Introduction to GNSS

Dinesh Manandhar, Associate Professor

Center for Spatial Information Science (CSIS), The University of Tokyo

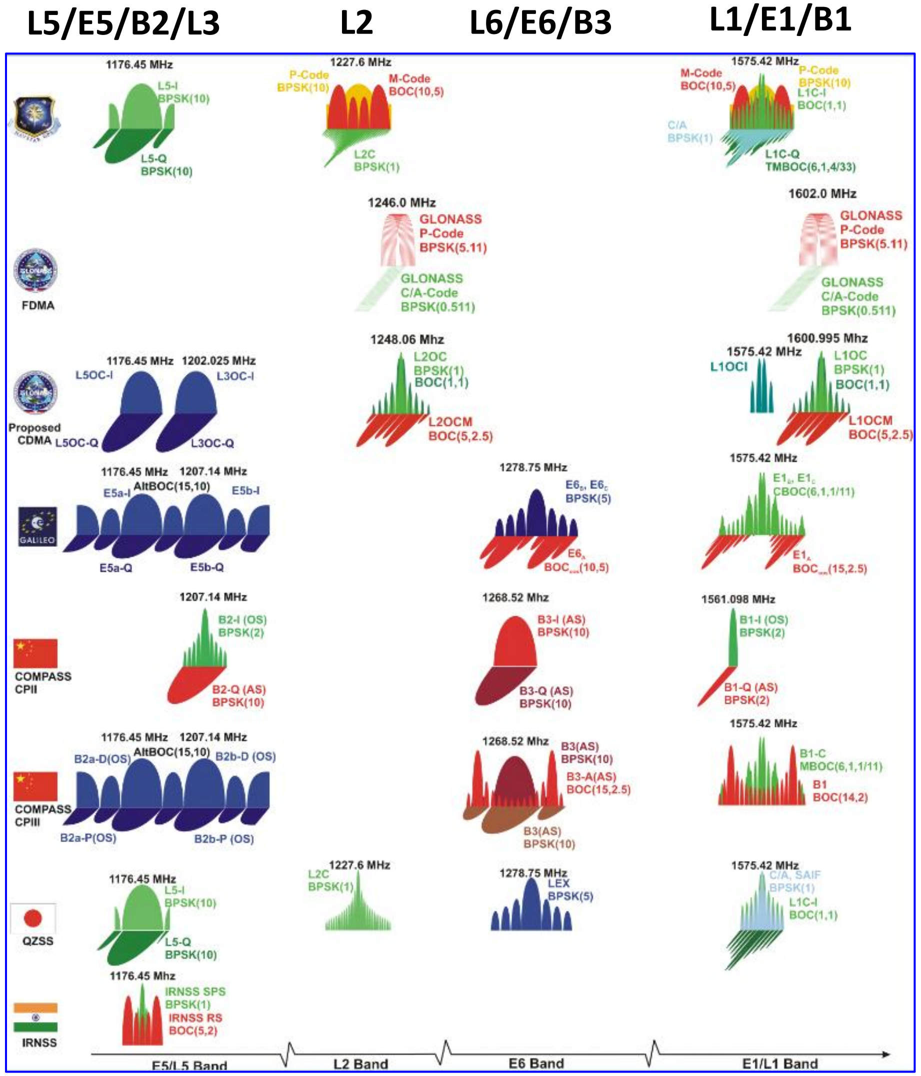
dinesh@csis.u-tokyo.ac.jp

GNSS Introduction

- GNSS or Global Navigation Satellite System is an acronym used to represent all navigation satellite systems such as

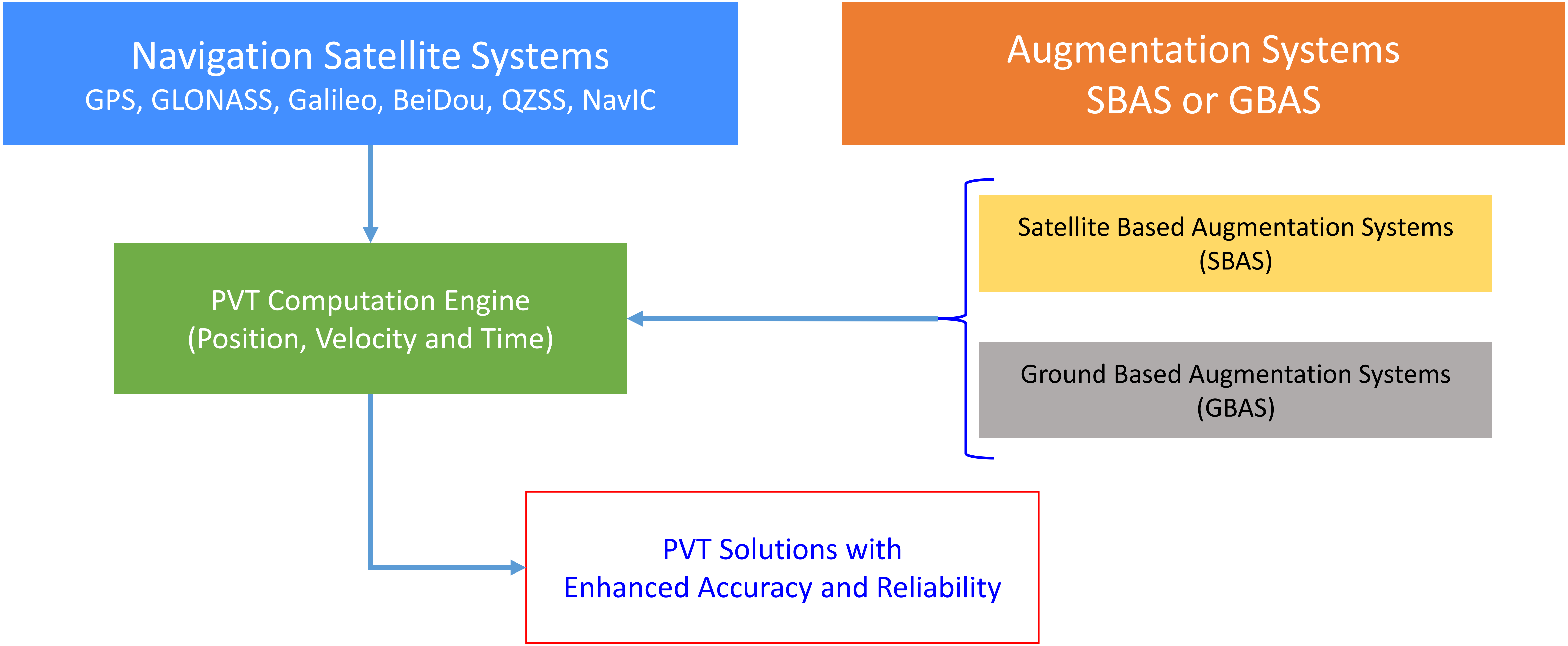
Satellite	Country	Coverage
GPS	USA	Global
GLONASS	Russia	Global
Galileo	Europe	Global
BeiDou (BDS)	China	Global
QZSS (Michibiki)	Japan	Regional
NavIC	India	Regional
KPS (to be launched by 2034)	Korea	Regional

- ✓ GPS and GLONASS have signals for civilian and military usage
  - ❖ Military signals are encrypted and not available for civilian use
- ✓ Galileo and BeiDou also have Restricted Signals
- ✓ All civilian signals are freely available
- ✓ Technical information for civilian signals is made public
  - ❖ Necessary to develop a receiver
  - ❖ It's called ICD (Interface Control Document) or IS (Interface Specification) Document



https://gssc.esa.int/navipedia/images/c/cf/GNSS_All_Signals.png

Systems Related with Navigation



ICAO defines regulations related to the use of GNSS and SBAS for aviation

Satellite Based Augmentation System (SBAS)

- Satellite Based Augmentation System (SBAS) are used to augment GNSS Data
  - Provide Higher Accuracy and Integrity
  - Correction data for satellite orbit errors, satellite clock errors, atmospheric correction data and satellite health status are broadcasted from satellites
- SBAS Service Providers
  - WAAS, USA (131,133,135,138)
  - MSAS, Japan (129,137)
  - EGNOS, Europe (120,121,123,124,126,136)
  - BDSBAS, China (130,143,144)
  - GAGAN, India (127,128,132)
  - SDCM, Russia (125,140,141)
  - KASS, Korea (134), Also Navigation System (KPS)
  - AUS-NZ, Australia (122)
  - NSAS, Nigeria, (147)
  - ASAL, Algeria (148)

* PRN ID are given in the bracket

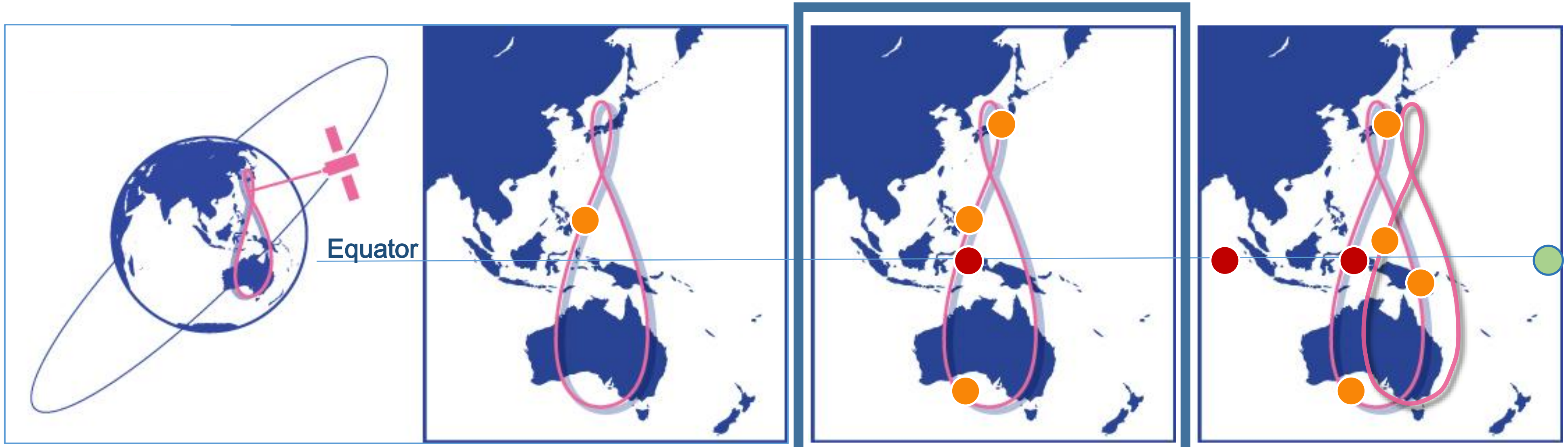
QZSS (Japanese version of GPS)

QZSS 1st Satellite was Launched on 11th SEP 2010 and Declared Operational on 1st NOV 2018

Declaration Ceremony of QZSS Operation

http://qzss.go.jp/events/ceremony_181105.html

QZSS Constellation Plan



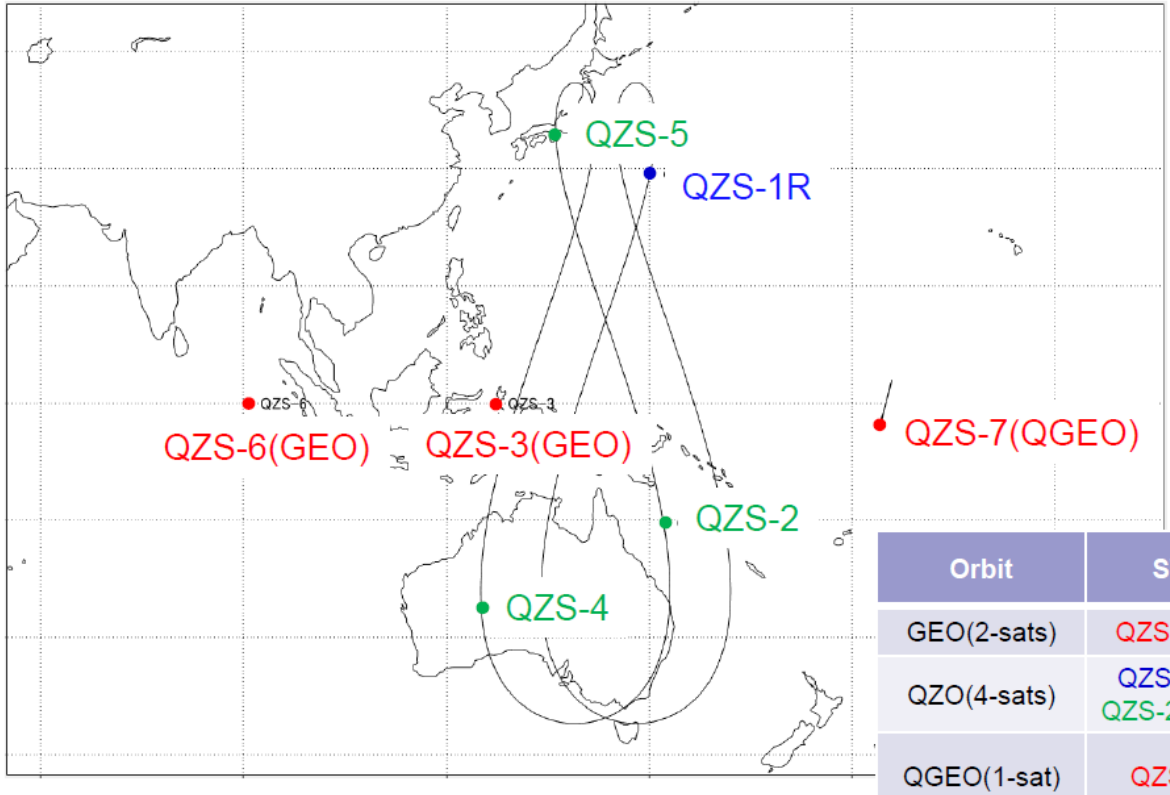
	1 sat constellation	4 sat. constellation	7 sat. constellation
Number of Satellites	QZO ●: 1	QZO ●: 3, GEO ●: 1	QZO●:4, GEO●:2, QGO●:1
Purpose	Research & Development	Operational Complements GPS for positioning	Operational, Autonomous Positioning Capability with QZSS only
Government Authority	JAXA	Cabinet Office	Cabinet Office
Operation	2010～（10 years）	2018～（15 years）	2023～（15 years）
Service Time / day (Japan)	8 hours / day	24 hours / day	24 hours / day

QZO: Quasi-zenith Orbit / GEO: Geosynchronous Orbit / QGO: Quasi-geostationary Orbit

Source: MGA 2019, Mitsubishi

2. QZSS 7SV Constellation Design

QZSS Constellation Plan



7-QZSS Ground Track

Orbit	SV	Center Longi. (deg.)
GEO(2-sats)	QZS-3, 6	127E, 90.5E
QZO(4-sats)	QZS-1R, QZS-2, 4, 5	148E(nom) 139E(nom)
QGEO(1-sat)	QZS-7	185E(nom)

*QGEO: Quasi Geostationary Earth Orbit (i>1deg, e=0.008)

Cabinet Office
National Space Policy Secretariat

8

This slide is taken from presentation slides of S. Kogure, Introduction to Michibiki and EWS, presented on 13th July 2021

QZSS Signals and PRN ID: Current Status

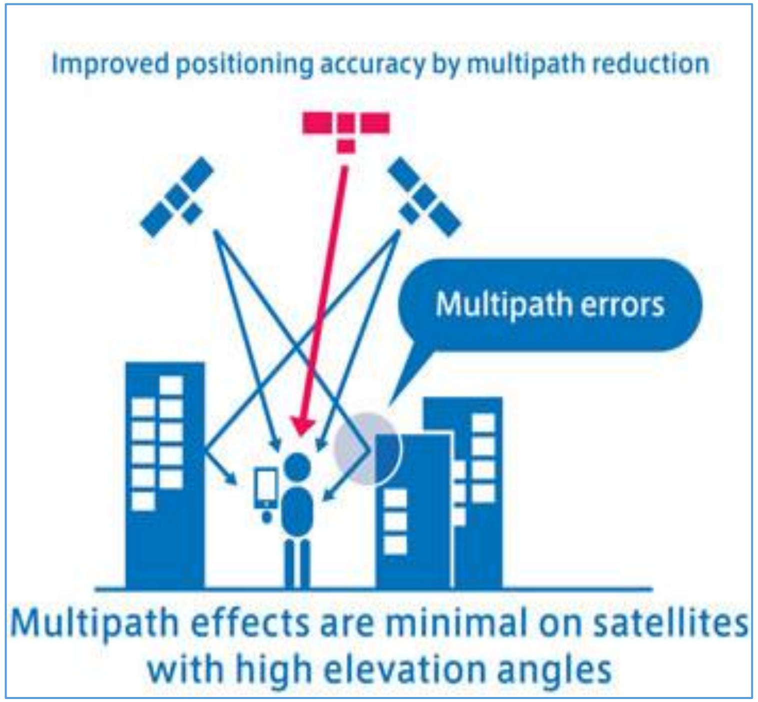
PRN	SVN	Satellite	Launch Date (UTC)	Orbit	Positioning Signals
193	J001	QZS-1	2010/9/11	QZO	L1C/A, L1C, L2C, L5
183					L1S
193					L6
194	J002	QZS-2	2017/6/1	QZO	L1C/A, L1C, L2C, L5
184					L1S
196					L5S
194					L6
199	J003	QZS-3	2017/8/19	GEO	L1C/A, L1C, L2C, L5
189					L1S
197					L5S
137					L1Sb
199					L6
-					Sr/Sf
195	J004	QZS-4	2017/10/9	QZO	L1C/A, L1C, L2C, L5
185					L1S
200					L5S
195					L6

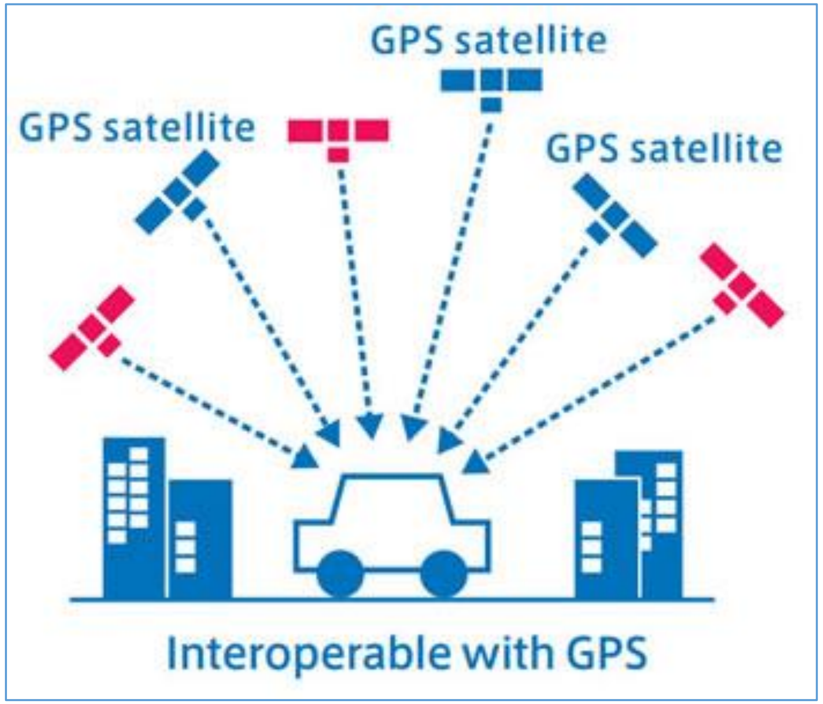
PRN	SVN	Satellite	Launch Date (UTC)	Orbit	Positioning Signals
196	J005	QZS-1R	2021/10/26	QZO	L1C/A, L1C, L2C, L5
186					L1S
186					L5S
196					L6

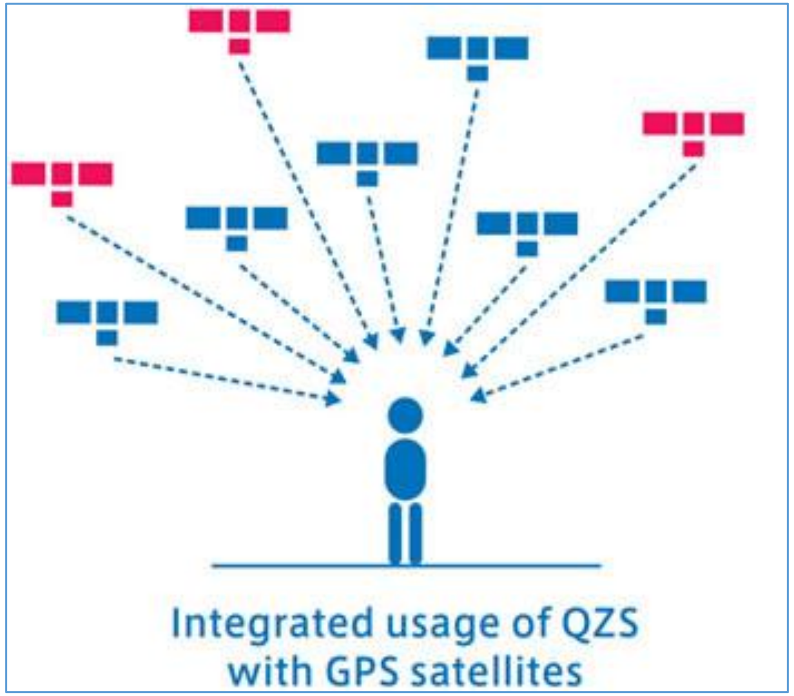
Source: https://qzss.go.jp/technical/satellites/index.html

Characteristics of QZSS

- QZSS signal is designed in such a way that it is **interoperable with GPS**
- QZSS is visible near zenith; improves visibility & DOP in dense urban area
- Provides Orbit Data of other GNSS signals
- Provides **Augmentation Data for Sub-meter and Centimeter level position accuracy**
- Provides Messaging System during Disasters





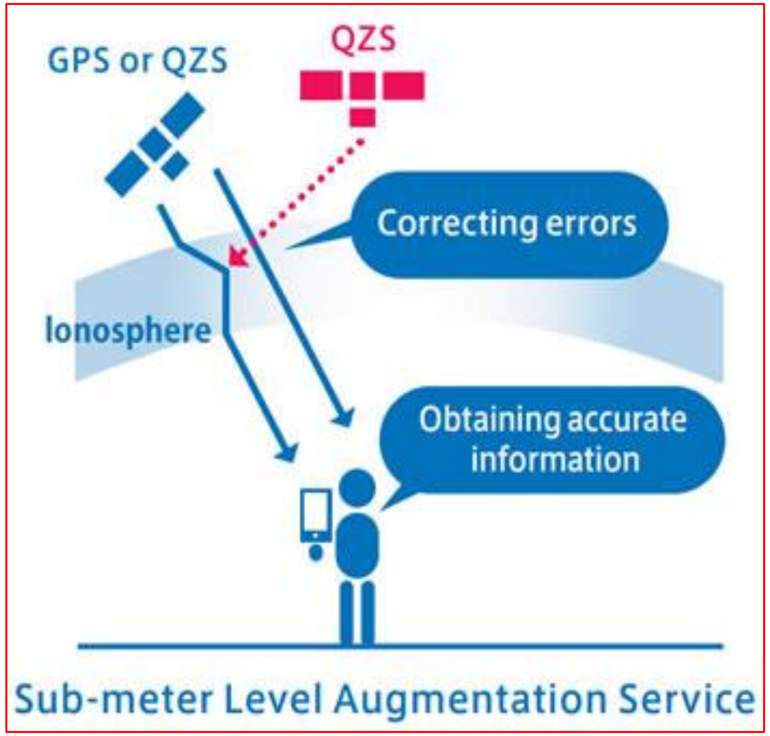


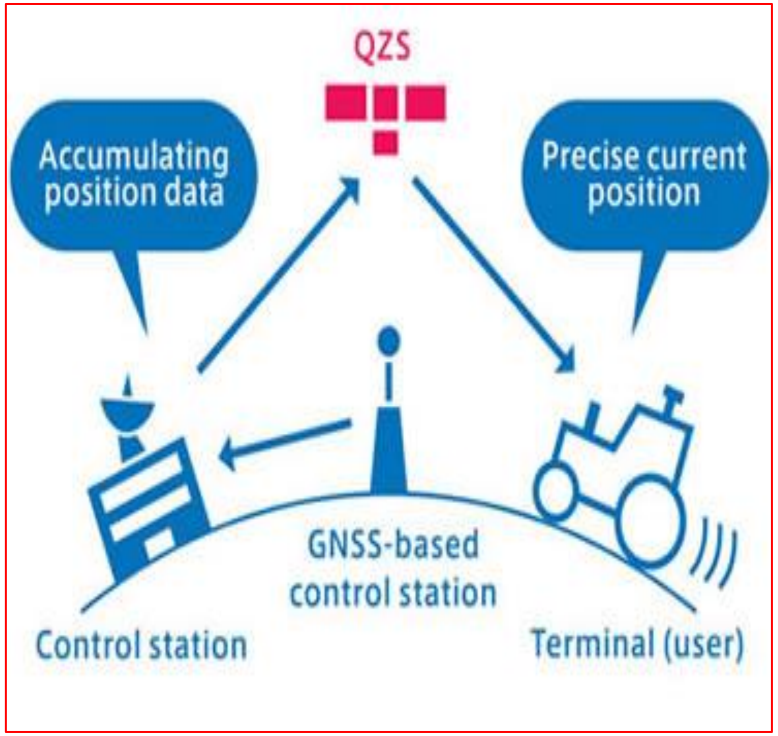
Merits of QZSS

- Disaster and Crisis Management
- Short Message broadcast during Disaster

- Sub-Meter Level Augmentation Service (SLAS)

- High-Accuracy Positioning Services
- CLAS and MADOCA

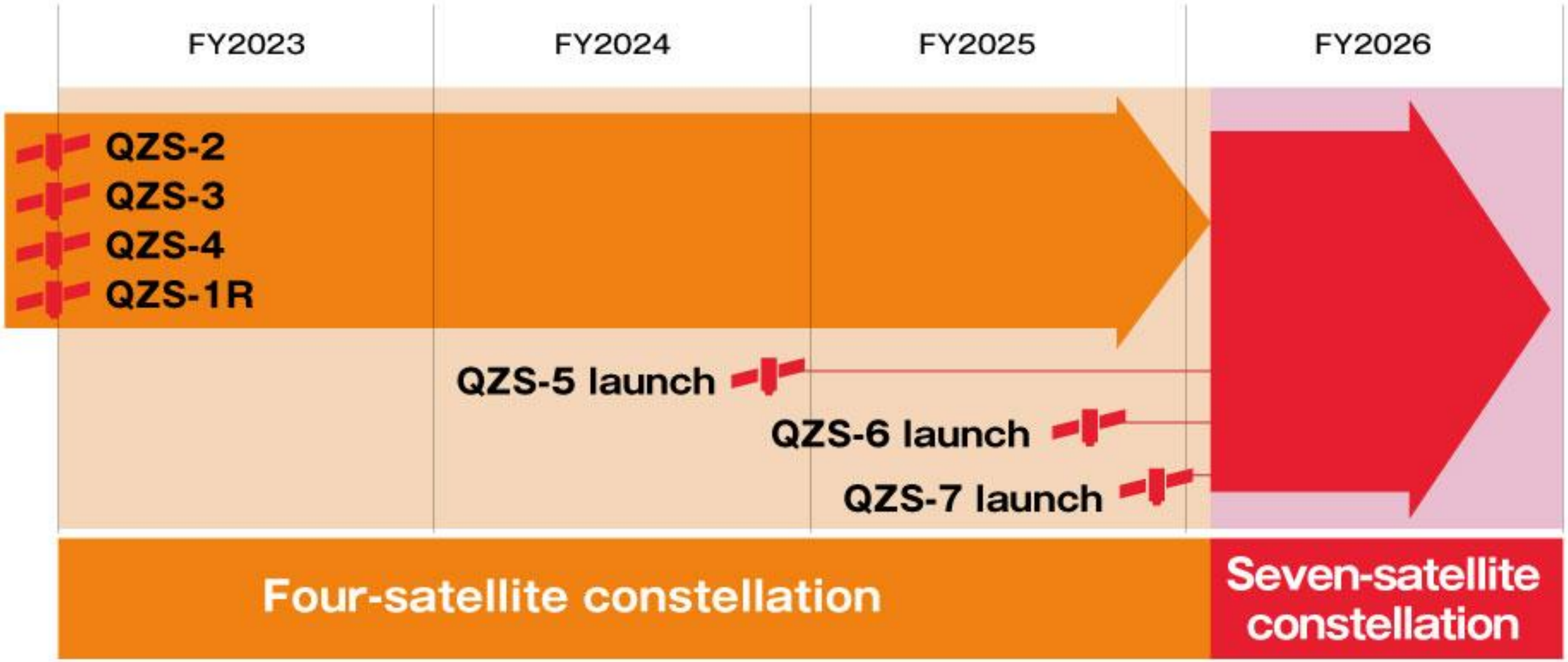




QZSS Signals: High-Accuracy, Authentication and DC Report

Signal Name	Purpose	Signal Band	Accuracy	Convergence Time	Availability	Remarks
CLAS	High Accuracy	L6D	2 – 5 cm	Few minutes	Japan only	
MADOCA	High Accuracy	L6E	10 – 20 cm	10 – 20 minutes	QZSS Visible Area	Convergence time can be reduced by using local correction data
DC Report	Disaster Crisis (DC) Report during disasters	L1S	Not Applicable	Not Applicable (Available every 3 sec)	QZSS Visible Area	Also called Early Warning Message. Basically for Japan. Additional Message Types are defined for other countries as well.
Q-Anpi	2-Way communication during disasters	S	Not Applicable	Not Applicable	QZSS Visible Area	
SAS	Signal Authentication	L1, L5, L6	Not Applicable	Not Applicable (TTFA, TBA See QZSS IS Document)	QZSS Visible Area	Authenticates QZSS, GPS, and Galileo signals LNAV, CNAV, CNAV-2, I/NAV, and F/NAV Messages

QZSS Launch Schedule



The QZS-5 or the Sixth satellite was launched on 2nd February 2025 successfully.

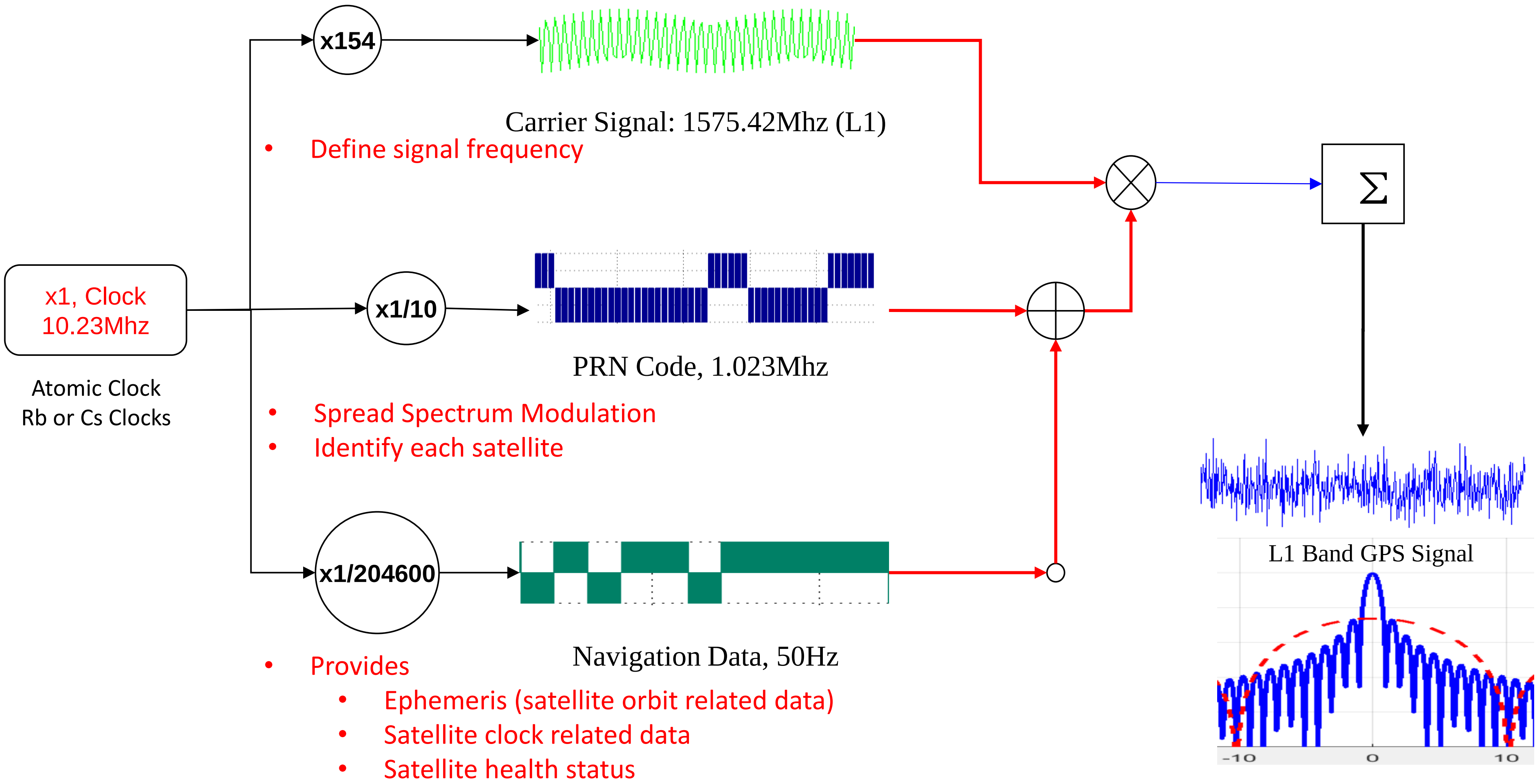
Source: https://qzss.go.jp/en/overview/services/seven-satellite.html

How does a GPS/GNSS Receiver Work?

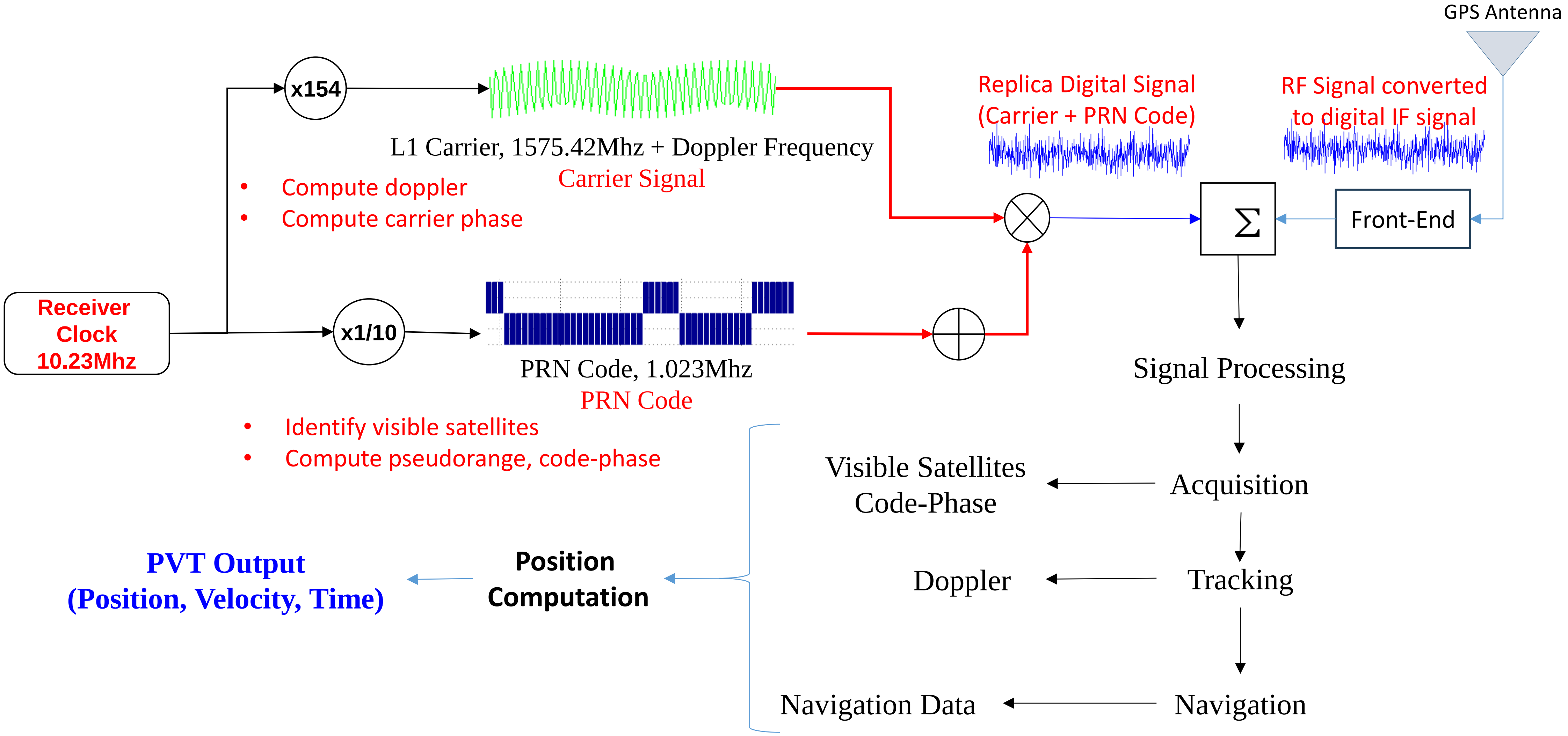
GPS L1C/A Signal Structure

- Carrier Signal
  - It defines the frequency of the signal
  - For example:
    - GPS L1 is 1575.42MHz, L2 is 1227.60MHz and L5 is 1176.45MHz
- PRN Code
  - Necessary to modulate carrier signal
  - Used to identify satellite ID in the signal
  - Should have good auto-correlation and cross-correlation properties
- Navigation Data
  - Includes satellite orbit related data (ephemeris and almanac data)
  - Includes satellite clock related information (clock errors etc.)
  - Includes satellite health information

GPS L1C/A Signal Structure (Satellite Side)

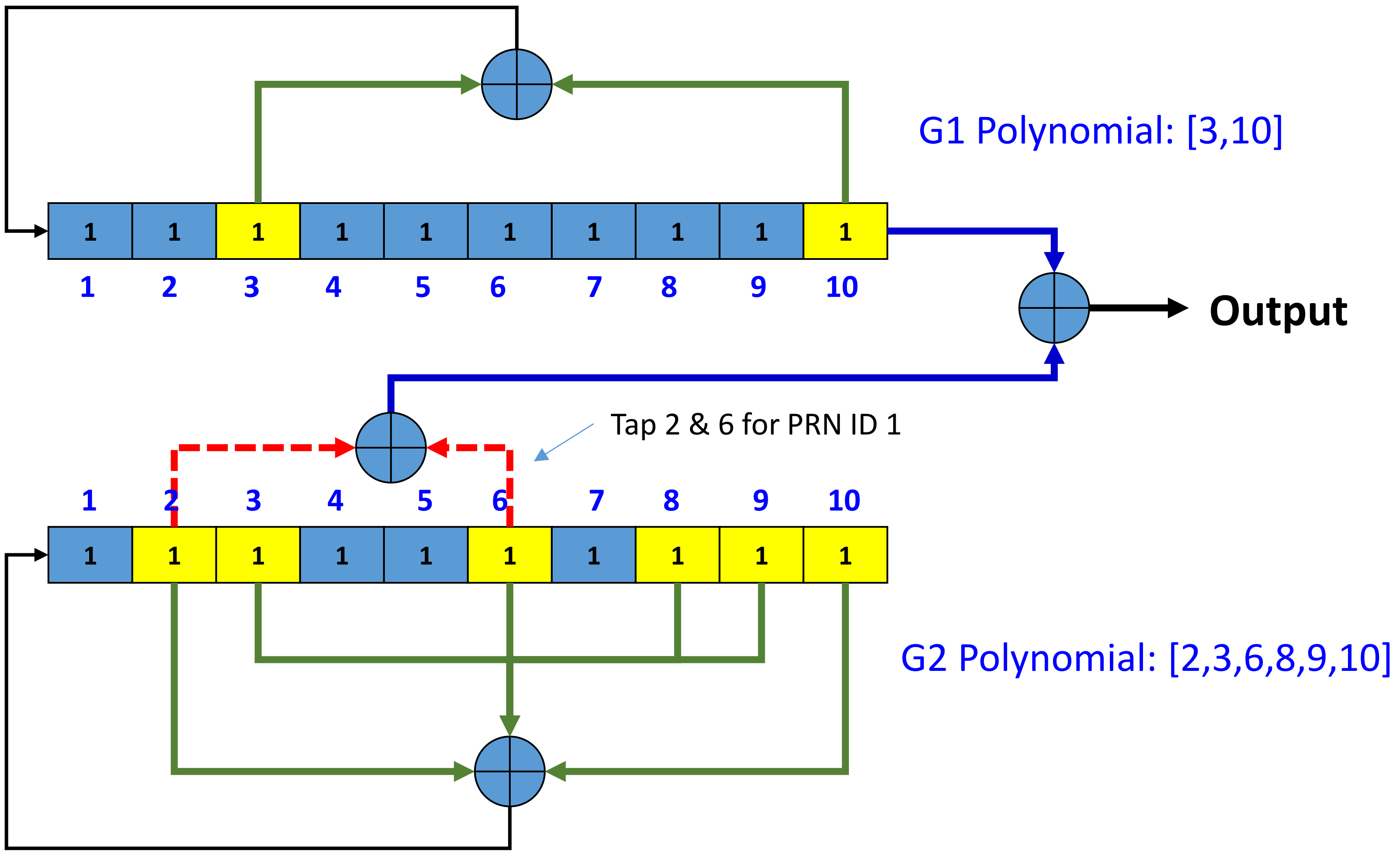


GPS L1C/A Receiver Signal Processing



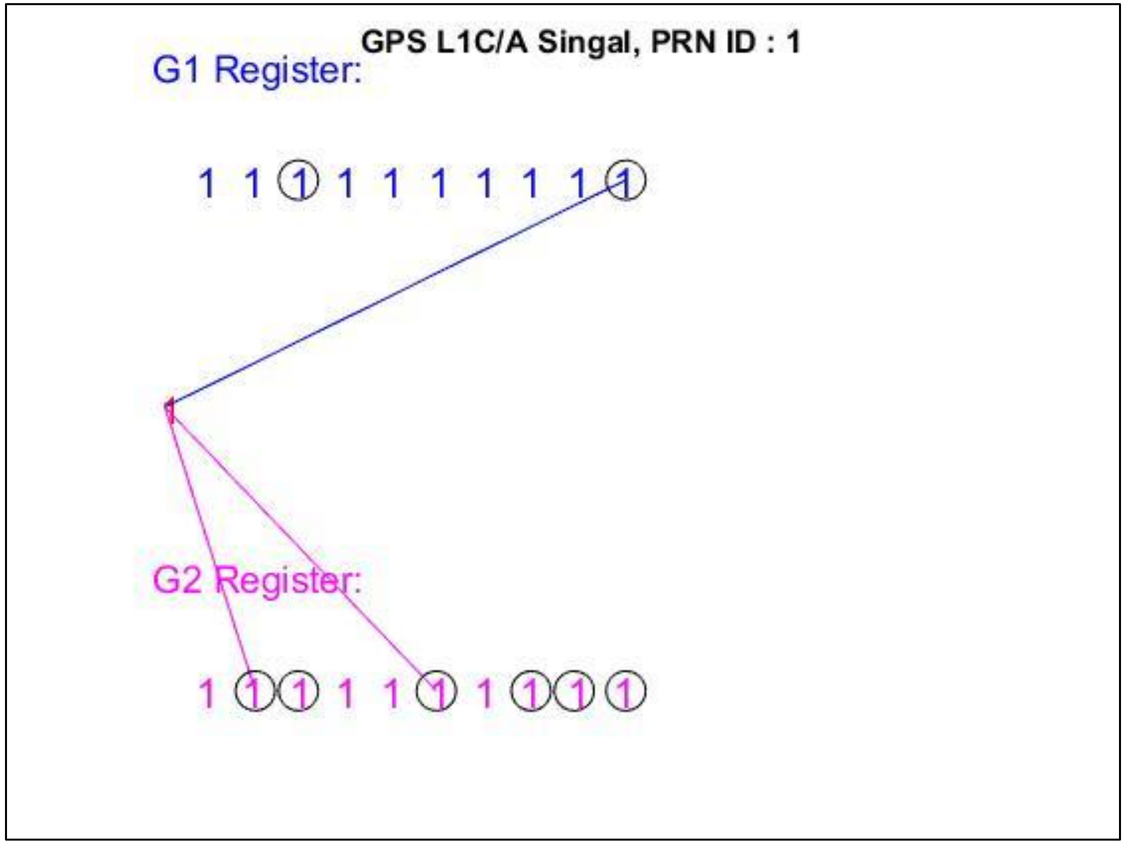
Generation of GPS L1C/A PRN Code

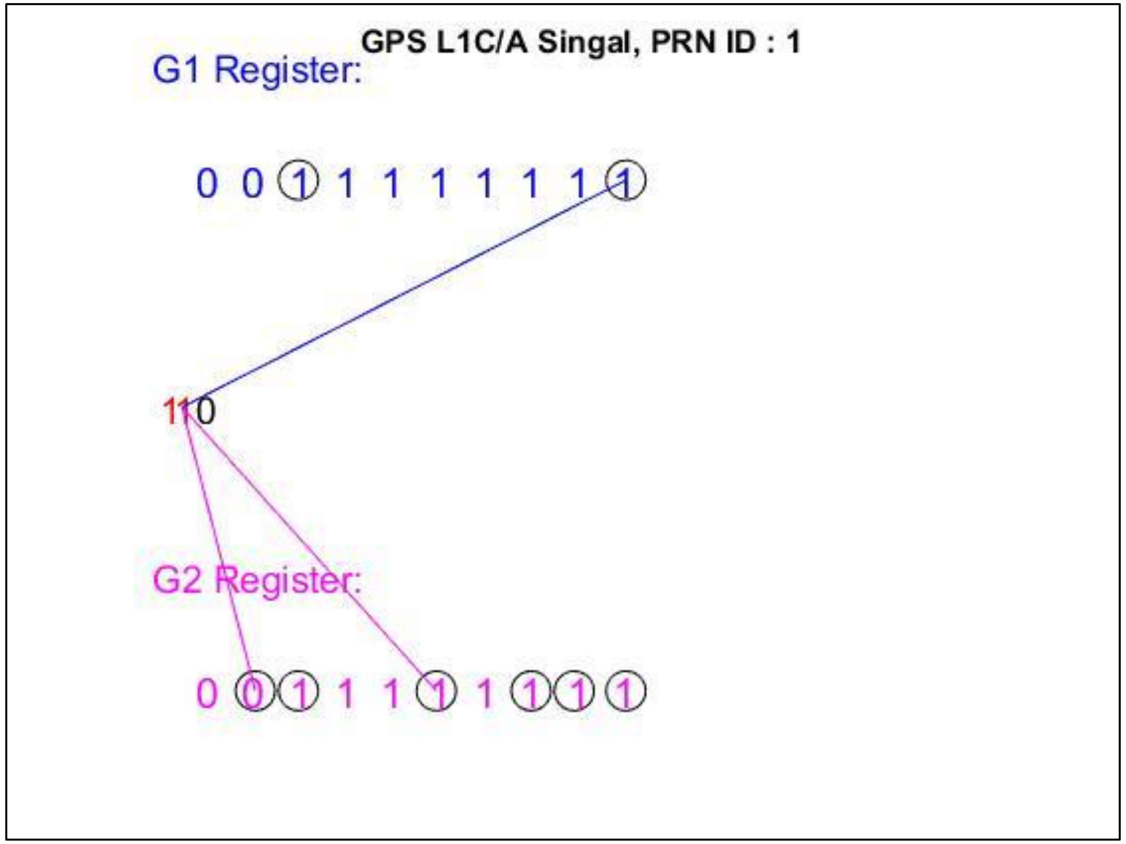
- Based on Gold Codes
- Use two 10 bit registers, G1 and G2
  LFSR (Linear Feed Shift Register)
- All initial bits of registers are set at 1
- Taps 3 and 10 are used for G1
- Taps 2,3,6,8,9,10 are used for G2
- Two additional taps are selected based on PRN ID. See GPS IS document for the list of the taps.
- Example, Taps 2 and 7 are used for PRN ID 1.



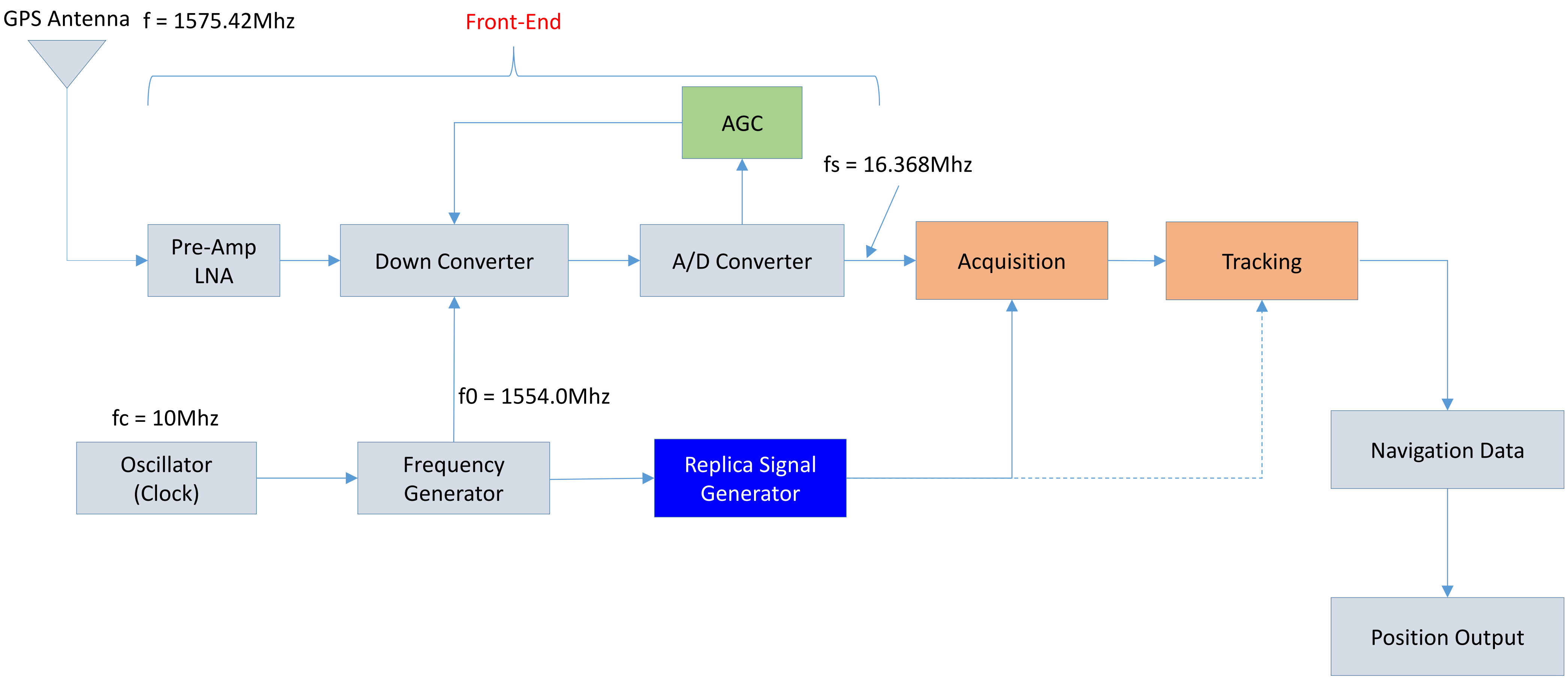
Refer video recording of webinar for details on PRN Code:
https://www.youtube.com/watch?v=elWbDBHTJ6I&t=2s

PRN Code Output #1





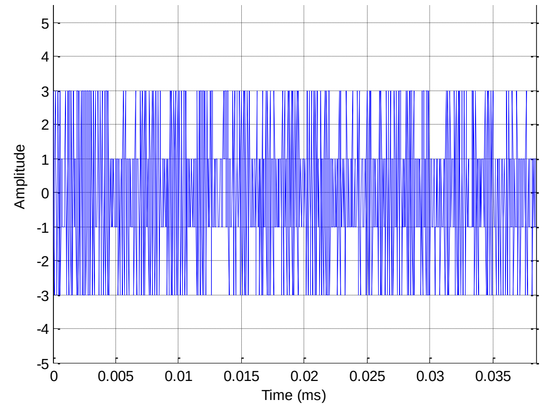
Block Diagram of GPS Receiver



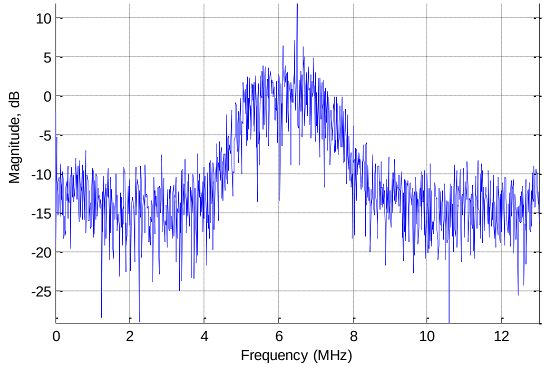
fc, f0, fs are only example values.
These values differ depending upon the design of the front-end

How does GPS Signal Look Like?

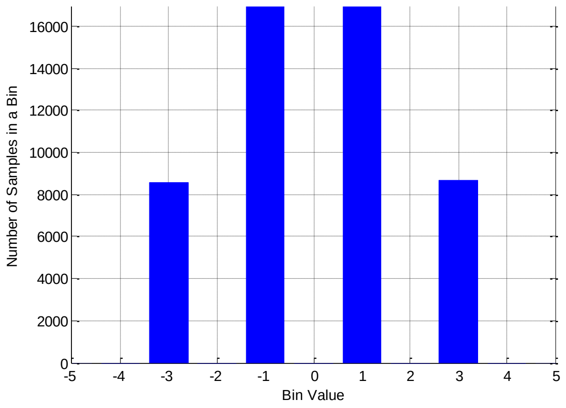
Time-domain Plot of GPS IF Signal



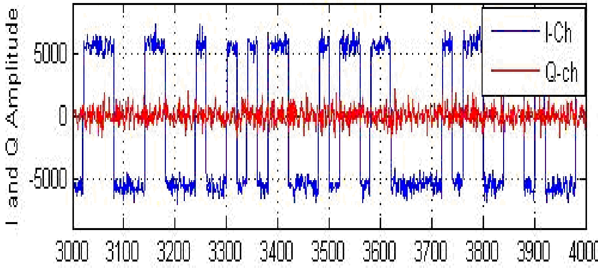
Frequency-domain Plot of GPS IF Signal (Fourier Transform)

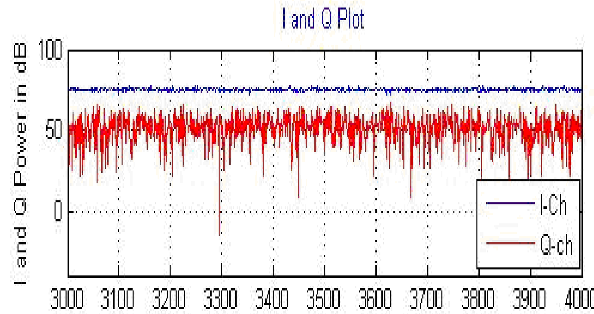


Histogram of GPS IF Signal

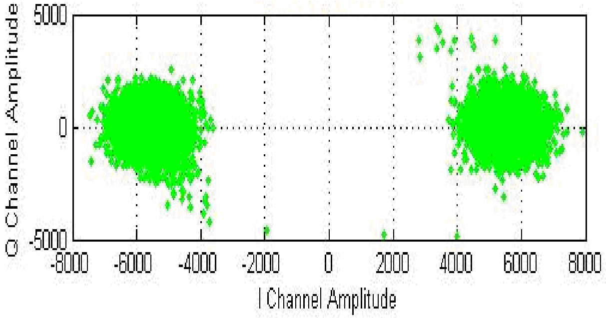


Tracking Output (I and Q Channels)

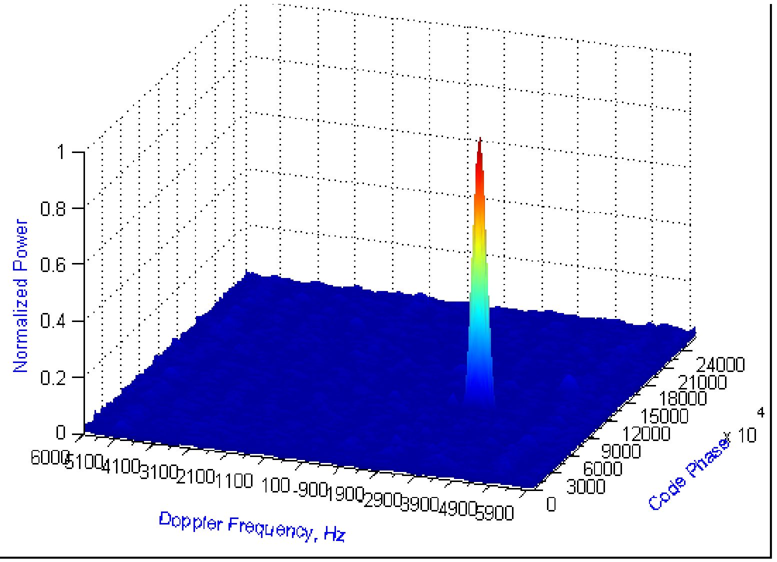




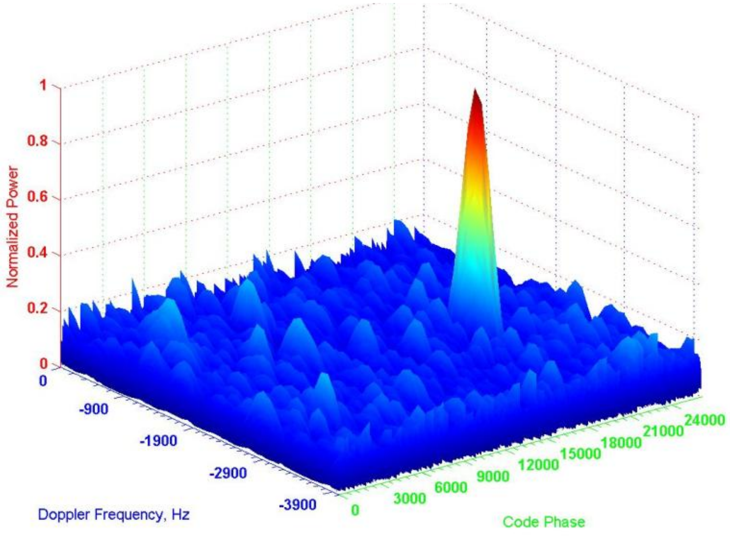
Scatter Plot of I and Q Channels, shows BPSK Modulation



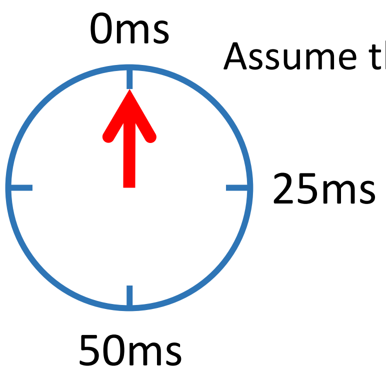
Acquisition of GPS L1C/A Signal with Low Noise



Acquisition of GPS L1C/A Signal with Higher Noise

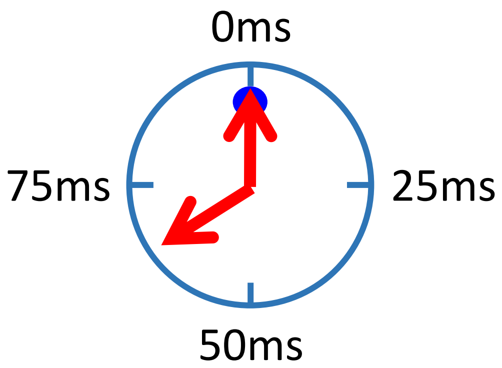


GNSS: How does it work?
Determine the Distance using Radio Wave

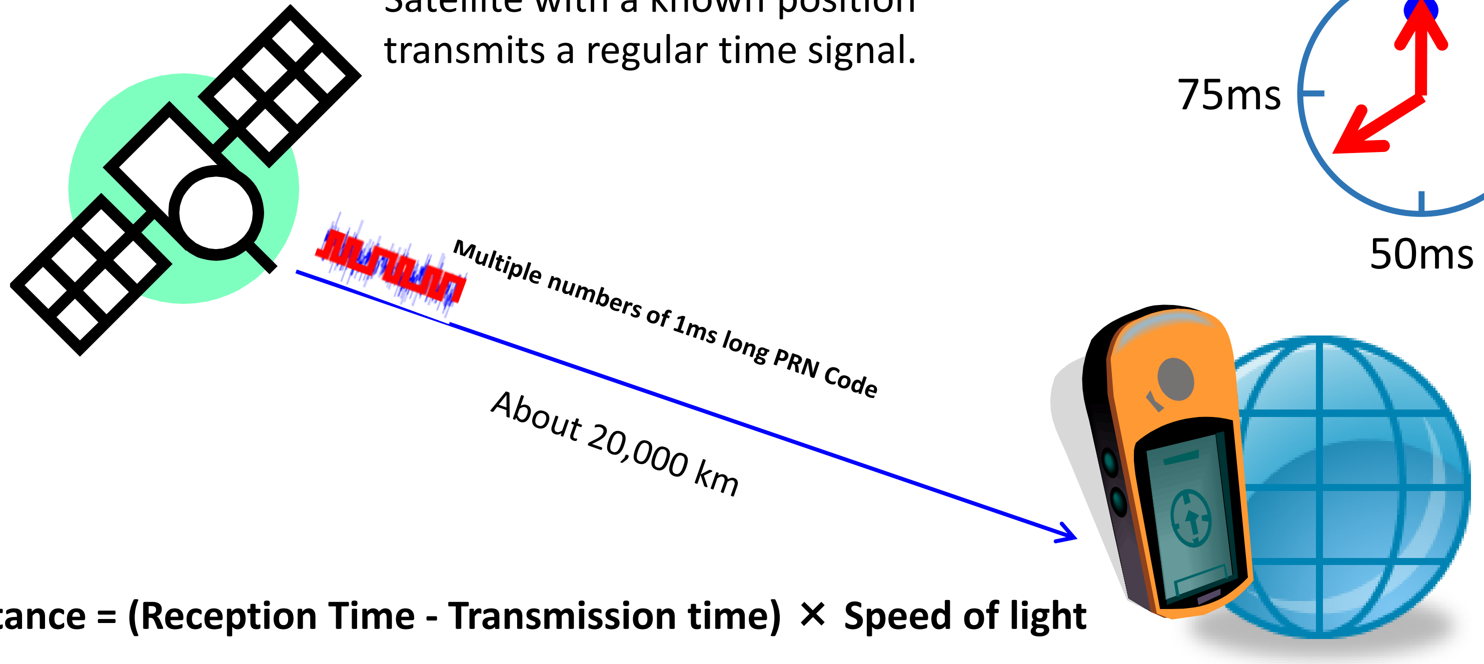


Assume that the Satellite Transmits Signal at 0ms.

If Receiver receives the same Signal after 67ms,
Distance = 67x300,000 = 20,100Km



Satellite with a known position
transmits a regular time signal.

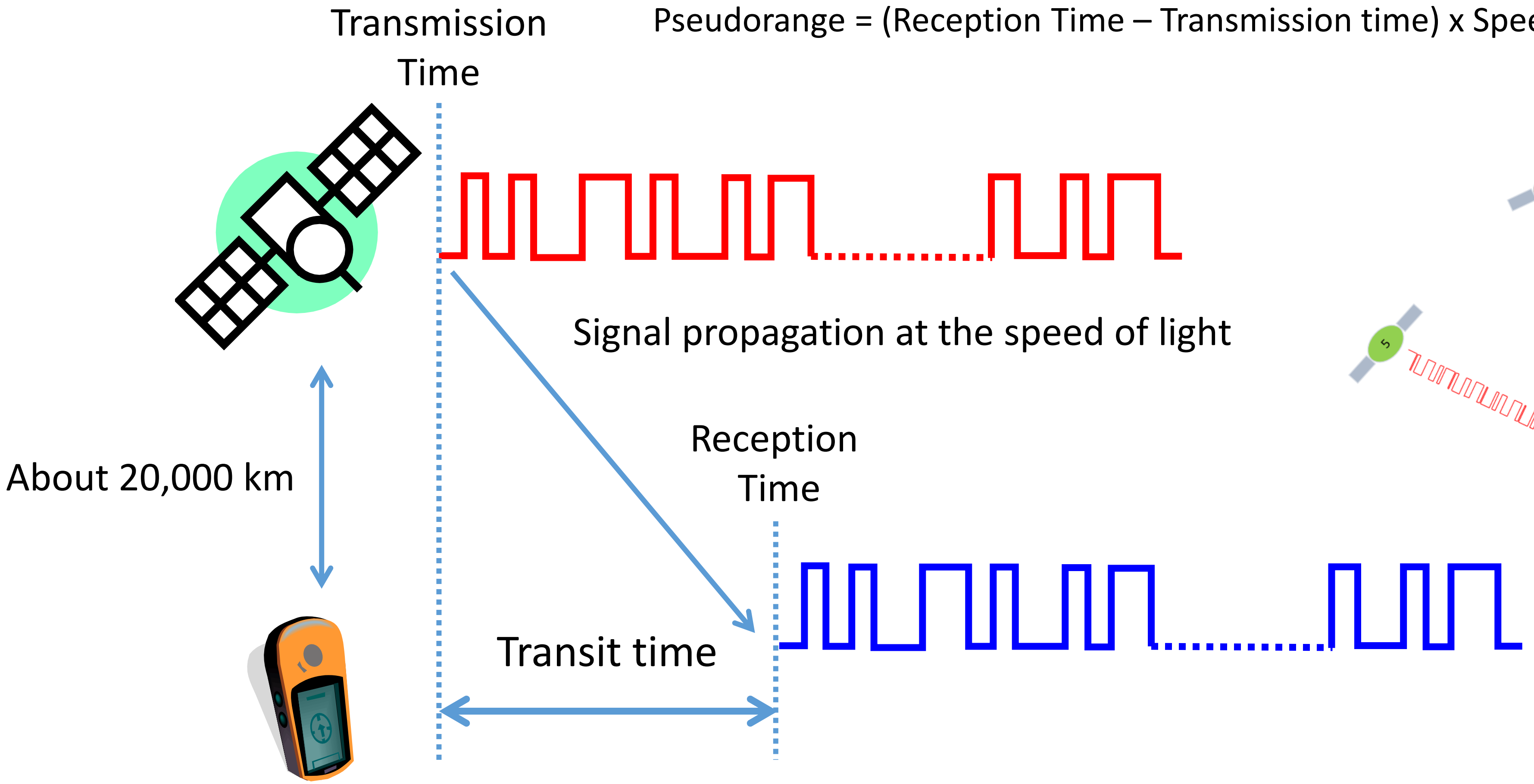


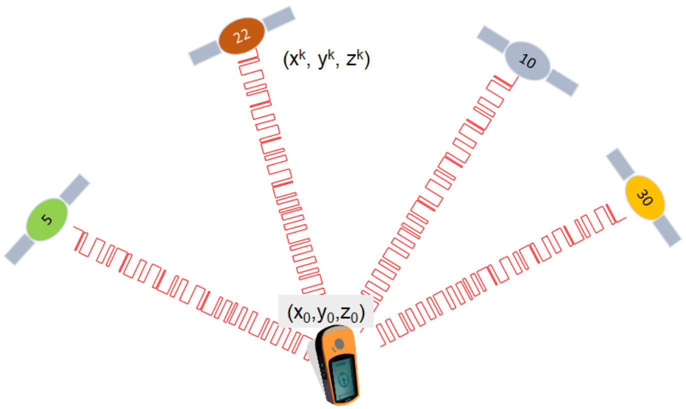
Distance = (Reception Time - Transmission time) × Speed of light

Speed of Light: 300,000 km/s

Pseudorange (Code-Phase Measurement) - 1

Pseudorange = (Reception Time – Transmission time) x Speed of Light





A GPS receiver measures the signal transmission time from the code phase at signal reception time.

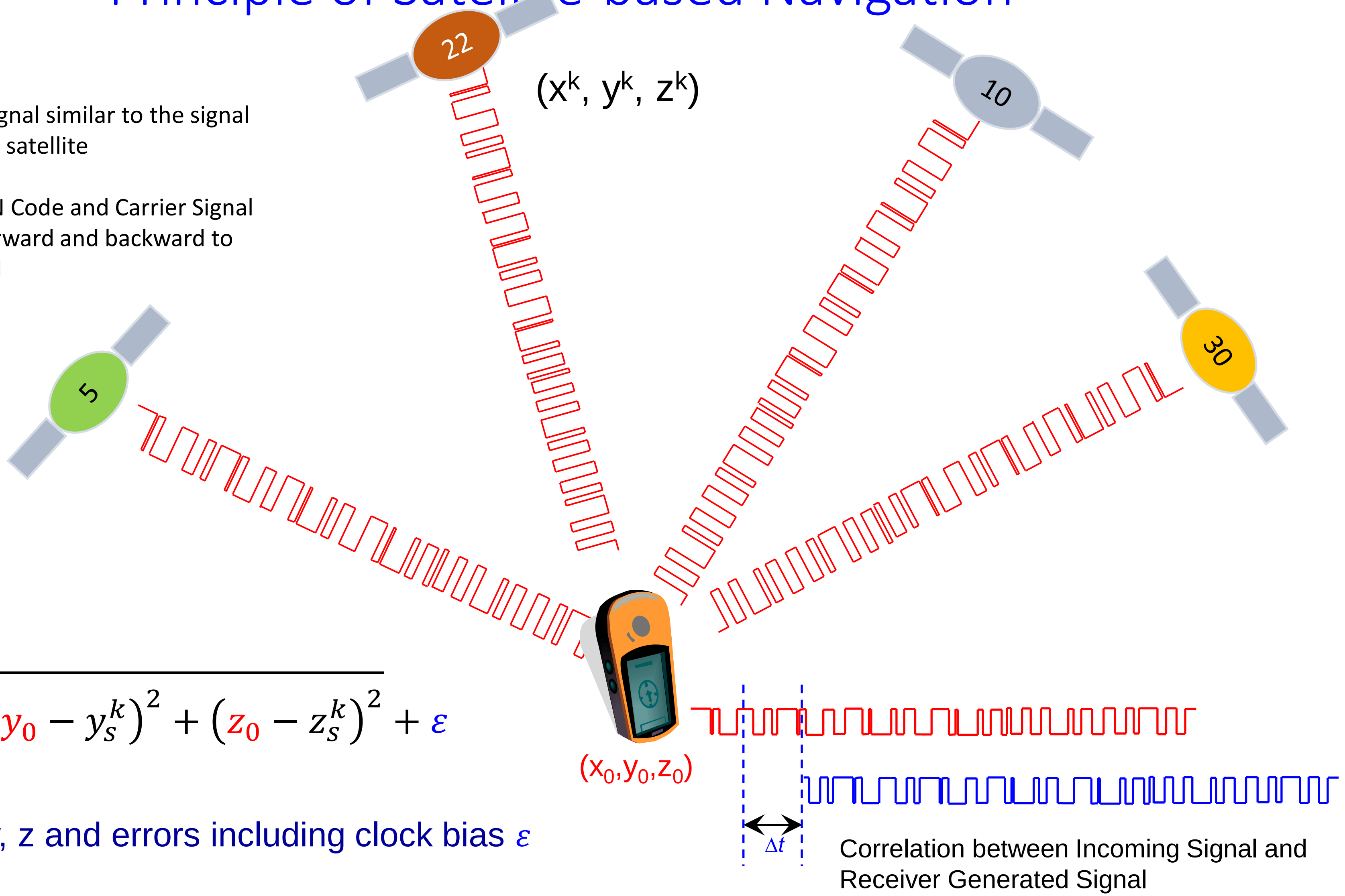
GNSS: How does it work?
Principle of Satellite-based Navigation

Receiver generates its own GPS signal similar to the signal coming from the satellite for each satellite

➔ Its called Replica Signal

➔ The Replica Signal includes PRN Code and Carrier Signal

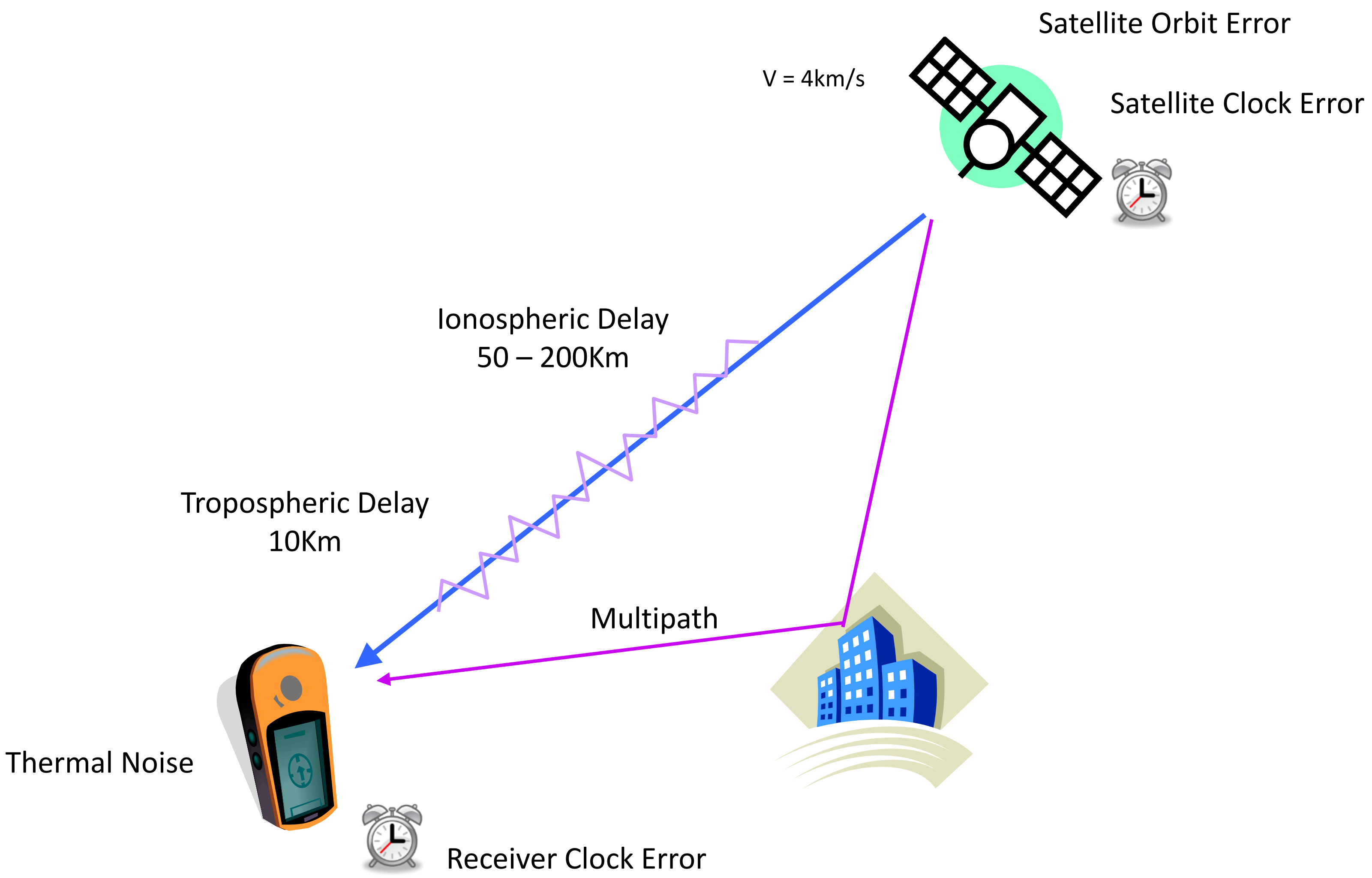
➔ This Replica Signal is moved forward and backward to match with the incoming signal



$$\rho^k = \sqrt{(x_0 - x_s^k)^2 + (y_0 - y_s^k)^2 + (z_0 - z_s^k)^2} + \varepsilon$$

If k ≥ 4, solve for x, y, z and errors including clock bias ε

Error sources



Pseudorange equation

Ideal Case: $\rho_0 = c(t_r - t_s)$

Real Case: $\rho = \rho_0 + c(\delta t_r - \delta t_s) + Iono + Tropo + Multipath + \xi$

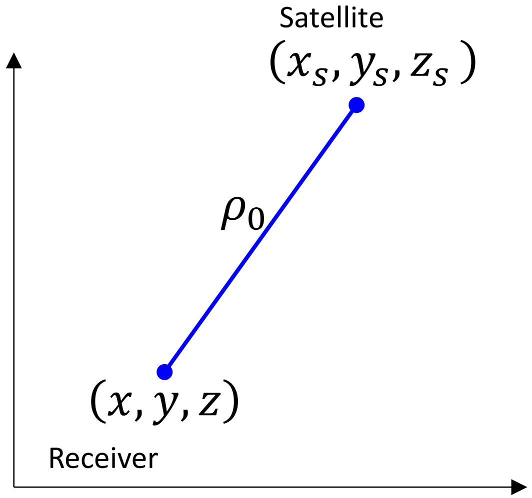
- Receiver Clock Error
- Satellite Clock Error
- Ionospheric Delay
- Tropospheric Delay
- Multipath Error
- Thermal Noise

Simplified Equation: $\rho = \rho_0 + c(\delta t_r - \delta t_s) + \varepsilon$

Pseudorange model

$$\rho = \underbrace{\sqrt{(x - x_s)^2 + (y - y_s)^2 + (z - z_s)^2}}_{\rho_0} + c(\delta t_r - \delta t_s) + \varepsilon$$

Where:
x, y, z : Unknown receiver position
delta tr: Unknown receiver clock error
epsilon : minimize this error by finding an optimal solution

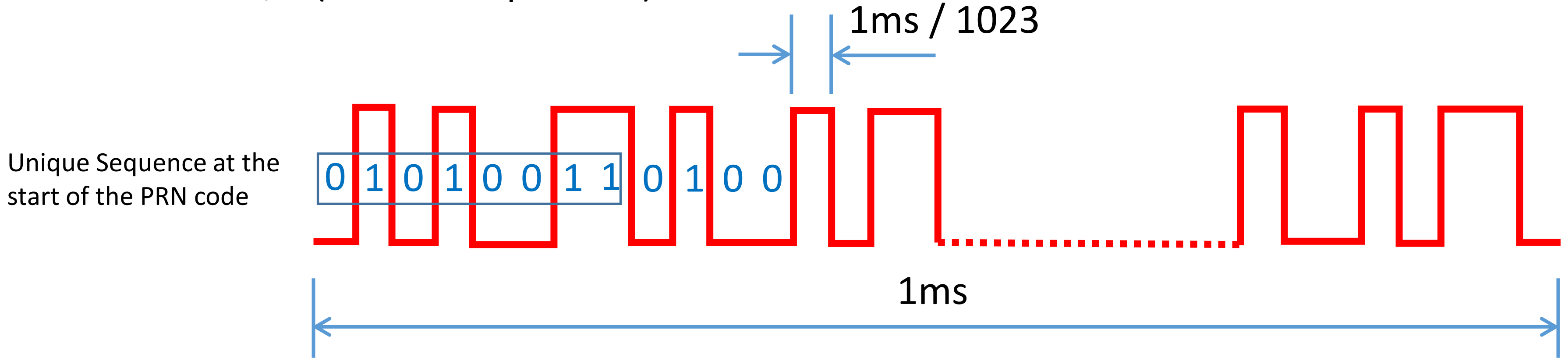


Range between satellite and receiver

- In order to solve the above equations, we need “n” simultaneous nonlinear equations from “n” pseudorange observations.
- We need at least 4 independent observations in order to determine 4 unknown parameters, x, y, z and receiver clock error.

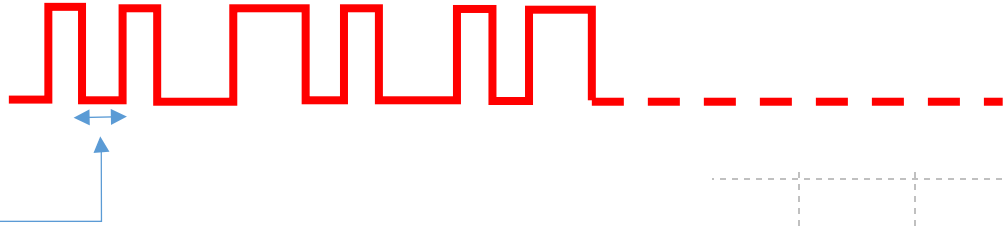
PRN (Pseudo Random Noise) Code

- PRN Code is a sequence of randomly distributed zeros and ones that is one millisecond long.
  - This random distribution follows a specific code generation pattern called Gold Code.
  - There are 1023 zeros and ones in one millisecond.
- Each GPS satellite transmits a unique PRN Code.
  - GPS receiver identifies satellites by its unique PRN code or ID.
- It continually repeats every millisecond
  - The receiver can detect where the PRN code terminated or repeated.
  - A unique sequence of bits indicates start of a PRN code.
- It helps to measure signal transit time and compute pseudorange between the receiver and the satellite
- Its also called C/A (Coarse Acquisition) code in GPS



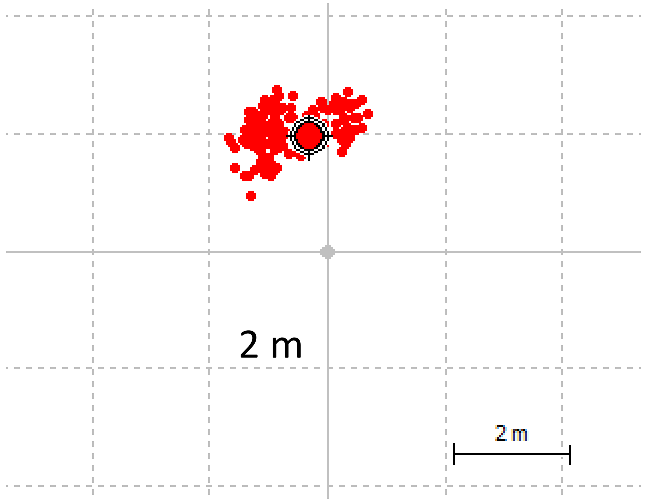
Pseudorange (Code-Phase Measurement) - 2

1-sequence of PRN Code is 1023 bits, 1ms long.
This corresponds to 300Km



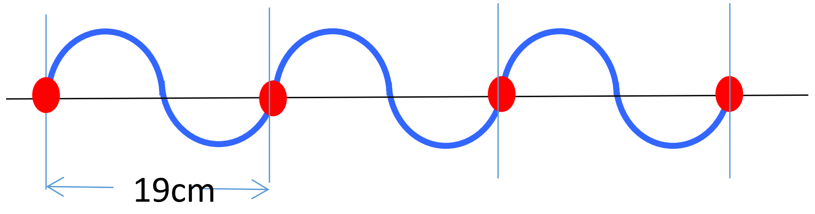
1-bit or chip corresponds to 1/1023 ms.
This is about 293m (say 300m) in distance.

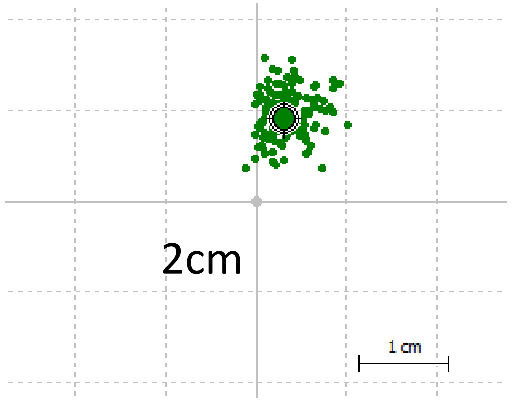
In the receiver, signals are resampled at certain frequency, say 10MHz.
This means every chip will be further divided into 10 smaller chips.
If it is possible to detect code phase at 1/10 of this sampled chip, then range measurement accuracy would be about 300/10/10 = 3m.
However, there are various types of noises and this accuracy may not be possible.
Normally, GPS L1C/A guarantees an accuracy within 10m.
Thus, using Code-Phase (PRN code) measurement, the accuracy will be limited to few meters level.



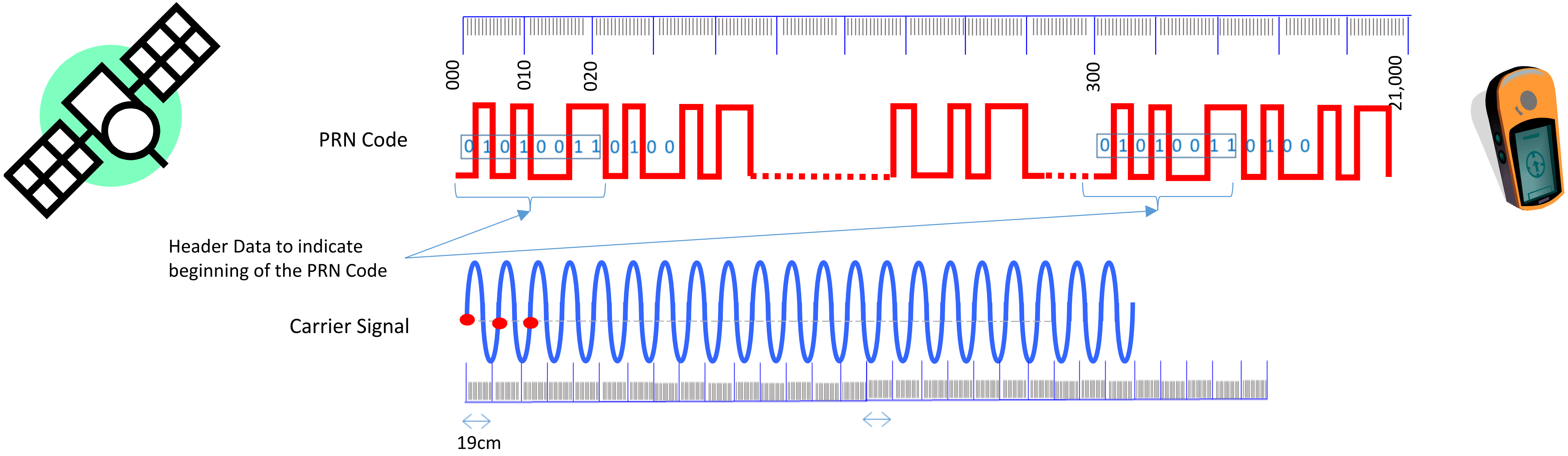
Carrier-Phase Measurement – 1

- Carrier-Phase measurement is done by counting the number of cycles coming from the satellite to the receiver.
- However, there are many complexities in measuring total number of cycles (N) from the satellite to the receiver.
  - This is called integer ambiguity
  - This is due to the fact that all cycles are the same and there are no headers to tell the receiver when a new cycle has arrived after number of cycles as in PRN code.
    - A PRN code has a header to tell the receiver that this is the beginning of the PRN code that is 1023 chips long.
    - There are algorithms to solve this problem of ambiguity resolution.
- One complete cycle for GPS L1 band is 19cm long.
  - Thus, if we can measure one wavelength, we can get 19cm accuracy
  - If we can measure 1/10th of a cycle, we get about 2cm accuracy.
  - Thus, Carrier-Phase measurement can provide centimeter level accuracy.





Code-Phase (PRN Code) vs. Carrier-Phase Measurement

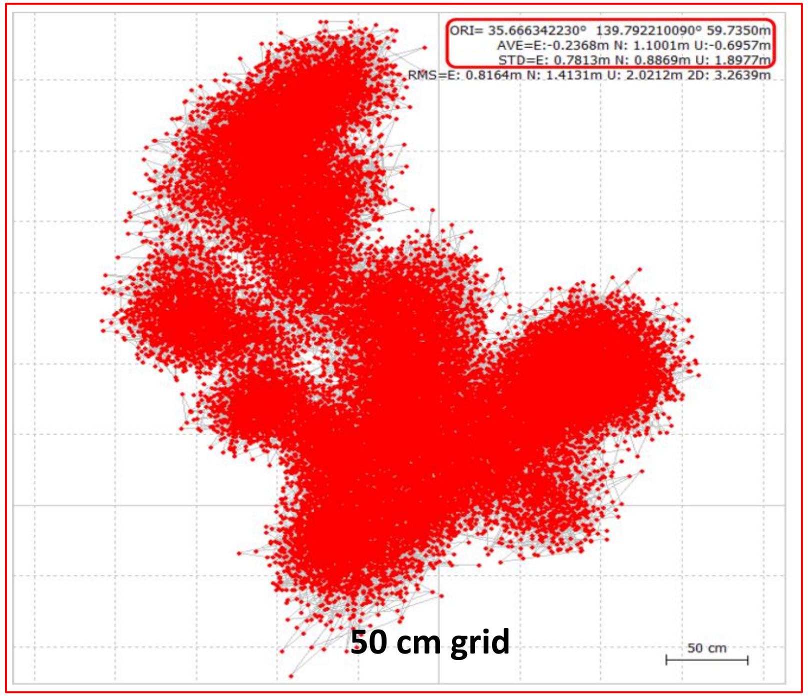


Code-Phase Measurement	Carrier-Phase Measurement
Measuring distance between the satellite and the receiver with a tape that has distance markings as well as distance values written. So that we can measure correct distance.	Measuring distance between the satellite and the receiver with a tape that has distance markings but distance values are not written. We only know that each distance marker is 19cm apart. So, we need to count at certain point the number of cycles separately that’s coming to the receiver.
Only provide meter level accuracy	Provides centimeter level accuracy

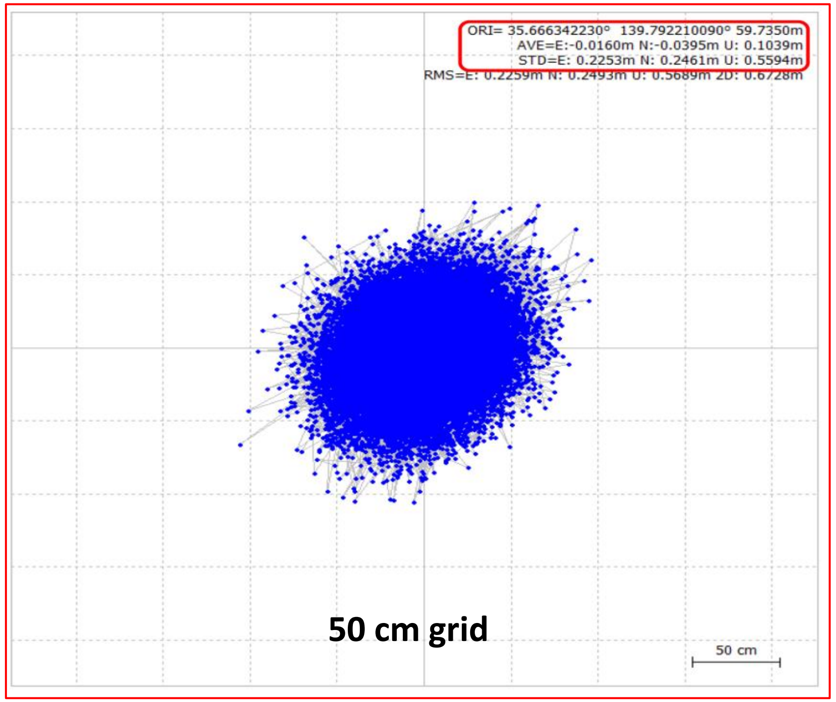
How to Improve GPS Accuracy?

GPS Position Accuracy

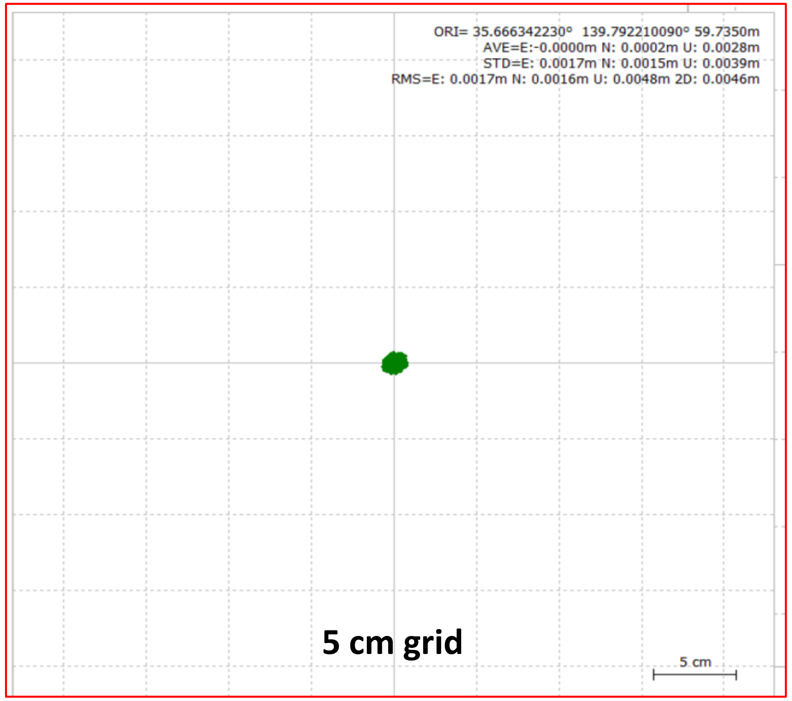
How to achieve accuracy from few meters to few centimeters?



SPP (Single Point Position)

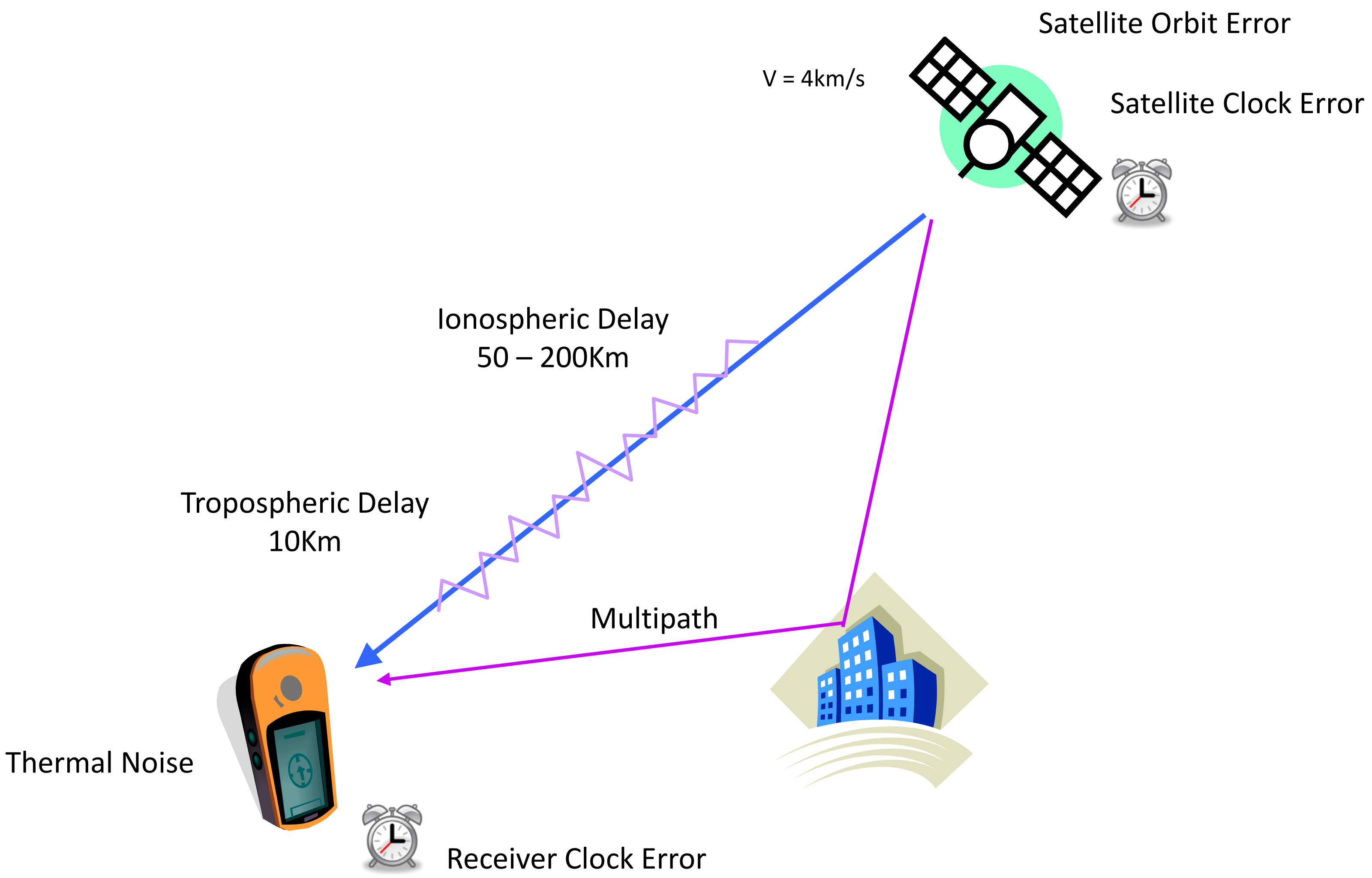


DGPS (Differential GPS)
Code-phase observation



RTK (Real Time Kinematic)
Carrier-phase observation

Error sources



Errors in GPS Observation (L1C/A Signal)

Error Sources	One-Sigma Error , m		Comments
	Total	DGPS	
Satellite Orbit	2.0	0.0	Common errors are removed
Satellite Clock	2.0	0.0	
Ionosphere Error	4.0	0.4	Common errors are reduced
Troposphere Error	0.7	0.2	
Multipath	1.4	1.4	
Receiver Circuits	0.5	0.5	

If we can remove common errors, position accuracy can be increased.

Common errors are: Satellite Orbit Errors, Satellite Clock Errors and Atmospheric Errors (within few km)

Values in the Table are just for illustrative purpose, not the exact measured values.
Table Source : http://www.edu-observatory.org/gps/gps_accuracy.html#Multipath

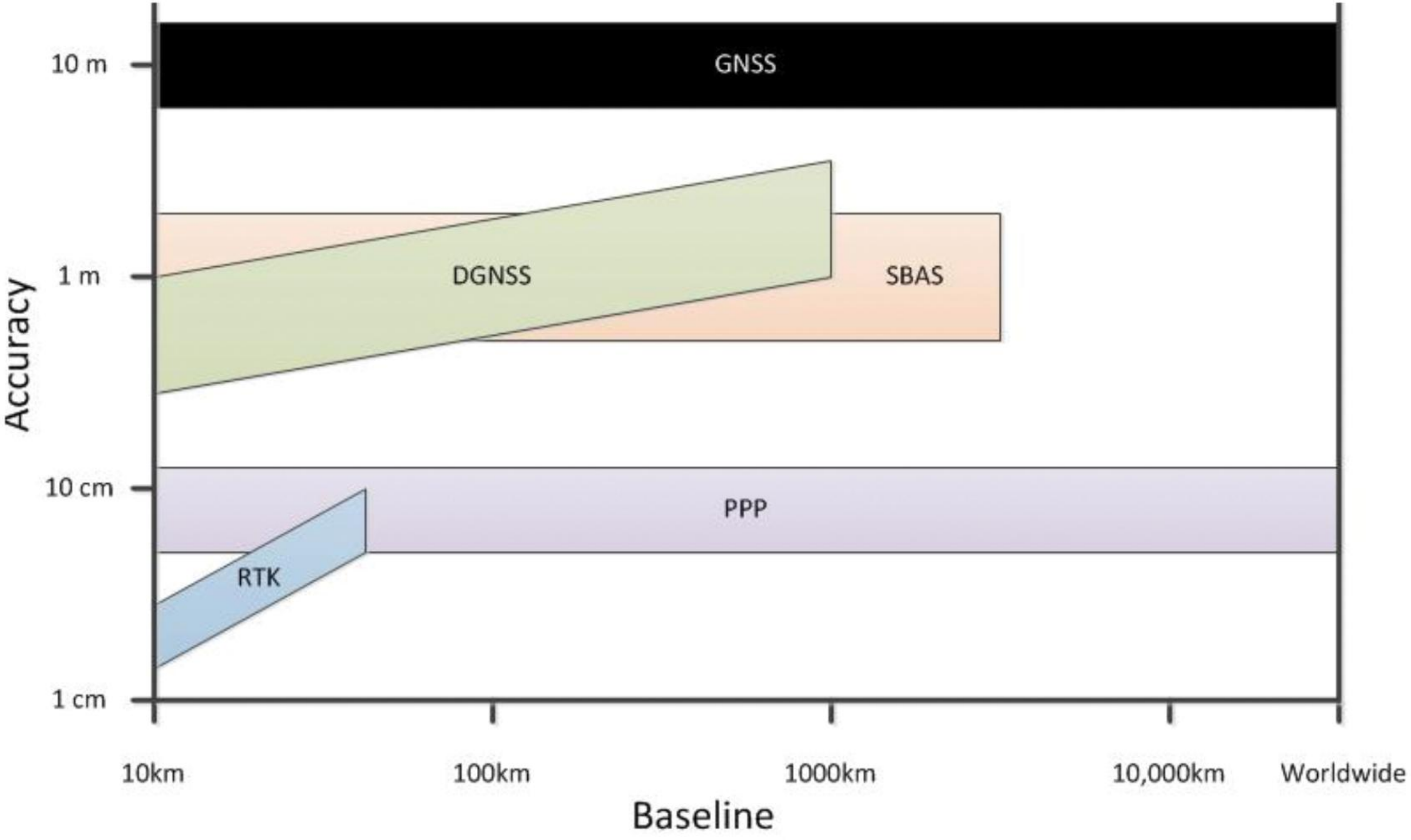
How to Improve Accuracy?

- Both Code-Phase and Carrier-Phase observations are necessary
  - Carrier-phase provides centimeter level resolution
- Need to remove or minimize the following errors:
  - Satellite Related Error
    - Satellite orbit errors
    - Satellite clock errors
  - Space Related Errors
    - Ionospheric errors
    - Tropospheric erros
  - Receiver Related Errors
    - Receiver clock error
    - Receiver circuit related

Observation Methods for High-Accuracy

- Basically three types of Observation
  - DGPS (Differential GPS)
    - Code-phase observation
    - Requires Base-station (Reference Station)
  - RTK (Real Time Kinematic)
    - Code-phase and Carrier-Phase Observation
    - Requires Base-station (Reference Station)
  - PPP (Precise Point Positioning)
    - Code-phase and Carrier-phase observation
    - Does not require base-station

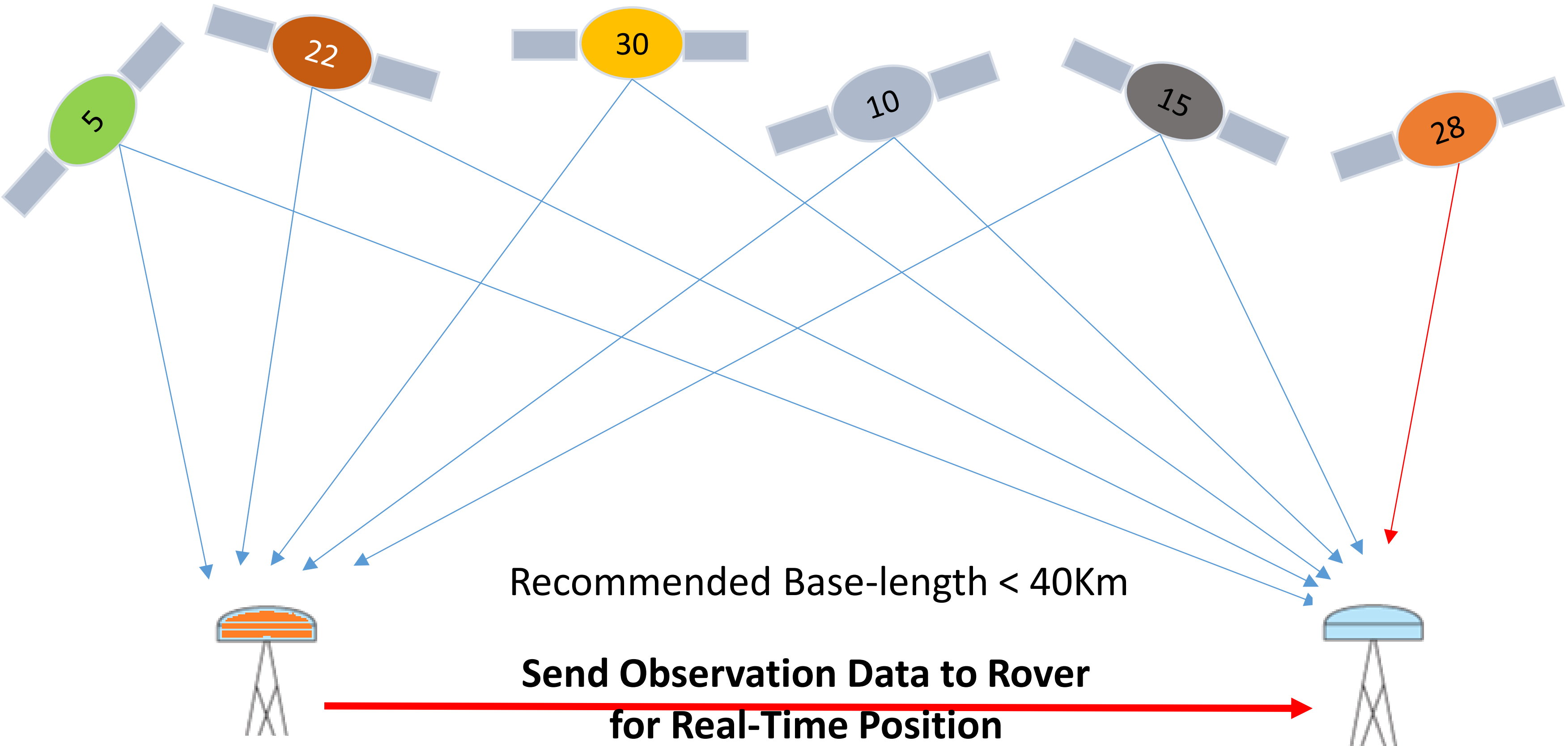
Which Method: DGPS, SBAS, RTK, PPP?



http://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/

How to Improve Accuracy?

Use Differential Correction (DGPS / RTK)



Base-Station

Antenna is installed at a known-position

For RTK, both base and rover receivers need to use data from the same satellites

Rover

User in the Field

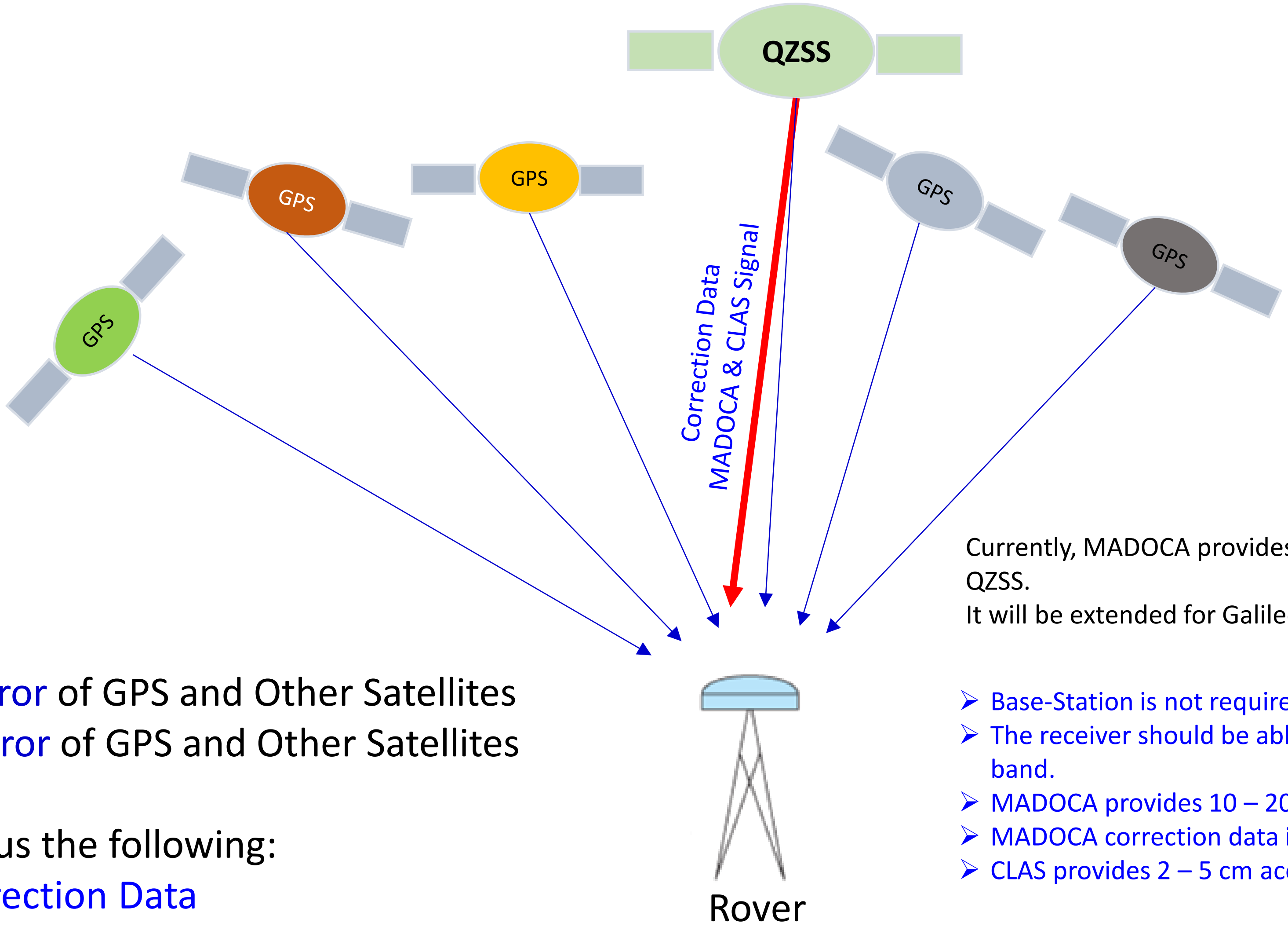
(Either fixed or moving)

Use RINEX data for post-processing

Base-station Antenna position shall be known in advance

How to Improve Accuracy?

Use QZSS Service MADOCA or CLAS



Correction Data:

MADOCA:

Satellite Orbit Error of GPS and Other Satellites

Satellite Clock Error of GPS and Other Satellites

CLAS:

All of MDOCA plus the following:

Ionospheric Correction Data

Currently, MADOCA provides correction data for GPS, GLONASS and QZSS.
It will be extended for Galileo in future.

- Base-Station is not required.
- The receiver should be able to receive MADOCA / CLAS signal in L6 band.
- MADOCA provides 10 – 20cm accuracy (Global)
- MADOCA correction data is also available online
- CLAS provides 2 – 5 cm accuracy (Japan Only)

Data Formats:

Standard Formats: NMEA, RINEX, RTCM, BINEX

Proprietary Data Formats: UBX, SBF, JPS, Txx/Rxx etc.

References: https://www.nmea.org/

National Marine Electronics Association (NMEA) Format

- NMEA is format to output measurement data from a sensor in a 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

References: https://www.nmea.org/

NMEA Data Format

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 (do not read it as four thousand eight hundred seven… Read it as 48 degrees, 07.038 minutes)
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 (RTK FIX) 5 = RTK Float 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 *

RINEX Data Format

- 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 Septenrtio 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
- The latest RINEX version is 3.04, 23 NOV 2018
  - Note: Not all the software and receivers are yet compatible with the latest version
  - Make sure which version of RINEX works the best with your software

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 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
```

RINEX “O” File, Continued from previous slide

```
   S37 86400        0        0 86400        0        0        0        0       PRN / # OF OBS
   S40 56700        0        0 56700        0        0        0        0       PRN / # OF OBS
CARRIER PHASE MEASUREMENTS: PHASE SHIFTS REMOVED                                COMMENT
                                                                                END OF HEADER
 17  5  1  0  0  0.0000000  0 19G10G12G14G15G18G24G25G31G32R01R02R03
                                R11R12R13S28S29S37S40
  21375379.406 7  21375388.078 9                 112328384.475 7  87528640.180 9
                                  21375388.41448
  20991588.469 7  20991594.418 9                 110311559.942 7  85957091.970 9
                                  20991594.71548
  23097788.500 6                                 121379711.146 6  94581624.25147
                                  23097793.85247
  24539464.648 6  24539473.480 8                 128955722.954 6 100484989.893 8
                                  24539473.66046
  21890081.000 6                                 115033147.870 6  89636240.02147
                                  21890086.53547
  22760846.398 6  22760855.313 9                 119609048.681 6  93201876.319 9
                                  22760854.86347
  20303284.266 7  20303294.227 9                 106694510.219 7  83138615.317 9
                                  20303294.01248
  23440741.258 6  23440748.211 8                 123181935.734 6  95985961.100 8
                                  23440748.62147
  21395760.742 7  21395769.145 9                 112435502.496 7  87612113.685 9
                                  21395769.30548
```

BINEX: Binary Exchange Data Format

- BINEX is a data format to exchange GNSS raw data between the receivers for systems
- Defined by Record IDs
  - Record 0x00 = 0 for site/monument/marker/reference point/setup metadata
  - Record 0x01 = 1 for GNSS navigation information
  - Record 0x02 = 2 for generalized GNSS
  - Record 0x03 = 3 for generalized ancillary site data
  - Record 0x04 = 4 for receiver internal state data
  - Record 0x05 = 5 for processed results, e.g. PVT
  - Record 0x7d = 125 for receiver internal state data prototyping
  - Record 0x7e = 126 for ancillary site data prototyping
  - Record 0x7f = 127 for GNSS data prototyping
- Records may have Sub-Record IDs

RTCM

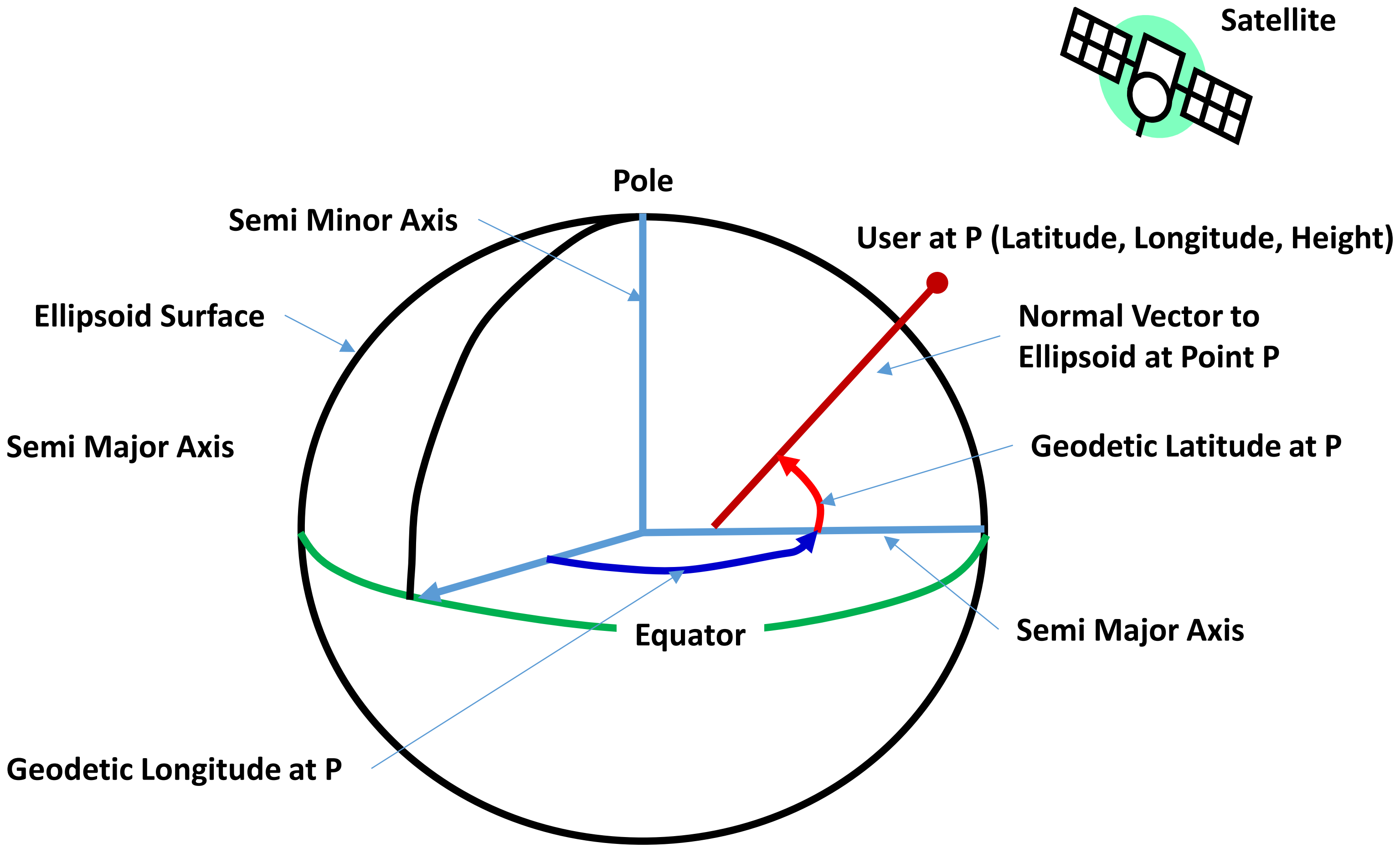
- RTCM : Radio Technical Commission for Maritime Services
  - An internationally accepted data transmission standard for base-station data transmission to a rover. The standards are defined and maintained by RTCM SC-104
  - Provides GNSS Raw Data in compressed format
  - Major standard for real-time data exchange
- RTCM SC-104 (Special Committee 104)
  - Defines data formats for Differential GPS, RTK
- The Current Version is RTCM-3 (10403.3)
- Refer https://www.rtcm.org/ for detail information and document
  - 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

RTCM

- MT 1- 100 : Experimental Messages
- MT 1001 – 1230 : GNSS Messages
- MT 4001 – 4095 : Proprietary Messages
- Example: Observation Messages
  - GPS L1 MT: 1001, 1002
  - GPS L1/L2 MT: 1003, 1004
  - GLONASS L1 MT: 1009, 1010
  - GLONASS L1/L2 MT: 1011, 1012
  - Station Coordinates MT: 1005,1006
  - Antenna Description MT: 1007,1008
- Example: MT1004
  - Extended L1&L2 GPS RTK Observables
  - This GPS message type is the most common observational message type, with L1/L2/SNR content.

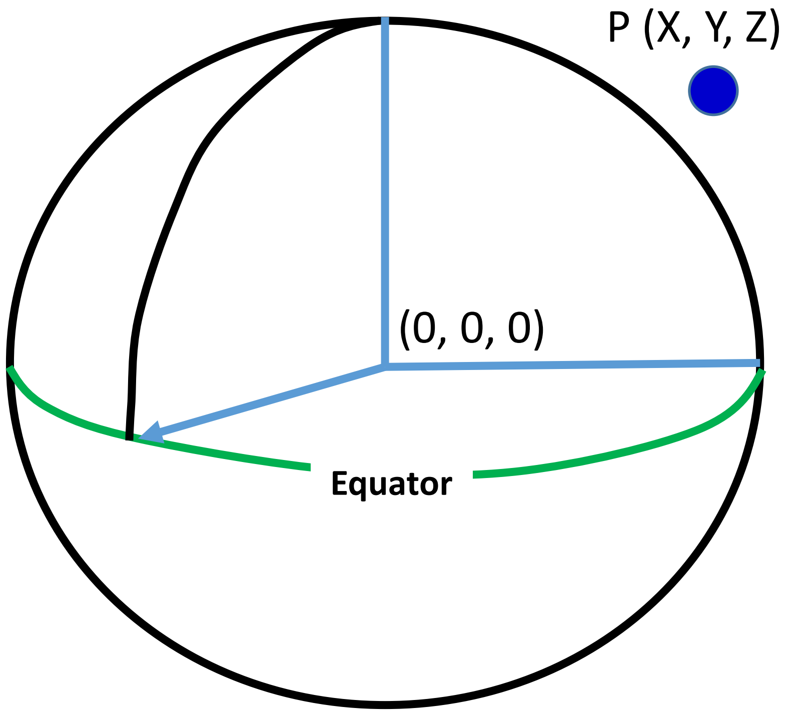
Coordinate Systems

Geodetic Coordinate System



ECEF (Earth Centered, Earth Fixed)

ECEF Coordinate System is expressed by assuming the center of the earth coordinate as (0, 0, 0)



Coordinate Conversion from ECEF to Geodetic and vice versa

Geodetic Latitude, Longitude & Height to ECEF (X, Y, Z)

$$X = (N + h)\cos\varphi\cos\lambda$$

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

$$Z = [N(1 - e^2) + h]\sin\varphi$$

$$\varphi = Latitude$$
$$\lambda = Longitude$$
h = Height above Ellipsoid

a = semi-major axis
b = semi-minor axis
e^2 = 1 – (b^2/a^2)

ECEF (X, Y, Z) to Geodetic Latitude, Longitude & Height

$$\varphi = \text{atan}\left(\frac{Z+e^2 b\, sin^3\theta}{p-e^2 a cos^3\theta}\right)$$

$$\lambda = \text{atan2}(y, x)$$

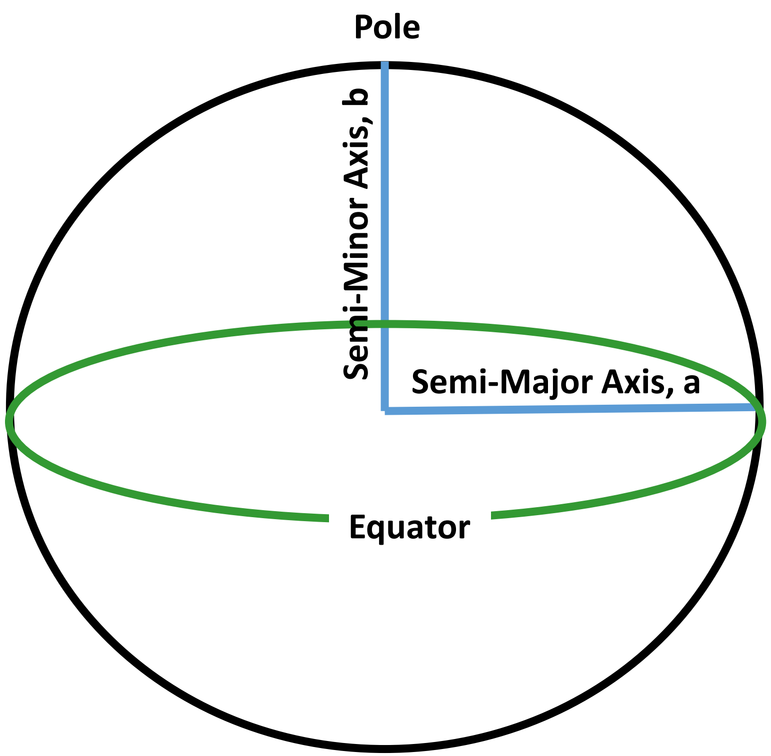
$$h = \frac{P}{\cos\varphi} - \text{N}(\varphi)$$

$$P = \sqrt{x^2 + y^2}$$

$$\theta = atan\left(\frac{Za}{Pb}\right)$$

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

Geodetic Datum: Geometric Earth Model



GPS uses WGS-84 Datum

But, topographic maps and many other maps use different datum. Before using GPS data on these maps, its necessary to convert GPS coordinates from WGS-84 to local coordinate system and datum. Many GPS software have this tool. Also, GPS receivers have built-in datum selection capabilities.

Check your receiver settings before using.

WGS-84 Geodetic Datum Ellipsoidal Parameters

Semi-Minor Axis, b = 6356752.3142m

Semi-Major Axis, a = 6378137.0m

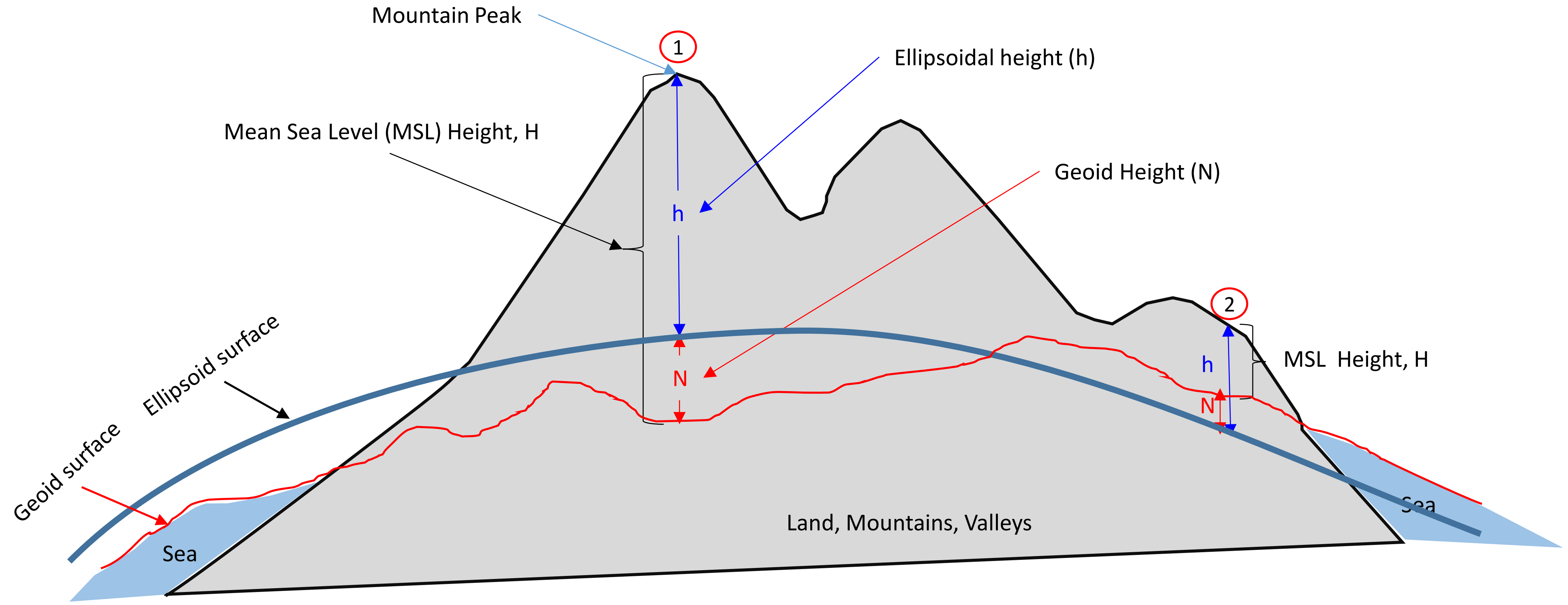
Flattening, f = (a-b)/a

= 1/298.257223563

First Eccentricity Square = e^2 = 2f-f^2

= 0.00669437999013

Ellipsoid, Geoid and Mean Sea Level (MSL)



MSL Height (H) = Ellipsoidal height (h) – Geoid height (N)
Geoid Height is negative if its below Ellipsoidal height

Example at point (1) : h = 1200m, N = -30m
H = h – N = 1200 – (-30) = 1200 + 30 = 1230m

Example at point (2) : h = 300m, N = +15m
H = h – N = 300 – 15 = 285m

Height Data Output in u-blox Receiver, NMEA Sentence, $GNGGA Sentence

MSL (Altitude)

Geoid Separation
Geoid Height

$GNVTG,,T,,M,0.010,N,0.018,K,D*30

$GNGGA,012039.00,3554.18235,N,13956.35867,E,2,12,0.48,54.4,M,39.6,M,0.0,0000*5D

$GNGSA,A,3,03,04,06,09,17,19,22,28,194,195,02,,0.92,0.48,0.78,1*06

$GNGSA,A,3,11,12,04,24,19,31,33,,,,,,0.92,0.48,0.78,3*00

$GNGSA,A,3,30,01,03,14,08,28,33,04,02,07,10,13,0.92,0.48,0.78,4*08

$GPGSV,5,1,17,01,18,076,,02,04,279,36,03,43,045,43,04,34,109,41,1*6C

$GPGSV,5,2,17,06,38,295,43,09,26,152,40,11,02,107,29,17,74,330,47,1*67

$GPGSV,5,3,17,19,53,320,45,22,22,048,39,28,36,213,43,41,18,249,39,1*6D

$GPGSV,5,4,17,50,46,201,40,193,52,172,43,194,16,193,40,195,85,163,46,1*5E

$GPGSV,5,5,17,199,46,201,37,1*66

$GAGSV,2,1,07,04,25,175,40,11,28,299,37,12,65,007,43,19,50,105,40,7*72

$GAGSV,2,2,07,24,27,245,41,31,09,198,36,33,33,082,42,7*43

$GBGSV,4,1,15,01,48,172,43,02,19,248,36,03,39,225,43,04,44,148,42,1*7C

$GBGSV,4,2,15,06,00,185,29,07,39,214,41,08,53,305,43,10,44,248,42,1*7C

$GBGSV,4,3,15,13,33,283,42,14,23,043,38,27,55,323,48,28,61,092,48,1*71

$GBGSV,4,4,15,30,05,306,36,32,17,206,42,33,48,055,46,1*4F

$GNGLL,3554.18235,N,13956.35867,E,012039.00,A,D*76

NMEA - GxGGA (Global Positioning System Fix Data)

Parameter	Value	Unit	Description
UTC	012040.00	hhmmss.sss	Universal time coordinated
Lat	3554.18235	ddmm.mmmm	Latitude
Northing Indicator	N		N=North, S=South
Lon	13956.35868	dddmm.mmmm	Longitude
Easting Indicator	E		E=East, W=West
Status	2		0=Invalid, 1=2D/3D, 2=DGNSS, 4=Fixed RTK, 5=Float RTK, 6=Dead Reckoning
SVs Used	12		Number of SVs used for Navigation
HDOP	0.48		Horizontal Dilution of Precision
Alt (MSL)	54.4	m	Altitude (above means sea level)
Unit	M		M=Meters
Geoid Sep.	39.6	m	Geoid Separation = Alt(HAE) - Alt(MSL)
Unit	M		M=Meters
Age of DGNSS Corr	0.0	s	Age of Differential Corrections
DGNSS Ref Station	0000		ID of DGNSS Reference Station

The NMEA sentences in this figure are from u-blox receiver.
NMEA format uses "Mean Sea Level" for height data (shown in blue texts).
Also it provides Geoid Height (Geoid Separation) value.
GPS by default is Ellipsoidal height and this height is converted to Mean Sea Level height using the geoid Height (shown in red texts) .
This means, u-blox receiver uses a built-in database of Geoid Height.

U-blox also outputs Ellipsoidal height in proprietary message $PUBX,00 (marked as altRef)
$PUBX,00,time,lat,NS,long,EW,**altRef**,navStat,hAcc,vAcc,SOG,COG,vVel,diffAge,HDOP,VDOP,TDOP,numSvs,reserved,DR,*cs<CR><LF>
altRef ➔ Altitude above user datum ellipsoid

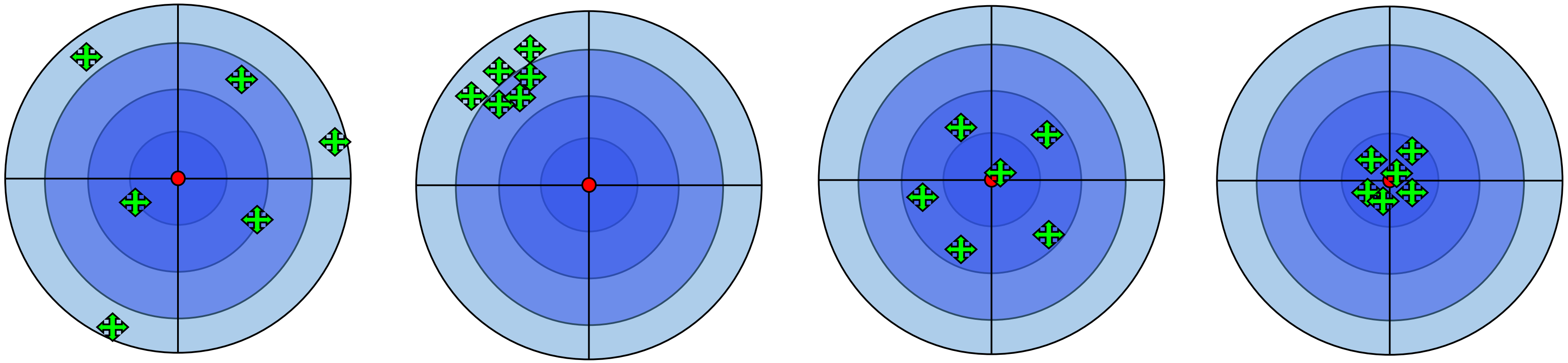
Points to Be Careful in GPS Survey

- Datum
  - Which Datum is used for GPS Survey?
  - By default, GPS uses WGS-84
  - But, your Map may be using different datum like Everest
    - Make Sure that Your Map and Your Coordinates from the GPS are in the same Datum, if not, datum conversion is necessary
    - You can get necessary transformation parameters from your country's survey department
- Height
  - Which Height is used?
  - By default GPS uses Ellipsoidal Height
  - But, your Map may be using Mean Sea Level (MSL or Topographic) Height
    - You need to convert from Ellipsoidal Height into MSL Height
    - Use Ellipsoidal and Geoid height Difference Data for your survey region
      - You can get it from your country's survey office

GNSS Errors

Background Information: 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



Neither Precise nor Accurate | Precise but Not Accurate | Accurate but Not Precise? | Precise and Accurate

GNSS Measurement Errors

Measure	Abbreviation	Definition
Root Mean Square	RMS	The square root of the average of the squared errors
Twice Distance RMS	2D RMS	Twice the RMS of the horizontal errors
Circular Error Probable	CEP	A circle's radius, centered at the true antenna position, containing 50% of the points in the horizontal scatter plot
Horizontal 95% Accuracy	R95	A circle's radius, centered at the true antenna position, containing 95% of the points in the horizontal scatter plot
Spherical Error Probable	SEP	A sphere's radius centered at the true antenna position, containing 50% of the points in the three dimensional scatter plot

Source: GPS Accuracy: Lies, Damn Lies, and Statistics, GPS World, JAN 1998
https://www.gpsworld.com/gps-accuracy-lies-damn-lies-and-statistics/

Commonly Used GNSS Performance Measurements

- TTFF
  - True Time to First Fix
  - Parameter: Cold Start, Warm Start, Hot Start
- Standard Accuracy
  - Accuracy attainable without any correction techniques
- DGPS Accuracy
  - Accuracy attainable by differential correction data
  - Code-phase correction
- RTK Accuracy
  - Accuracy attainable by differential correction data
  - Use both Code-Phase and Carrier Phase correction

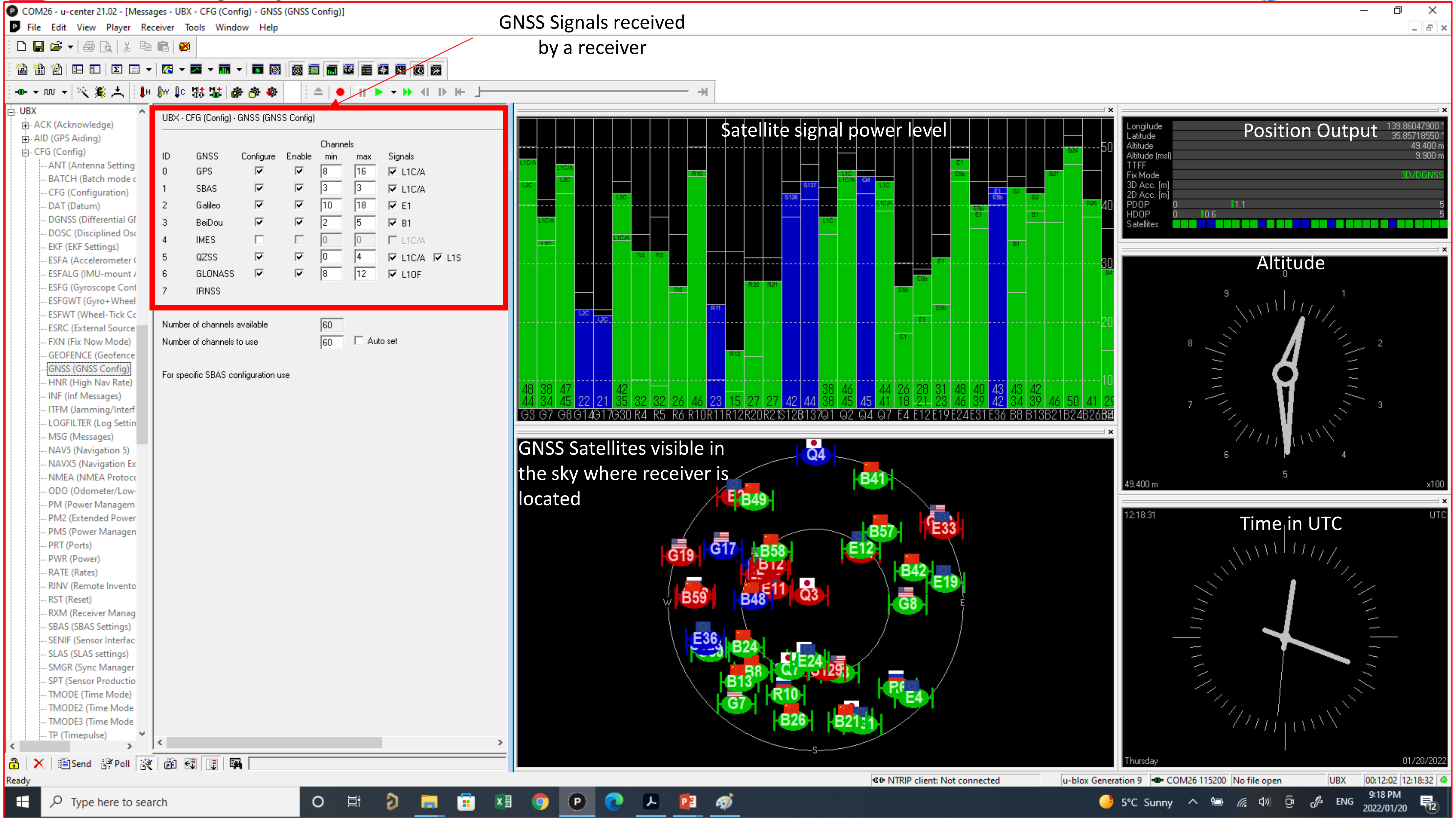
TTFF and Typical Example Values

- TTFF
  - Cold Start : < 36 seconds
    - Time required to output first position data since the receiver power is on
    - No reference data like time or almanac are available
  - Warm Start : < 6 seconds
    - Time required to output first position data since the receiver power is on with the latest satellite almanac data in the receiver's memory
    - Time and almanac related reference data are already known
  - Hot Start : < 1 second
    - Receiver has already output position data
    - Time to reacquire an already tracked satellite due to temporary blockage by buildings or trees

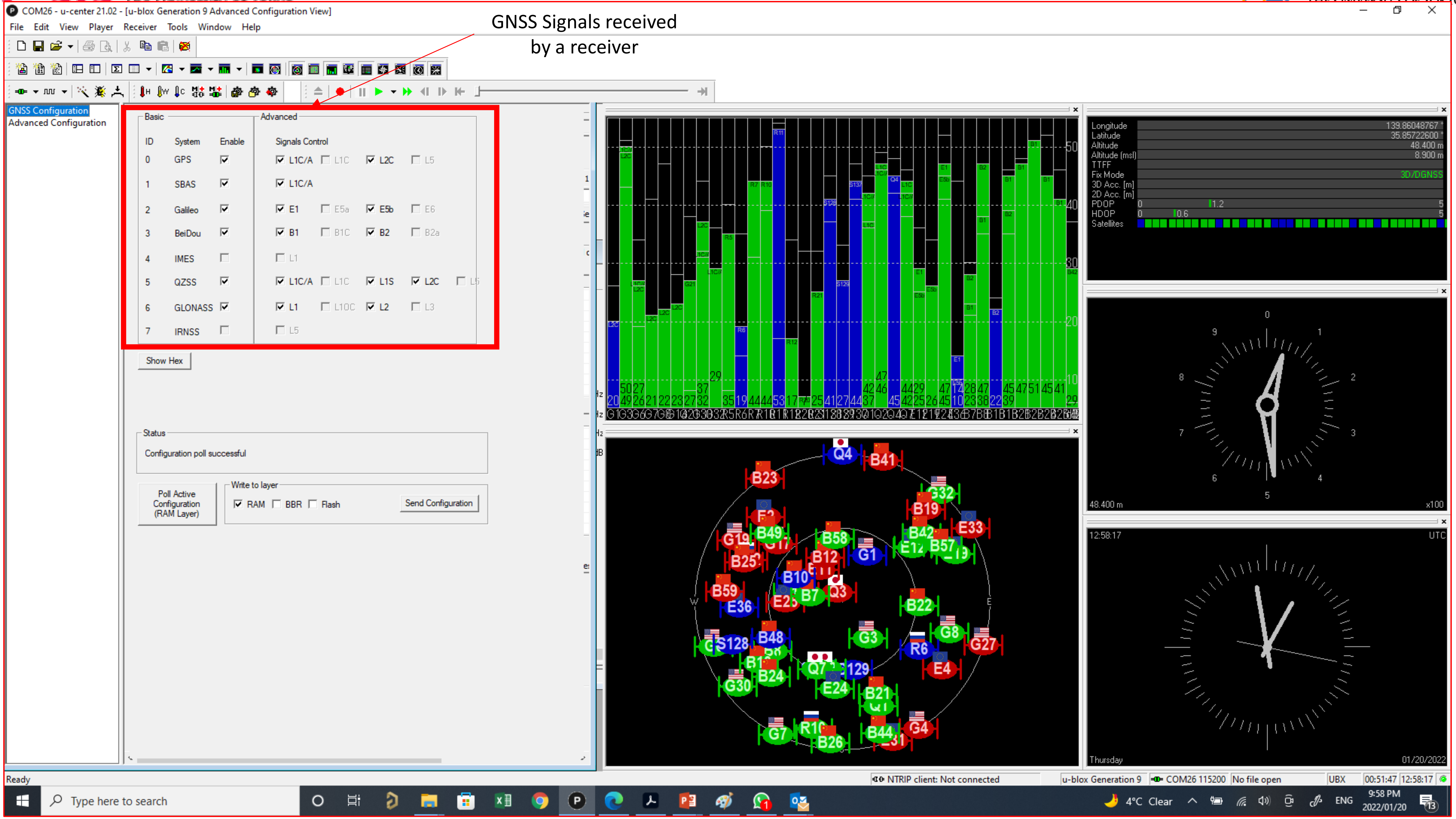
Performance Measurement of RTK Accuracy

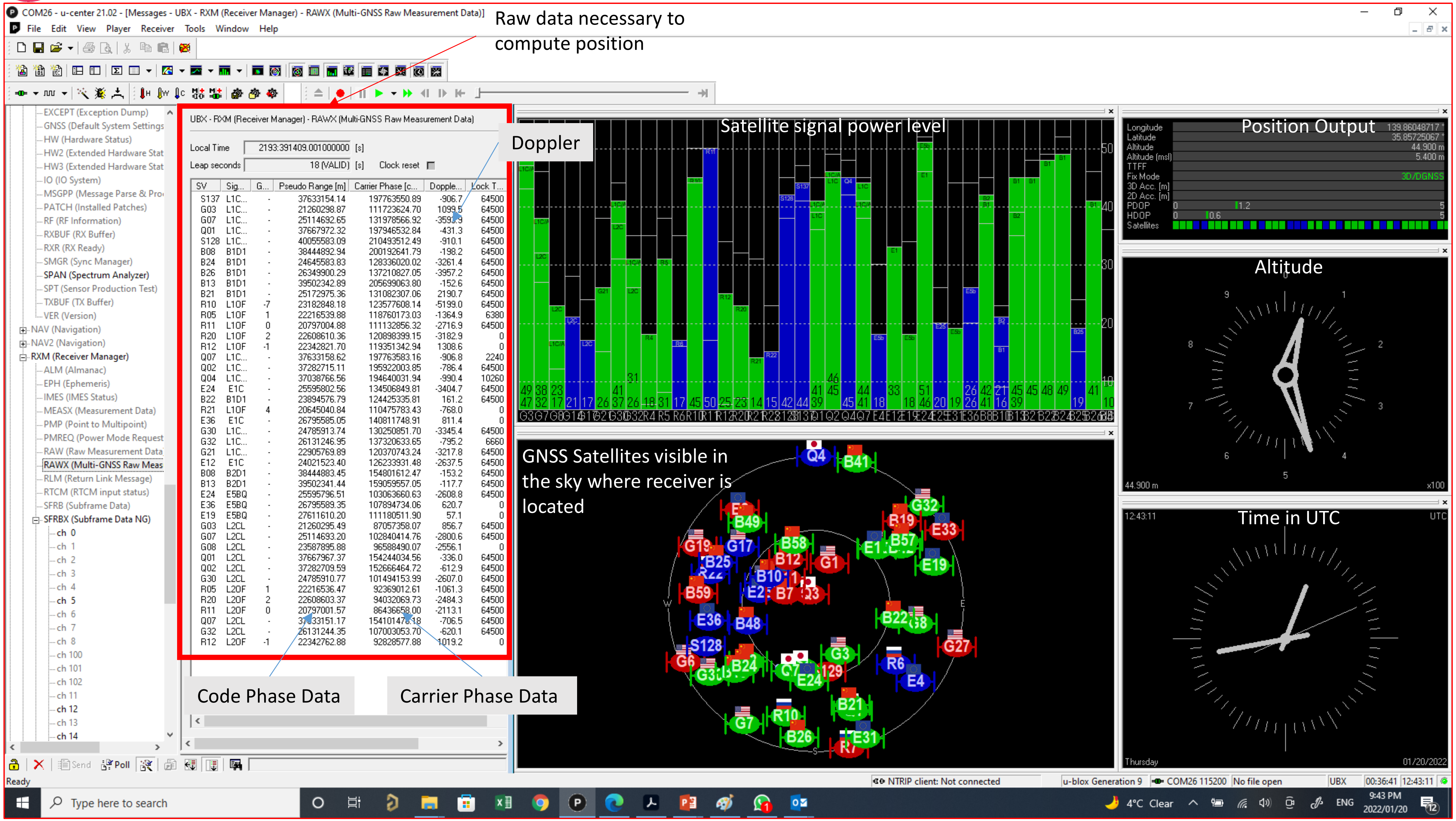
- A fix error and a variable error with respect to base-length is given
  - Such as : x cm + y ppm
  - Example: 2cm + 1ppm
    - There is a fix error of 2cm plus 1ppm error due to base-length between the Base and Rover
    - 1ppm → 1 parts per million
    - → 1cm of error in 1 million centimeter distance between the Base and the Rover
    - → 1cm of error in 1000000 centimeter distance between the Base and the Rover
    - → 1cm of error in 10000 meter distance between the Base and the Rover
    - → 1cm of error in 10 kilometer distance between the Base and the Rover
    - → **1cm of error for every 10Km of distance between the Base and the Rover**
    - → 4cm of error for 40Km of distance between the Base and the Rover
    - **Thus the total error is : 2cm + 4cm due to 40Km of base length**
  - The longer the base-length, the larger the error
    - Do not assume that this error is linear
    - And it may not be valid for longer base-lines
    - Normally the recommended base-length for RTK for a Geodetic Receiver is 40Km

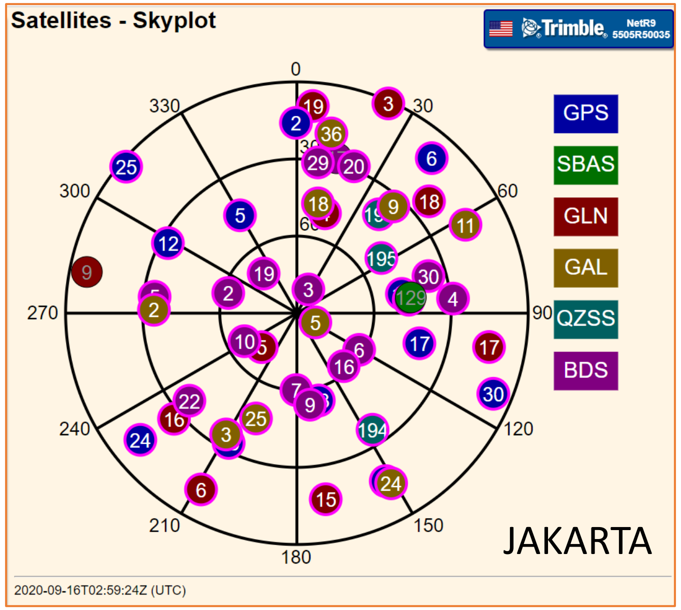
References

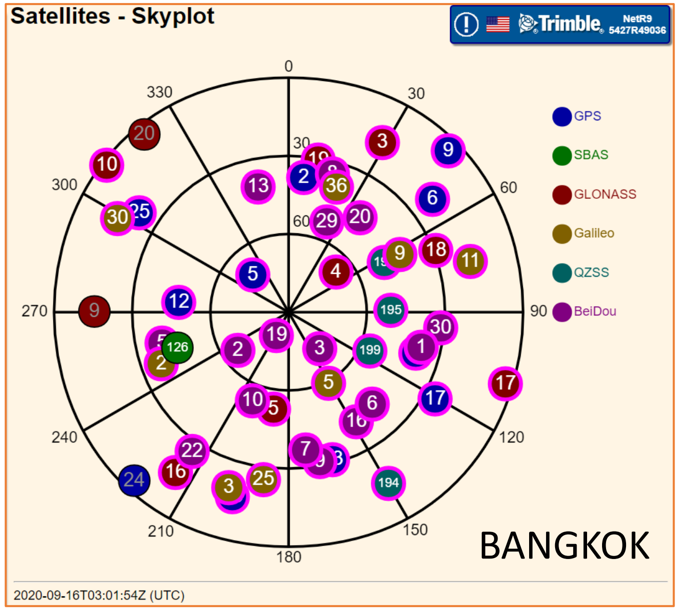

COM26 - u-center 21.02 - [Messages - UBX - CFG (Config) - GNSS (GNSS Config)]
GNSS Signals received by a receiver
UBX - CFG (Config) - GNSS (GNSS Config)
Satellite signal power level
Position Output
Altitude
GNSS Satellites visible in the sky where receiver is located
Time in UTC

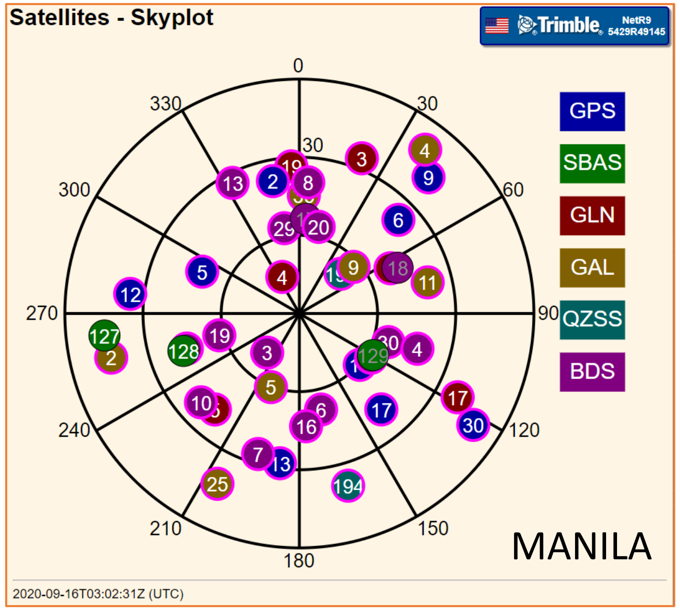
GNSS Signals received by a receiver

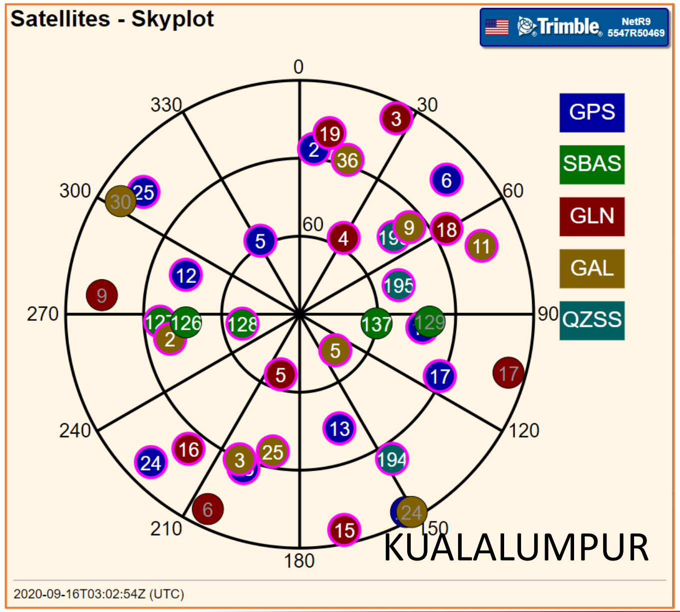


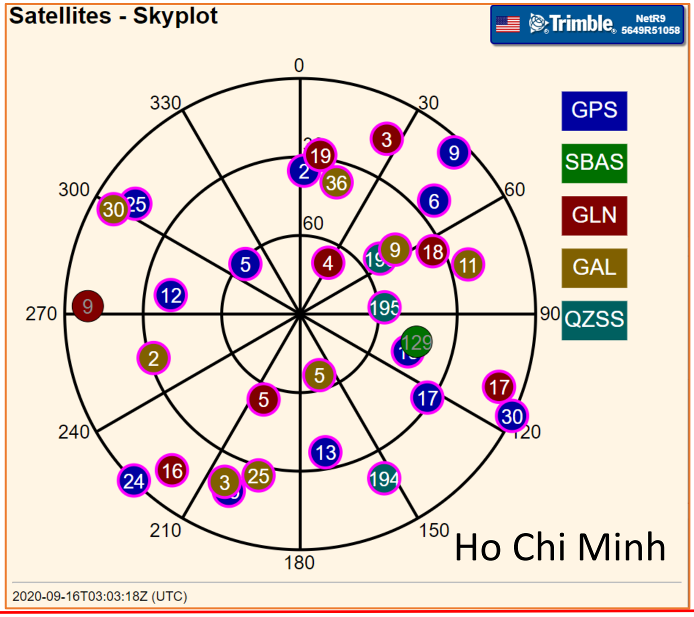

COM26 - u-center 21.02 - [Messages - UBX - RXM (Receiver Manager) - RAWX (Multi-GNSS Raw Measurement Data)]
Raw data necessary to compute position
UBX - RXM (Receiver Manager) - RAWX (Multi-GNSS Raw Measurement Data)
Doppler
Satellite signal power level
Position Output
Altitude
GNSS Satellites visible in the sky where receiver is located
Time in UTC
Code Phase Data
Carrier Phase Data

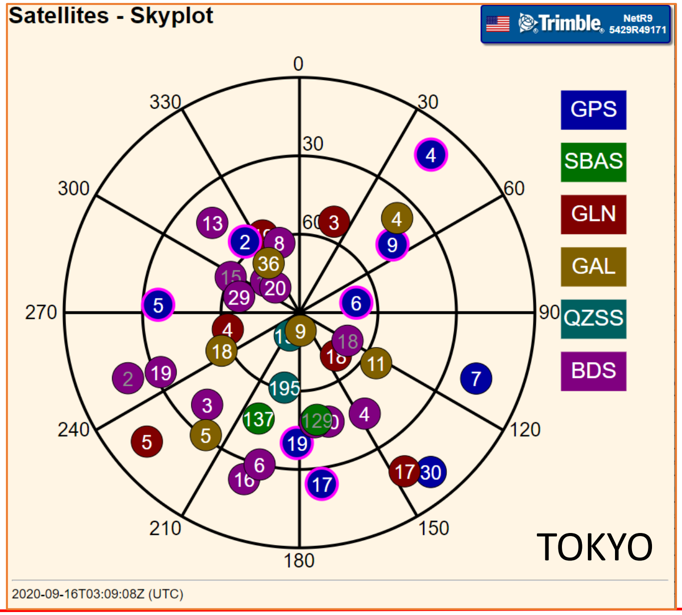








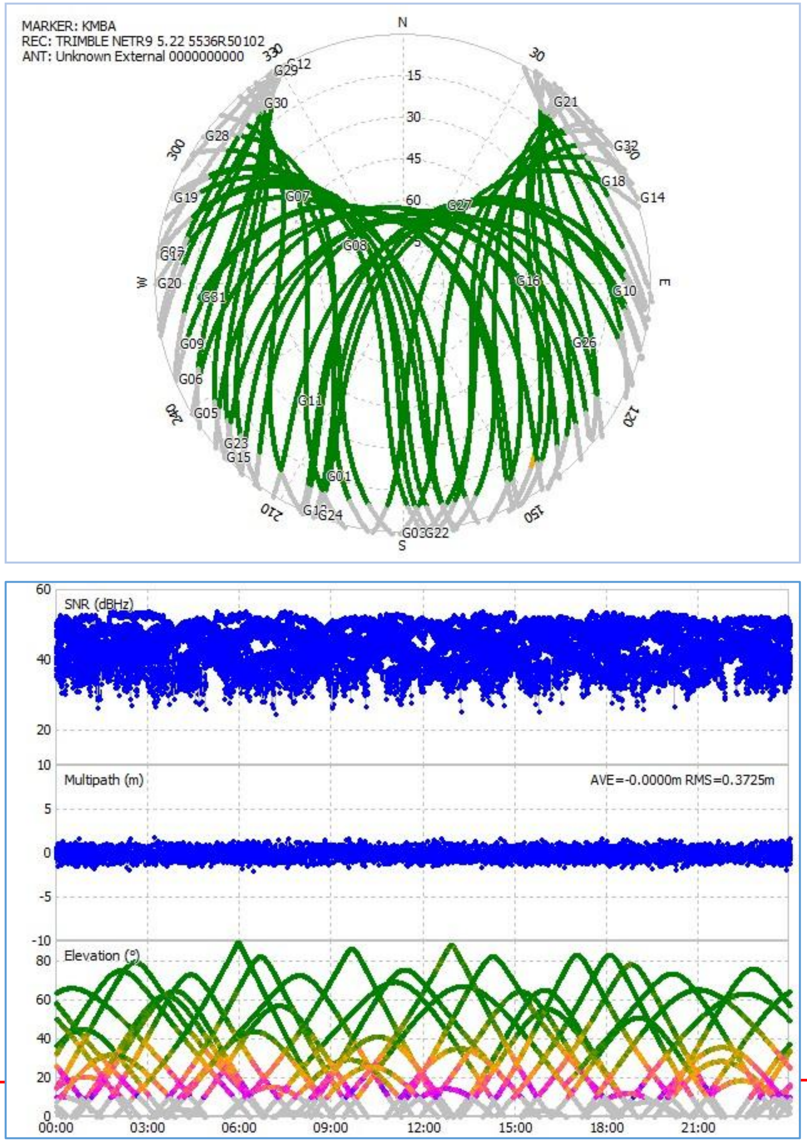




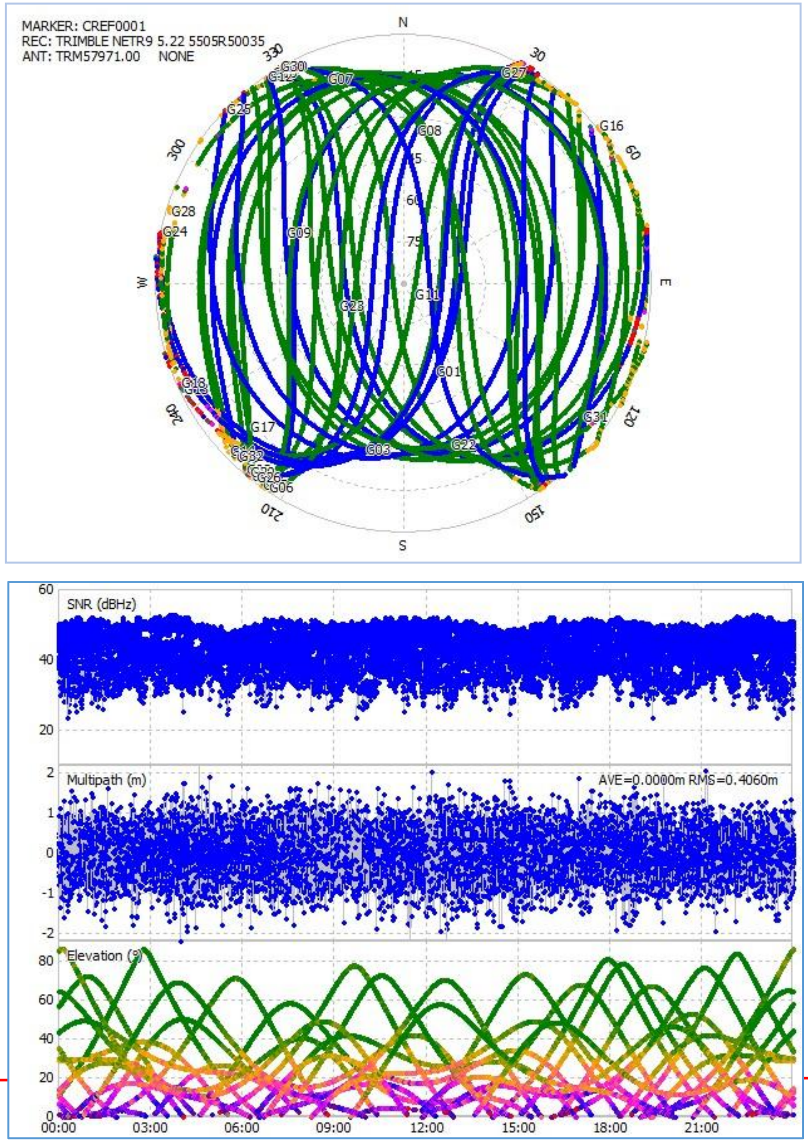
We do not have BeiDou data in Kualalumpur and Ho Chi Minh stations because of license limitation in the receiver

GPS Skyplots: Tokyo, Jakarta and Maputo

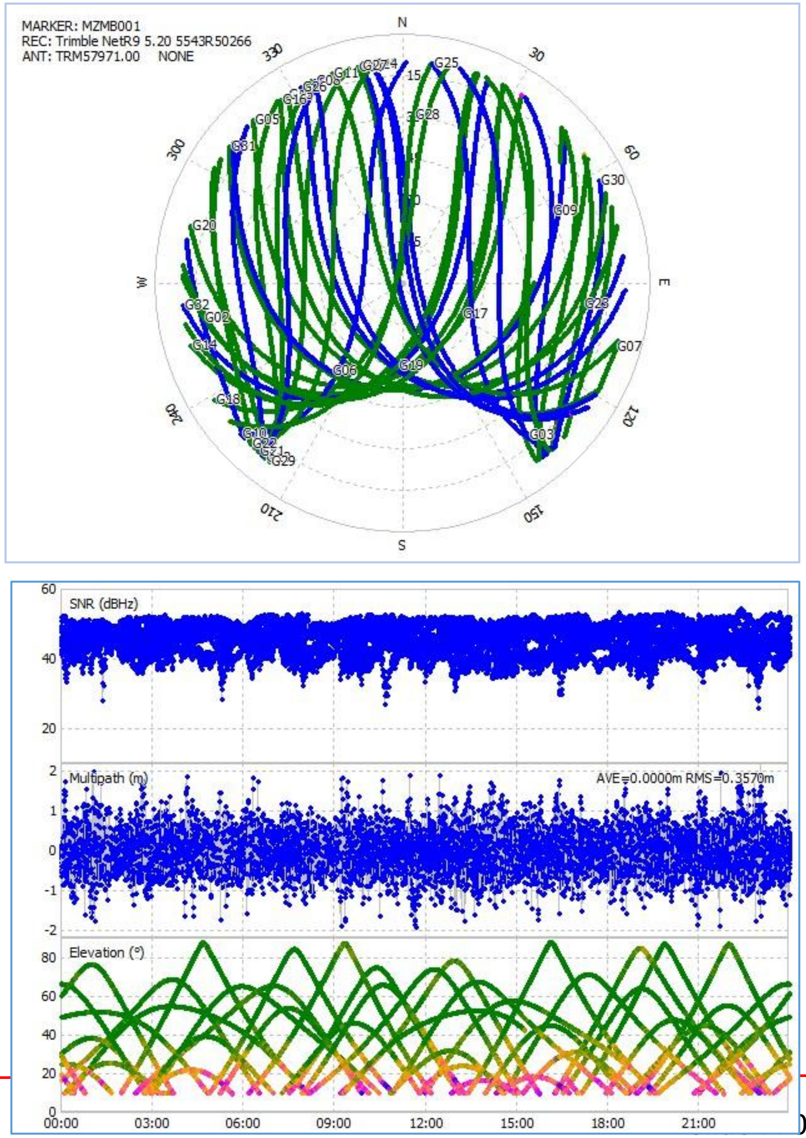
Tokyo Base-Station



Jakarta Base-Station

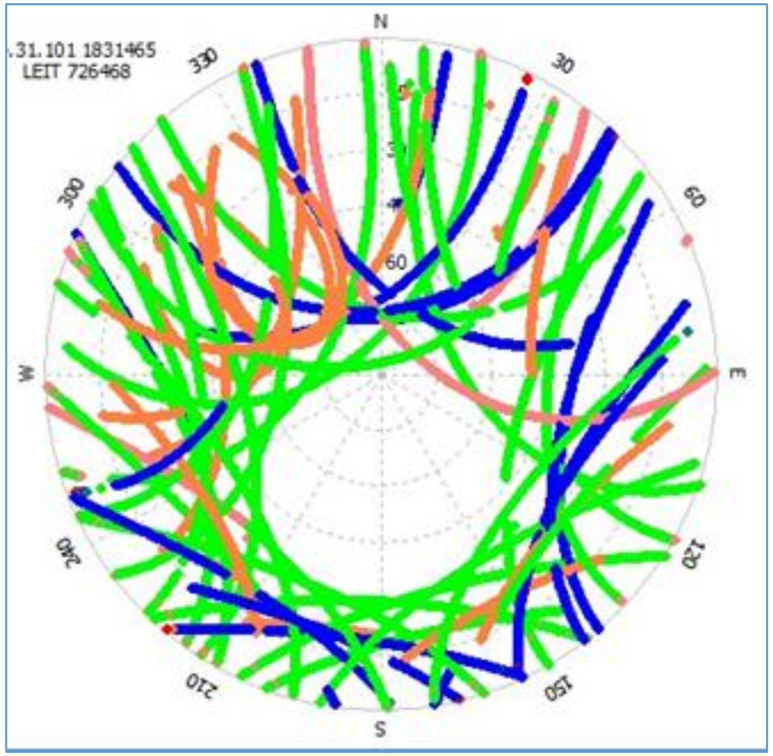


Maputo Base-Station

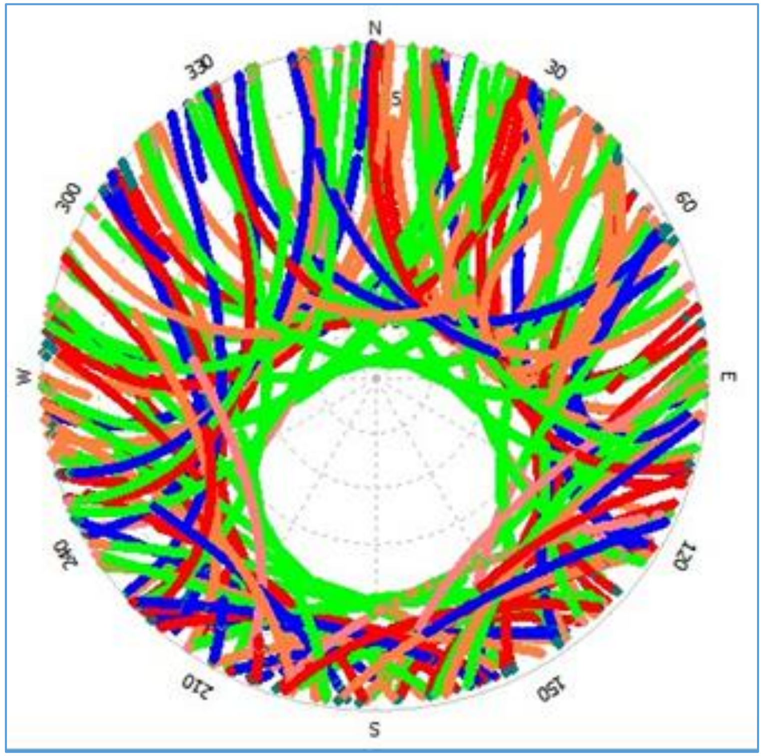


GNSS Signal Visibility: Skyplot

Antartica_DUMG00ATA



Antartica_MAW100ATA



Gabon_NKLG00GAB