UTokyo/ICG GNSS Training
3 – 6 January 2023

GNSS Introduction

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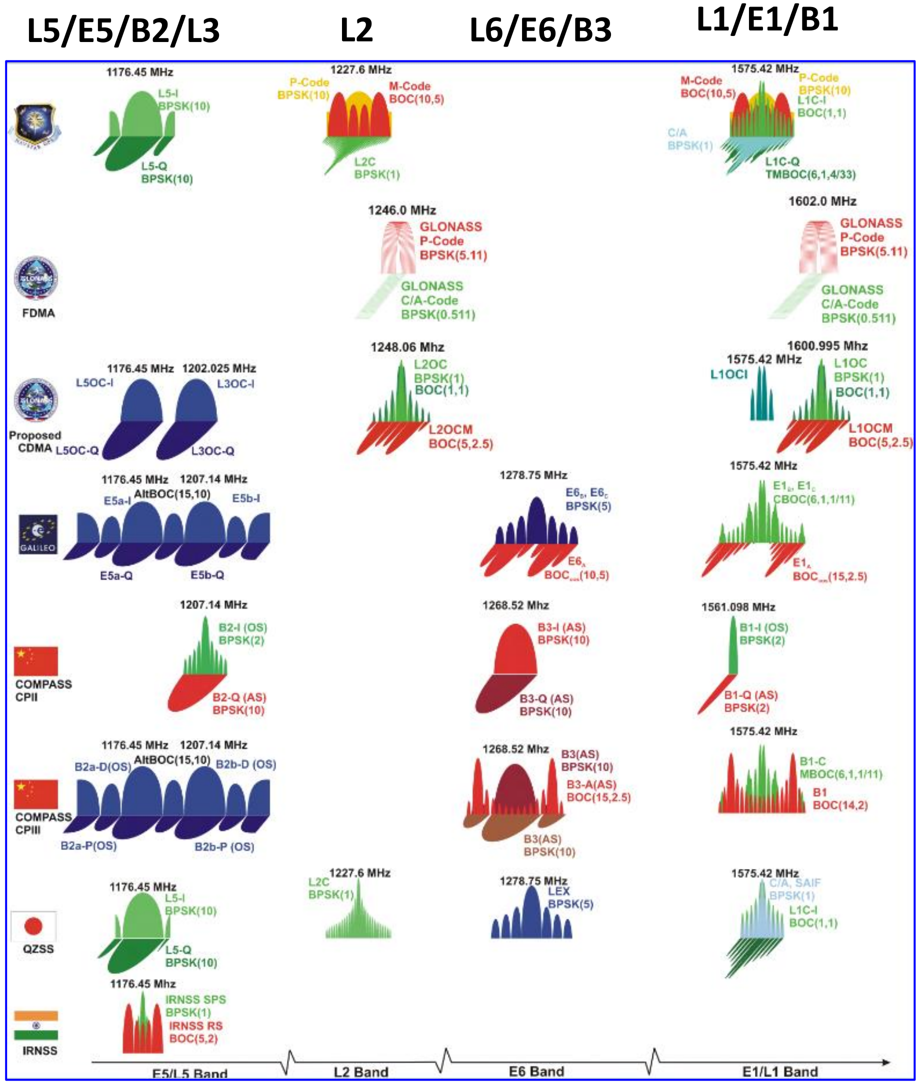
3 – 6 January 2023

What is GNSS?

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

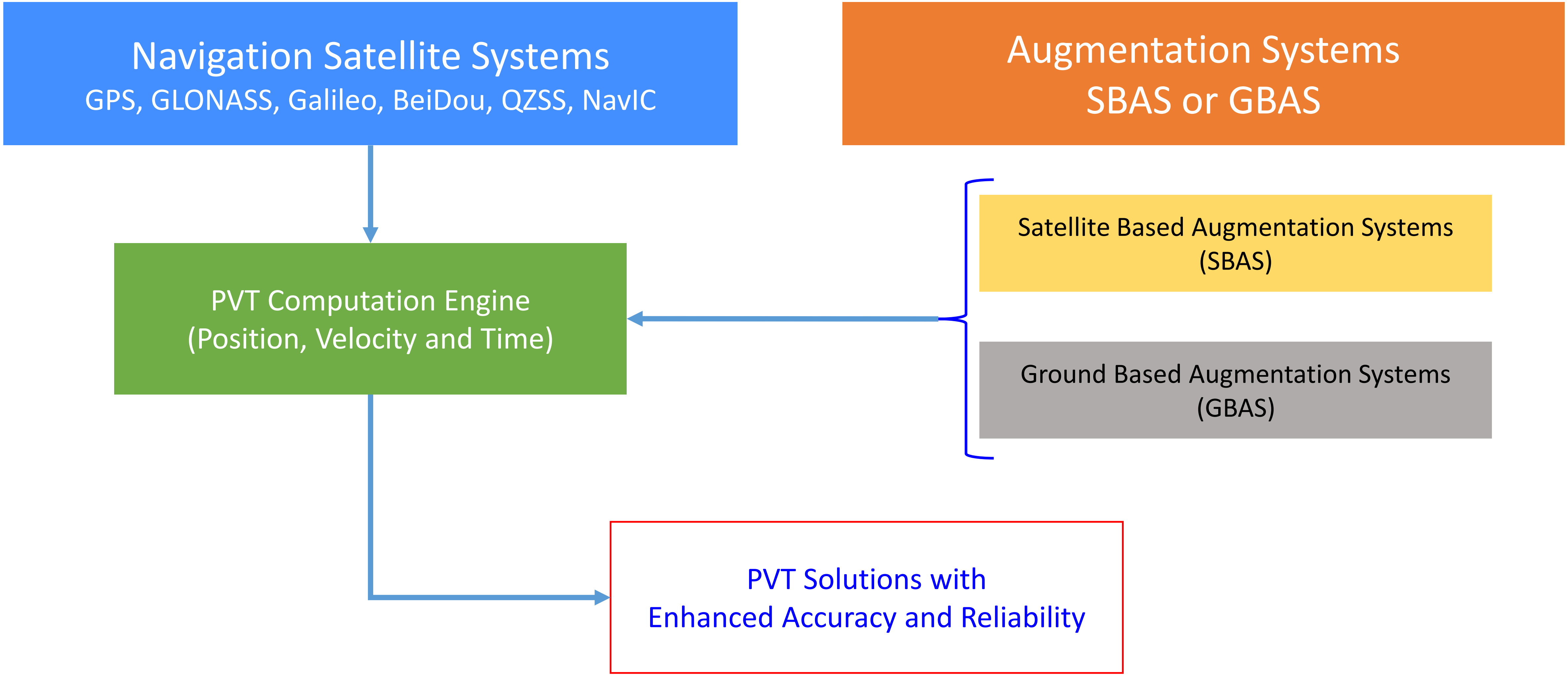
Satellite	Country	Coverage
GPS	USA	Global
GLONASS	Russia	Global
Galileo	Europe	Global
BeiDou (BDS)	China	Global
QZSS (Michibiki)	Japan	Regional
NavIC	India	Regional

- ✓ 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 Open and Restricted Signals
- ✓ All civilian signals are freely available
- ✓ Technical information for civilian signals are made public
  - ❖ Necessary to develop a receiver
  - ❖ Its called ICD (Interface Control Document) or IS (Interface Specification)



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

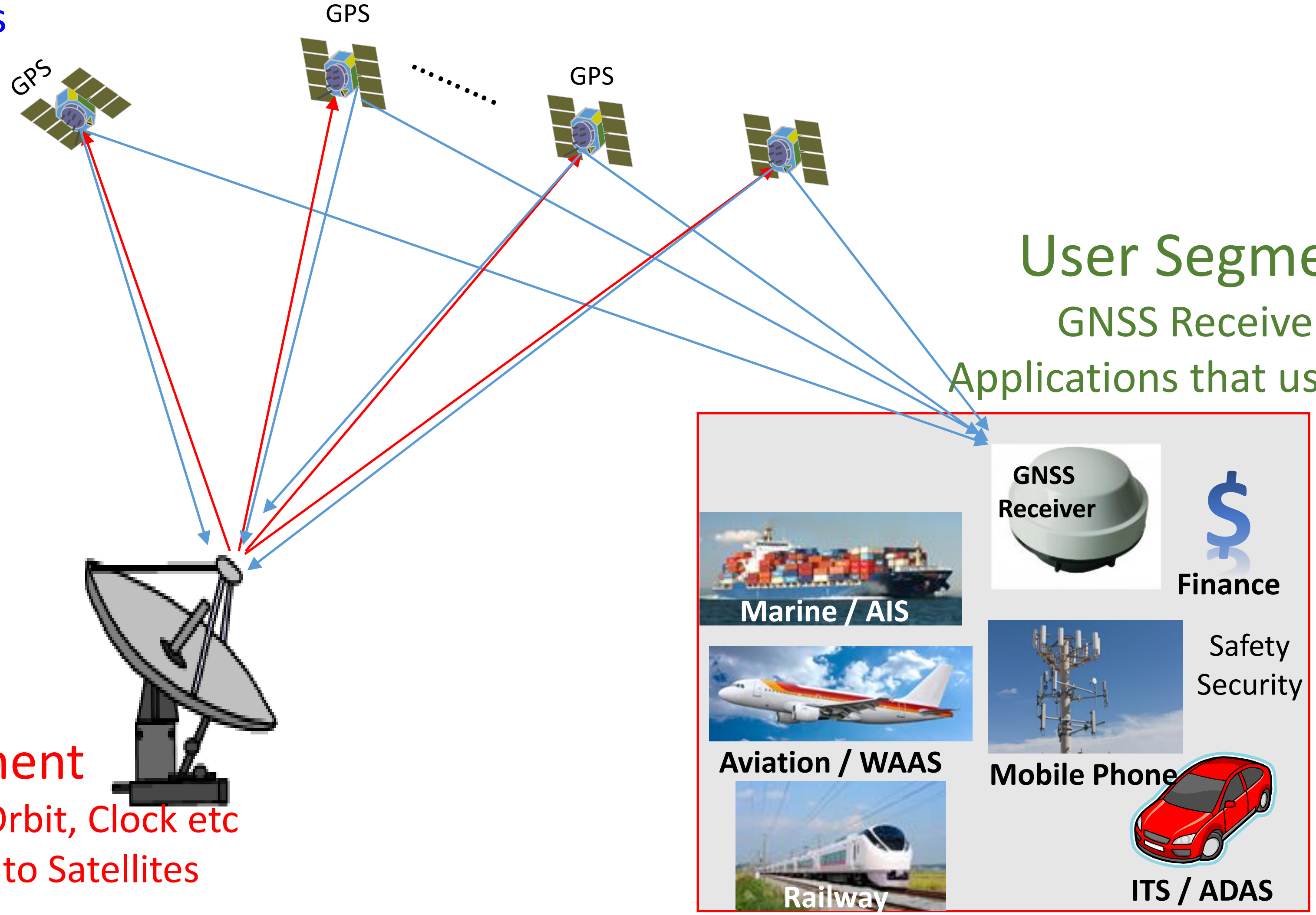
Systems Related with Navigation



GNSS System Architecture

Space Segment

GNSS Satellites



User Segment

GNSS Receivers

Applications that use GNSS

Control Segment

Monitor Satellite Health, Orbit, Clock etc

Upload Navigation Data to Satellites

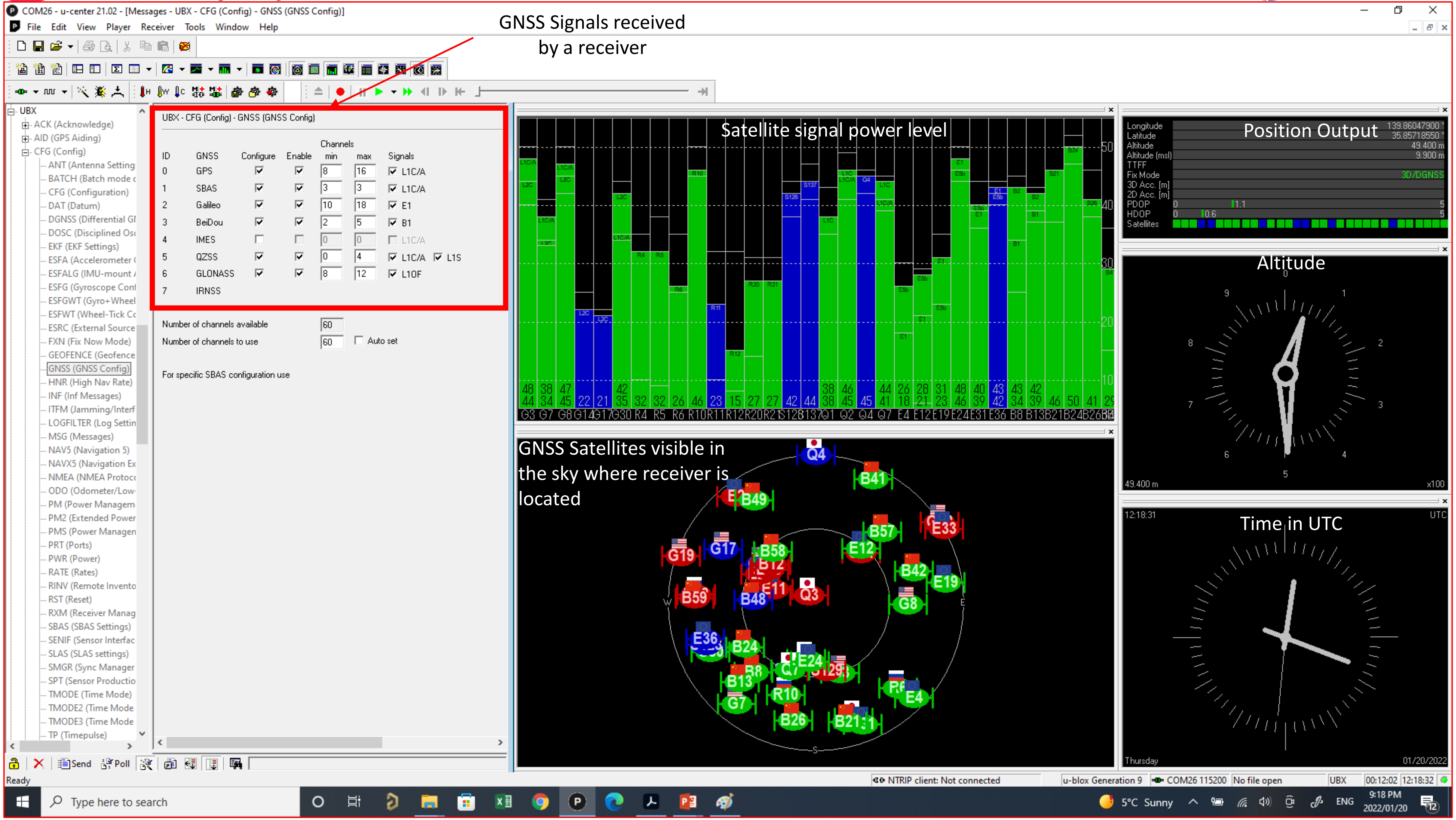
Satellite Based Augmentation System (SBAS)

- 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 KPS Navigation System
  - AUS-NZ, Australia (122)
  - Nigeria SBAS (ASCENA), (147)
  - ASAL, Algeria (148)

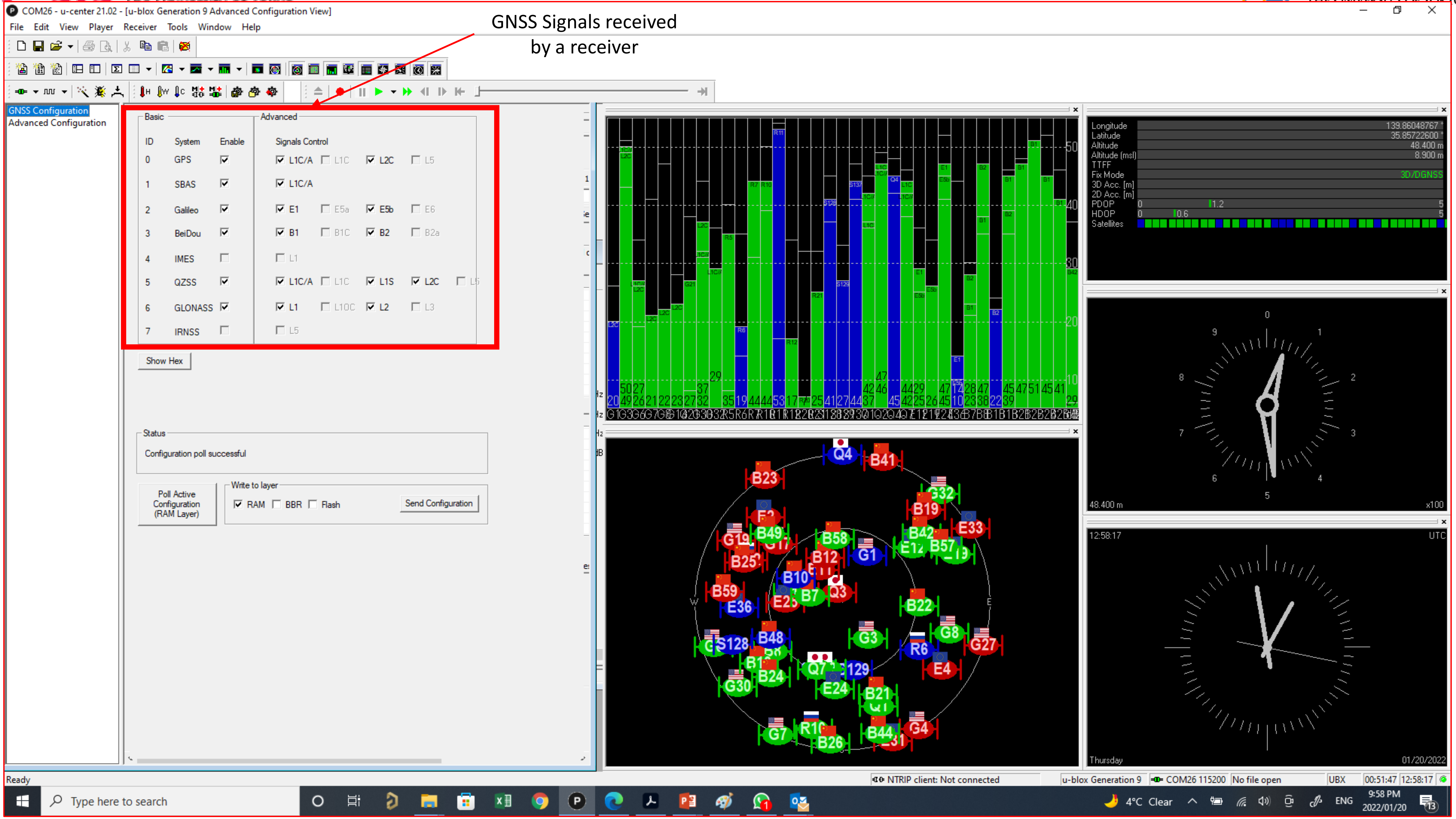
PRN code numbers are given in the bracket

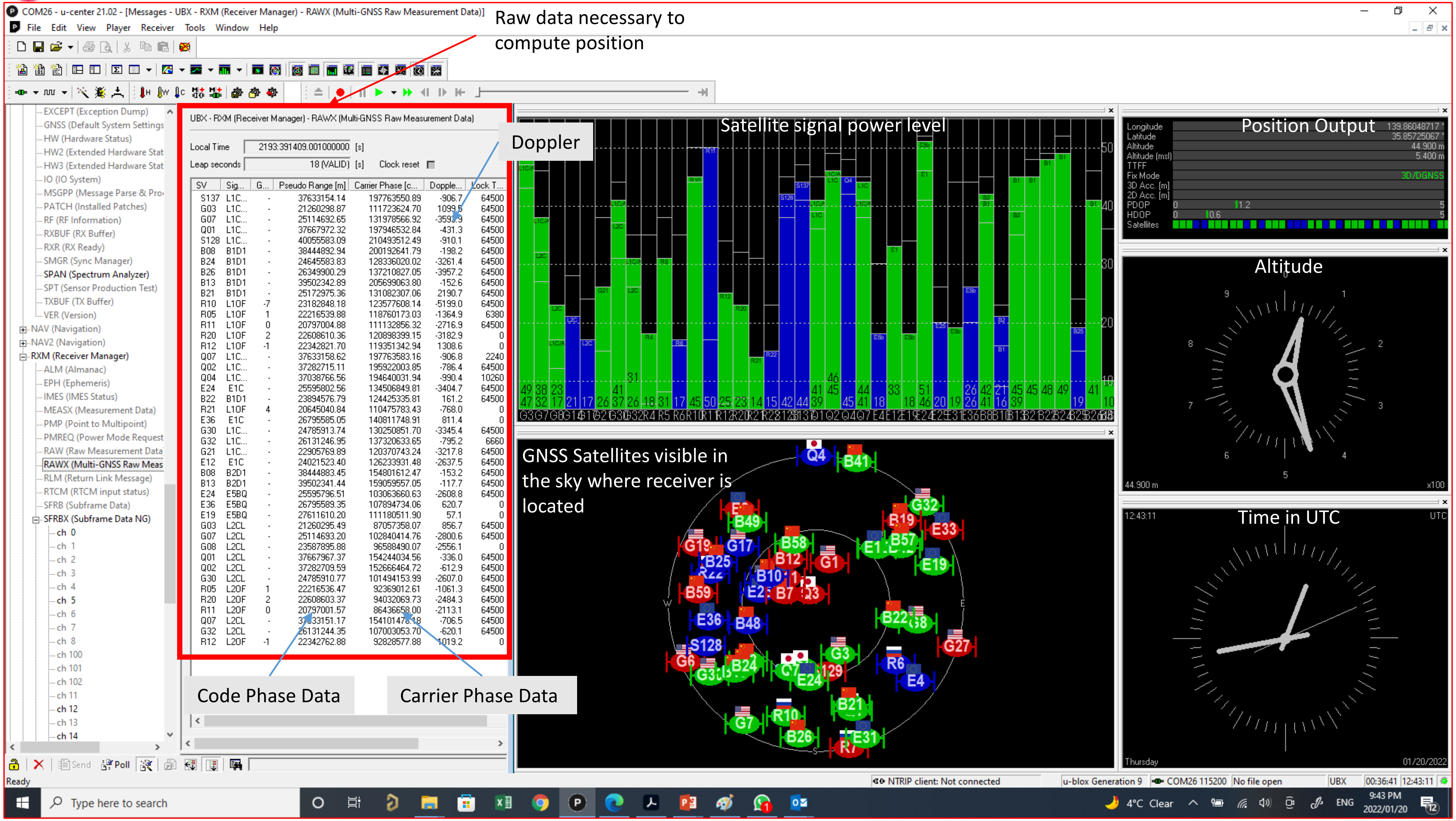
Satellite Based Augmentation System (SBAS)

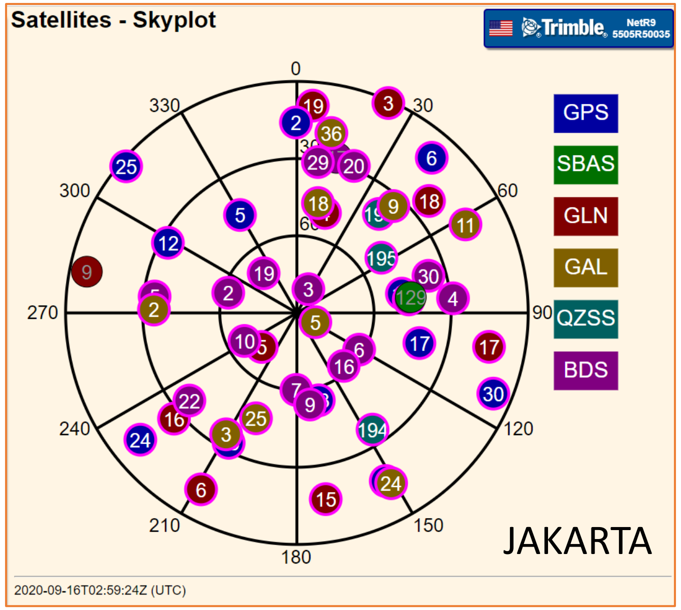
- Satellite Based Augmentation System (SBAS) are used to augment GNSS Data
  - Provide Higher Accuracy and Integrity
  - Correction data for satellite orbit errors, satellite clock errors, atmospheric correction data and satellite health status are broadcasted from Geo-stationary satellites
  - Used by ICAO for Aviation
- SBAS Service Providers
  - WAAS, USA
  - MSAS, Japan
  - EGNOS, Europe
  - GAGAN, India
  - SDCM, Russia
  - ASCENA SBAS
  - Korea (Also navigation system)
  - Australia

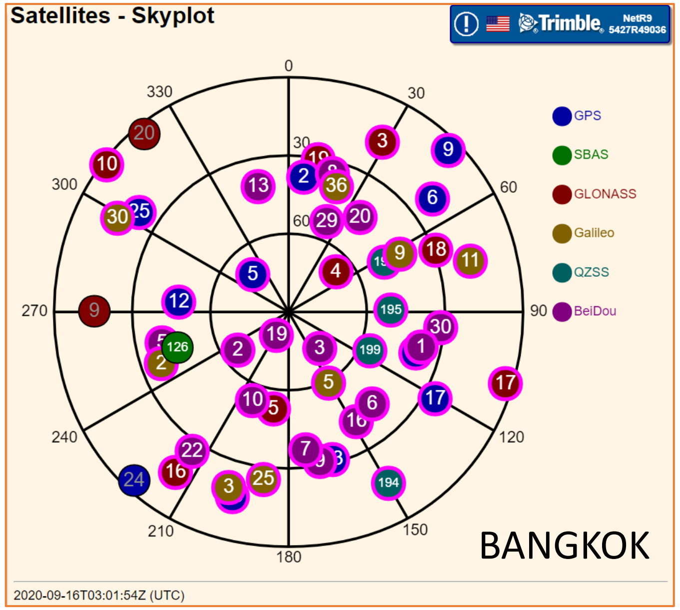

GNSS Signals received by a receiver
Satellite signal power level
Position Output
Altitude
Time in UTC
GNSS Satellites visible in the sky where receiver is located
UBX - CFG (Config) - GNSS (GNSS Config)
ID GNSS Configure Enable Channels min max Signals
0 GPS 8 16 L1C/A
1 SBAS 3 3 L1C/A
2 Galileo 10 18 E1
3 BeiDou 2 5 B1
4 IMES 0 0 L1C/A
5 QZSS 0 4 L1C/A L1S
6 GLONASS 8 12 L1OF
7 IRNSS
Number of channels available 60
Number of channels to use 60 Auto set
For specific SBAS configuration use

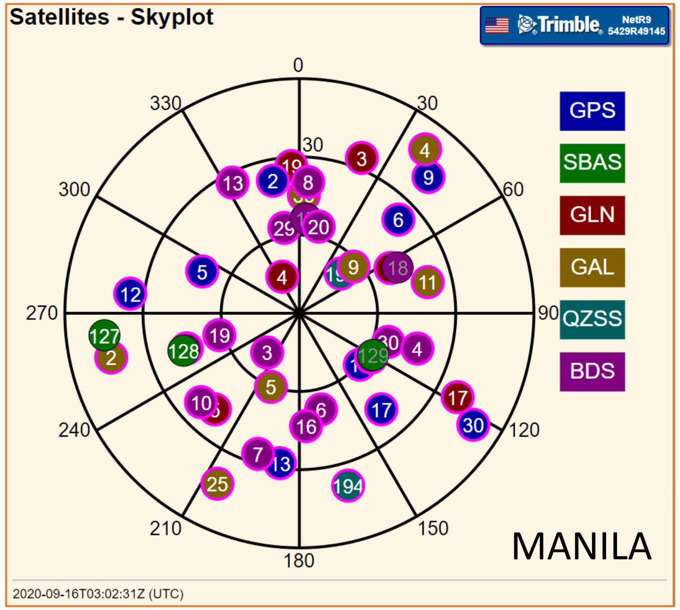
GNSS Signals received by a receiver

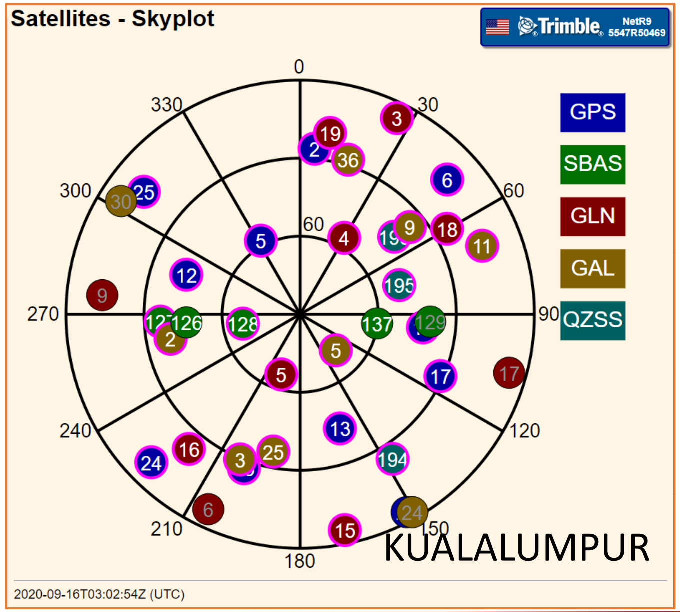


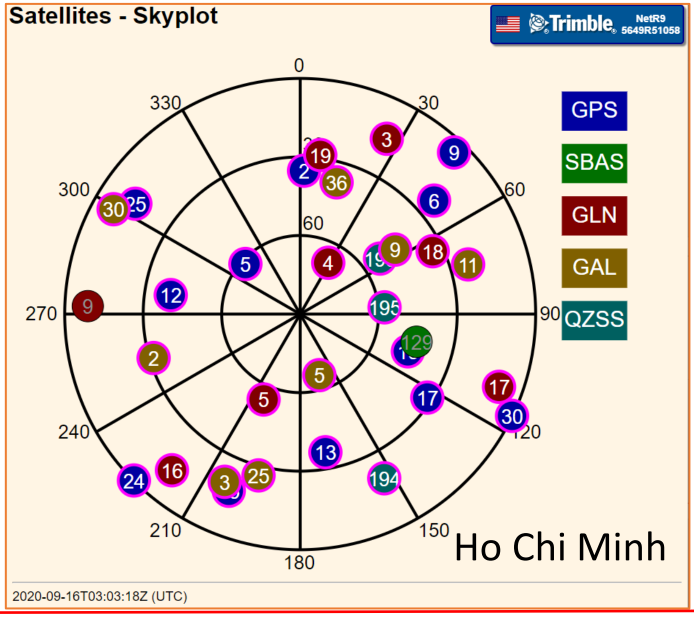

Raw data necessary to compute position
UBX - RXM (Receiver Manager) - RAWX (Multi-GNSS Raw Measurement Data)
Doppler
Satellite signal power level
Position Output
Altitude
GNSS Satellites visible in the sky where receiver is located
Time in UTC
Code Phase Data
Carrier Phase Data

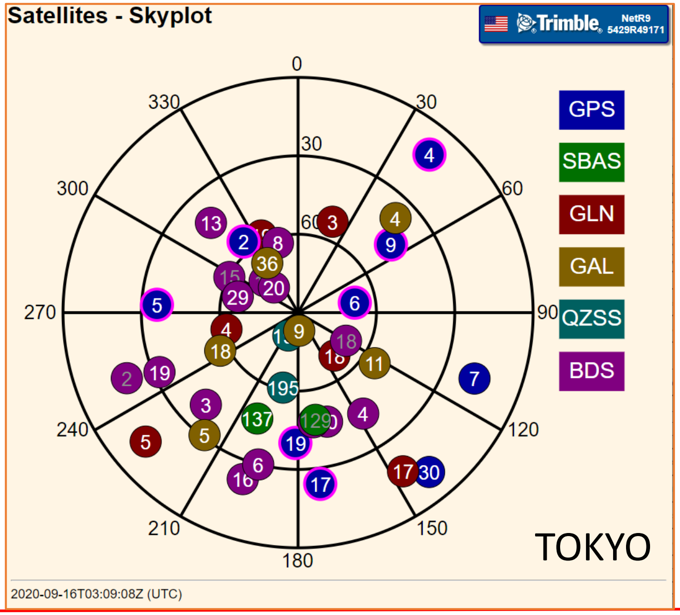












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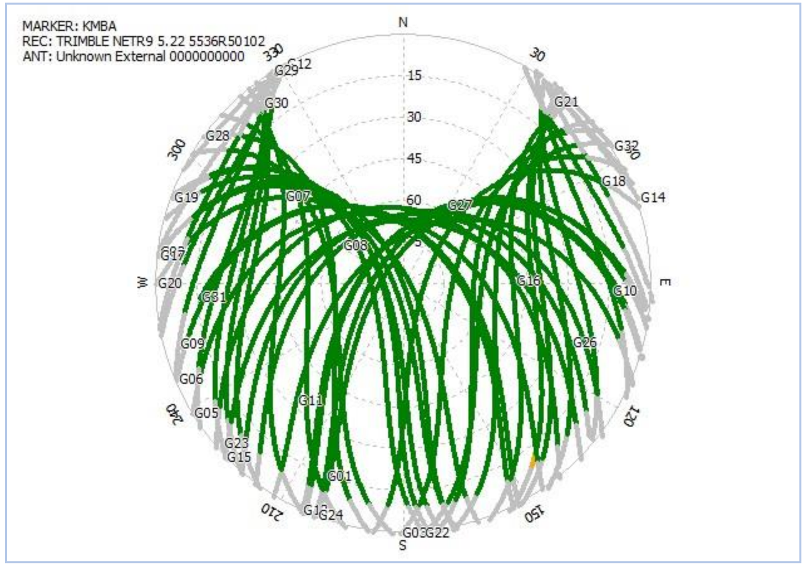
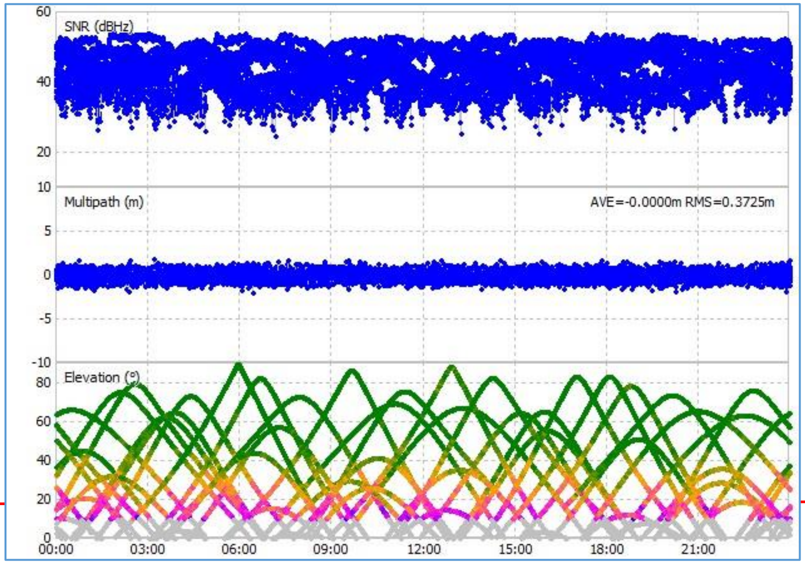
We do not have BeiDou data in Kualalumpur and Ho Chi Minh stations because of license limitation in the receiver

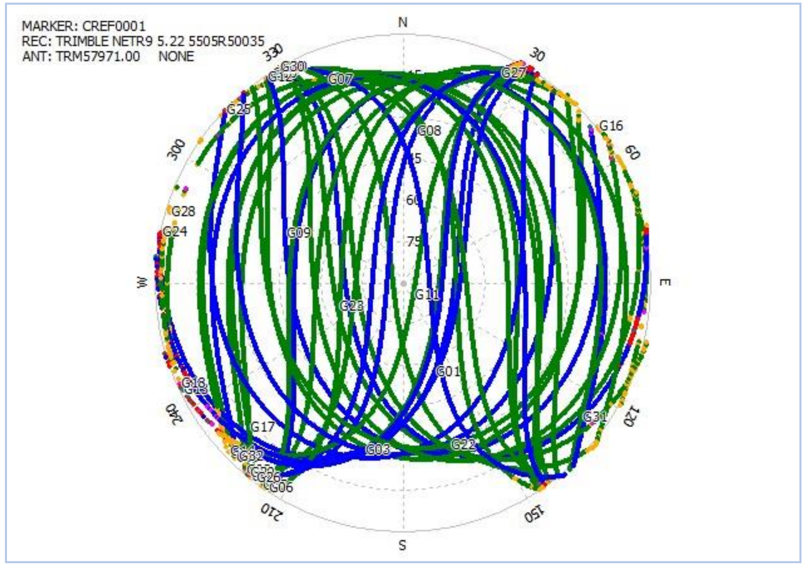
GPS Skyplots: Tokyo, Jakarta and Maputo

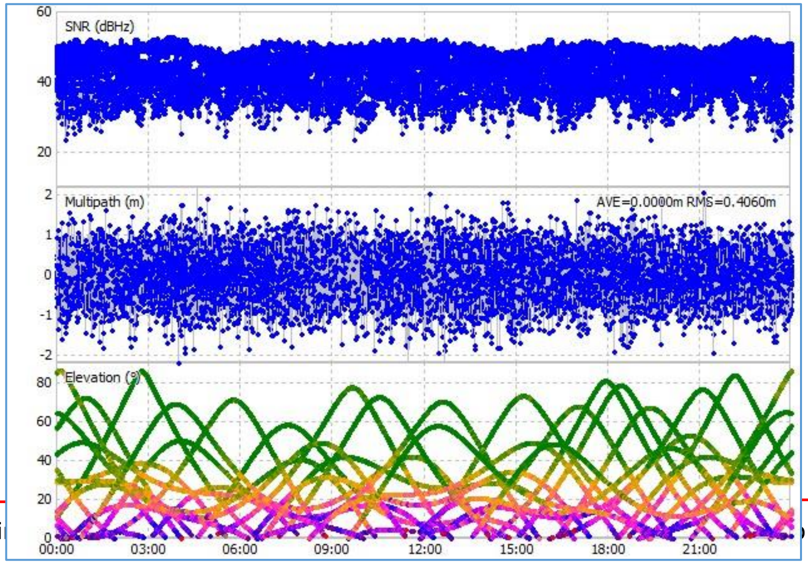
Tokyo Base-Station



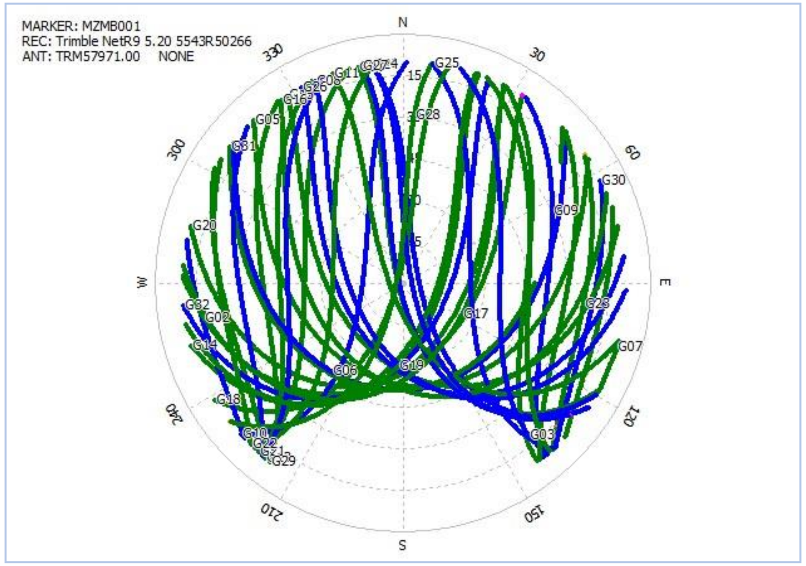


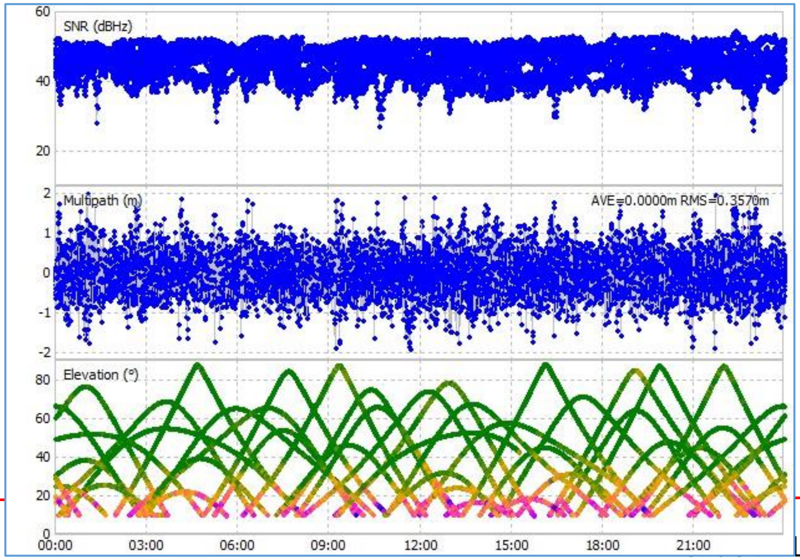
Jakarta Base-Station





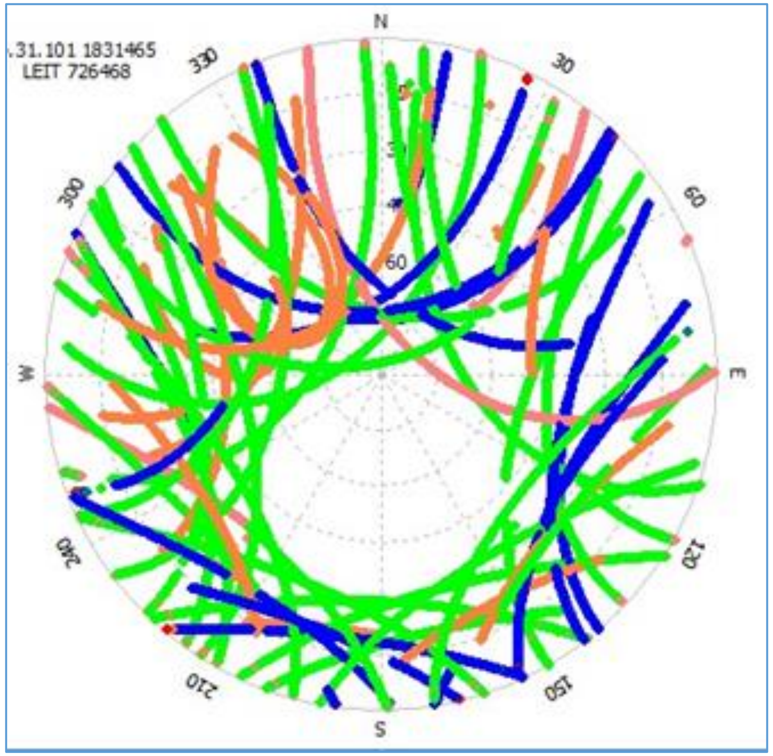
Maputo Base-Station



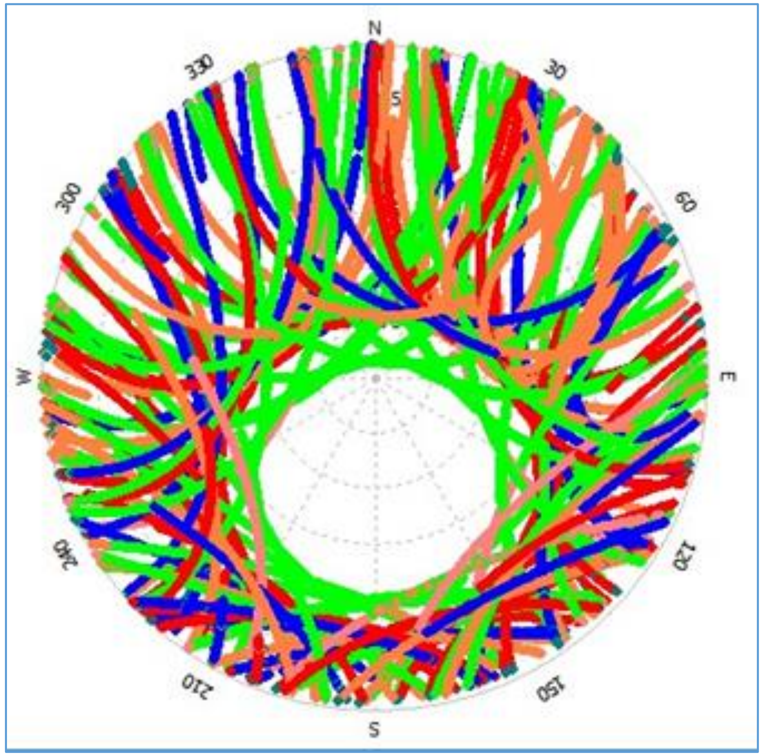


GNSS Signal Visibility: Skyplot

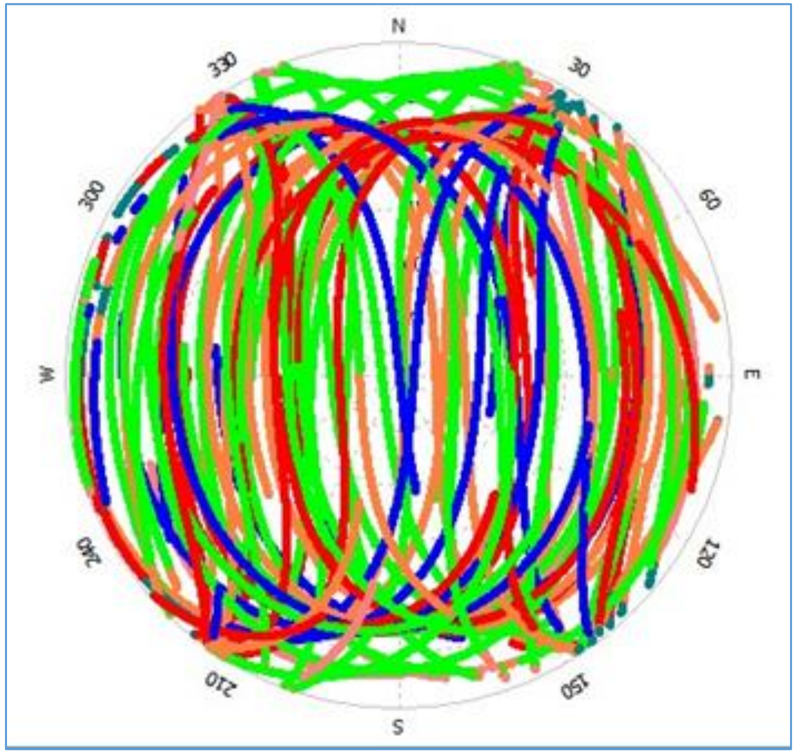
Antartica_DUMG00ATA



Antartica_MAW100ATA



Gabon_NKLG00GAB



GNSS Overview

Please refer the following link for detail information on each system's constellation, services and current status and future plans:

https://www.unoosa.org/oosa/en/ourwork/icg/meetings/icg-16/icg-annual-meeting-2022-presentations.html

GPS Constellation

37 Satellites • 31 Set Healthy
Baseline Constellation: 24 Satellites

Satellite Block	Quantity	Average Age (yrs)	Oldest
GPS IIR	12 (5*)	20.7	25.1
GPS IIR-M	8 (1*)	14.9	16.9
GPS IIF	12	8.6	12.3
GPS III	5	2.4	3.7

*Not set healthy

As of 27 Aug 22

GPS Signal in Space (SIS) Performance
Week ending on 3 Sept 22

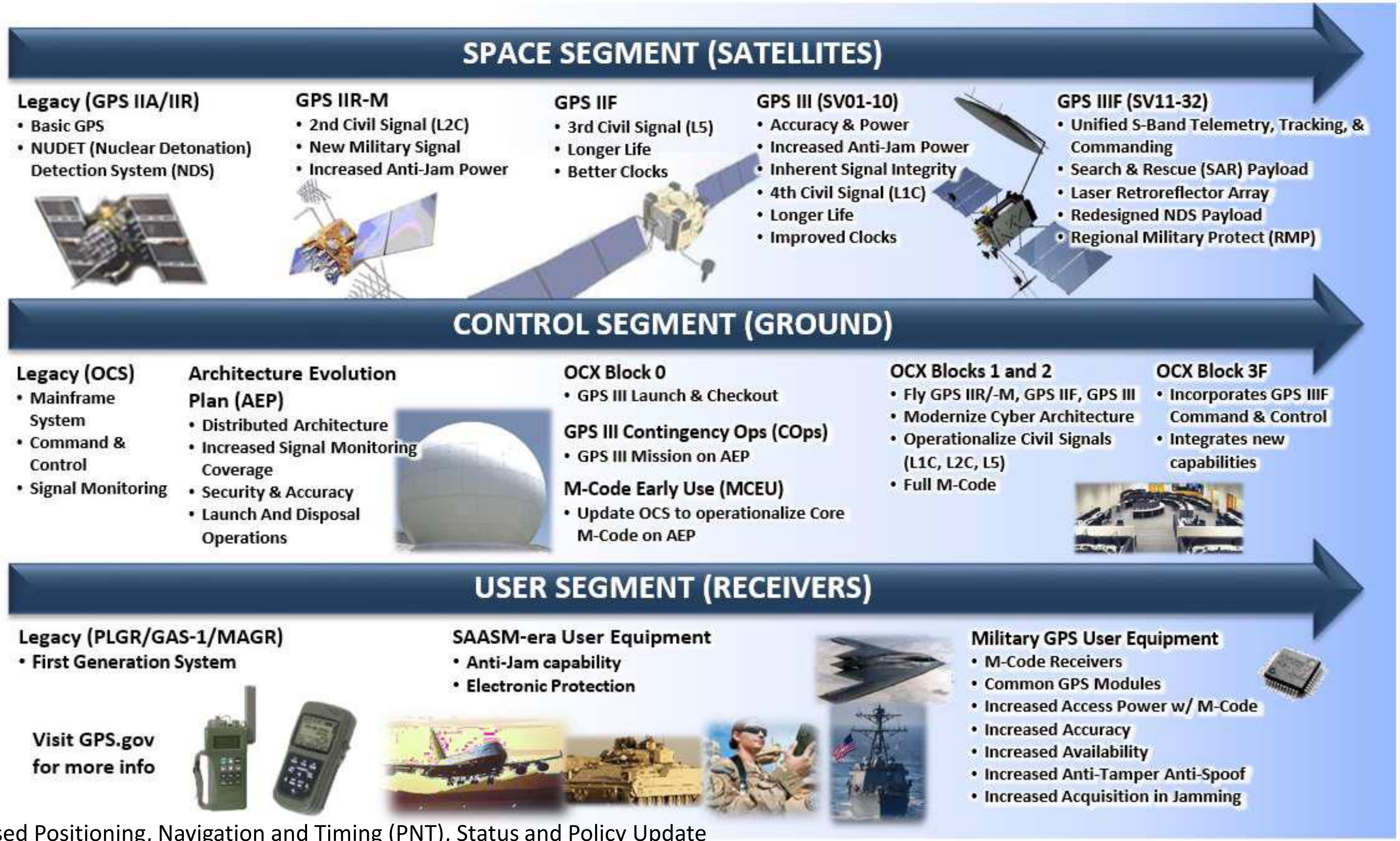
Average URE*	Best Day URE	Worst Day URE
49.1 cm	31.5 cm (20 Apr 21)	64.8 cm (20 May 22)

*All User Range Errors (UREs) are Root Mean Square values

Source: U.S. Space-Based Positioning, Navigation and Timing (PNT), Status and Policy Update
ICG16, 10 October 2022, Harold W. Martin III, Director, National Coordination Office

https://www.unoosa.org/documents/pdf/icg/2022/ICG16/01.pdf

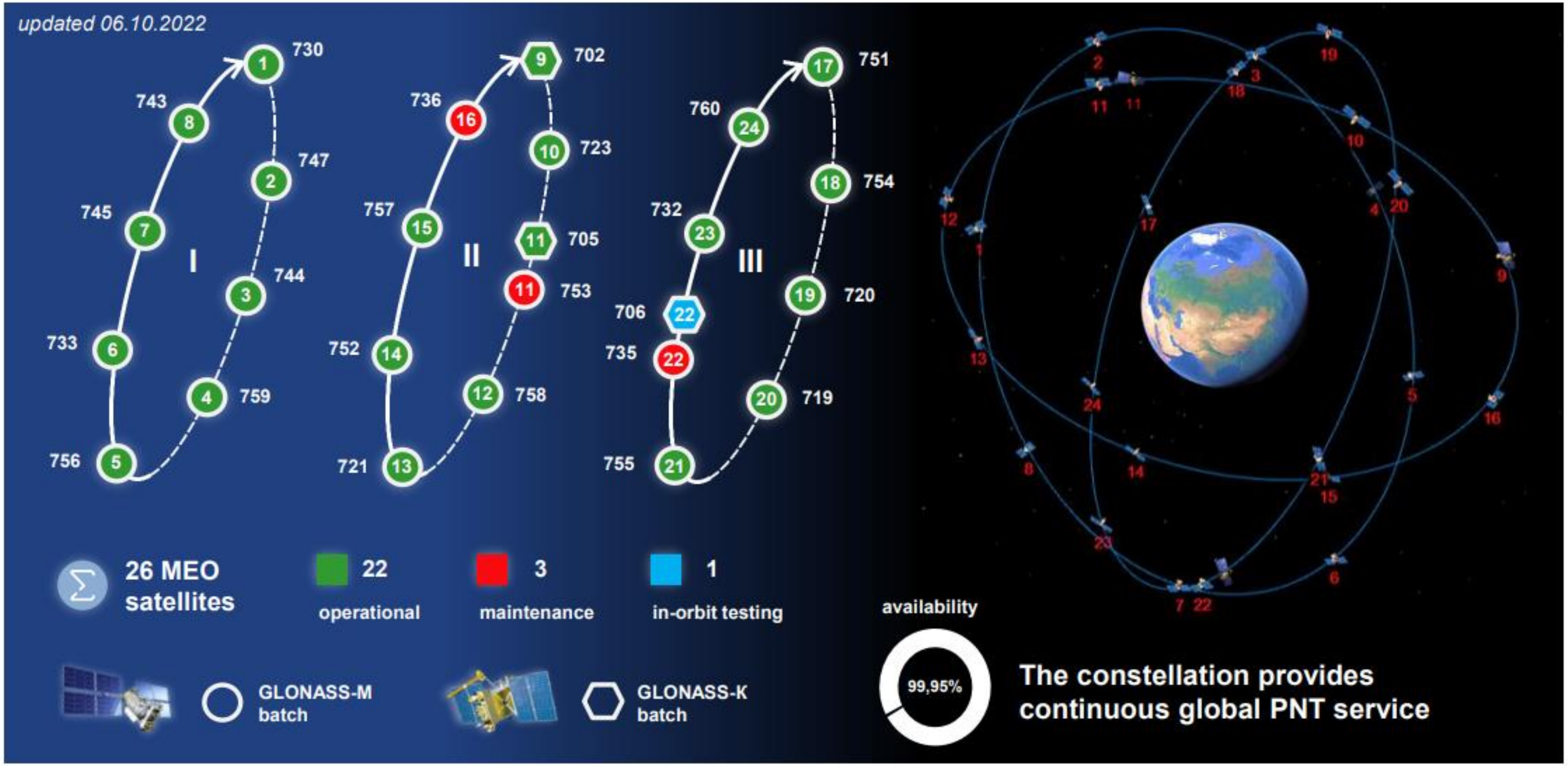
GPS Segments



Source: U.S. Space-Based Positioning, Navigation and Timing (PNT), Status and Policy Update
ICG16, 10 October 2022, Harold W. Martin III, Director, National Coordination Office

www.gps.gov

GLONASS Space Segment



Source: https://www.unoosa.org/documents/pdf/icg/2022/ICG16/02.pdf

GLONASS Constellation

GLONASS-K2 launch campaign

2022 – 2030

- By 2030 at least 12 MEO satellites will be operational
- broadcast of civil L1OC, L2OC, L3OC (CDMA) & L1OF, L2OF (FDMA) for backward receiver compatibility using a unified phased array antenna for all signals
- expected average SIS URE ~ 0.2 - 0.3 m
- expected clock stability ~ 5×10^{-15} due to new passive H-maser

Second and third generation constellation

GLONASS-K (3)
+ 7 satellites until 2025

GLONASS-M (23)
+ 1 satellite in 2023 or 2024

L3 capability

6 GLONASS-M & 10 GLONASS-K satellites in orbit will be capable to broadcast GLONASS L3OC CDMA signal by 2025

Ionospheric correction

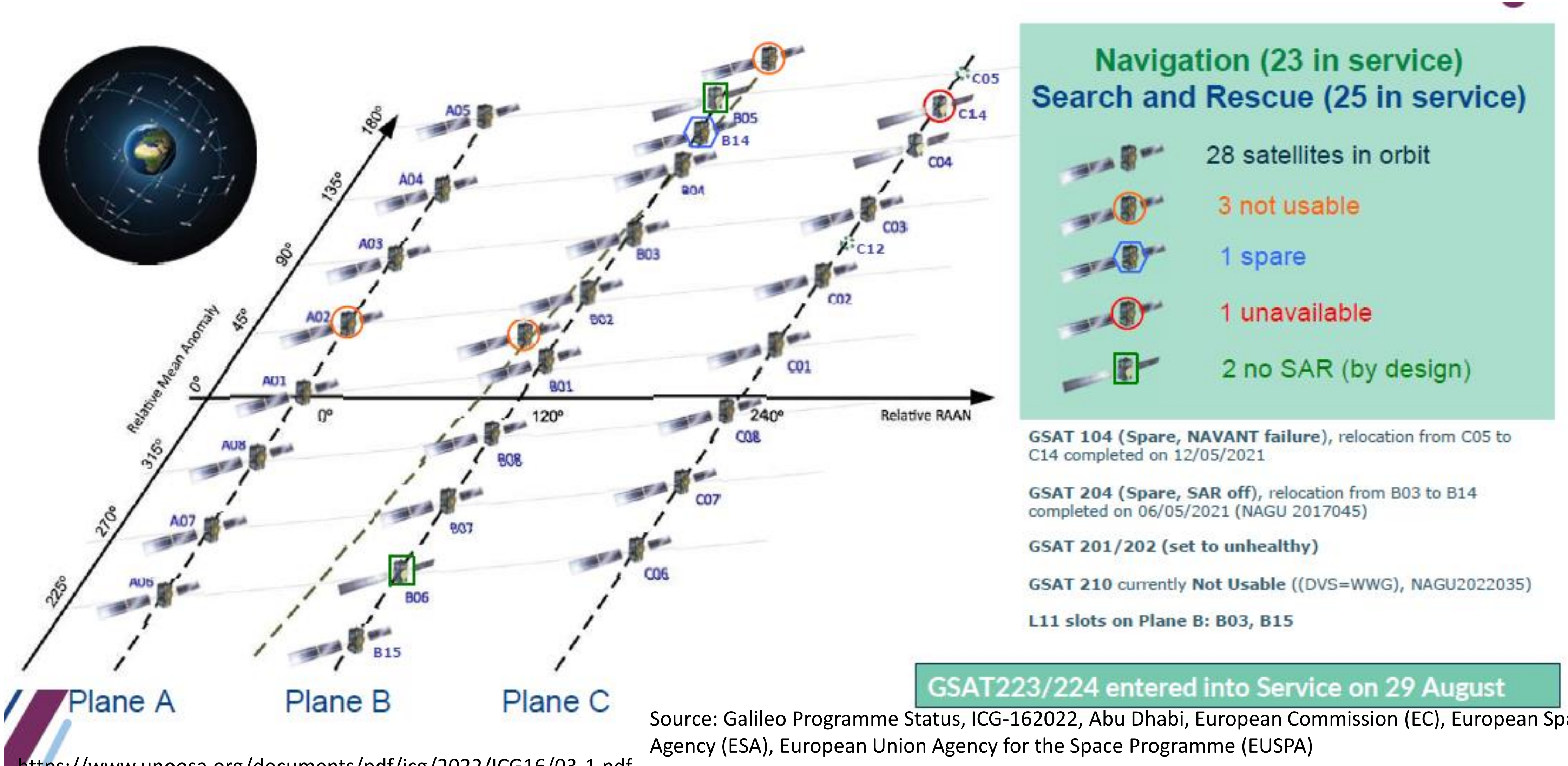
Global ionospheric model is already broadcast via L3OC signal (in accordance with ICD) and will be broadcast L1OF & L2OF signals after its introduction to their ICD

Payloads

5 GLONASS-K satellites will carry COSPAS-SARSAT payload

Source: https://www.unoosa.org/documents/pdf/icg/2022/ICG16/02.pdf

Galileo Constellation



GSAT 104 (Spare, NAVANT failure), relocation from C05 to C14 completed on 12/05/2021

GSAT 204 (Spare, SAR off), relocation from B03 to B14 completed on 06/05/2021 (NAGU 2017045)

GSAT 201/202 (set to unhealthy)

GSAT 210 currently **Not Usable** ((DVS=WWG), NAGU2022035)

L11 slots on Plane B: B03, B15

GSAT223/224 entered into Service on 29 August

Source: Galileo Programme Status, ICG-162022, Abu Dhabi, European Commission (EC), European Space Agency (ESA), European Union Agency for the Space Programme (EUSPA)

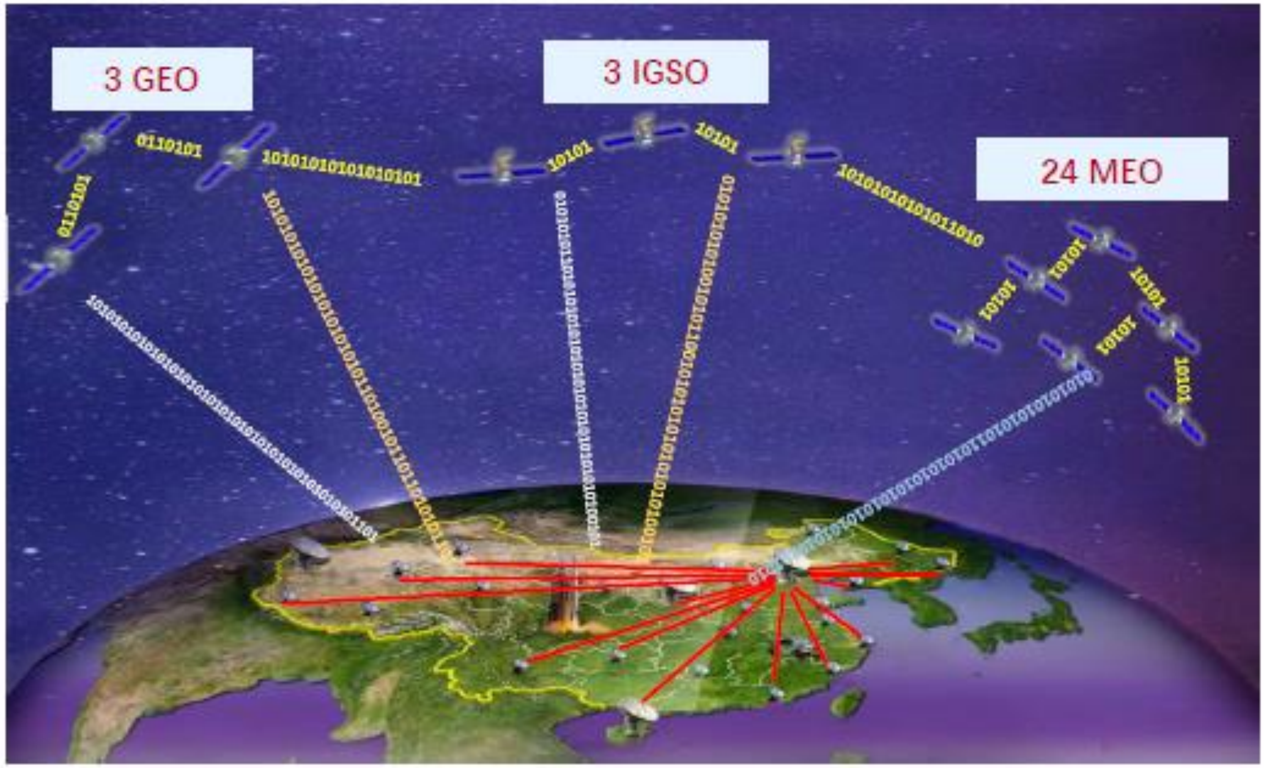
https://www.unoosa.org/documents/pdf/icg/2022/ICG16/03-1.pdf

Galileo Services

- **Open Service (OS)**:
  - Galileo open and free of charge service set up for positioning and timing services.
- **Open Service Navigation Message Authentication (OSNMA)**:
  - Free access service complementing the OS by delivering authenticated data, assuring users that the received Galileo navigation message is coming from the system itself and has not been modified.
- **High Accuracy Service (HAS)**:
  - A service complementing the OS by providing an additional navigation signal and added-value services in a different frequency band. The HAS signal can be encrypted in order to control the access to the Galileo HAS services.
- **Public Regulated Service (PRS)**:
  - Service restricted to government-authorised users, for sensitive applications that require a high level of service continuity.
- **Search and Rescue Service (SAR)**:
  - Europe's contribution to COSPAS-SARSAT, an international satellite-based search and rescue distress alert detection system.
- **Commercial Authentication Service (CAS)**:
  - A service complementing the OS, providing a controlled access and authentication function to users.

Source: https://www.euspa.europa.eu/galileo/services

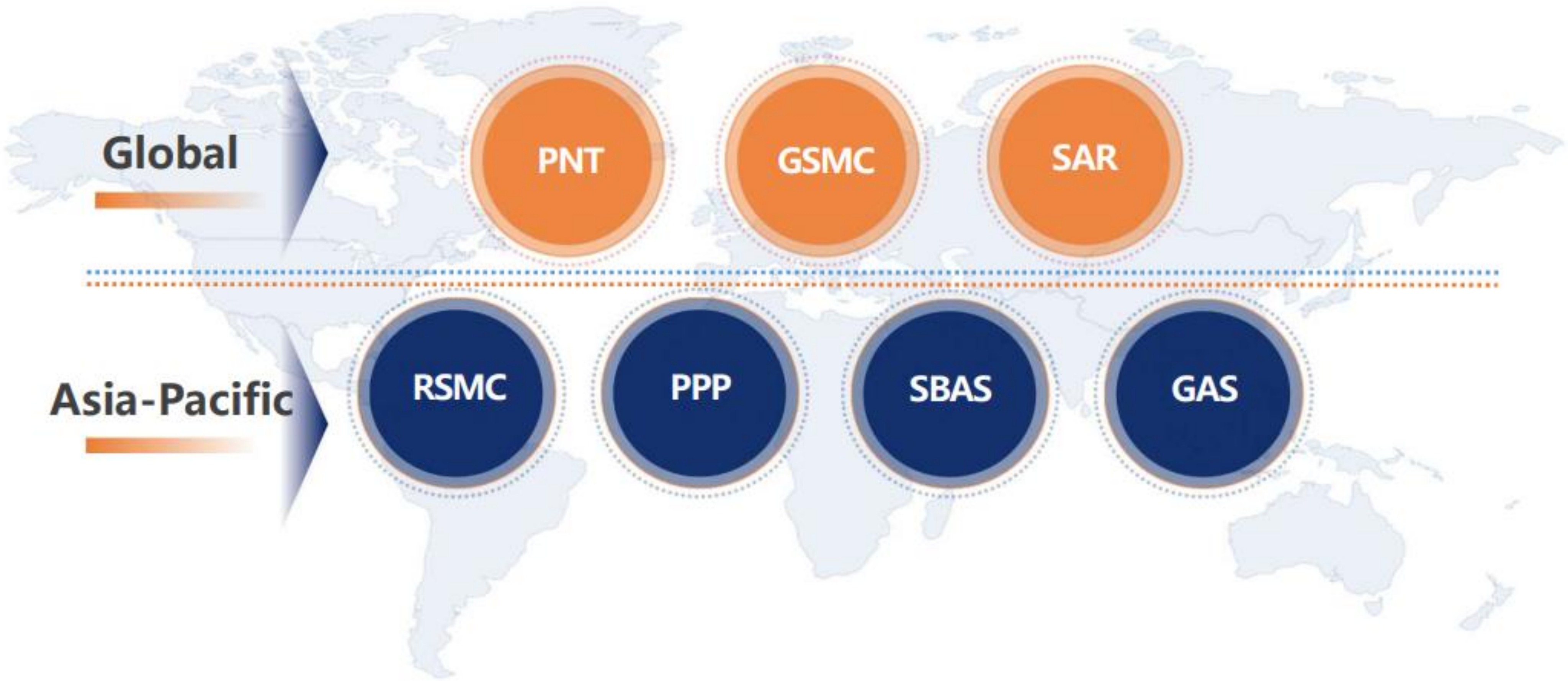
BeiDou System and Constellation



- BDS is mainly comprised of three segments: Space Segment, Ground Segment, User Segment.
- Up to now, BDS-3 constellation consists of 3 GEO satellites, 3 IGSO satellites, and 24 MEO satellites.

Source:
BeiDou Navigation Satellite System Construction and Development, 16th Meeting of the International Committee on Global Navigation Satellite Systems, LI Zuohu, China Satellite Navigation Office, Oct. 10, 2022
http://en.beidou.gov.cn

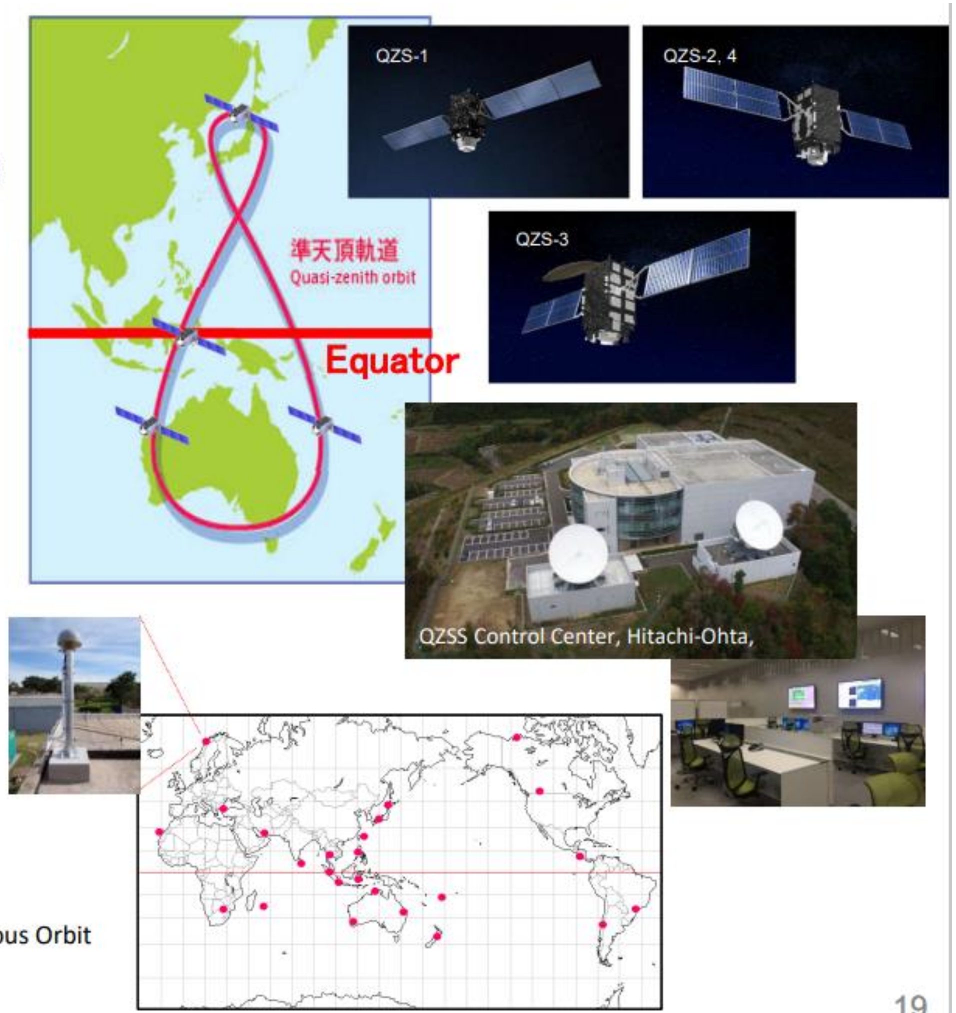
BeiDou System Services



https://www.unoosa.org/documents/pdf/icg/2022/ICG16/04.pdf

QZSS Overview

- ***Constellation:***
  - One GEO satellite, QZS-3, 127E Longitude
  - Three QZO satellites (IGSO*)
- ***Ground System***
  - Two master control centers
    - Hitachi-Ota and Kobe
  - Seven TTC Stations
    - Located south-western islands
  - Over 30 monitor stations around the world with the cooperation of countries



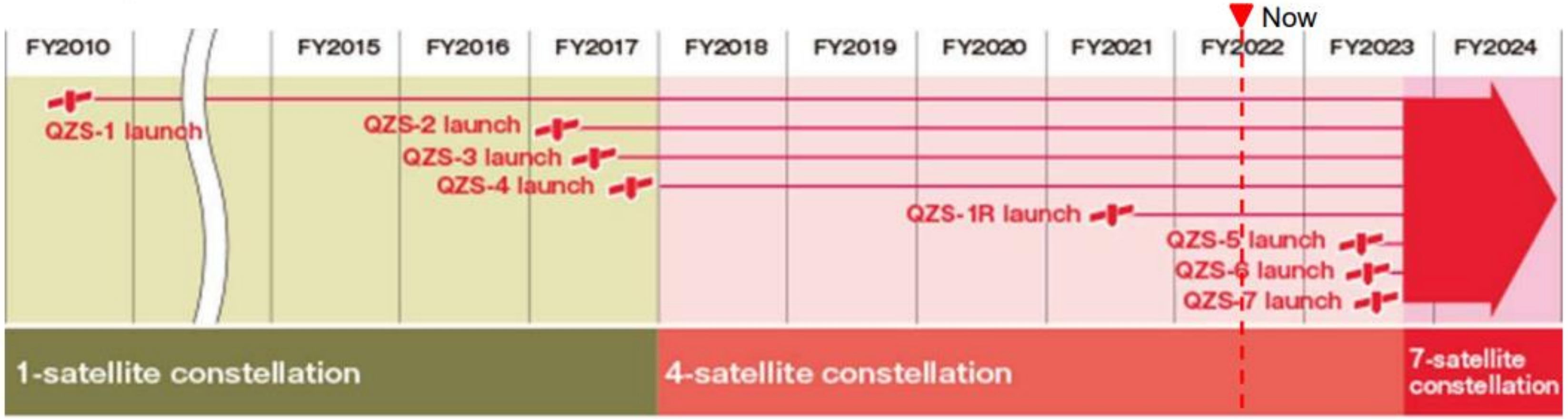
* Inclined Geosynchronous Orbit

Cabinet Office
National Space Policy Secretariat

Source: https://www.unoosa.org/documents/pdf/icg/2022/ICG16/06.pdf

QZSS Development Plan

- The seven satellites constellation is scheduled to complete around JFY2023. We are currently developing three new satellites and upgrading the ground system for them.



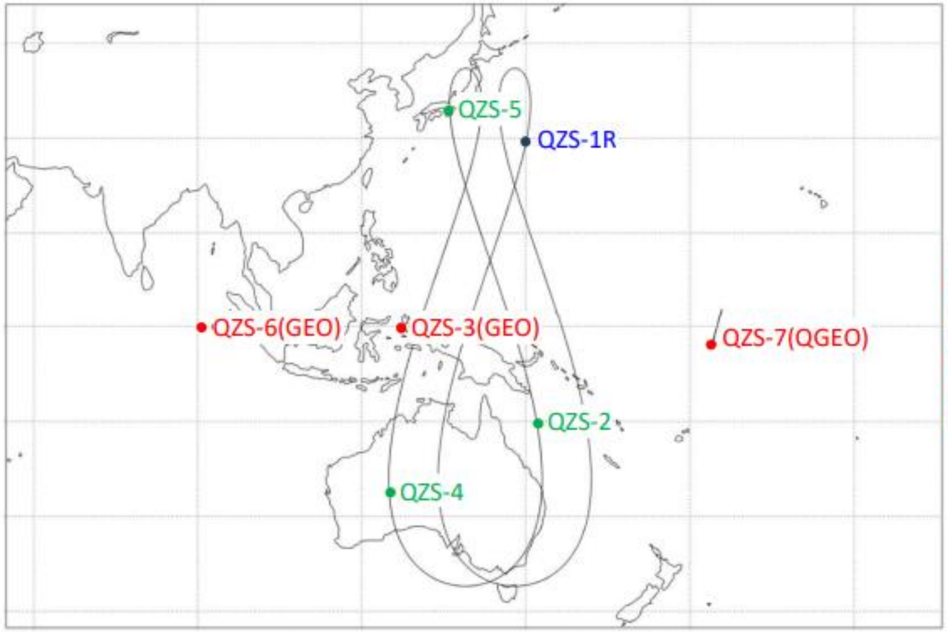
- With the completion of three more new satellites, we will be able to provide a positioning/timing by ourselves under certain conditions and new services, a message authentication service, MADOCA-PPP and extended EWSs.

Cabinet Office
National Space Policy Secretariat

https://www.unoosa.org/documents/pdf/icg/2022/ICG16/06.pdf

QZSS 7 Satellite Constellation

- The three additional satellites will be placed on an IGSO, a GEO on 90.5 East Longitude and a Quasi-Geostationary Orbit on 175 West Longitude. This constellation aims to be as follows:
  - More than one satellites can always be seen at high elevation angle.
  - More than four satellites can be seen as long as possible.
  - The DOP, Dilution Of Precision, can be as low as possible



Cabinet O
National Space Policy Secretariat

Seven-QZS Ground Track

Satellite orbit	Satellite Number	Orbital Position
IGSO（4 satellites）	QZS-1R QZS-2 QZS-4 QZS-5	148 deg E 139 deg E 139 deg E 139 deg E
GEO（2 satellites）	QZS-3 QZS-6	127 deg E 90.5 deg E
QGEO（1 satellite）	QZS-7	175 deg W

Low DOP

High DOP

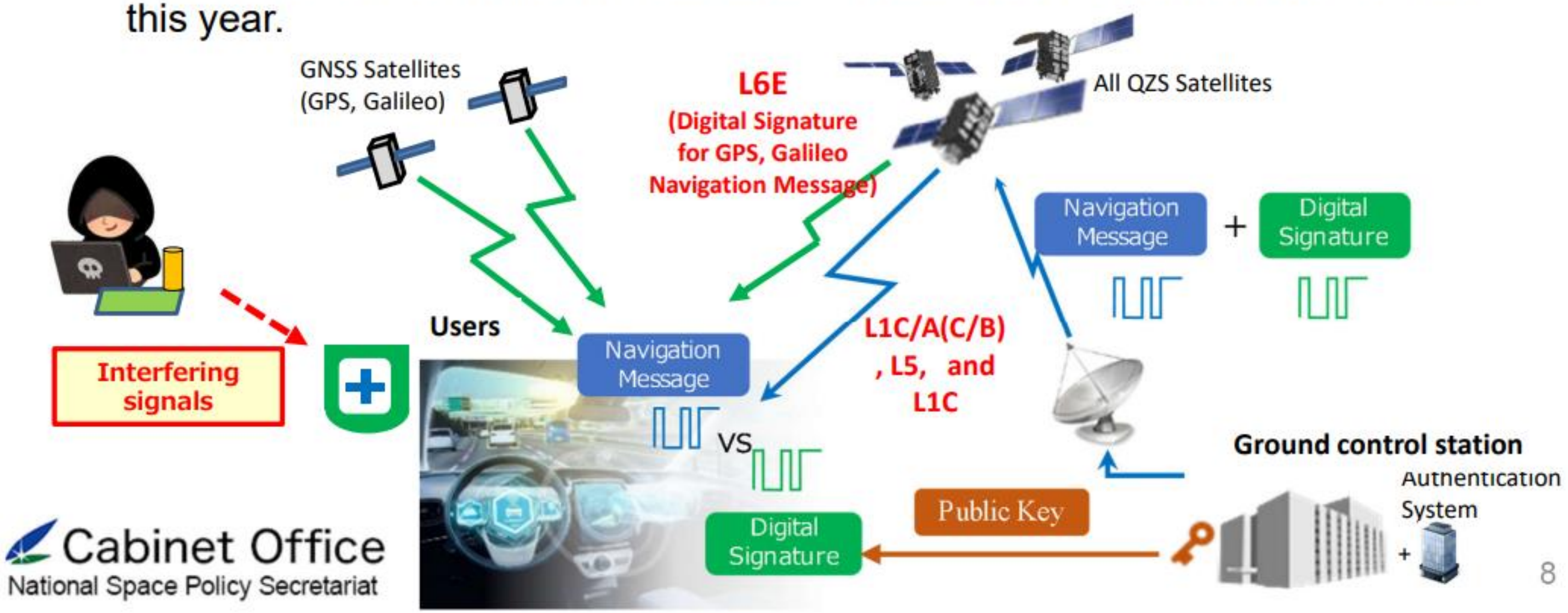
6

QZSS Signals

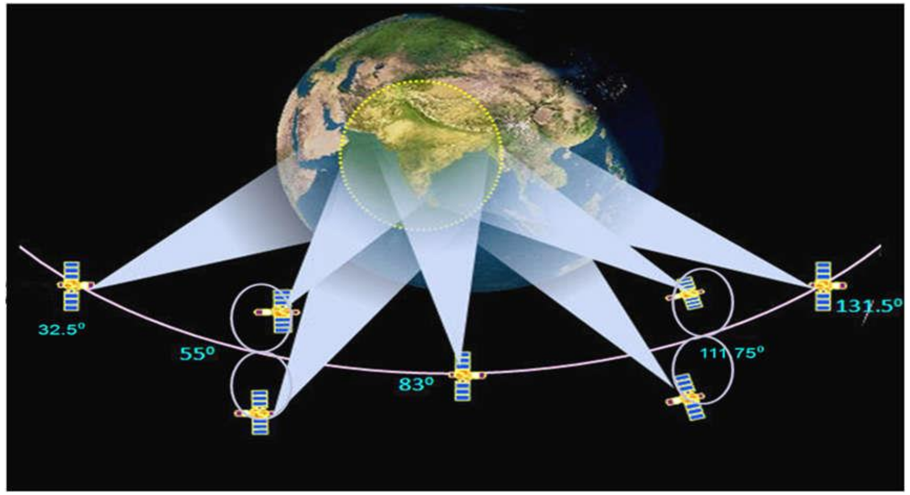
Signal	Frequency MHz	Service	Compatibility	QZS-1/1R IGSO	QZS-2/4 IGSO	QZS-3 GEO
L1C/A	1575.42	Positioning	Complement GPS	✓	✓	✓
L1C		Positioning	Complement GPS	✓	✓	✓
L1C/B		Positioning	Complement GPS	✓ *only QZS1R	-	-
L1S		Augmentation(SLAS)	DGPS (Code Phase Positioning)	✓	✓	✓
		Messaging	Short Messaging	✓	✓	✓
L1Sb		Augmentation(SBAS)	SBAS (L1) Service	-	-	✓
L2C	1227.60	Positioning	Complement GPS	✓	✓	✓
L5 I/Q	1176.45	Positioning	Complement GPS	✓	✓	✓
L5S		Experimental(L5 SBAS)	L5 SBAS (DFMC)	✓ *only QZS1R	✓	✓
L6D	1278.75	Augmentation(CLAS)	PPP-RTK (Carrier Phase Positioning)	✓	✓	✓
L6E		Experimental(MADOCA)	PPP, PPP-AR (Carrier Phase Positioning)	✓ *only QZS1R	✓	✓

QZSS Signal Authentication Services

- QZSS Navigation Message Authentication service, QZNMA, will be lunched in 2024 as part of the resilience enhancement against spoofing attacks.
- Navigation messages in the following signals are authenticated with using Elliptic Curve Digital Signature Algorithm (ECDSA P256).
  - QZSS signals (L1C/A(C/B), L1C, L5) are directly protected by self-authentication
  - GNSS signals (GPS: L1C/A, L1C, L5, Galileo:E1b, E5a) are protected by cross-authentication (L6E)
- A tentative Interface Specification (IS-QZSS-SAS) will be issued by the end of this year.



NavIC and GAGAN System



NavIC: Indian Regional Navigation Satellite System

- Provides SPS (civilian) and RS (Restricted) services in L5 and S band
- Service area: India and 1500km beyond its geo-political boundary.

GAGAN: GPS Aided GEO Augmented Navigation

- Provides Air Navigation services (Safety of Life) over Indian Flight Information Region (FIR)
- GAGAN certified for RNP 0.1 and APV 1.0

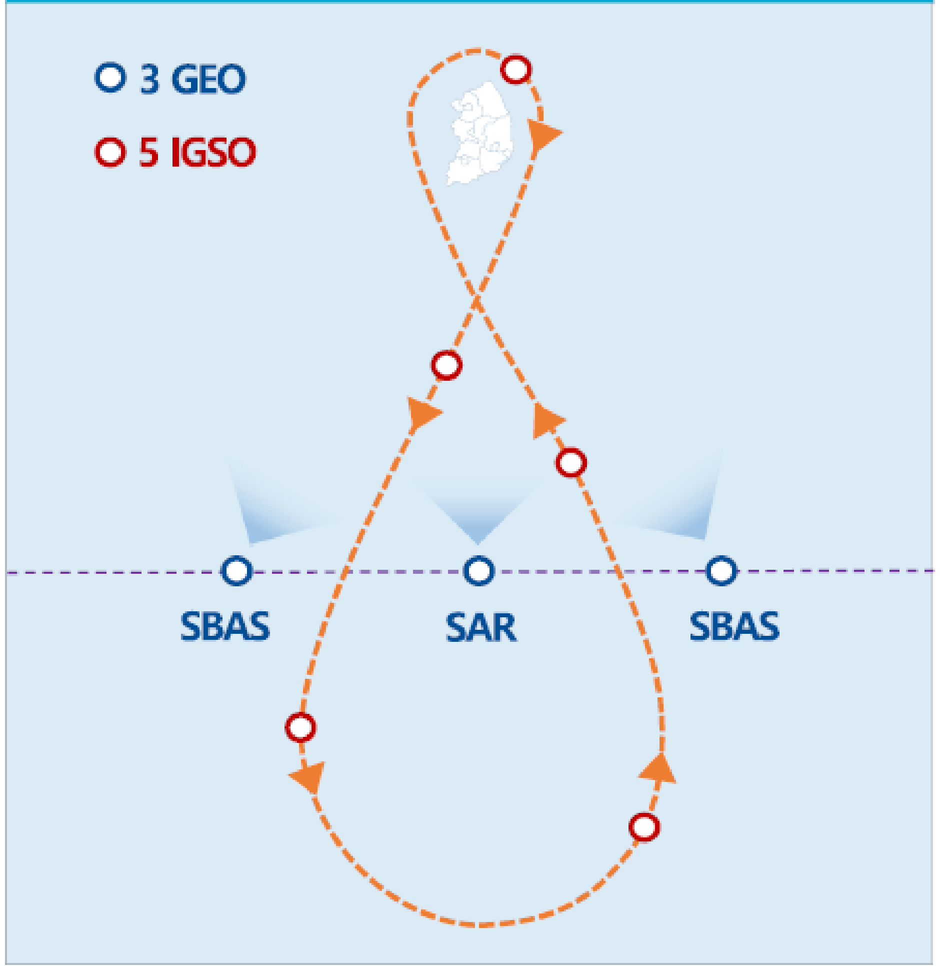
NavIC System Architecture

Space Segment	
Nominal Constellation	7 satellites (3 GSO, 4 IGSO)
Ground Segment	
Navigation Centres	2
One way ranging stations	17
Two way ranging stations	5
Network Timing Centre	2 (upgraded with in-house timescale)
Spacecraft Control Centre	2
Frequency band	L5, S and L1*
Service	SPS and RS

Source: NavIC and GAGAN System Updates, Hemanth Kumar Reddy, Group Director - Space Navigation Group Indian Space Research Organization (ISRO), India, ICG-16, October 2022

KPS Configuration and KPS Segments (Korea)

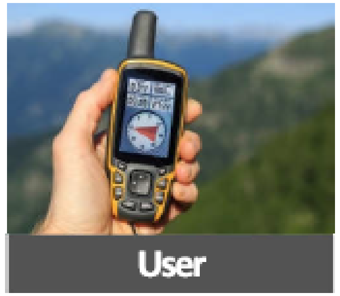
KPS Satellite Constellation



KPS Segments

- 3 GEO Satellites
- 5 IGSO Satellites
- Payloads : Navigation, Time-sync., SBAS, and SAR

- Operation Centers
- Satellite Control Centers
- Antenna Stations
- Monitoring Stations
- Mission Control Stations



- Research and Development Receiver
- Reference Station Receiver
- Test and Evaluation Receiver
- User Receivers

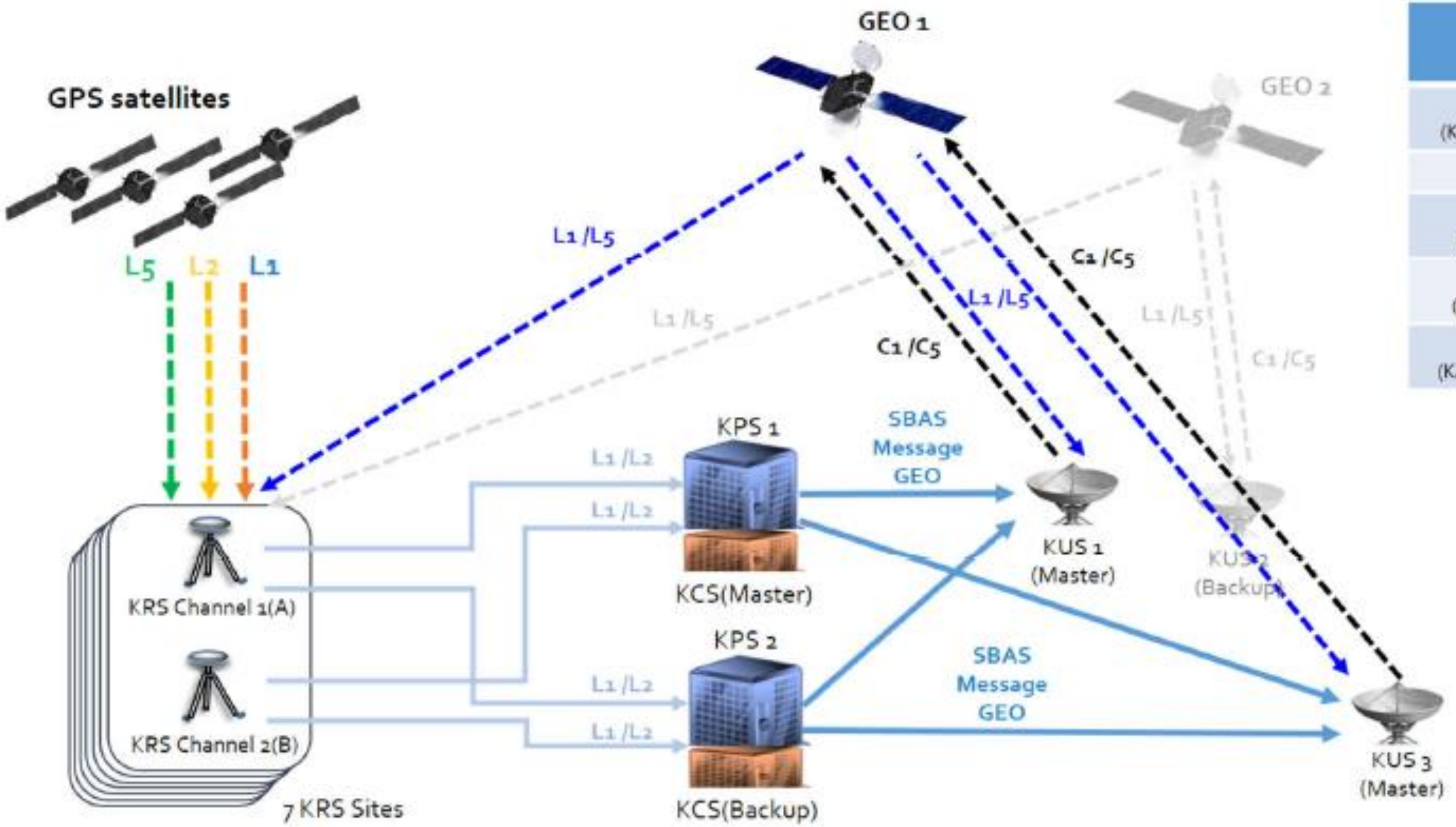
Source: KPS and KASS Update, Ministry of Science and ICT, 10th October 2022, ICG Meeting

KPS Development Plan

System Design ('22~'24)	• SDR/PDR/CDR of KPS system • International cooperation for orbits, frequencies, sites acquisition • Navigation signal and constellation design
System Development ('25~'28)	• Development of satellite bus and payloads • Development of satellite control center and antenna station • Launch of the 1st IGSO satellite in 2027
Deployment and Validation ('29~'35)	• Development and launch of the 4 IGSO and 3 GEO satellites • Development of all of the ground segment • Test during IOC and FOC

Source: KPS and KASS Update, Ministry of Science and ICT, 10th October 2022, ICG Meeting

KASS

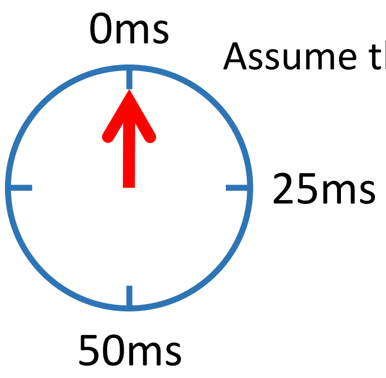


S/S (Sub System)	Qty. (Baseline)
KRS (KASS Reference Station)	7
GEOs	2(1)
KUS (KASS Uplink Station)	3
KCS (KASS Control Station)	2
KPS (KASS Processing Station)	2

Source: KPS and KASS Update, Ministry of Science and ICT, 10th October 2022, ICG Meeting

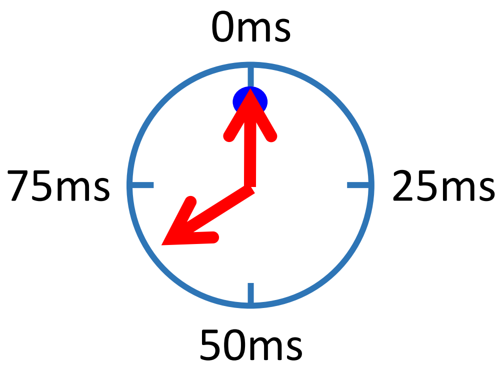
GNSS Working Principle

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

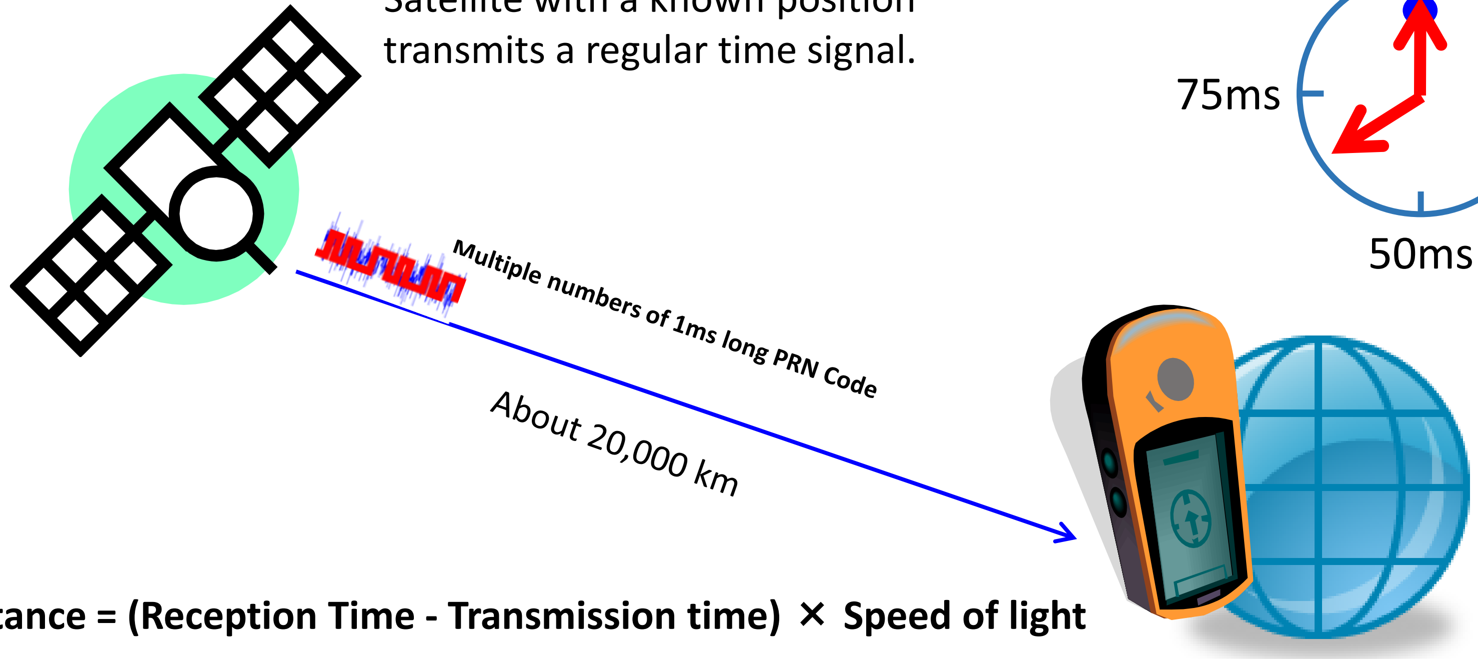


Assume that the Satellite Transmits Signal at 0ms.

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



Satellite with a known position transmits a regular time signal.

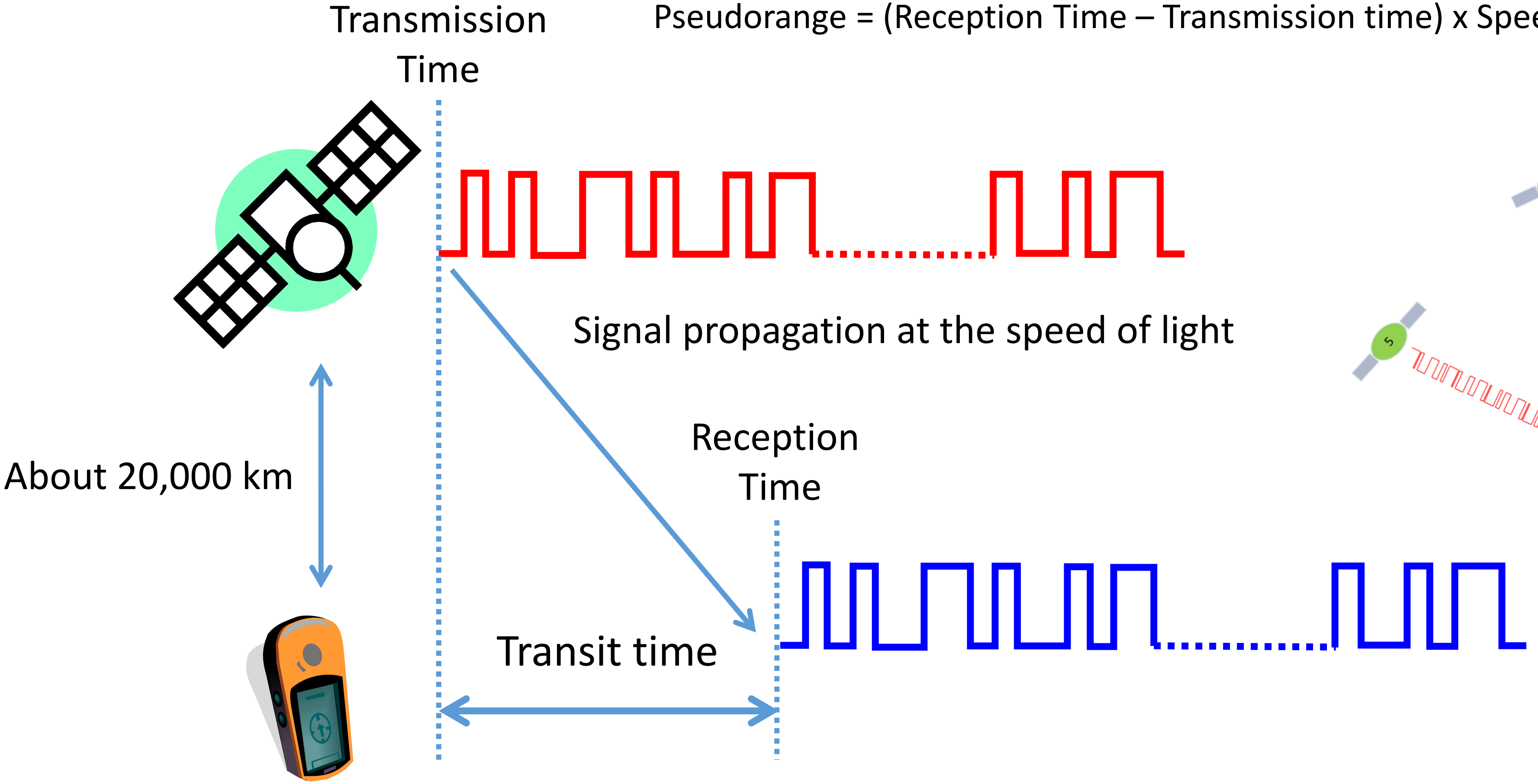


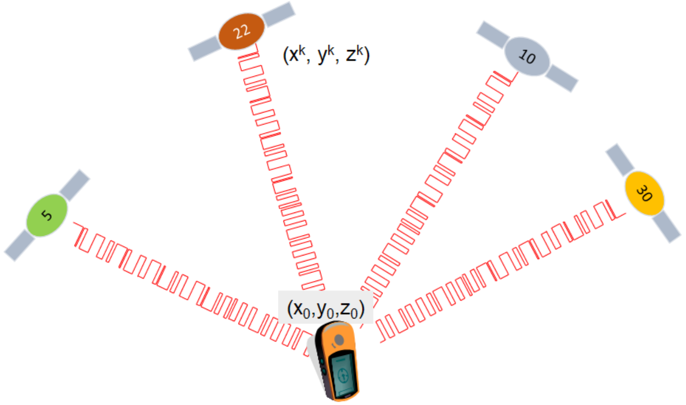
Distance = (Reception Time - Transmission time) ✕ Speed of light

Speed of Light: 300,000 km/s

Pseudorange (Code-Phase Measurement) - 1

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



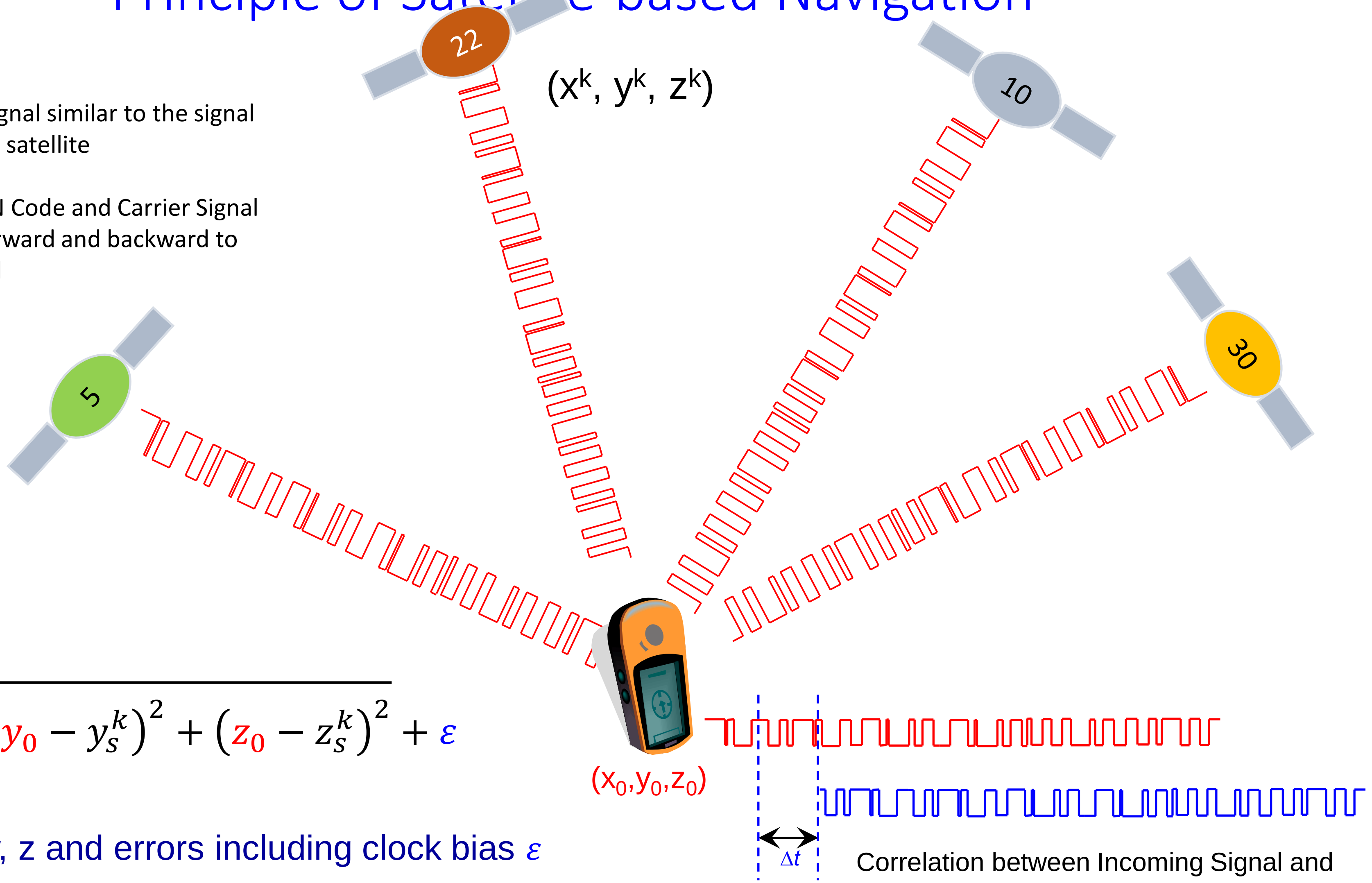


A GPS receiver measures the signal transmission time from the code phase at signal reception time.

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

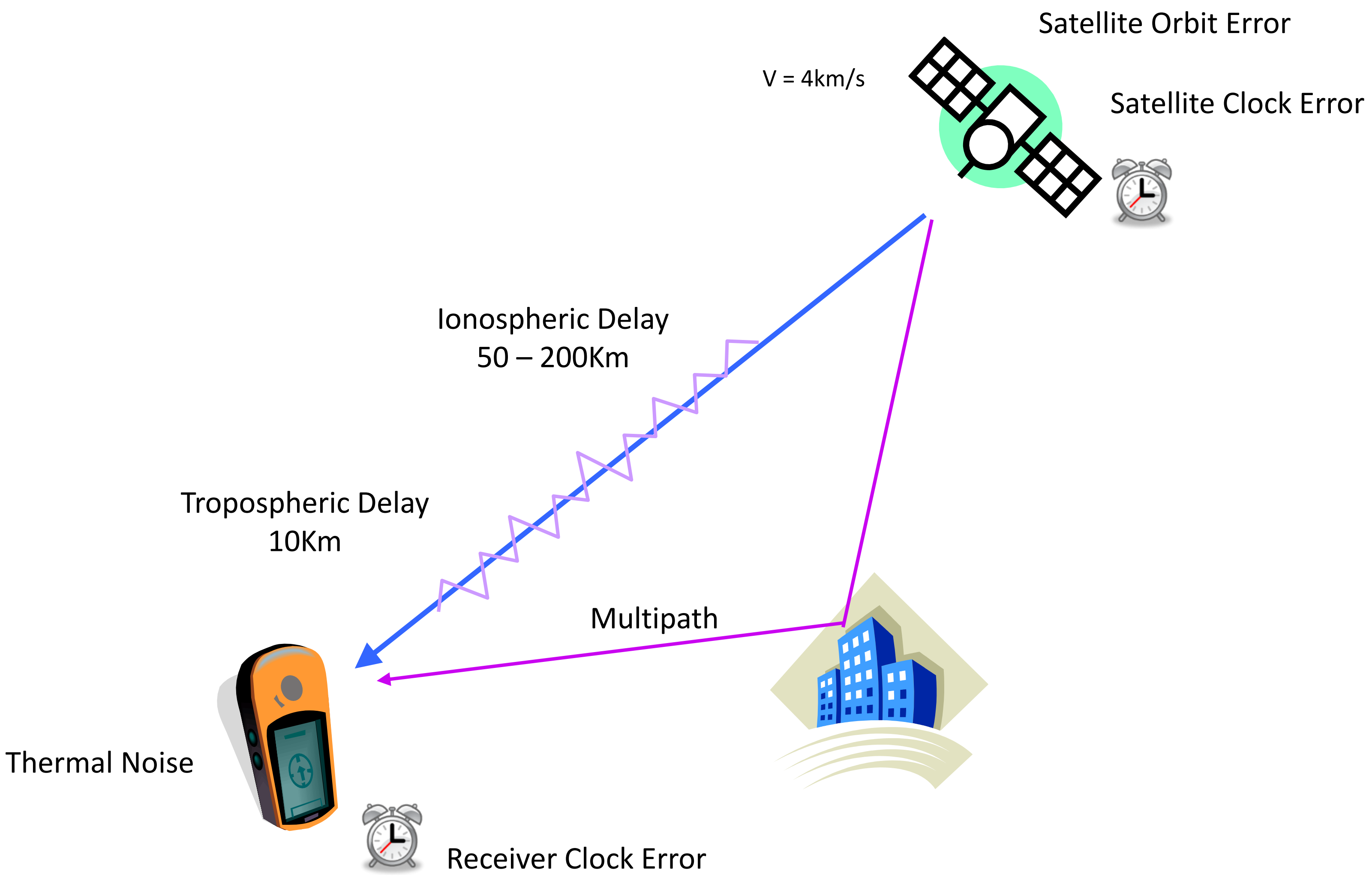


Correlation between Incoming Signal and Receiver Generated Signal

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

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

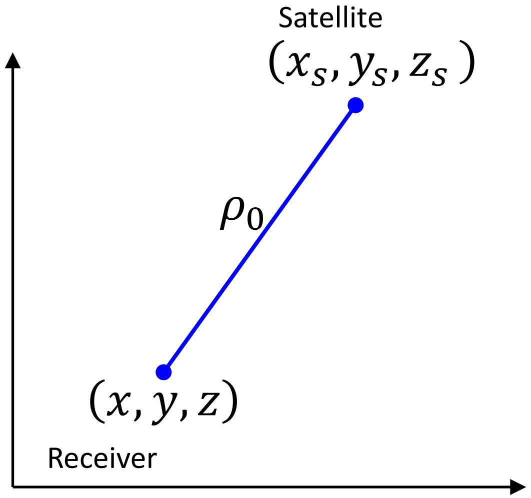
- δt_r: Receiver Clock Error
- δt_s: Satellite Clock Error
- $Iono$: Ionospheric Delay
- $Tropo$: Tropospheric Delay
- $Multipath$: Multipath Error
- ξ: Thermal Noise

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

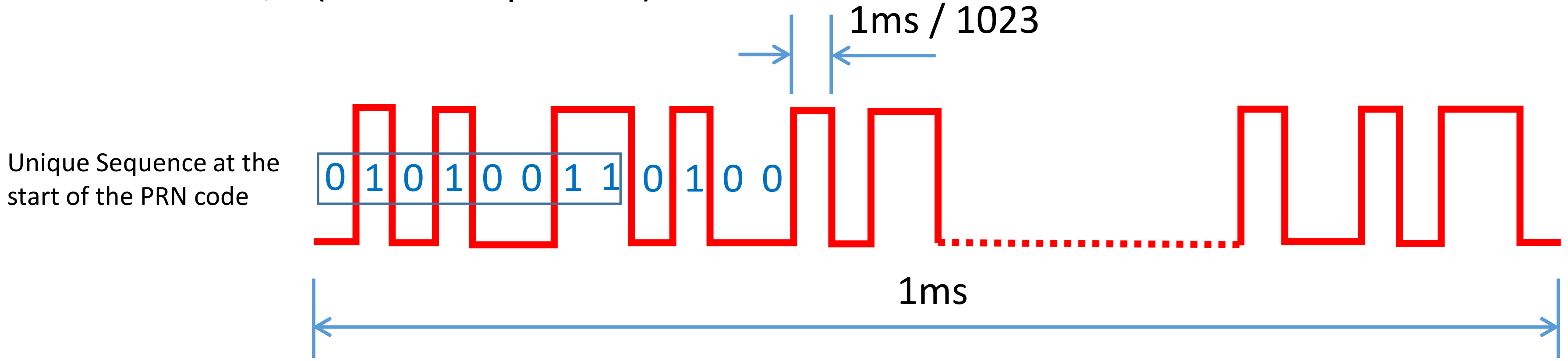


Range between satellite and receiver

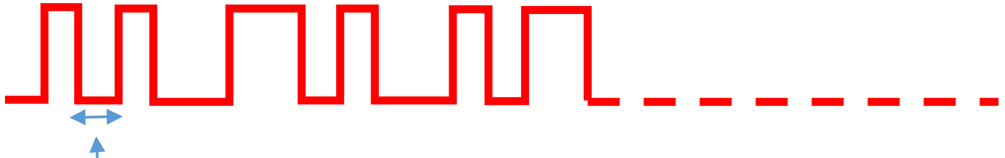
- In order to solve the above equations, we need "n" simultaneous nonlinear equations from "n" pseudorange observations.
- We need at least 4 independent observations in order to determine 4 unknown parameters, x, y, z and receiver clock error.

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



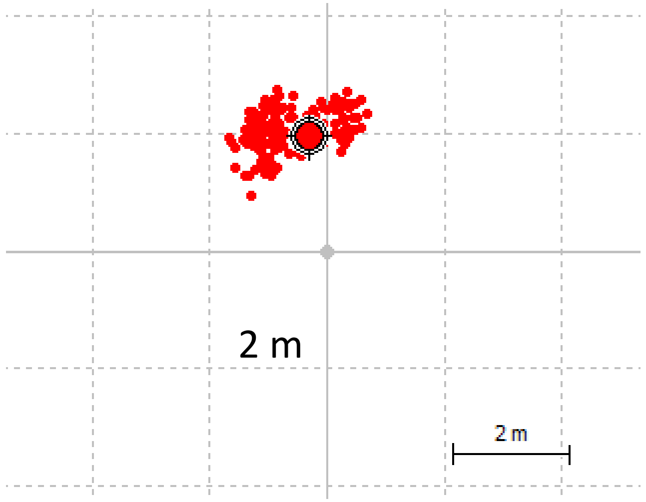
Pseudorange (Code-Phase Measurement) - 2



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

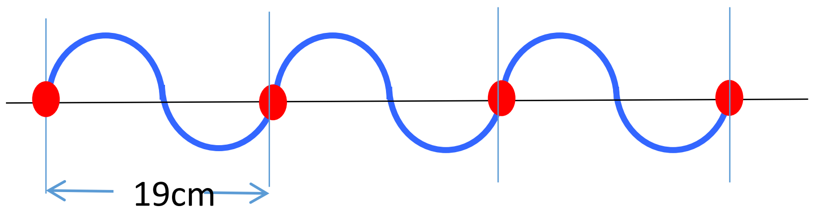
1-bit or chip corresponds to 1/1023 ms.
This is about 293m (say 300m) in distance.

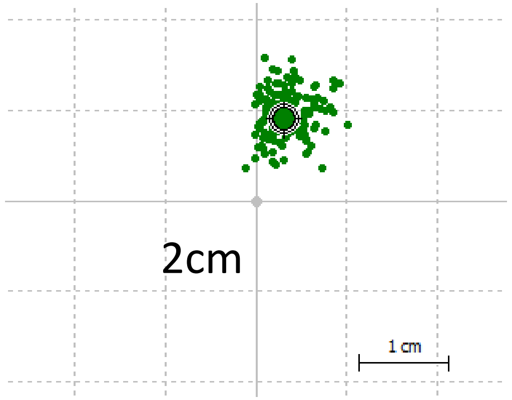
In the receiver, signals are resampled at certain frequency, say 10MHz.
This means every chip will be further divided into 10 smaller chips.
If it is possible to detect code phase at 1/10 of this sampled chip, then range measurement accuracy would be about 300/10/10 = 3m.
However, there are various types 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.



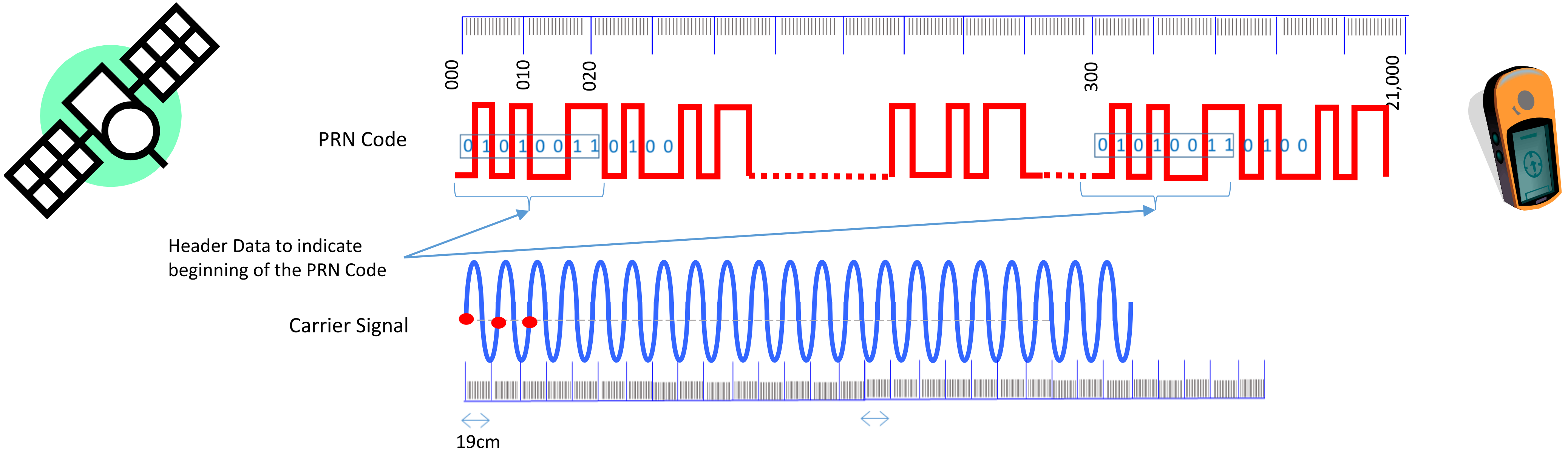
Carrier-Phase Measurement – 1

- 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.



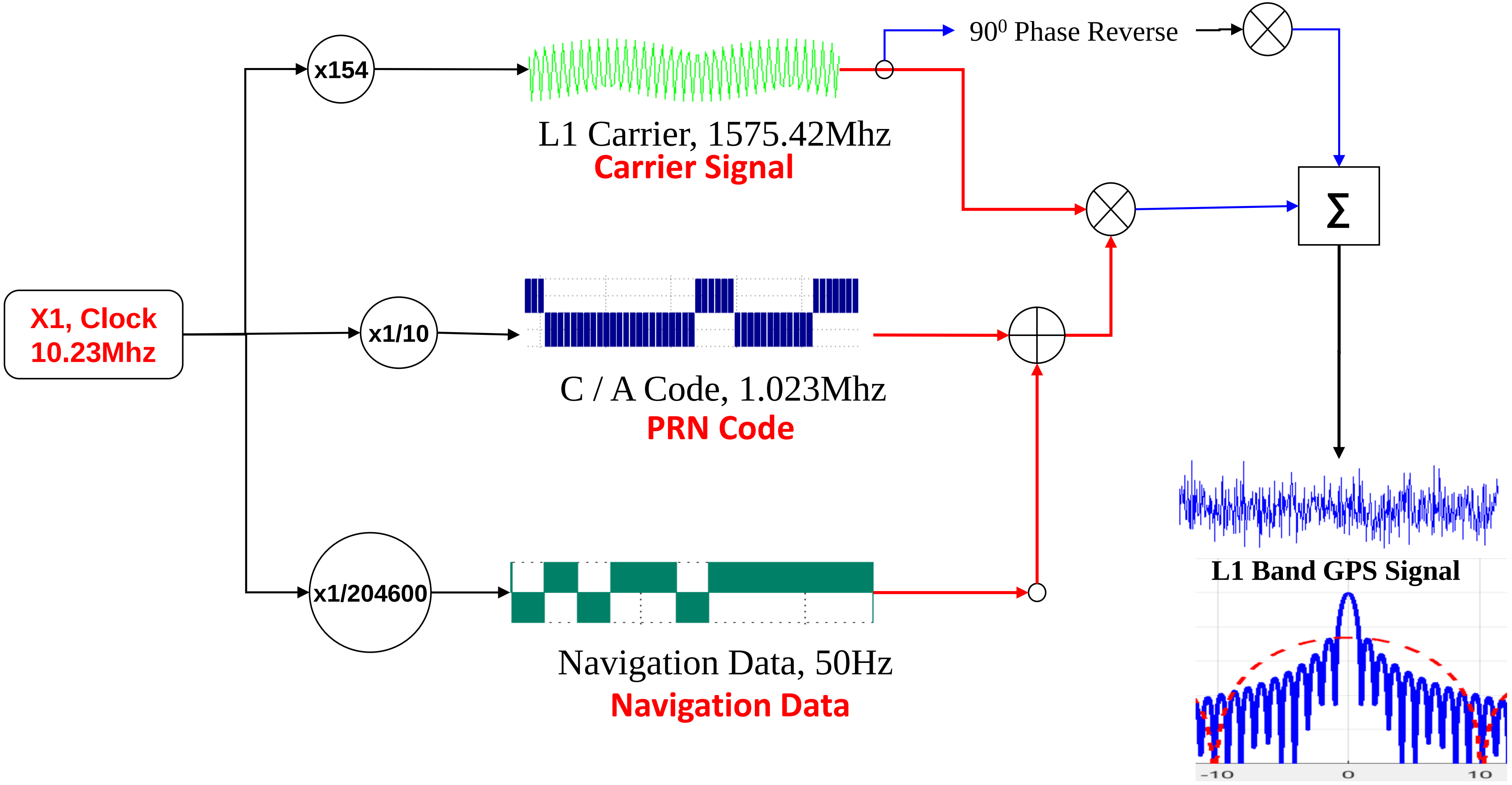


Code-Phase (PRN Code) vs. Carrier-Phase Measurement



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

GPS L1C/A Signal Structure



GPS Signals

Band	Frequency, MHz	Signal Type	Code Length msec	Chip Rate, MHz	Modulation Type	Data / Symbol Rate, bps/sps	Notes
L1	1575.42	C/A	1	1.023	BPSK	50	Legacy Signal
		C_{Data}	10	1.023	BOC(1,1)	50 / 100	From 2014
		C_{Pilot}	10	1.023	TMBOC	No Data	BOC(1,1) & BOC(6,1)
		P(Y)	7 days	10.23	BPSK		Restricted
L2	1227.60	CM	20	0.5115	BPSK	25 / 50	Modulated by TDM of (L2CM xor Data) and L2CL
		CL	1500	0.5115		No Data	
		P(Y)	7days	10.23	BPSK		
L5	1176.45	I	1	10.23	BPSK	50 / 100	Provides Higher Accuracy
		Q	1			No Data	

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

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
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 *

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

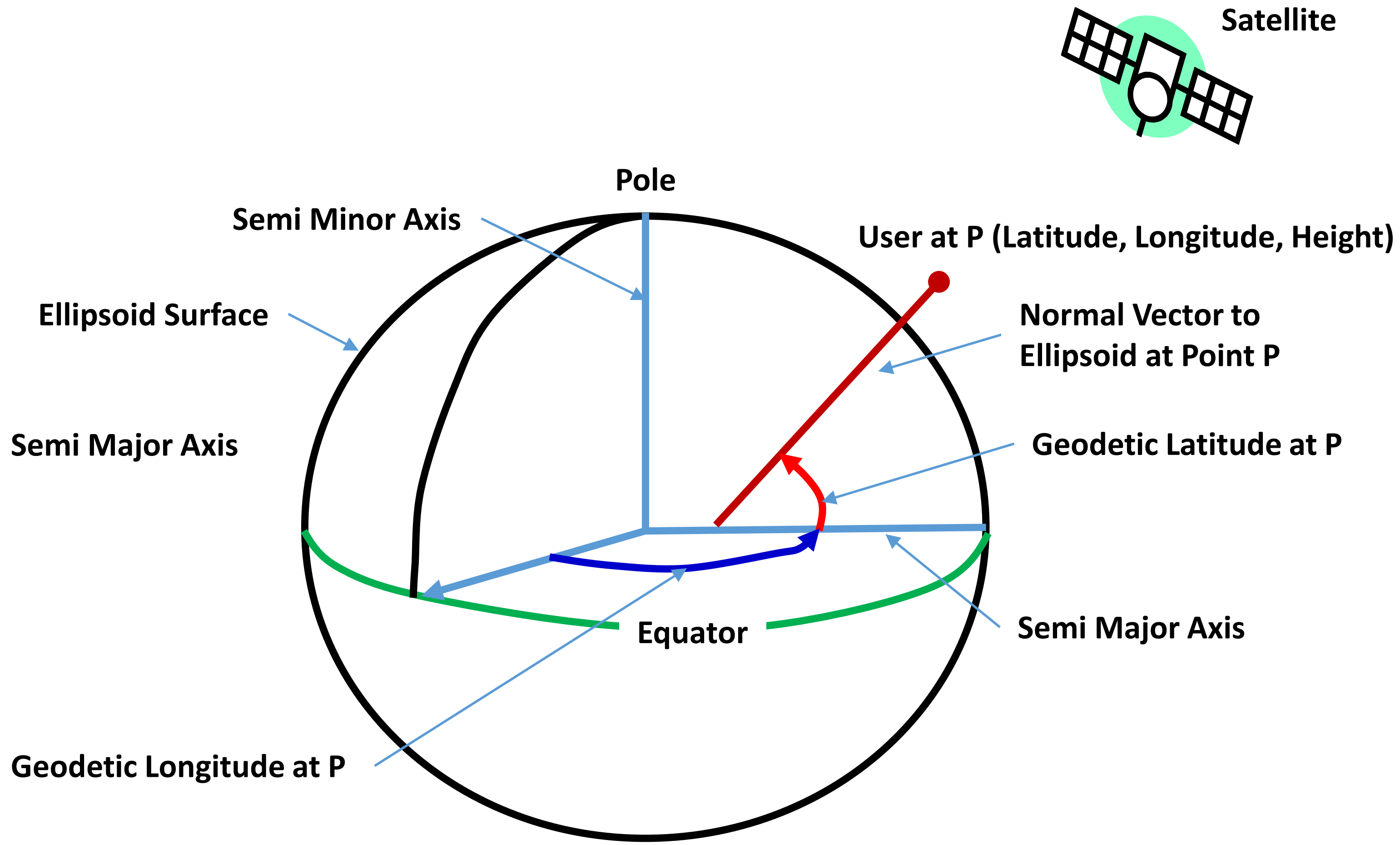
```
     S37 86400        0        0 86400        0        0        0        0      PRN / # OF OBS
     S40 56700        0        0 56700        0        0        0        0      PRN / # OF OBS
CARRIER PHASE MEASUREMENTS: PHASE SHIFTS REMOVED                                COMMENT
                                                                                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
```

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

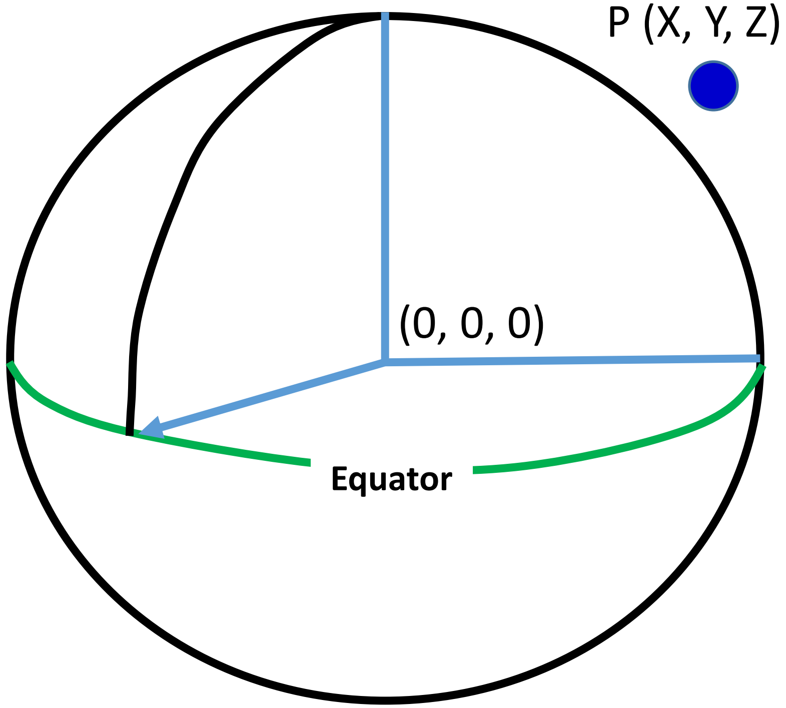
Coordinate Systems

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

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

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

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

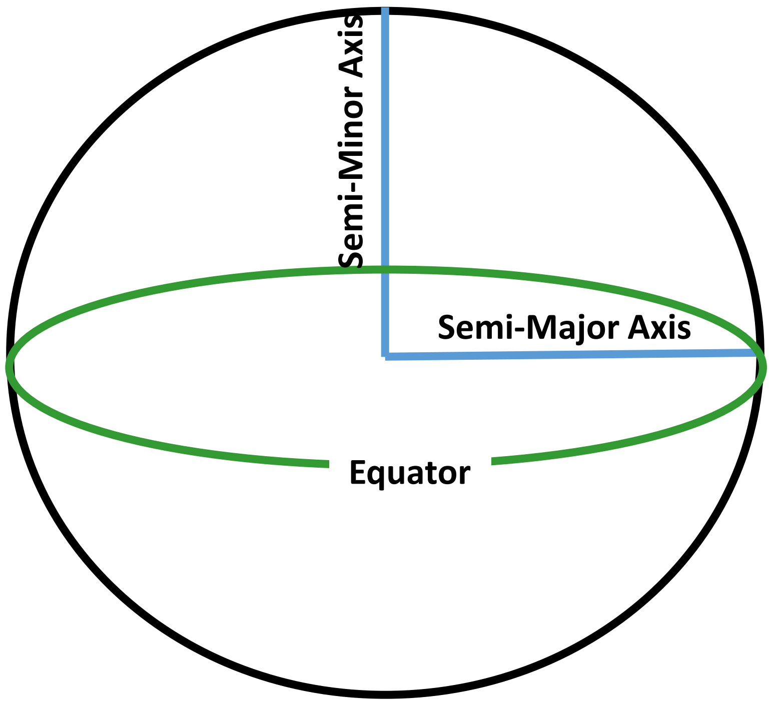
$$h = \frac{P}{\cos\varphi} - \text{N}(\varphi)$$

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

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

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

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

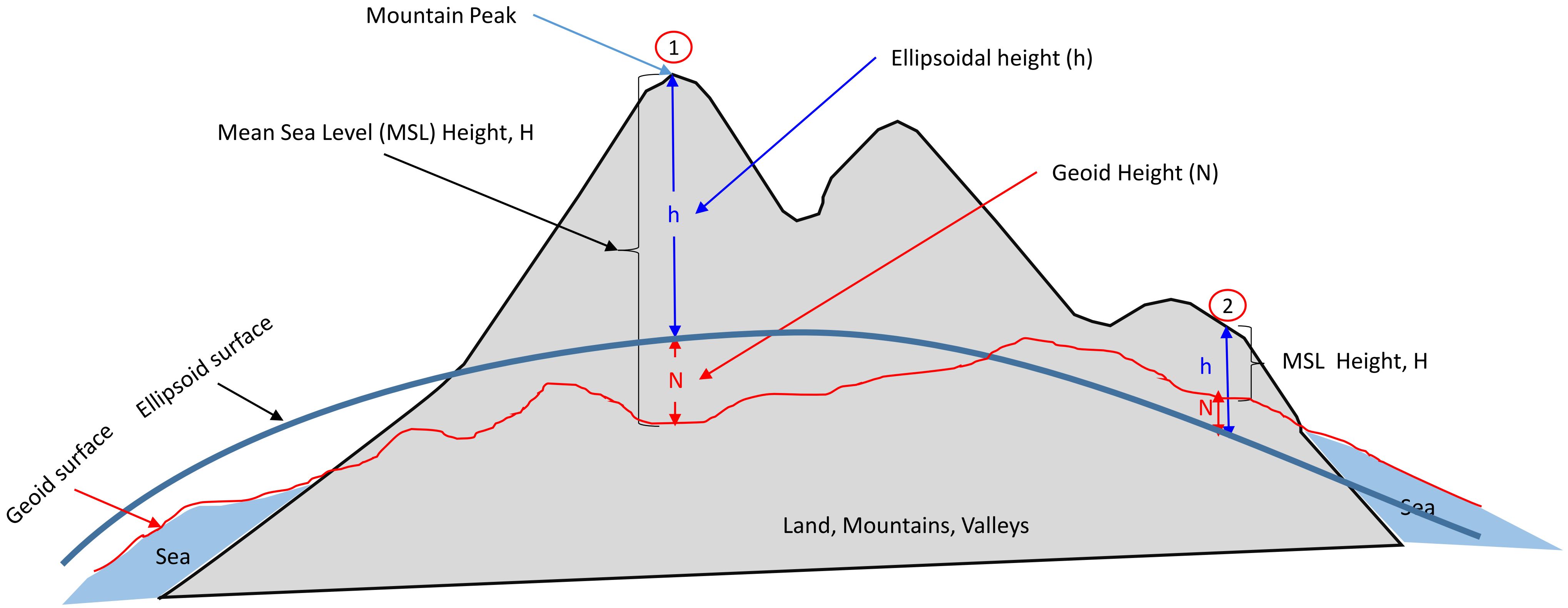
Flattening, f = (a-b)/a

= 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

$GNLLL,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

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

$GNLLL,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).
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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

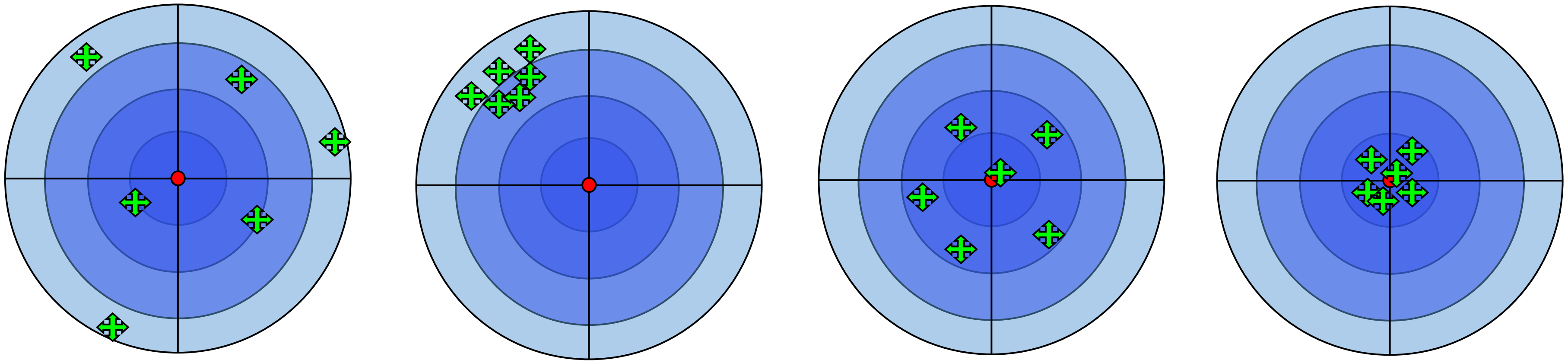
Points to Be Careful in GPS Survey

- 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

Useful Software

GNSS Software

- U-Center
  - Software to log and visualize GNSS data logged by u-blox receiver
    - Format: UBX
- RTKLIB
  - Powerful and popular software for GNSS data processing for high-accuracy
    - Real-time or Post-Processing
    - Raw data pre-processing, data format conversion etc.
    - SPP, DGPS, RTK, PPK, PPP data processing
- MADOCA PPP Related Software
  - MAD-WIN, MAD-PI, MADROID
- Android Device Software
  - RTKDROID, MADROID, SW-MAPS