represents the combined effect of multipath and receiver measurement noise.

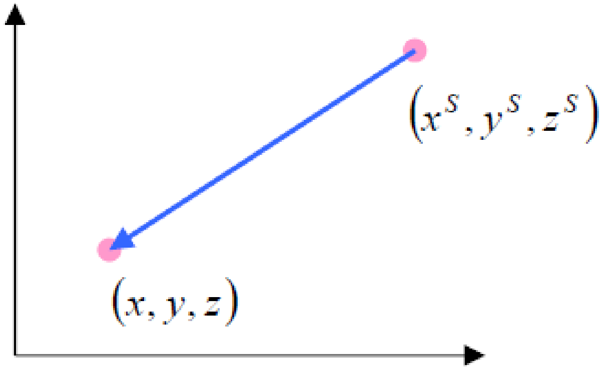
GPS Observables: Pseudorange

Range Equation

Satellite position at signal transmission time: $\left(x^S, y^S, z^S\right)$

Receiver position at signal reception time: $\left(x, y, z\right)$

$$r = \sqrt{\left(x - x^S\right)^2 + \left(y - y^S\right)^2 + \left(z - z^S\right)^2}$$



Pseudorange Model

Receiver clock error

$$\rho = \underbrace{\sqrt{\left(x - x^S\right)^2 + \left(y - y^S\right)^2 + \left(z - z^S\right)^2}}_{r} + c\left(\delta t_R - \delta t^S\right) + \varepsilon$$

Satellite clock error

Given satellite position & clock in navigation message

Unknown receiver position & clock

Estimate optimal solution to minimize the error

where ε represents the combined effect of multipath and receiver measurement noise.

GPS Observables: Pseudorange

- Pseudo-range measurements can be made using either the C/A code or P-code.
- The P-code generally provides higher observations because 300 m resolution of the C/A code is 10 times lower than the P-code.
- However, recent technological advancement in receiver technologies have resulted in higher precision C/A code measurements such as narrow code correlation etc. some of the ranging errors can be corrected, such as the tropospheric delay can be corrected using a tropospheric delay model, and ionospheric delays can be corrected using a dual frequency GPS receiver.
- The errors will cause inaccuracy in the calculation of user position. It should be noted that the user clock error cannot be corrected through received information. Thus, it will remain as an unknown.

GPS Observables: Carrier Phase

- The carrier phase observable is a measure of the difference between the carrier signal generated by the receiver's internal oscillator and the carrier signal from the satellite.
- The Carrier phase observable is the number of full carrier cycles and the fractional cycle, between the antennas of the satellite and the receiver.
- The main problem in carrier phase tracking is that the GPS receiver has a way of distinguishing one carrier cycle from another.
- The best it can do is to measure the fractional phase and keep track of changes to the phase. Hence the initial phase is undermined or ambiguous, by an integer number of cycles.

GPS Observables: Carrier Phase

- To use the carrier phase as an observable for positioning this unknown number of cycles or the phase ambiguity must be estimated.

$$\phi = \rho + \mathrm{d}\rho + c(\mathrm{d}t - \mathrm{d}T) + \lambda N - d_{\mathrm{ion}} + d_{\mathrm{trop}} + d_{\phi\mathrm{mp}} + \epsilon_{\phi}$$

where ϕ is the carrier phase observation in unit of metres,

$d_{\phi\mathrm{mp}}$ the multipath on the carrier phase,

ϵ_{ϕ} the carrier phase observation noise,

λ the wave length of carrier phase,

N the integer ambiguity,

ρ the satellite position error,

$\mathrm{d}\rho$ the effect of ephemeris error,

$\mathrm{d}t$ the satellite clock error with respect to GPS time,

$\mathrm{d}T$ the receiver clock error with respect to GPS time,

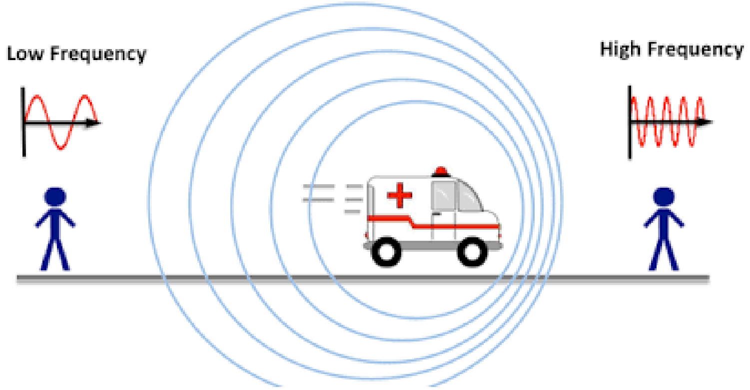
d_{ion} the ionospheric delay,

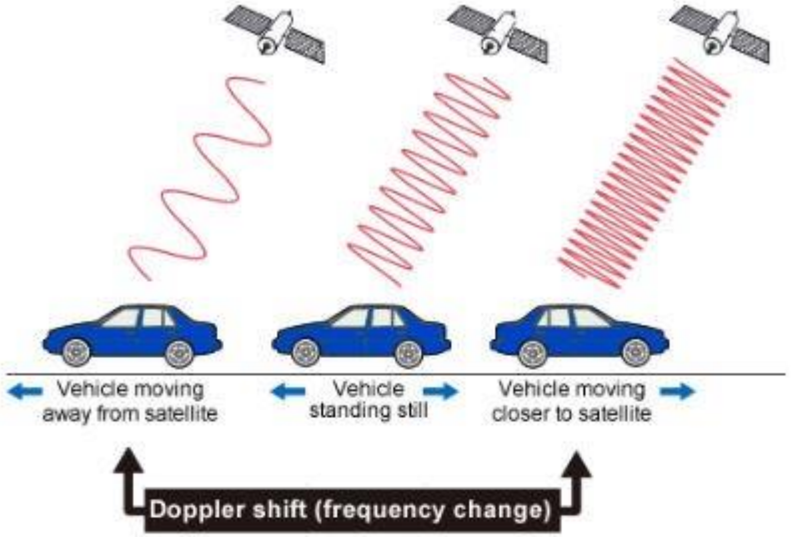
d_{trop} the tropospheric delay, and

c the velocity of light.

GPS Observables: Doppler Effect

- The apparent change in the frequency of a wave caused by relative motion between the source of the wave and the observer.
- The receiver must estimate the Doppler shift of each received signal in order to be able to receive it.
- The Doppler shift of a given signal is the time derivative of its carrier phase. As such, the Doppler shift is primarily determined by the relative velocity of the satellite's and receiver's antennas, plus a common offset that is proportional to the receiver's clock frequency error.





GPS Observables: Doppler Effect

The following formulas show the Doppler effect of the radio wave and light wave.

$$f_m = f_s \times \frac{\sqrt{1-(V/c)^2}}{1-(V/c)\cos\theta}$$

$$\Delta f = f_m - f_s$$

f_m	: Observed frequency
f_s	: Frequency of signal source
Δf	: Change in frequency of carrier wave
V	: Speed of signal source viewed from an observer
θ	: Moving direction of signal source viewed from an observer.
c	: Light speed

Carrier wave frequency of GPS satellites (L1 band fs=1575.42 MHz) is controlled very precisely. Measuring the frequency and applying it to the above formula derives the speed V.

The ground speed cannot be measured by the carrier wave frequency of only one GPS satellite because GPS satellite is moving at high speed, and also has the effect of the rotation of the earth.

Therefore, the receivers uses carrier waves from multiple GPS satellites (more than four) to measure the frequency, and then calculates the speed of the moving object by the same way of positioning measurement method.

Contents - II

Correction Techniques

- Multi-frequency and Multi-constellation

Improved GPS (Relative Positioning) :

- DGPS/DGNSS
- RTK
- SBAS
- GBAS
- PPP

Multi-frequency

- Using multi-frequency receivers is the most effective way to remove ionospheric error from the position calculation.
- Ionospheric error varies with frequency, so it impacts the various GNSS signals differently.
- By comparing the delays of two GNSS signals, L1 and L2, for example, the receiver can correct for the impact of ionospheric errors.
- Multi-frequency receivers also provide more immunity to interference. If there is interference in the L2 frequency band around 1227 MHz, a multi-frequency receiver will still track L1 and L5 signals to ensure ongoing positioning.

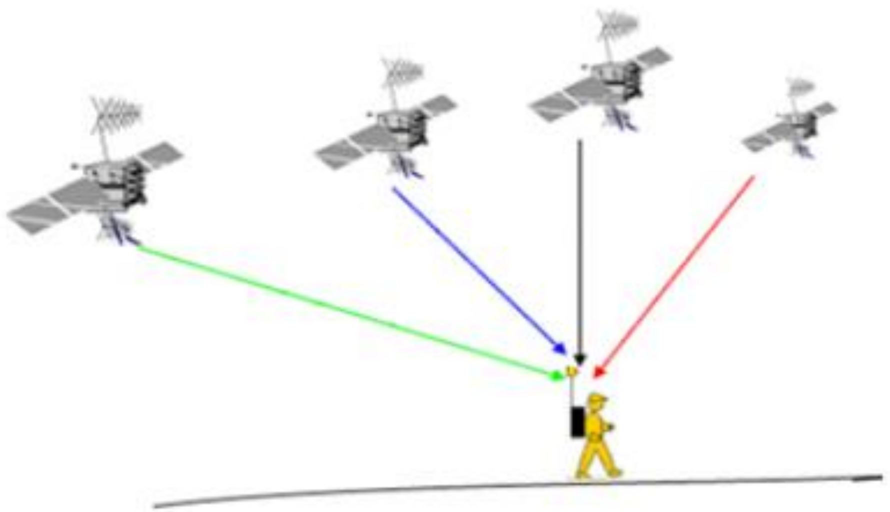
Multi-Constellation

- Multi-constellation receiver can access signals from several constellations: GPS, GLONASS, BeiDou and Galileo for example.
- The use of other constellations in addition to GPS, results in there being a larger number of satellites in the field of view, which has the following benefits:
  - Reduced signal acquisition time.
  - Improved position and time accuracy.
  - Reduction of problems caused by obstructions such as buildings and foliage.
  - Improved spatial distribution of visible satellites, resulting in improved dilution of precision.

Absolute vs Relative Positioning

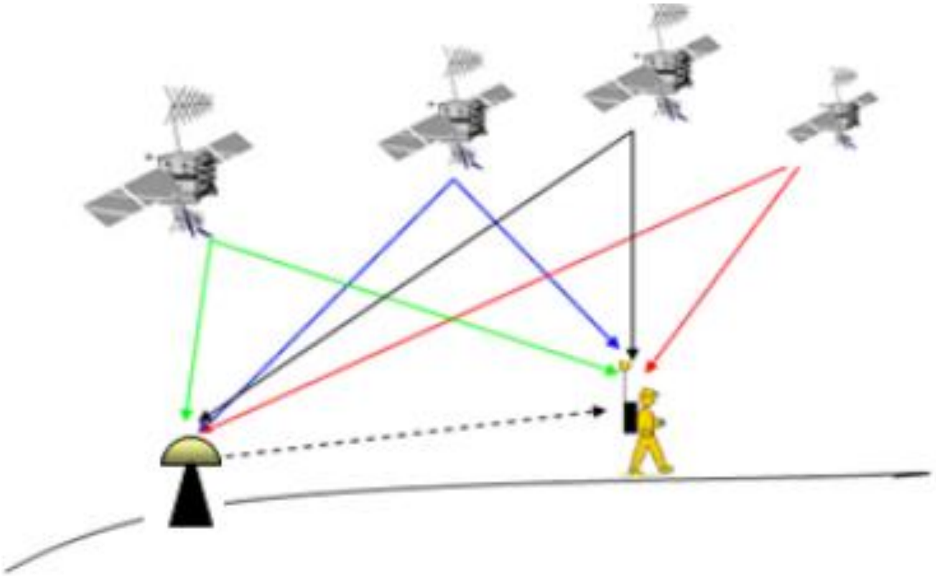
Absolute Positioning

- Consists of one GNSS receiver and four or more satellites
- Expected precession ~3 to 10 meters



Relative/Differential Positioning

- Data from a precisely known reference station is used to correct the position data gathered from a roving GNSS receiver.

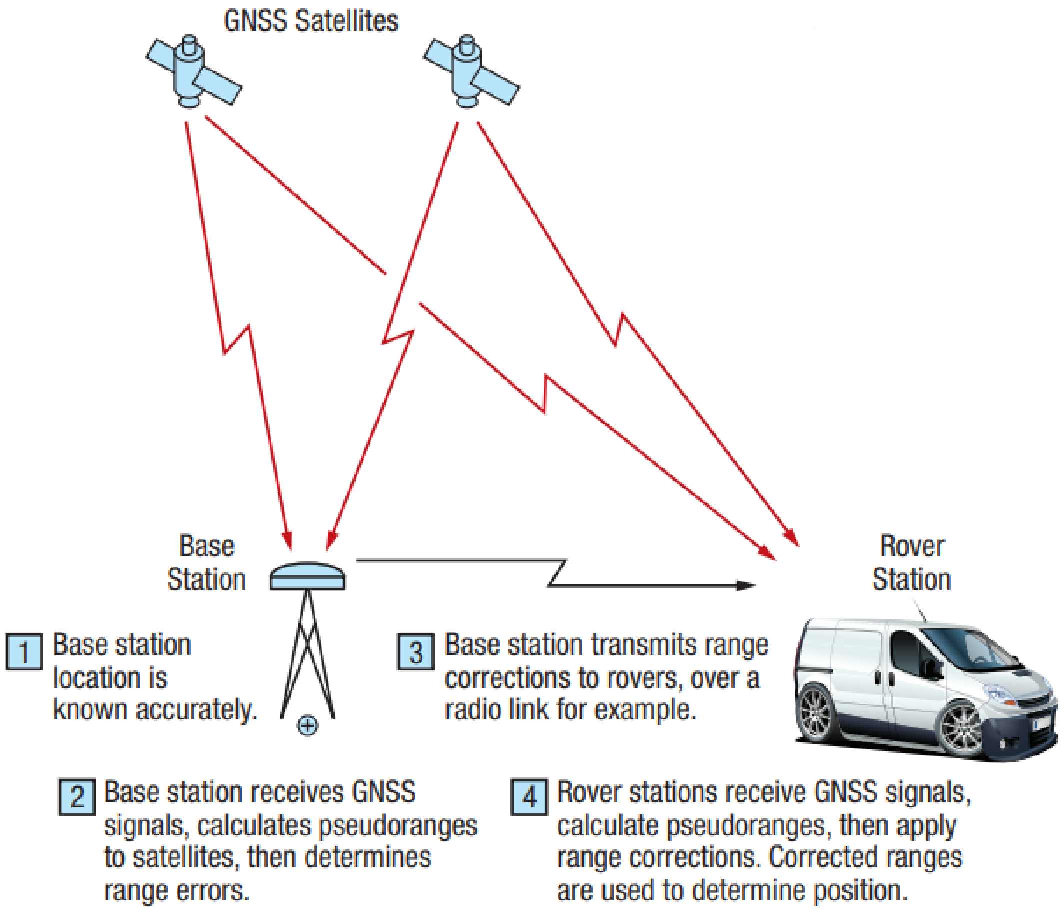


Positional accuracy in **relative positioning**
Typical error: 0.5 - 5m (horizontal accuracy), based on code measurements
Typical error: 2mm – 2cm (horizontal accuracy), based on carrier phase measurements.

DGPS/DGNSS

In differential GNSS, the position of a fixed GNSS receiver (base station), is determined to a high degree of accuracy using high grade GPS receiver.

- The base station determines ranges to the GNSS satellites in view using:
  - The pseudorange measurement.
  - The location of the satellites determined from the precisely known orbit ephemerides and satellite time.
- The base station compares the surveyed position to the position calculated from the satellite ranges.
- Differences between the positions can be attributed to satellite ephemeris and clock errors, but mostly to errors associated with atmospheric delay.
- The base station sends these errors to other receivers (rovers), which incorporate the corrections into their position calculations.

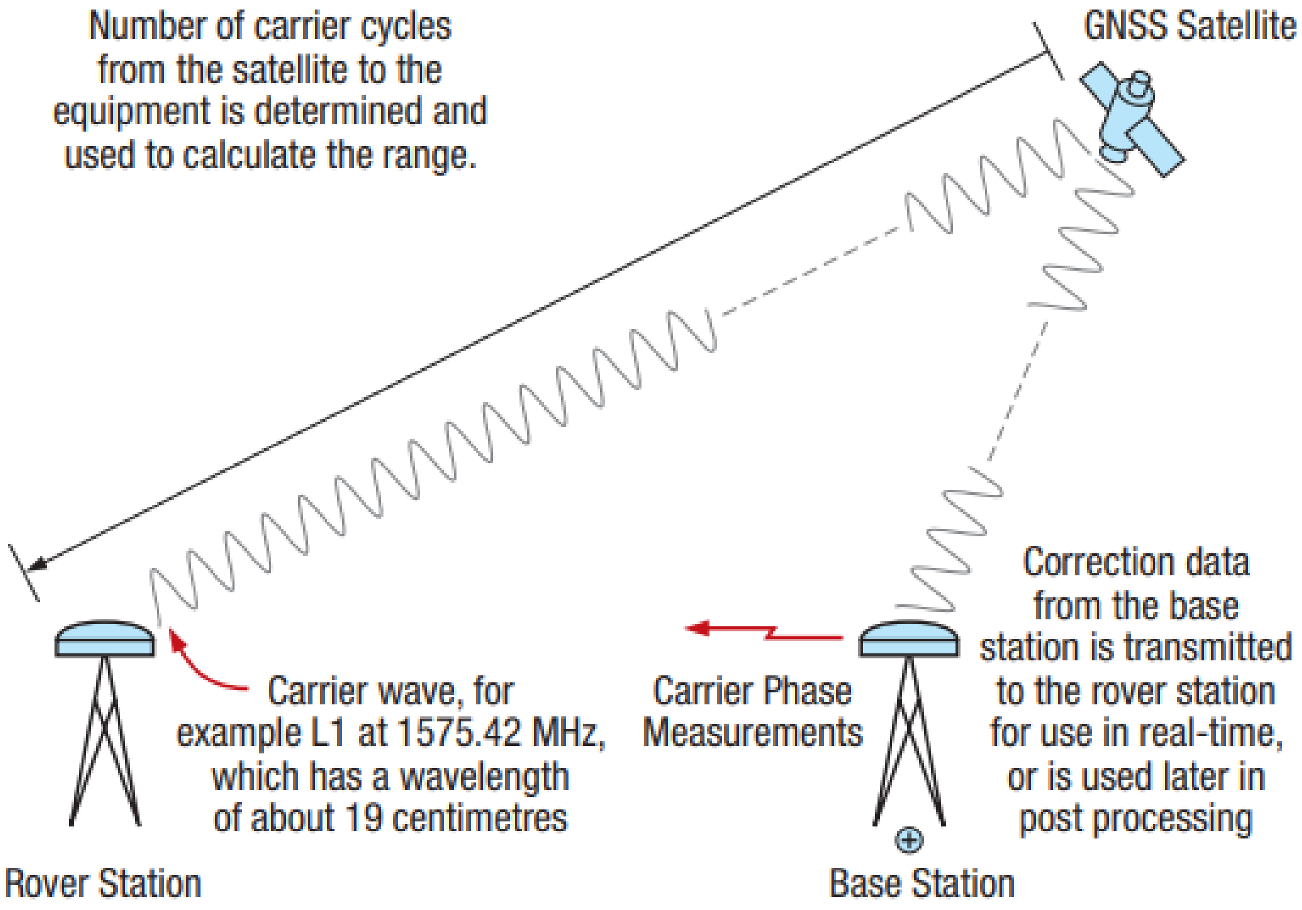


DGPS/DGNSS

- Differential positioning requires a data link between the base station and rovers, if corrections need to be applied in real-time, and at least four GNSS satellites in view at both the base station and the rovers.
- The absolute accuracy of the rover's computed position will depend on the absolute accuracy of the base station's position.
- Since GNSS satellites orbit high above the earth, the propagation paths from the satellites to the base stations and rovers pass through similar atmospheric conditions, if the base station and rovers are not too far apart.
- Differential GNSS works very well with base station-to-rover separations of up to tens of kilometers.

RTK

- RTK uses the carrier-based ranging for its position information, which can provide range values that are orders of magnitude more precise than code-based positioning.
- The base station for the RTK setup transmits the phase of the signal that it observes and sends that information to the rovers who then compare that to the phase that they observe.
- Corrections are as accurate as the known location of the base station and the quality of the base station's satellite observations.

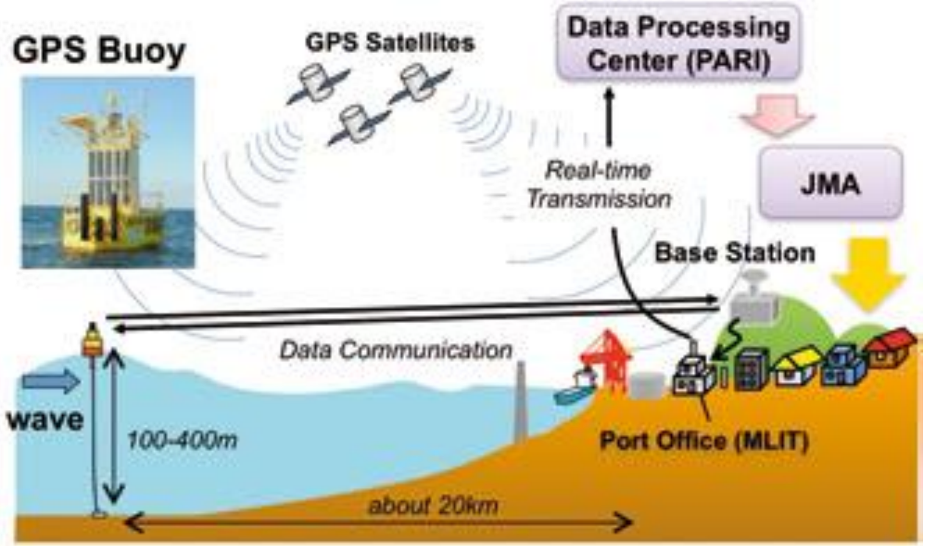


RTK Applications

https://muya-cors.com/knowledge-base/applications-gnss-cors

http://www.drotek.com http://www.emlid.com

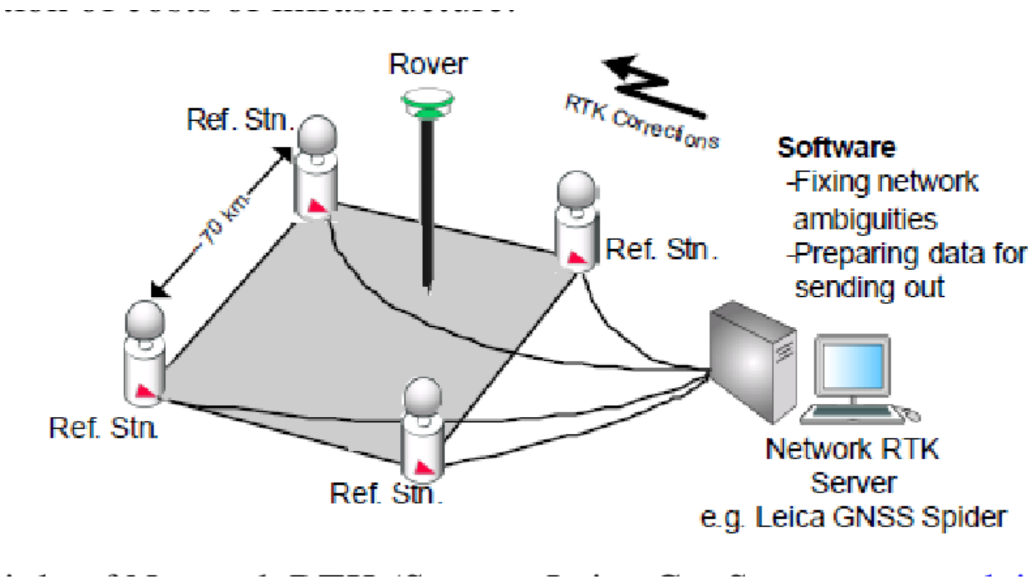
Tokyo Univ. of Marine Science and Technology : Nobuaki Kubo

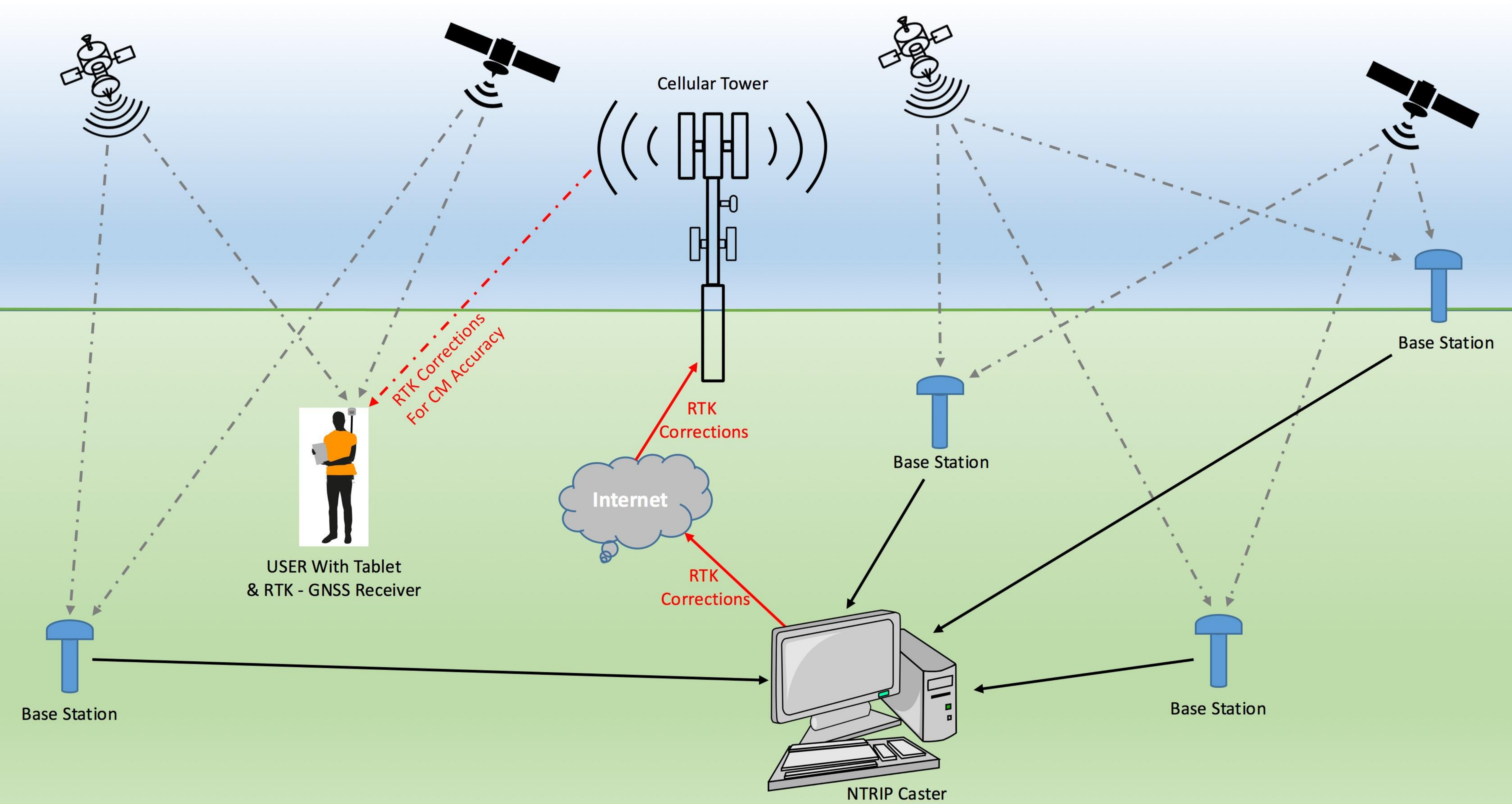


- **Computer aided construction**

Network RTK Positioning

- Network RTK (NRTK) is based on the use of several widely spaced permanent stations aka. CORS(Continuously Operating Reference Station).
- Depending on the implementation, positioning data from the permanent stations is regularly communicated to a central processing station.
- On demand from RTK user terminals, which transmit their approximate location to the central station, the central station calculates and transmits correction information or corrected position to the RTK user terminal.
- The benefit of this approach is an overall reduction in the number of RTK base stations required. Depending on the implementation, data may be transmitted over cellular radio links or other wireless medium.





Cellular Tower
RTK Corrections
For CM Accuracy
RTK
Corrections
Internet
RTK
Corrections
USER With Tablet
& RTK - GNSS Receiver
Base Station
Base Station
Base Station
Base Station
NTRIP Caster
calculates & relays corrections

NRTK

A network of permanent stations for real-time positioning is an infrastructure consisting of three parts:

- First part consists of CORSs with accurately known position, that transmit their data to a control center in real-time.

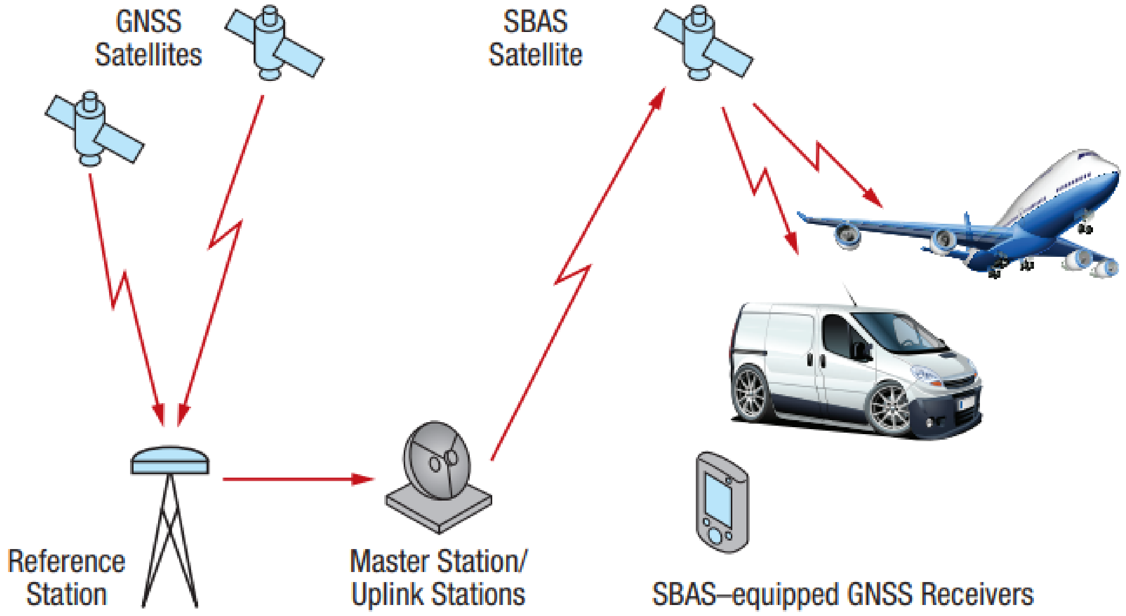
- The second part consists of a control center which receives and processes the data of the stations in real-time, ambiguity fixing phase for all satellites of each permanent station and calculating ionospheric and tropospheric delays, clock biases etc.

- The third part is the set of network products that can be provided from the control center to the user. The less elaborate product is the raw measurement file of each permanent station that the user may require for post processing purposes

Satellite Based Augmentation Systems(SBAS)

SBAS systems are geosynchronous satellite systems that provide services for improving the accuracy, integrity and availability of basic GNSS signals.

- Accuracy is enhanced through the transmission of wide-area corrections for GNSS range errors.
- Integrity is enhanced by the SBAS network quickly detecting satellite signal errors and sending alerts to receivers that they should not track the failed satellite.
- Signal availability can be improved if the SBAS transmits ranging signals from its satellites.



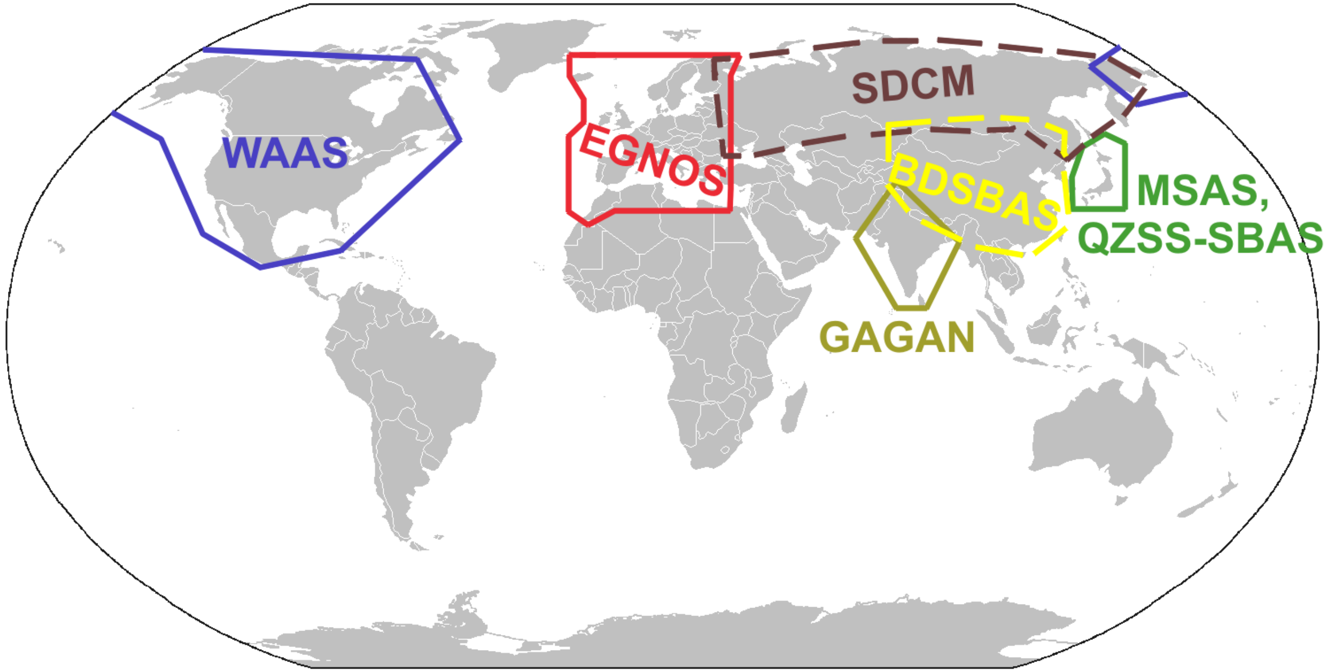
- Reference stations, which are geographically distributed throughout the SBAS service area, receive GNSS signals and forward them to the master station. Since the locations of the reference stations are accurately known, the master station can accurately calculate wide-area corrections.
- Corrections are up-linked to the SBAS satellite then broadcast to GNSS receivers throughout the SBAS coverage area. User equipment receives the corrections and applies them to range calculations.

SBAS

- Wide Area Augmentation System (WAAS)
- European Geostationary Navigation Overlay Service (EGNOS)
- Multi-functional Satellite Augmentation System (MSAS)
- GPS-Aided GEO Augmented Navigation System (GAGAN)
- System for radio-navigation fields Differential Correction and Monitoring (SCDM)

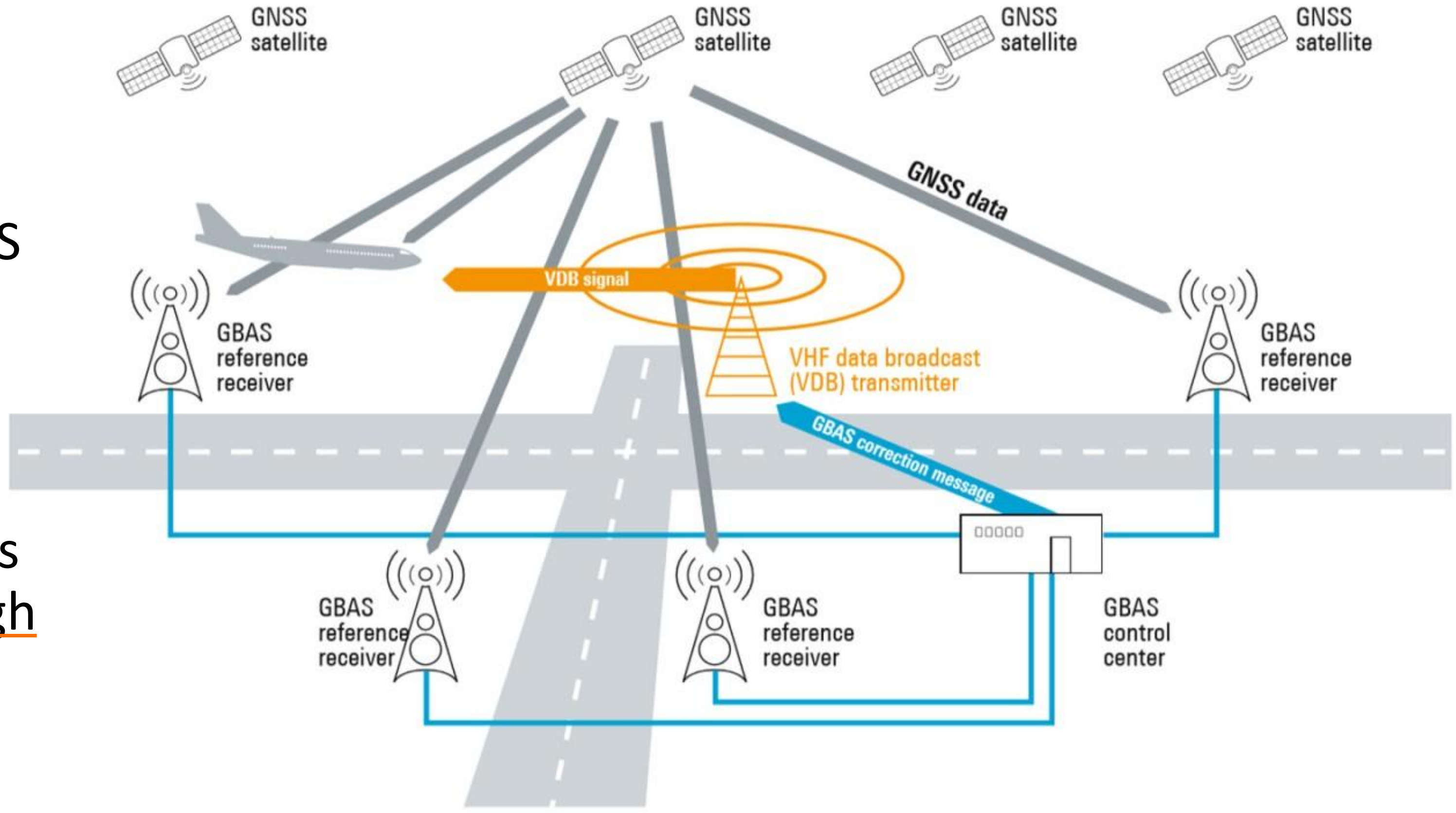
Provides users with

- ephemeris data and time-and-frequency parameters corrections;
- vertical ionospheric delay factor;
- navigational field integrity data



Ground Based Augmentation System(GBAS)

- A Ground Based Augmentation System (GBAS) provides differential corrections and satellite integrity monitoring to receivers using a VHF radio link.
- Also known as a Local Area Augmentation System (LAAS), a GBAS consists of several GNSS antennas placed at known locations, a central control system and a VHF radio transmitter. GBAS covers a relatively small area (by GNSS standards) and is used for applications that require high levels of accuracy, availability and integrity.
- Airports are an example of a GBAS application.



GNSS Augmentation Applications

CIVIL AVIATION

- Landing approach according to ICAO categories
- Local flight

AGRICULTURAL INDUSTRY

- Motion control mechanization in small-seeded crop cultivation and yield mapping.
- Precise and effective field binding and automatic motion control during large-seeded crop cultivation.

ROAD FACILITIES

- Road processing monitoring to traffic lane
- Precise and effective construction sites binding within absolute coordinate systems

RIVER TRANSPORT

- Coastal ship navigation
- Precise and effective waterway signing and marking

RAILWAY TRANSPORT SECURITY

- Train position monitoring on adjacent railway lines.
- Shunting locomotive target optimization control

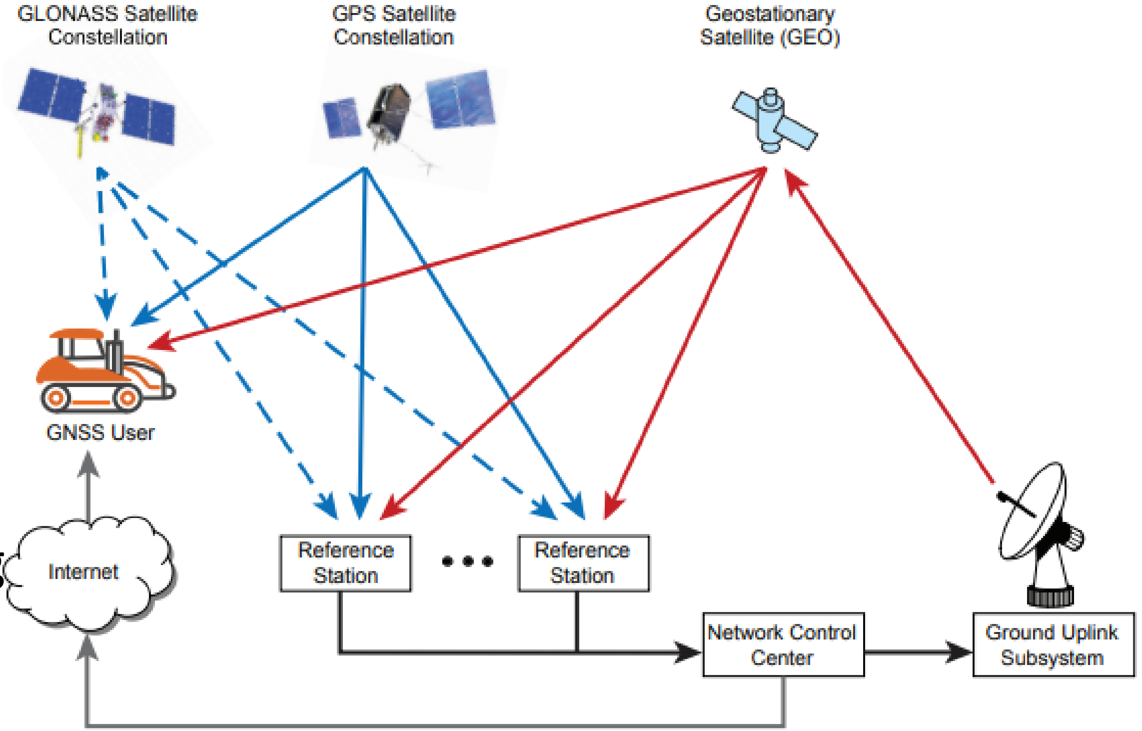
GEODESICS AND MAPPING

- Mapping database update.
- Pipelines and cable run mapping
- Natural resources mapping
- Real estate and construction area mapping

https://www.unoosa.org/documents/pdf/psa/activities/2015/RussiaGNSS/Presentations/6.pdf

Precise Point Positioning (PPP)

- PPP is a positioning technique that removes or models GNSS system errors to provide a high level of position accuracy from a single receiver.
- A PPP solution depends on GNSS satellite clock and orbit corrections, generated from a network of global reference stations.
- Once the corrections are calculated, they are delivered to the end user via satellite or over the Internet.
- These corrections are used by the receiver, resulting in decimeter-level or better positioning with no base station required.
- Similar in structure to an SBAS system, a PPP system provides corrections to a receiver to increase position accuracy. However, PPP systems typically provide a greater level of accuracy and charge a fee to access the corrections. PPP systems also allow a single correction stream to be used worldwide, while SBAS systems are regional.



Applications

- GPS Seismometer
- GPS Meteorology
- POD (Precise Orbit Determination) of LEO Satellite
- Precise Time Transfer

PPP

The main error sources for PPP are mitigated in following ways:

- DUAL-FREQUENCY OPERATION: The first order ionospheric delay is proportional to the carrier wave frequency. Therefore, the first-order ionospheric delay can totally be eliminated by using the combinations of dual-frequency GNSS measurements.
- EXTERNAL ERROR CORRECTION DATA: This includes satellite orbit and clock corrections. In the case of TerraStar service, the corrections generated are broadcast for end-users by Inmarsat telecommunication satellites.
- MODELING: The tropospheric delay is corrected using the UNB model developed by the University of New Brunswick. However, the wet part of tropospheric delay is highly varying, and it cannot be modeled with sufficient accuracy. Thus, residual tropospheric delay is estimated when estimating position and other unknowns. Modeling is also used in the PPP receiver to correct the solid earth tides effect.
- PPP FILTER ALGORITHMS: An Extended Kalman Filter (EKF) is used for the PPP estimation. Position, receiver clock error, tropospheric delay and carrier-phase ambiguities are estimated EKF states.

DGNSS vs RTK

- The configuration of Differential GNSS (DGNSS) and RTK systems are similar in that both methods require a base station receiver setup at a known location, a rover receiver that gets corrections from the base station and a communication link between the two receivers.

- The difference is that RTK (a carrier phase method) is significantly more accurate than DGNSS (a code-based method).

- The advantage of DGNSS is that it is useful over a longer baseline (distance between base station and rover receivers) and a DGNSS system is less expensive.

- The technology required to achieve the higher accuracy of RTK performance makes the cost of a RTK-capable receiver higher than one that is DGNSS-capable only.

SBAS vs PPP

- PPP systems use the carrier phase method and SBAS systems use the code method. The other part of the accuracy advantage is that the private corrections services typically used by PPP systems provide higher quality corrections and are multi-frequency, multi-constellation.

- The advantage of SBAS systems is that the corrections services are free for everyone to use. While the private corrections services provide higher quality corrections and are available world-wide, a paid subscription is required to access the signals.

RTK vs PPP

	RTK	Real-Time PPP
Coverage	Local/Regional (< 1000km)	Global
Typical Accuracy	1-3 cm HRMS	2-10 cm, much depending on orbit/clock quality
Effect of Ref Movement	Hard to separate ref and user movement	Less effect by distributed ref stations
System Complexity	Simple, at least one ref station	Complicated, need many ref stations
Latency of Corrections	~ 1 s	5 ~ 25 s
Biases	Basically cancelled by DD	Need careful handling

Data Format: NMEA

- National Marine Electronics Association (NMEA) is format to output measurement data from a sensor in **pre-defined format in ASCII**
- In the case of GPS, It outputs GPS position, velocity, time and satellite related data
- NMEA sentences (output) begins with a “Talker ID” and “Message Description”
  - Example: $GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*47
  - “$GP” is Talker ID
  - “GGA” is Message Description to indicate for Position Data

GGA - Fix data which provide 3D location and accuracy data.

$GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*47

Where: GGA Global Positioning System Fix Data

123519	Fix taken at 12:35:19 UTC
4807.038, N	Latitude 48 deg 07.038' N
01131.000, E	Longitude 11 deg 31.000' E
1 Fix quality:	
	0 = invalid ,
	1 = GPS fix (SPS),
	2 = DGPS fix,
	3 = PPS fix,
	4 = Real Time Kinematic
	5 = Float RTK
	6 = estimated (dead reckoning) (2.3 feature)
	7 = Manual input mode
	8 = Simulation mode
08	Number of satellites being tracked
0.9	Horizontal dilution of position
545.4,M	Altitude, Meters, above mean sea level
46.9,M	Height of geoid (mean sea level) above WGS84 ellipsoid
(empty field)	time in seconds since last DGPS update (empty field) DGPS station ID number
*47	the checksum data, always begins with *

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@csis.u-tokyo.ac.jp

https://www.sparkfun.com/datasheets/GPS/NMEA%20Reference%20Manual1.pdf

Data Format: RINEX

RINEX: Receiver Independent Exchange Format is a data exchange format for raw satellite data among different types of receivers.

- Different types of receivers may output position and raw data in proprietary formats
- For post-processing of data using DGPS or RTK it is necessary to use data from different types of receivers. A common data format is necessary for this purpose.
- Example: How to post process data from Trimble, Novatel and GeoMax receivers to compute a position?

RINEX only provides Raw Data. It does not provide position output.

- User has to post-process RINEX data to compute position
- Raw data consists of Pseudorage, Carrierphase, Doppler, SNR

RINEX basically consists of two data types

- “*.*N” file for Satellite and Ephemeris Related data. (Also called Navigation Data)
- “*.*O” file for Signal Observation Data like Pseudorange, Carrier Phase, Doppler, SNR (Also called Observation Data)

RINEX “N” File for GPS

```
     2.11           NAVIGATION DATA     GPS(GPS)            RINEX VERSION / TYPE
cnvtToRINEX 2.90.0  convertToRINEX OPR  05-Jul-17 03:38 UTC PGM / RUN BY / DATE
----------------------------------------------------------- COMMENT
    0.8382D-08  0.2235D-07 -0.5960D-07 -0.1192D-06          ION ALPHA
    0.8602D+05  0.6554D+05 -0.1311D+06 -0.4588D+06          ION BETA
   -0.931322574615D-09-0.355271367880D-14   405504     1947 DELTA-UTC: A0,A1,T,W
    18                                                      LEAP SECONDS
                                                            END OF HEADER
32 17 05 01 00 00  0.0-0.400723423809D-03-0.110276232590D-10 0.000000000000D+00
    0.370000000000D+02-0.806250000000D+01 0.455840416154D-08-0.192420920137D+01
   -0.353902578354D-06 0.111064908560D-02 0.826455652714D-05 0.515371503258D+04
    0.864000000000D+05-0.782310962677D-07 0.675647076441D-01-0.838190317154D-07
    0.958529124300D+00 0.221156250000D+03-0.265074890978D+01-0.796390315710D-08
   -0.389659088008D-09 0.100000000000D+01 0.194700000000D+04 0.000000000000D+00
    0.240000000000D+01 0.000000000000D+00 0.465661287308D-09 0.370000000000D+02
    0.795120000000D+05 0.400000000000D+01 0.000000000000D+00 0.000000000000D+00
24 17 05 01 00 00  0.0-0.341213308275D-04-0.454747350886D-12 0.000000000000D+00
    0.100000000000D+02 0.787812500000D+02 0.459340561950D-08 0.167267059468D+01
    0.404566526413D-05 0.564297637902D-02 0.102464109659D-04 0.515370226479D+04
    0.864000000000D+05-0.782310962677D-07 0.108986675687D+01 0.484287738800D-07
    0.945651423640D+00 0.170906250000D+03 0.490563049326D+00-0.815641117584D-08
   -0.128933942045D-09 0.100000000000D+01 0.194700000000D+04 0.000000000000D+00
    0.240000000000D+01 0.000000000000D+00 0.279396772385D-08 0.100000000000D+02
    0.792180000000D+05 0.400000000000D+01 0.000000000000D+00 0.000000000000D+00
```

RINEX “O” File for GPS, GLONASS, GALILEO, QZSS, SBAS

```
     2.11           OBSERVATION DATA    Mixed(MIXED)        RINEX VERSION / TYPE
cnvtToRINEX 2.90.0  convertToRINEX OPR  05-Jul-17 03:38 UTC PGM / RUN BY / DATE
------------------------------------------------------------ COMMENT
KMBA                                                        MARKER NAME
KMBA                                                        MARKER NUMBER
DM                  UT                                      OBSERVER / AGENCY
5536R50102          TRIMBLE NETR9       5.20                REC # / TYPE / VERS
                    UNKNOWN EXT                             ANT # / TYPE
 -3955510.8982  3357111.6791  3697796.5495                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1     0                                          WAVELENGTH FACT L1/2
     8    C1    C2    C3    L1    L2    L3    P1    P2      # / TYPES OF OBSERV
     1.000                                                  INTERVAL
  2017     5     1     0     0    0.0000000     GPS         TIME OF FIRST OBS
  2017     5     1    23    59   59.0000000     GPS         TIME OF LAST OBS
     0                                                      RCV CLOCK OFFS APPL
    18                                                      LEAP SECONDS
    59                                                      # OF SATELLITES
   G01 23351 23350     0 23350 46694     0     0 23344      PRN / # OF OBS
   G02 22293     0     0 22293 22286     0     0 22286      PRN / # OF OBS
   G03 19633 19632     0 19632 39259     0     0 19627      PRN / # OF OBS
   G05 25303 25302     0 25299 50599     0     0 25297      PRN / # OF OBS
   G06 24709 24708     0 24709 49411     0     0 24703      PRN / # OF OBS
   G07 27766 27764     0 27764 55505     0     0 27741      PRN / # OF OBS
```

```
     3.02           OBSERVATION DATA    M                   RINEX VERSION / TYPE
JPS2RIN v.2.0.99    JAVAD GNSS          20150823 020111 UTC PGM / RUN BY / DATE
AIUB                AIUB                                    OBSERVER / AGENCY
ZIMJ                                                        MARKER NAME
14001M006                                                   MARKER NUMBER
00634               JAVAD TRE_G3TH DELTA3.4.9 Apr,18,2013   REC # / TYPE / VERS
  4331290.7193   567541.4271  4633135.5216                  APPROX POSITION XYZ
00427               JAVRINGANT_DM   NONE                    ANT # / TYPE
        0.0770        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G   15 C1C L1C S1C C1W L1W S1W C2X L2X S2X C2W L2W S2W C5X  SYS / # / OBS TYPES
       L5X S5X                                              SYS / # / OBS TYPES
R   12 C1C L1C S1C C1P L1P S1P C2C L2C S2C C2P L2P S2P      SYS / # / OBS TYPES
E    6 C1X L1X S1X C5X L5X S5X                              SYS / # / OBS TYPES
S    6 C1C L1C S1C C5I L5I S5I                              SYS / # / OBS TYPES
    30.000                                                  INTERVAL
  2015     8    22     0     0    0.0000000     GPS         TIME OF FIRST OBS
  2015     8    22    23    59   30.0000000     GPS         TIME OF LAST OBS
    17                                                      LEAP SECONDS
G L1W -0.25000  31 G01 G02 G03 G04 G05 G06 G07 G08 G09 G11  SYS / PHASE SHIFT
                   G12 G13 G14 G15 G16 G17 G18 G19 G20 G21  SYS / PHASE SHIFT
                   G22 G23 G24 G25 G26 G27 G28 G29 G30 G31  SYS / PHASE SHIFT
                   G32                                      SYS / PHASE SHIFT
G L2X  0.25000  17 G01 G03 G05 G06 G07 G08 G09 G12 G15 G17  SYS / PHASE SHIFT
                   G24 G25 G26 G27 G29 G30 G31              SYS / PHASE SHIFT
R L1P -0.25000  24 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10  SYS / PHASE SHIFT
                   R11 R12 R13 R14 R15 R16 R17 R18 R19 R20  SYS / PHASE SHIFT
                   R21 R22 R23 R24                          SYS / PHASE SHIFT
R L2C  0.25000  24 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10  SYS / PHASE SHIFT
                   R11 R12 R13 R14 R15 R16 R17 R18 R19 R20  SYS / PHASE SHIFT
                   R21 R22 R23 R24                          SYS / PHASE SHIFT
    64                                                      # OF SATELLITES
                                                            END OF HEADER
> 2015 08 22 00 00  0.0000000  0 23
R04  22974737.146   123028686.917 7       44.000   22974737.246   123028704.928 7    ...
G02  22478344.414   118124534.885 7       46.250   22478343.534   118124533.876 5    ...
R20  23888209.055   127741028.661 6       37.500   23888212.965   127740992.676 6    ...
R02  20318059.054   108421116.270 9       54.250   20318059.244   108421113.277 8    ...
G06  24136132.701   126836262.001 6       40.500   24136135.111   126836265.009 4    ...
G05  21340435.652   112144785.476 8       51.750   21340435.272   112144777.490 7    ...
G09  22302805.087   117202111.970 8       49.750   22302804.637   117202105.980 6    ...
G13  23645905.611   124260097.925 6       41.500   23645904.221   124260092.935 4    ...
S26  38315809.005   201351931.595 6       41.750
R19  23326417.269   124780602.768 7       44.250   23326417.319   124780614.767 7    ...
R13  19926774.224   106407880.163 7       45.250   19926774.334   106407885.164 7    ...
G30  20509341.118   107777348.221 9       55.750   20509340.428   107777344.230 7    ...
G23  25525860.959   134139349.148 3       22.250
R14  23668929.119   126168733.370 6       37.000   23668932.349   126168691.375 6    ...
R11  24298495.410   129843739.774 5       35.500   24298496.220   129843864.802 5    ...
G07  20561101.494   108049355.672 8       52.750   20561101.614   108049350.680 7    ...
R03  19489544.203   104329109.052 8       52.750   19489543.753   104329108.055 8    ...
R12  20053385.874   107121625.992 8       49.750   20053384.974   107121618.997 8    ...
G28  24521139.156   128859433.514 5       35.250   24521136.166   128859439.562 2    ...
G16  25278952.989   132841800.227 5       31.250   25278948.679   132841806.246 2    ...
S36  38057490.463   199993684.534 7       44.000   38057479.473   149345722.958 7    ...
S20  38545811.058   202559533.331 6       40.750
S27  39603129.285   208115900.638 5       34.500   39603142.165   155411242.079 7    ...
> 2015 08 22 00 00 30.0000000  0 22
R04  22936843.077   122825764.851 7       45.000   22936843.087   122825782.863 7    ...
G02  22473258.256   118097806.453 7       45.750   22473258.076   118097805.453 5    ...
R20  23864004.390   127611587.562 6       36.250   23864003.860   127611551.589 5    ...
R02  20313957.707   108399231.035 9       54.000   20313957.807   108399228.042 8    ...
G06  24139490.690   126853897.391 6       40.250   24139493.050   126853900.413 3    ...
G05  21312443.414   111997687.237 8       51.500   21312443.094   111997679.243 7    ...
G09  22300480.603   117189899.868 8       49.000   22300480.353   117189893.875 6    ...
G13  23611903.088   124081417.065 7       42.000   23611904.318   124081412.081 4    ...
S26  38298526.257   201261105.799 7       42.000
R19  23319880.621   124745642.399 7       43.250   23319881.951   124745654.405 7    ...
R13  19896674.183   106247143.380 7       45.500   19896673.623   106247148.384 7    ...
G30  20485058.352   107649741.711 9       55.500   20485057.952   107649737.721 7    ...
R14  23626739.185   125943815.693 6       36.000   23626736.995   125943773.710 5    ...
R11  24306308.556   129885478.868 6       38.750   24306307.286   129885603.879 6    ...
G07  20549542.642   107988612.671 8       52.750   20549542.232   107988607.679 7    ...
R03  19464636.685   104195780.193 8       52.500   19464637.005   104195779.197 8    ...
R12  20047880.553   107092217.610 8       49.750   20047879.673   107092210.617 8    ...
G28  24485360.568   128671425.327 5       34.500   24485360.498   128671431.349 2    ...
G16  25277775.538   132835611.858 5       35.250   25277774.398   132835617.831 2    ...
S36  38040685.468   199905373.911 7       43.250   38040673.628   149279771.710 7    ...
S20  38529181.464   202472151.607 6       41.000
S27  39586360.154   208027789.488 5       34.250   39586375.274   155345444.697 7    ...
                                   .
                                   .
                                   .
```

Figure 4.2.: RINEX3 observation file (multiple GNSS).

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@csis.u-tokyo.ac.jp

RTCM

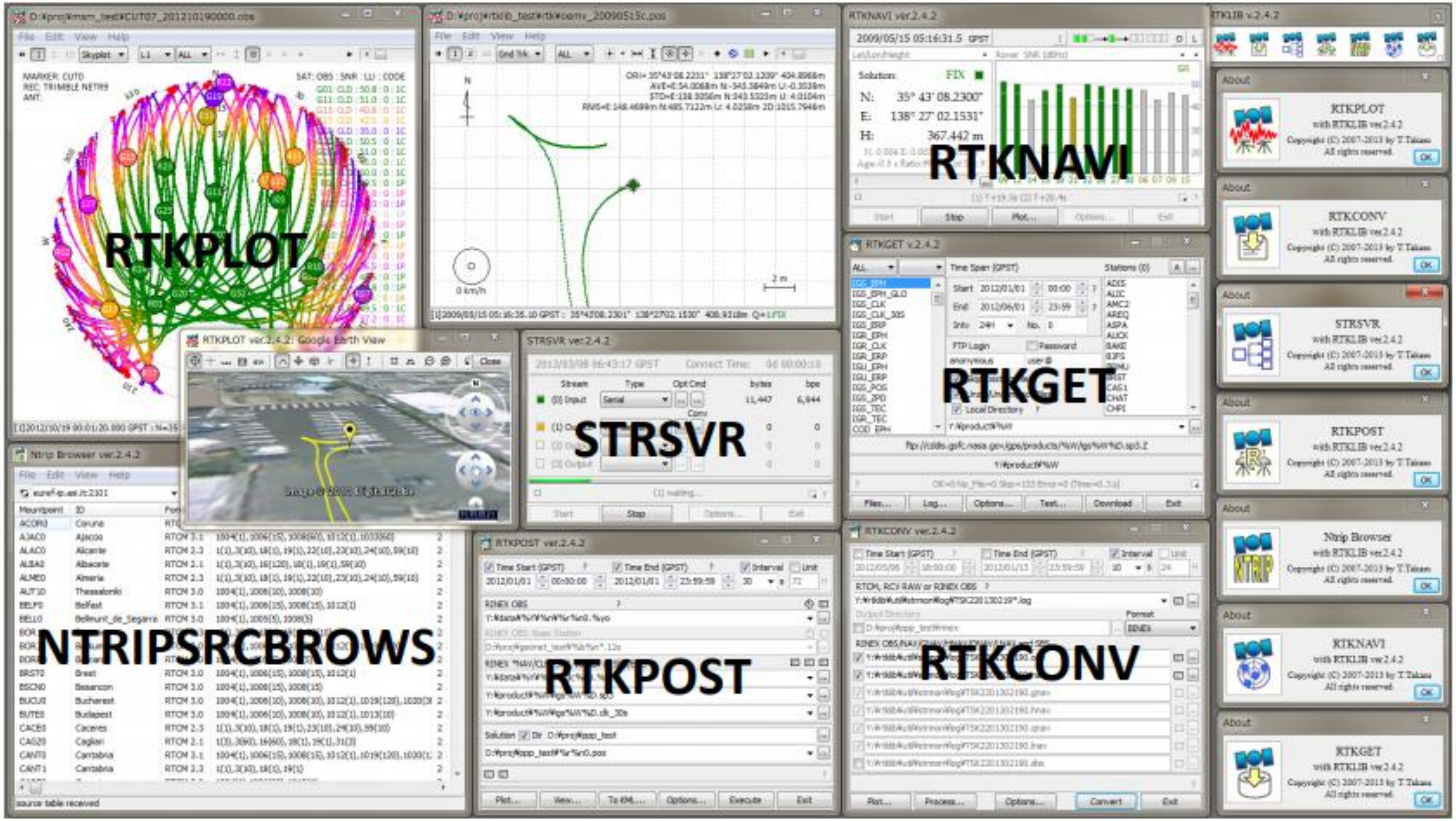
- RTCM : Radio Technical Commission for Maritime Services
  - An internationally accepted data transmission standard for base-station data transmission to a rover defined. The standards are defined and maintained by RTCM SC-104
- RTCM SC-104 (Special Committee 104)
  - Defines data formats for Differential GPS and
  - RTK (Real-Time Kinematic Operations)
- The Current Version is RTCM-3 (10403.3)
- Refer https://www.rtcm.org/ for detail information and document
  - Documents are not free
  - A normal user does not need RTCM document.
  - GNSS receivers with base-station capabilities will setup necessary messages for RTK
  - If you are developing a system or application you may need it

RTKLIB

- An Open-source Software Package for GNSS Positioning
- RTKLIB consists of a portable program library and several APs (application programs) utilizing the library.
- The features of RTKLIB are:
  - Supports standard and precise positioning algorithms with
    GPS, GLONASS, Galileo, QZSS, BeiDou and SBAS
  - Supports various positioning modes with GNSS for both real-time and post-processing:
    - Single, DGPS/DGNSS, Kinematic, Static, Moving-Baseline, Fixed, PPP-Kinematic, PPP-Static and PPP-Fixed
  - Supports standard formats and protocols for GNSS:
    - RINEX, NTRIP, NMEA, etc.
  - Supports external communication vai:
    - Serial, TCP/IP, NTRIP, local log file & FTP/HTTP.

http://www.rtklib.com/

RTKLIB: GUI APs



RTKLIB: CLI APs

- **RNX2RTKP (rnx2rtkp)**
  Post-processing Positioning
- **RTKRCV (rtkrcv)**
  Real-time Positioning
- **CONVBIN (convbin)**
  RINEX Translator
- **STR2STR (str2str)**
  Stream Server
- **POS2KML (pos2kml)**
  Google Earth Converter

	Function	GUI AP	CUI AP
(a)	AP Launcher	RTKLAUNCH	-
(b)	Real-Time Positioning	RTKNAVI	RTKRCV
(c)	Communication Server	STRSVR	STR2STR
(d)	Post-Processing Analysis	RTKPOST	RNX2RTKP
(e)	RINEX Converter	RTKCONV	CONVBIN
(f)	Plot Solutions and Observation Data	RTKPLOT	-
(g)	Downloader of GNSS Data	RTKGET	-
(h)	NTRIP Browser	SRCTBLBROWS	-

RTKLIB: Supported Recivers

Format	Data Message Types							
	GPS Raw Meas Data	GLONASS Raw Meas	GPS Ephemeris	GLONASS Ephemeris	ION/UTC Parameters	Antenna Info	SBAS Messages	Others
RTCM v.2.3	Type 18, 19	Type 18, 19	Type 17	-	-	Type 3, 22	-	Type 1, 9, 14, 16
RTCM v.3.1	Type 1002, 1004	Type 1010, 1012	Type 1019	Type 1020	-	Type 1005, 1006, 1007, 1008, 1033	-	SSR corrections
NovAtel OEM4/V, OEMStar	RANGEB, RANGECMPB	RANGEB, RANGECMPB	RAWEPHEMB	GLO-EPHEMERISB	IONUTCB	-	RAWWAAS-FRAMEB	-
NovAtel OEM3	RGEB, RGED	-	REPB	-	IONB, UTCB	-	FRMB	-
NovAtel Superstar II	ID#23	-	ID#22	-	-	-	ID#67	ID#20, #21
u-blox LEA-4T, LEA-5T	UBX RXM-RAW	-	UBX RXM-SFRB	-	UBX RXM-SFRB	-	UBX RXM-SFRB	-
Hemisphere Crescent, Eclipse	bin 96	-	bin 95	-	bin 94	-	bin 80	-
SkyTraq S1315F	msg 0xDD (221)	-	msg 0xE0 (224)	-	msg 0xE0 (224)	-	-	msg 0xDC (220)
JAVAD (GRIL/GREIS)	[R*],[r*],[*R],[*r],[P*],[p*],[*p],[D*],[*d],[E*],[*E],[F*]	[R*],[r*],[*R],[*r],[P*],[p*],[*p],[D*],[*d],[E*],[*E],[F*]	[GE],[GD],[gd]	[NE],[LD]	[IO],[UO],[GD]	-	[WD]	[~~],[::],[RD],[SI],[NN],[TC], QZSS Data, Galileo Data
Furuno GW10 II	msg 0x08	-	msg 0x24	-	msg 0x26	-	msg 0x03	msg 0x20

Assignment

- Install RTKLIB
- Explore the GUI APs

- Install SW Maps on Android
- Explore

https://qzss.go.jp/en/usage/useimage/index.html

References

Dr. Dinesh Manandhar, CSIS, The University of Tokyo https://home.csis.u-tokyo.ac.jp/~dinesh/Dinesh_T_files/GNSS_06_Introduction_SingalStructures.pdf

GNSS Precise Positioning and RTKLIB, Tokyo Univ. of Marine Science and Technology : Nobuaki Kubo https://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/15a_PPP_RTKLIB.pdf

https://www.tersus-gnss.com/technology

https://journals.indexcopernicus.com/api/file/viewByFileId/1209465.pdf GENERAL CONCEPTS ABOUT SOLID BODY ASTRODYNAMICS

https://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/03_gnss.pdf

https://www.intechopen.com/books/multifunctional-operation-and-application-of-gps/gnsss-signals-and-receivers

https://www.e-education.psu.edu/geog862/book/export/html/1407

https://www.researchgate.net/publication/336267096_Single-Baseline_RTK_Positioning_Using_Dual-Frequency_GNSS_Receivers_Inside_Smartphones/figures?lo=1

https://ee3550-gps.weebly.com/transmission-of-gps-signals.html

https://unstats.un.org/unsd/geoinfo/ungegn/docs/Training/Manila/day%202/08_MAROHOM_GNSS_Demo.pdf

https://www.intechopen.com/books/satellite-positioning-methods-models-and-applications/network-real-time-kinematic-nrtk-positioning-description-architectures-and-performances