GNSS Data Processing for High-Accuracy Positioning using Low-Cost Receiver Systems

GNSS Introduction: Data Formats, Coordinates Systems and Errors

Dinesh Manandhar

Associate Professor (Project)

CSIS, The University of Tokyo

dinesh@csis.u-tokyo.ac.jp

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What is GNSS?

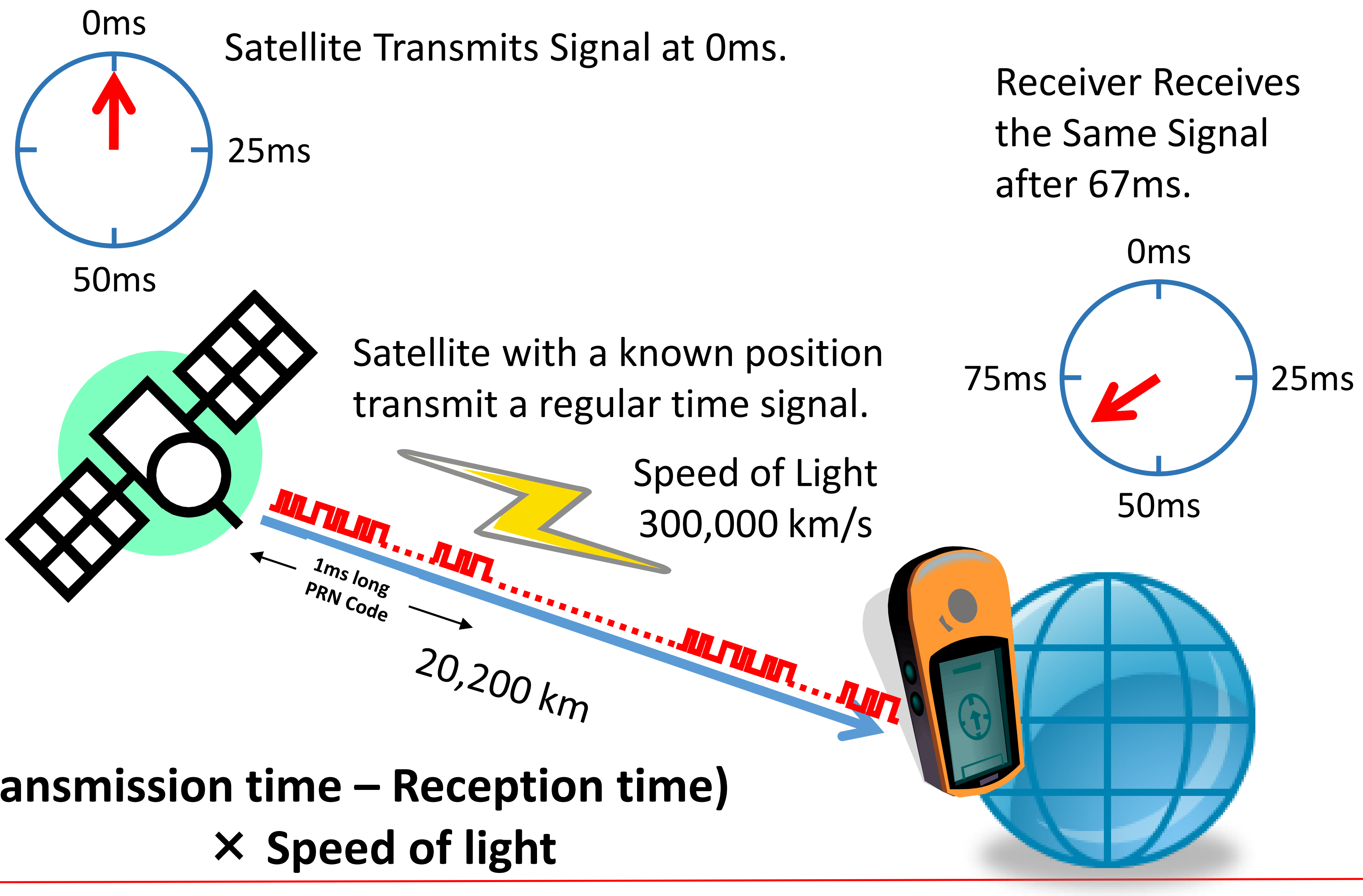
Global Navigation Satellite System (GNSS) is the standard generic term for all navigation satellites systems like GPS, GLONASS, GALILEO, BeiDou, QZSS, NAVIC.

- Global Constellation
  - GPS USA
  - GLONASS, Russia
  - Galileo, Europe
  - BeiDou (COMPASS) / BDS, China
- Regional Constellation
  - QZSS, Japan
  - NAVIC (IRNSS), India

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
  - Nigeria
  - Korea (Also navigation system)
  - Australia

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

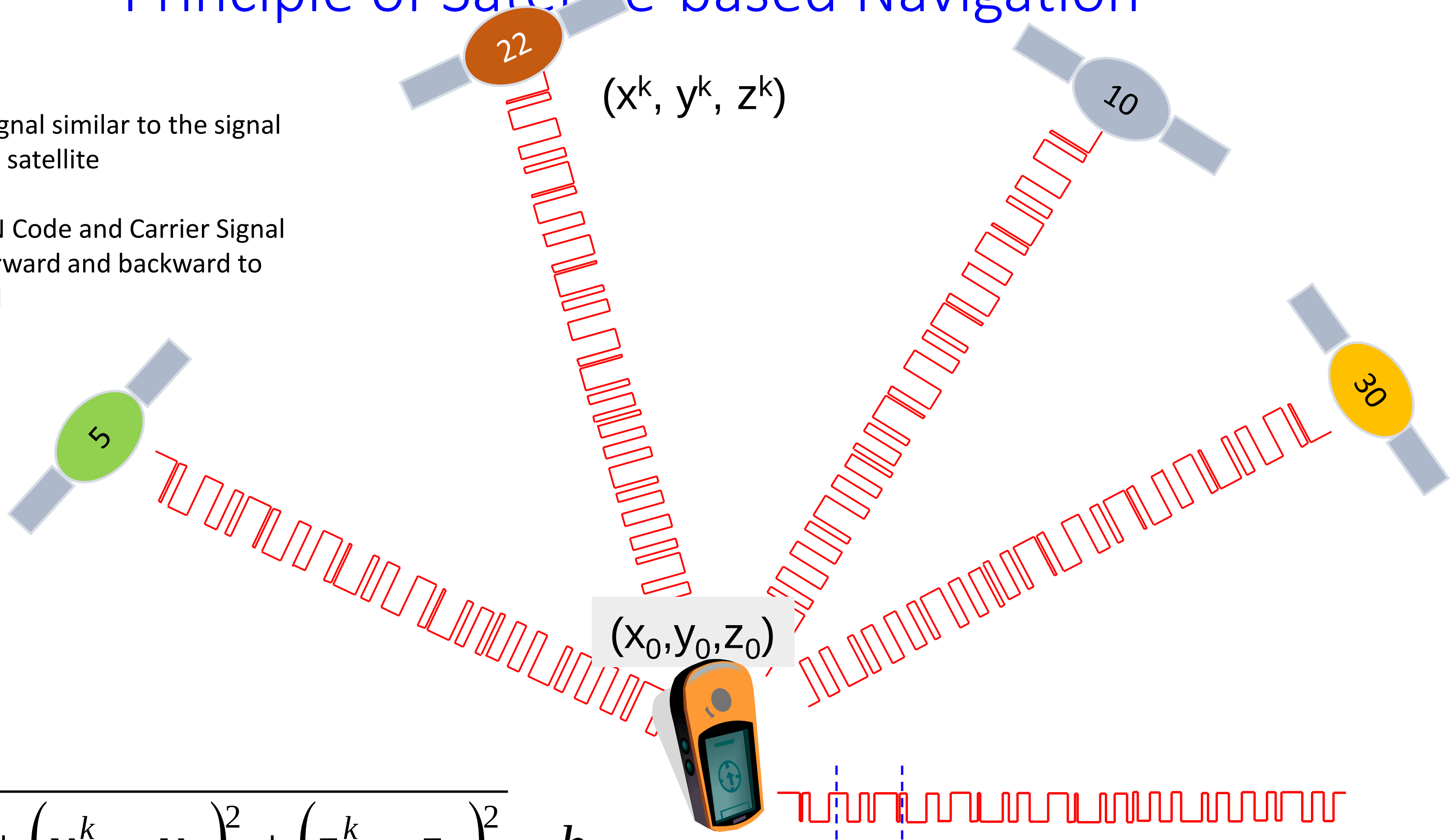


Distance = (Transmission time – Reception time)
× Speed of light

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

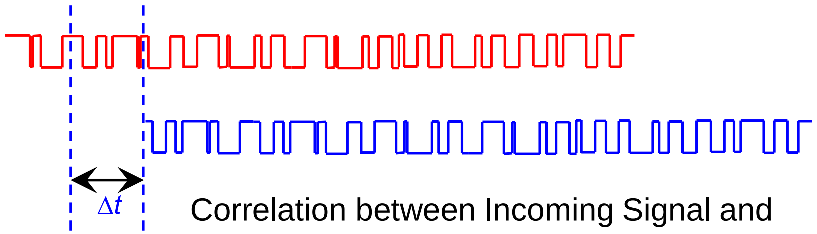
Receiver generates its own GPS signal similar to the signal coming from the satellite for each satellite

- ➔ 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



$$\rho^k = \sqrt{\left(x^k - x_0\right)^2 + \left(y^k - y_0\right)^2 + \left(z^k - z_0\right)^2} - b$$

If k ≥ 4, solve for x, y, z and clock bias, b

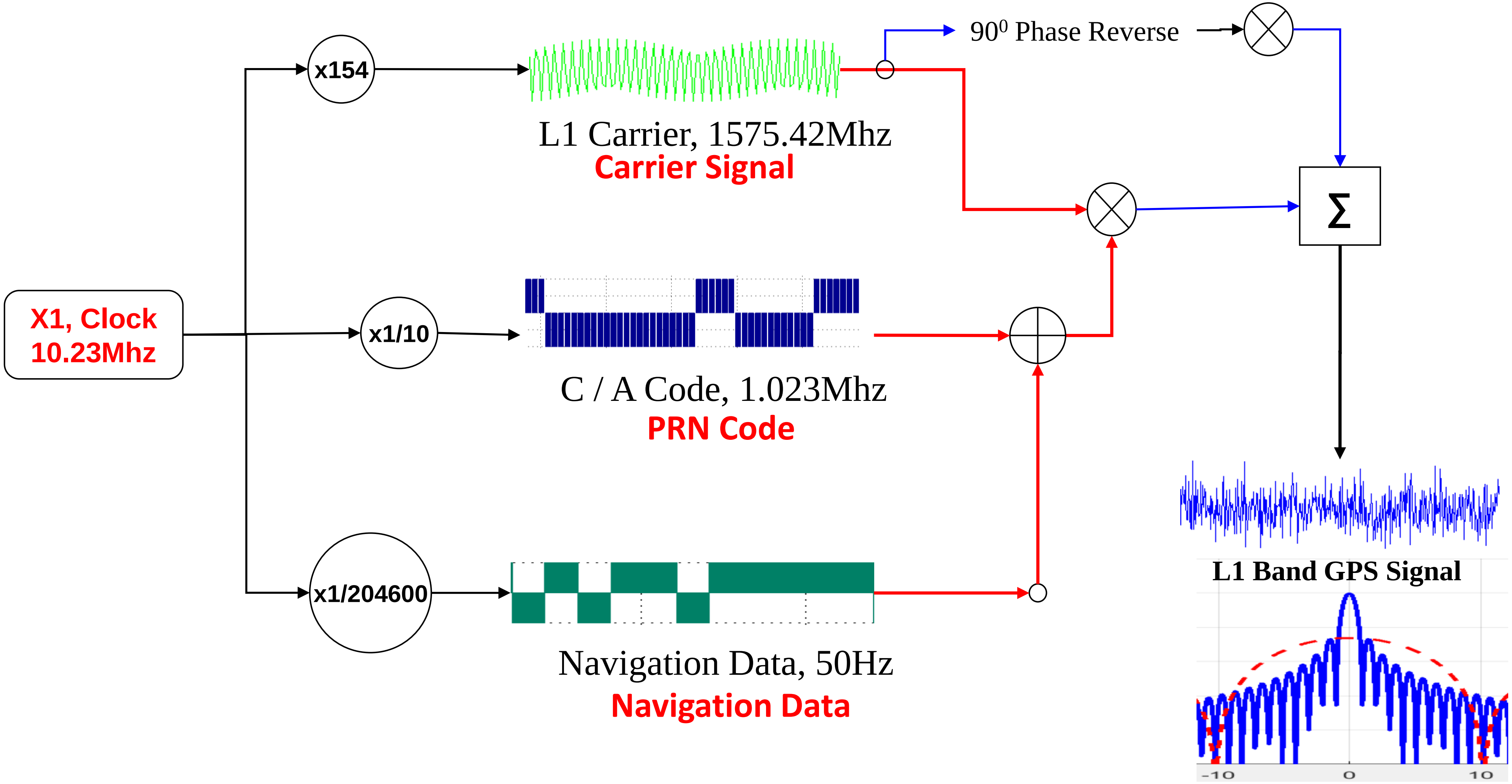


Correlation between Incoming Signal and Receiver Generated Signal

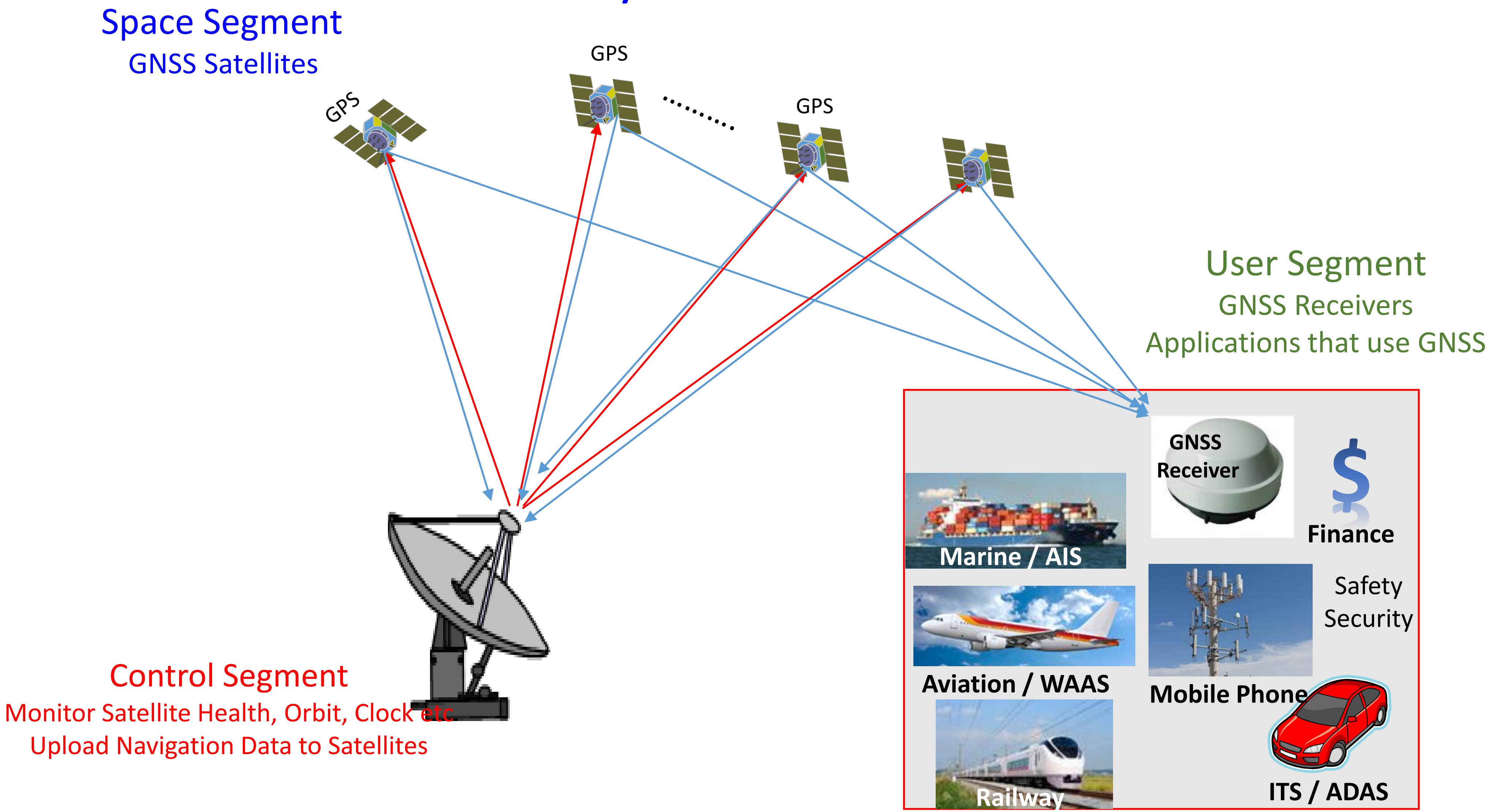
GPS L1C/A Signal Structure

- 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
  - Used to identify satellite ID in CDMA
  - Requires to modulate the data
  - Should have good auto-correlation and cross-correlation properties
- Navigation Data
  - Includes satellite orbit related data (ephemeris data)
  - Includes satellite clock related information (clock errors etc)

GPS L1C/A Signal Structure



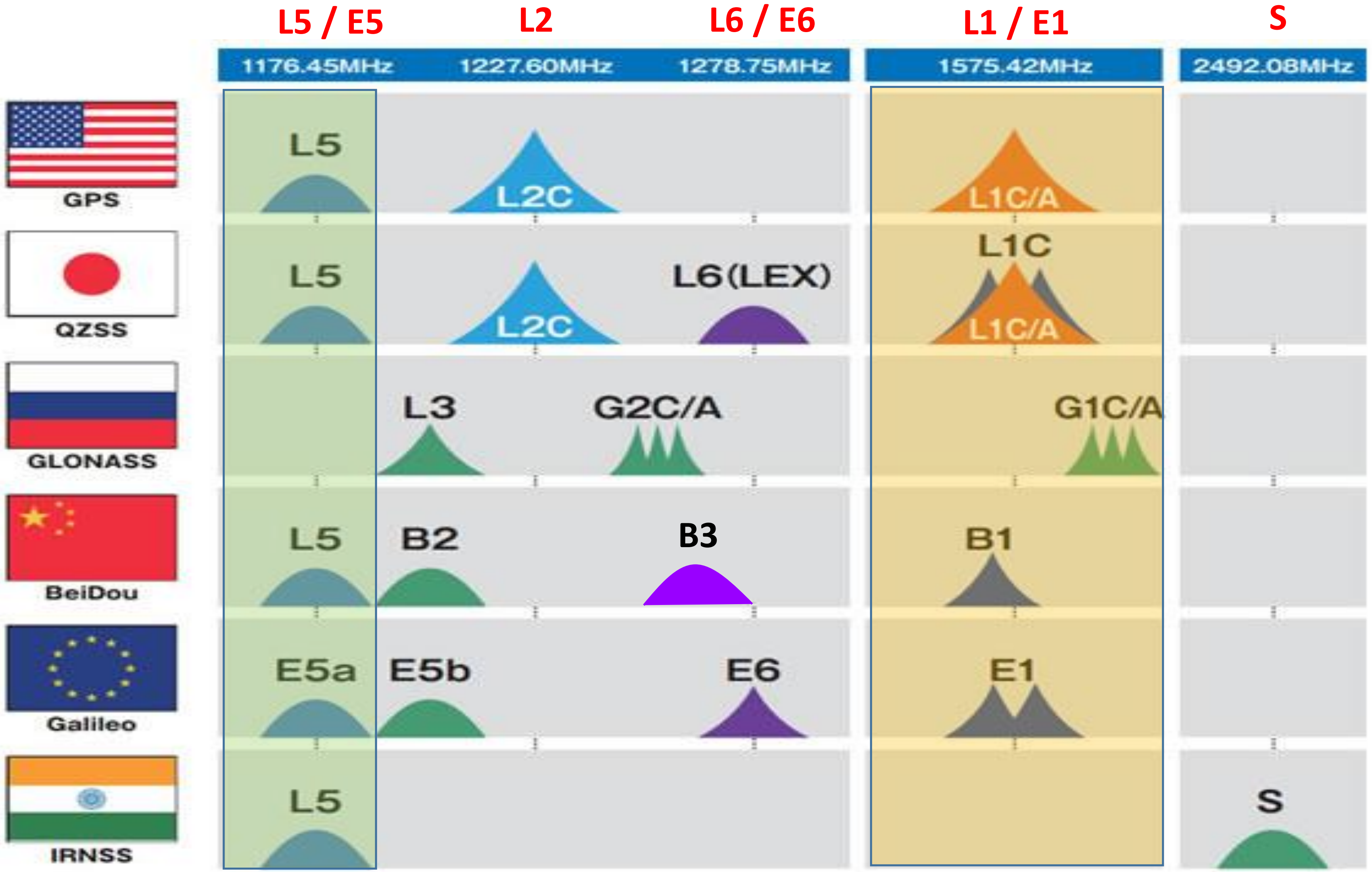
GNSS System Architecture

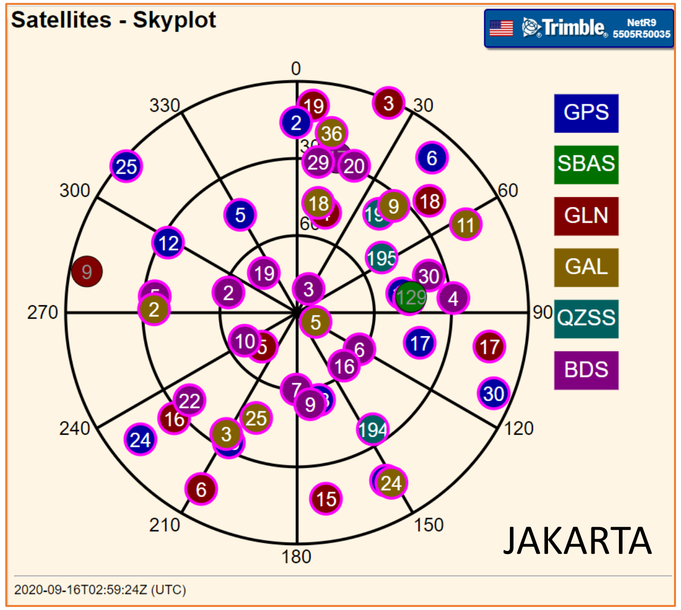


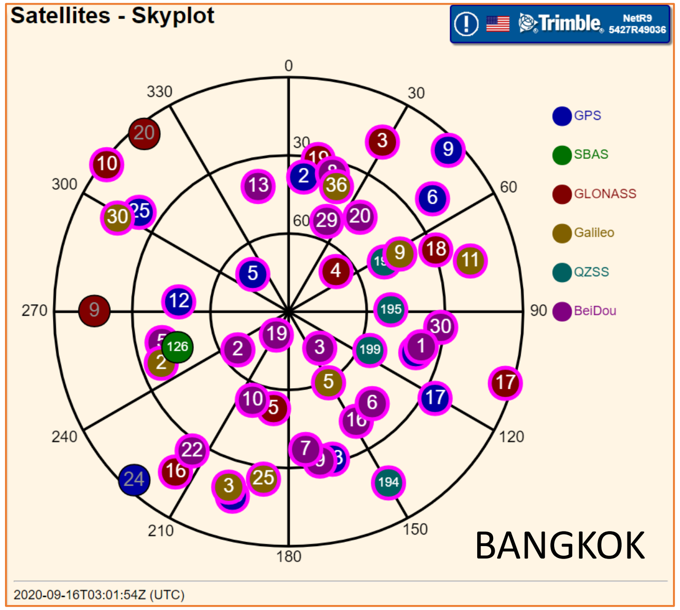
GPS Signals

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	

Multi-GNSS Signals




Satellites - Skyplot
Trimble NetR9 5505R50035
GPS
SBAS
GLN
GAL
QZSS
BDS
JAKARTA
2020-09-16T02:59:24Z (UTC)


Satellites - Skyplot
Trimble NetR9 5427R49036
GPS
SBAS
GLONASS
Galileo
QZSS
BeiDou
BANGKOK
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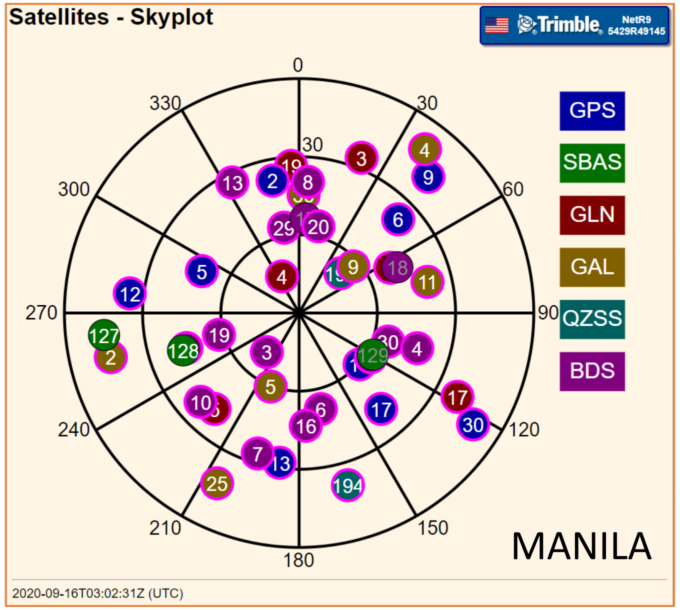
Satellites - Skyplot
Trimble NetR9 5429R49145
GPS
SBAS
GLN
GAL
QZSS
BDS
MANILA
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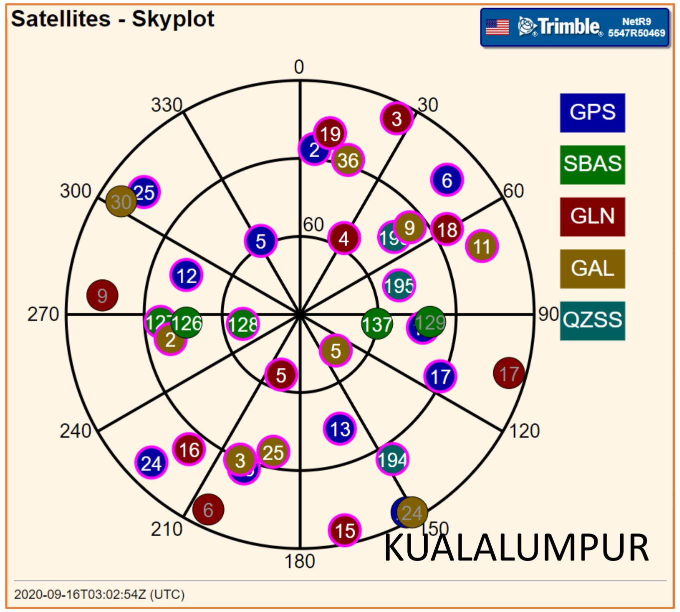
Satellites - Skyplot
Trimble NetR9 5547R50469
GPS
SBAS
GLN
GAL
QZSS
KUALALUMPUR
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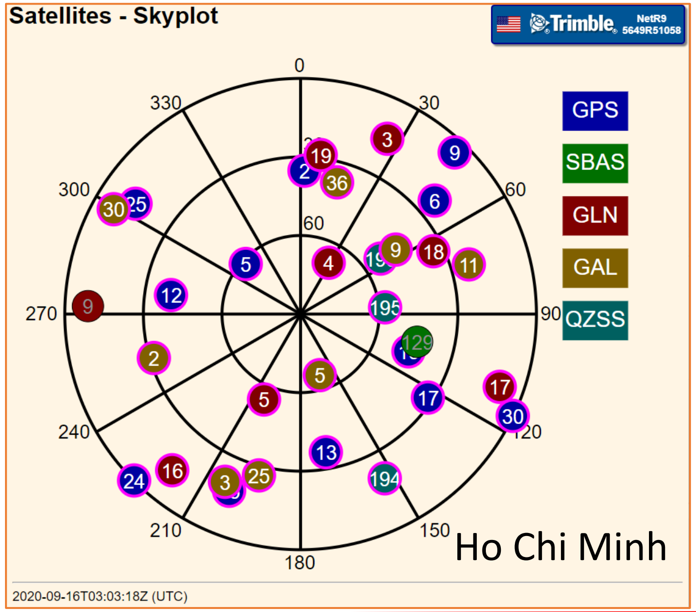
Satellites - Skyplot
Trimble NetR9 5649R51058
GPS
SBAS
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GAL
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Ho Chi Minh
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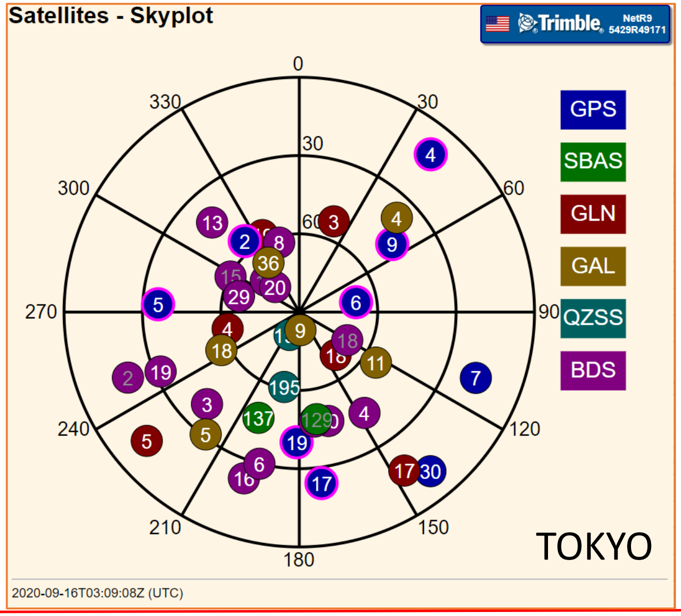
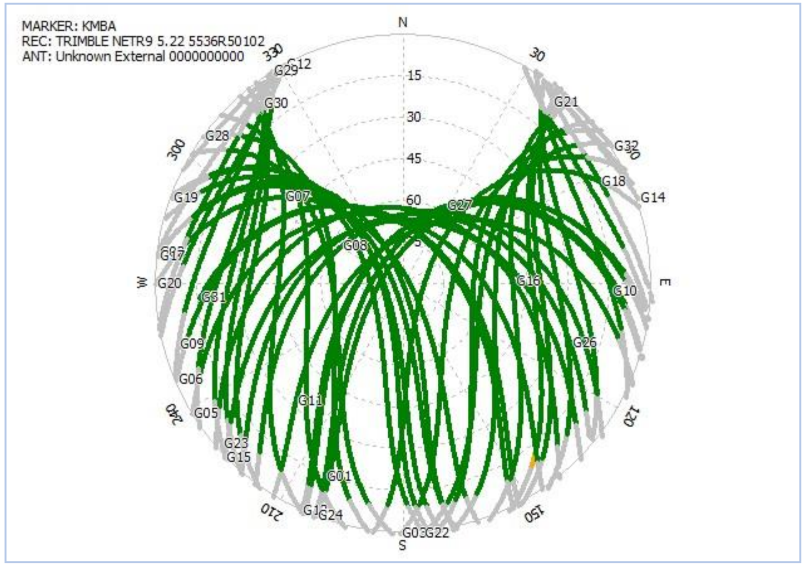
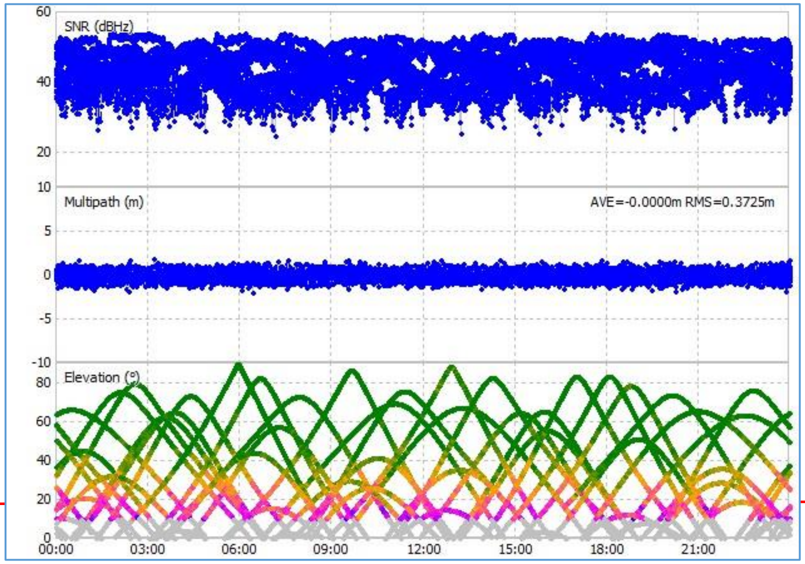

Satellites - Skyplot
Trimble NetR9 5429R49171
GPS
SBAS
GLN
GAL
QZSS
BDS
TOKYO
2020-09-16T03:09:08Z (UTC)

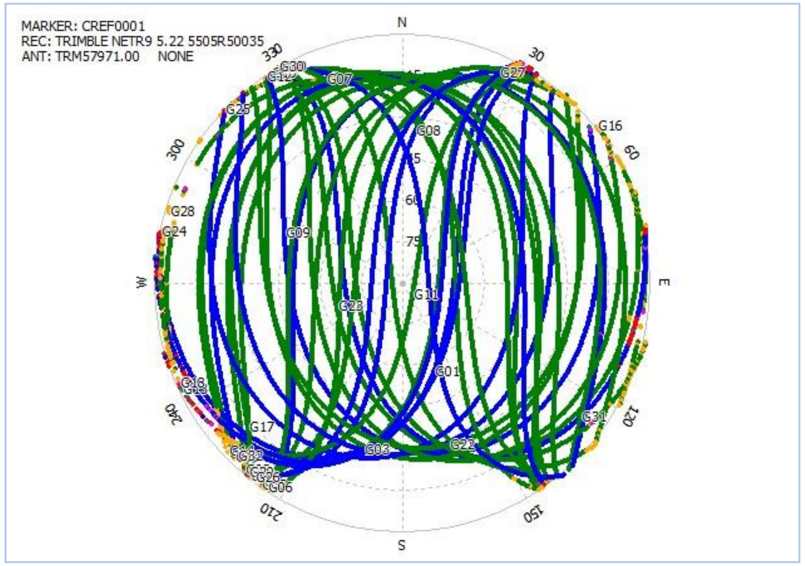
GPS Skyplots: Tokyo, Jakarta and Maputo

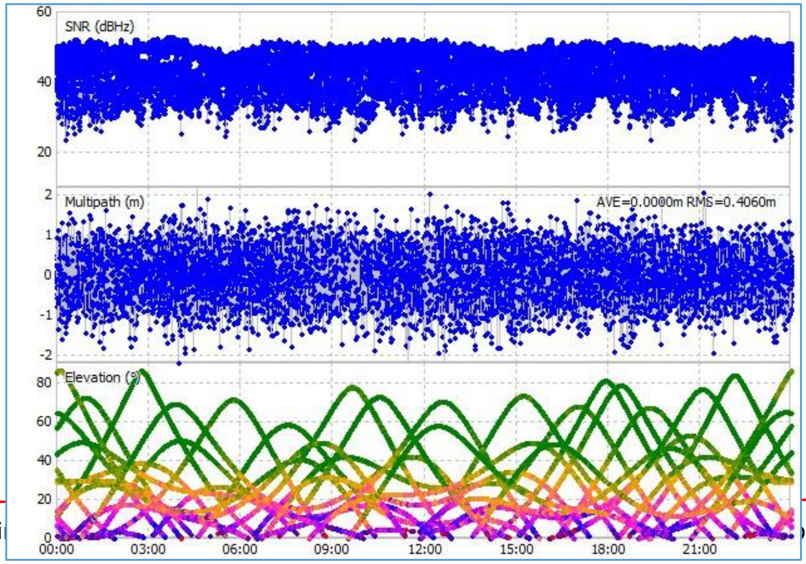
Tokyo-A Base-Station



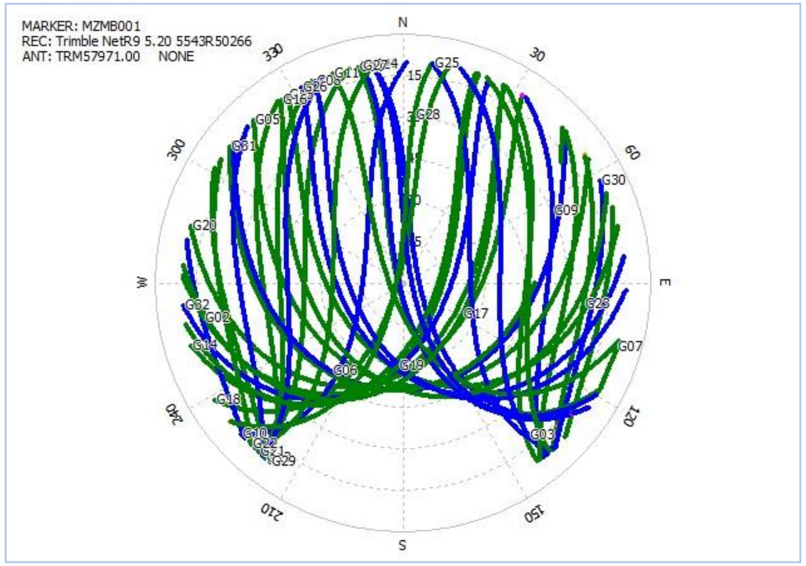


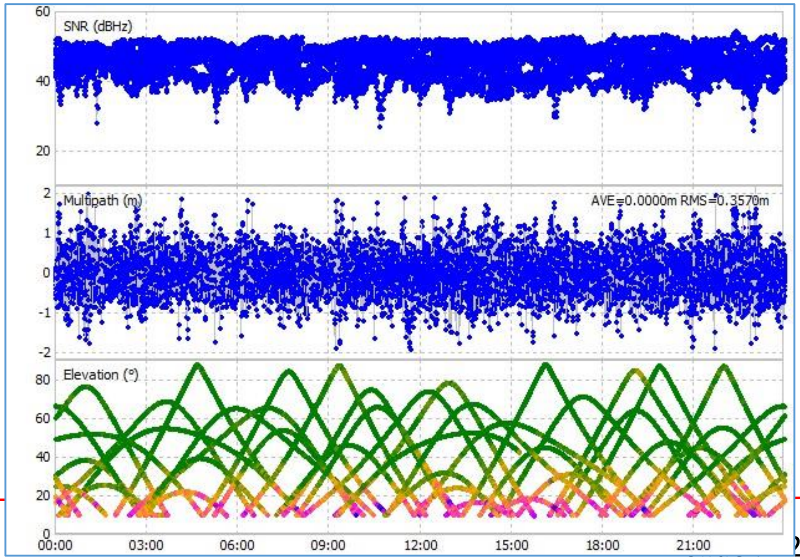
Jakarta Base-Station





Maputo Base-Station





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

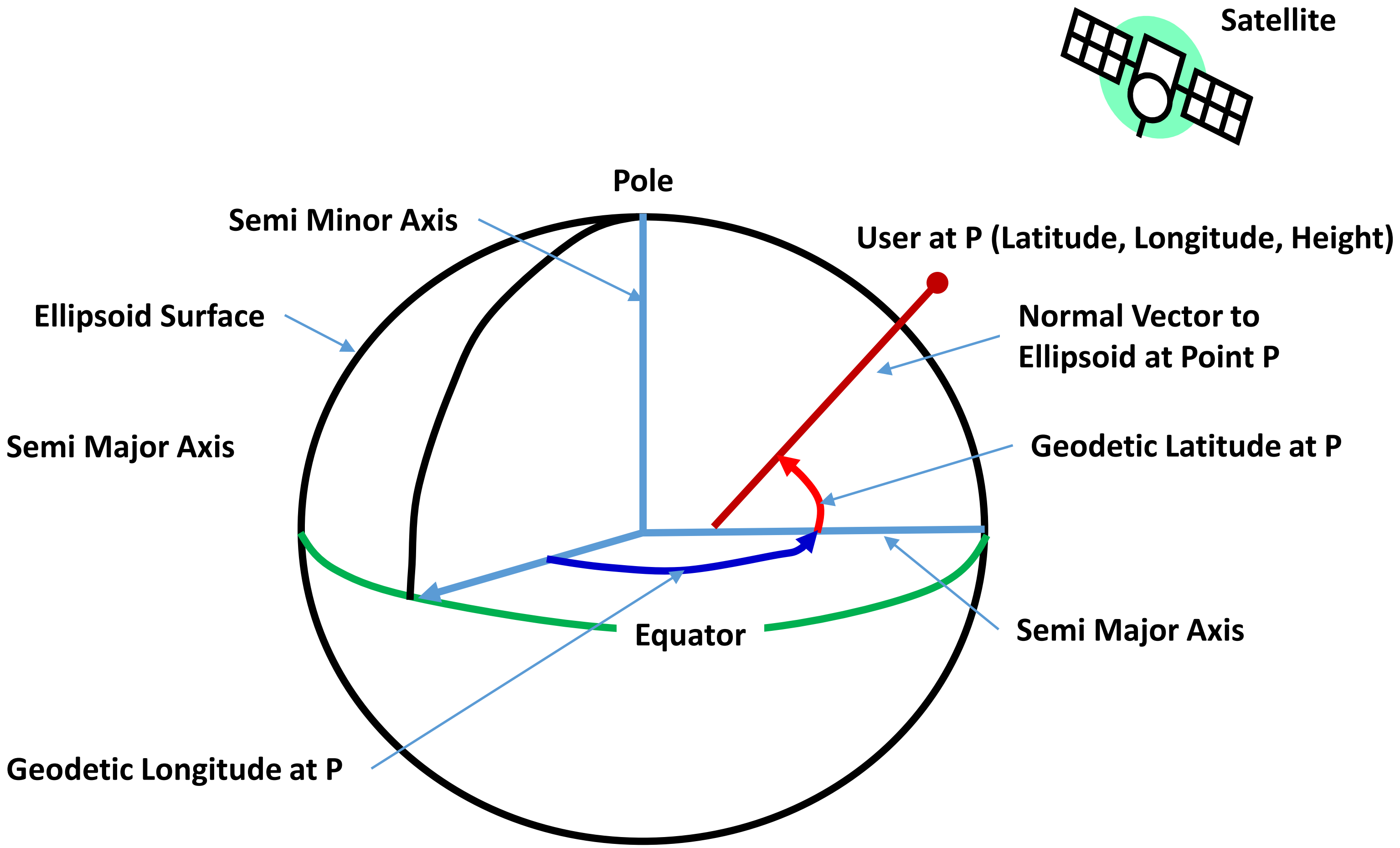
```
   S37 86400       0       0 86400       0       0       0       0      PRN / # OF OBS
   S40 56700       0       0 56700       0       0       0       0      PRN / # OF OBS
CARRIER PHASE MEASUREMENTS: PHASE SHIFTS REMOVED                        COMMENT
                                          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

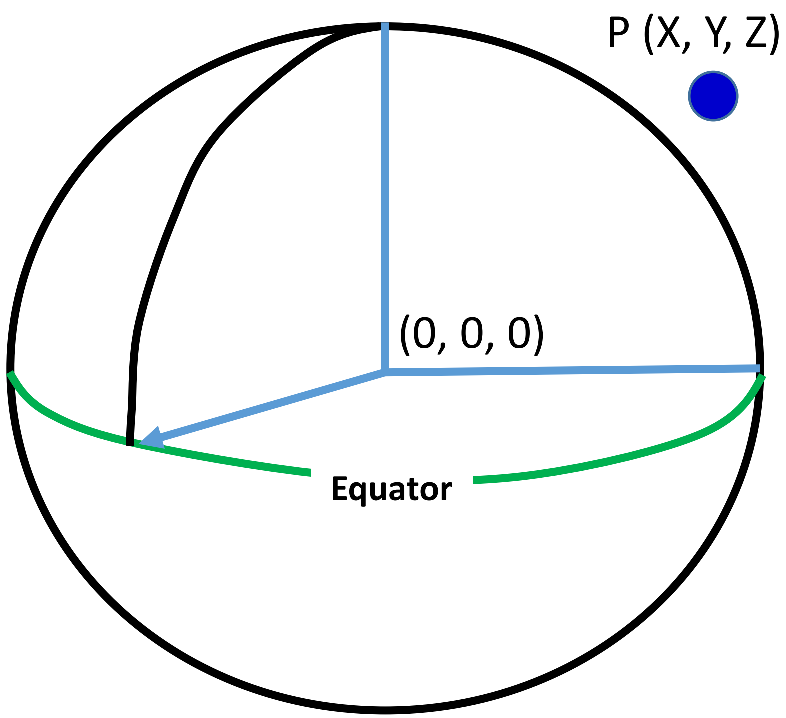
Coordinate Systems

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

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

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

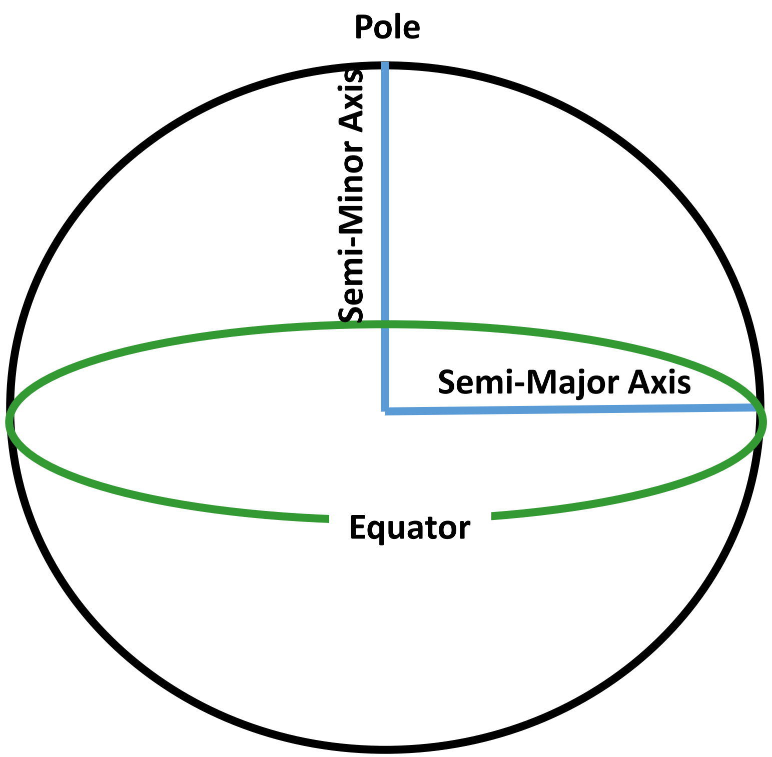
$$h = \frac{P}{\cos\varphi} - \mathrm{N}(\varphi)$$

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

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

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

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

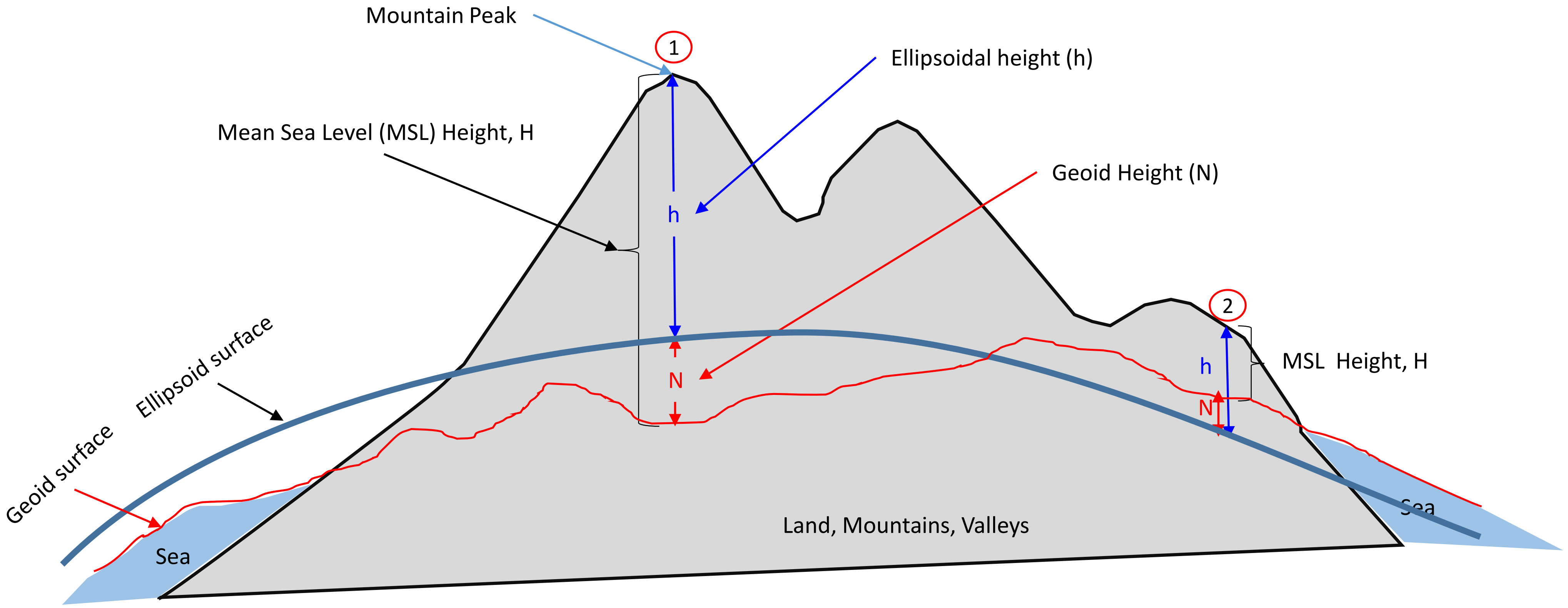
Flattening, f = (a-b)/a

= 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

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

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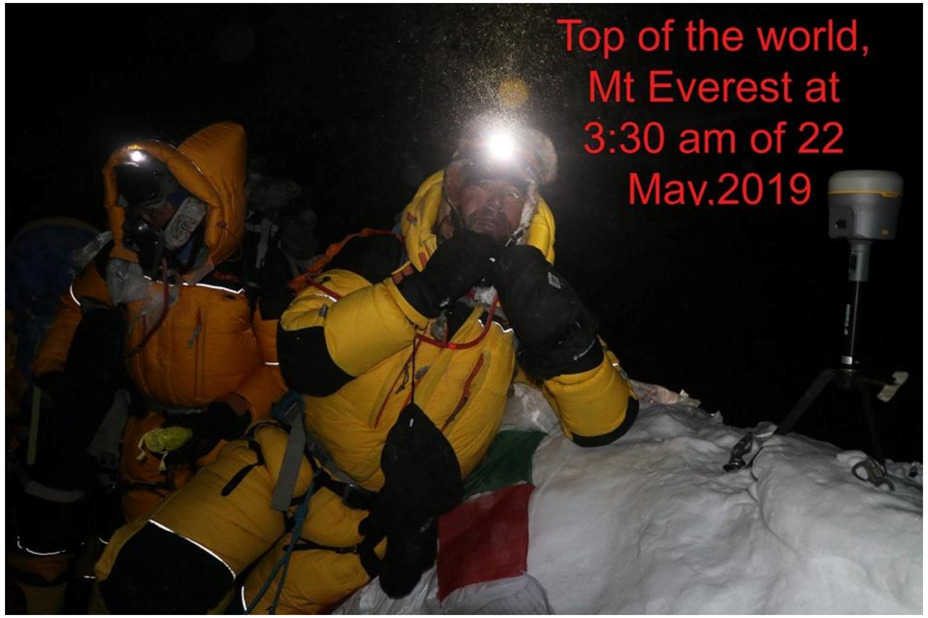
altRef ➔ Altitude above user datum ellipsoid

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

How to Measure the Height of Everest?

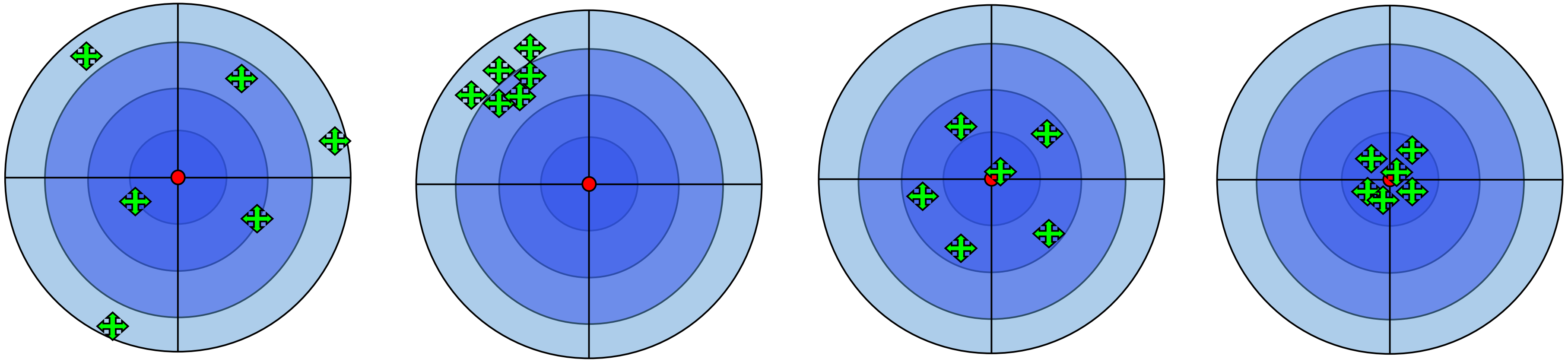
- Measure by GNSS receiver at the peak of the mountain
  - But it gives Ellipsoidal height, how to get Mean Sea Level height?
  - The peak is covered by snow and ice, how to get the true rock height?
  - High-accuracy requires long-time data observation but summiteers can stay for short duration only (about 30 minutes in average)



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

GNSS Applications

GNSS Applications - 1

- Surveying, Mapping and Geodesy
- Transportation
  - Car Navigation, ITS, ADAS, V2X
  - Railway Network
  - Marine : AIS, VMS
  - Aviation : SBAS / GBAS
  - UAV / DRONE
    - 3-D Mapping without GCP
- Vehicle Accidents / Emergency Services
  - eCall/ ERA-GLONASS / E-911
- Taxation / Insurance
  - Taxation based on location or distance traveled

GNSS Applications - 2

- Legal and Law Enforcement
  - Fishing Zone Management, Illegal Fishing Control
  - Crime Prevention
- Agriculture
  - Precise farming, Auto or Semi-Auto Driving of Tractors
  - Product Supply-Chain Management
- Location Based Applications
  - Services, Entertainment, Advertisement, Gaming, Marketing
- Warning during Disasters
  - EWS of QZSS, SAR of GALILEO
- Geo-Fencing / Geo-Securities
- Robotics
  - Navigation, Actions based on Location
- Scientific Applications
  - Space Weather : Scintillation, Radio Occultation, Plasma Bubble

GNSS Applications - 3

- Telecommunication
  - Synchronize cell towers, microsecond order for CDMA
  - Network Time Protocol , millisecond order
- Power Grid
  - Phase Synchronization between grids is required for higher efficiency and avoid power failures
- Time Stamping of
  - Financial and Banking Transactions
  - Legal, Clerical, Shipping Documents
- Scientific Timing Applications
  - Time stamping of events
    - e. g. Global VLBI Observation, earthquake occurrences, arrival of neutrino in particle physics