GNSS basic1

Tokyo University of Marine Science and Technology
Nobuaki Kubo

主な引用先

- 精説GPS（測位航法学会）
- よくわかる衛星測位と位置情報（日刊工業新聞社）
- 内閣府準天頂衛星のHP
- 高須様のHP
- Dr. Feng-Yu Chu氏の資料

- 上記以外は個別に記載

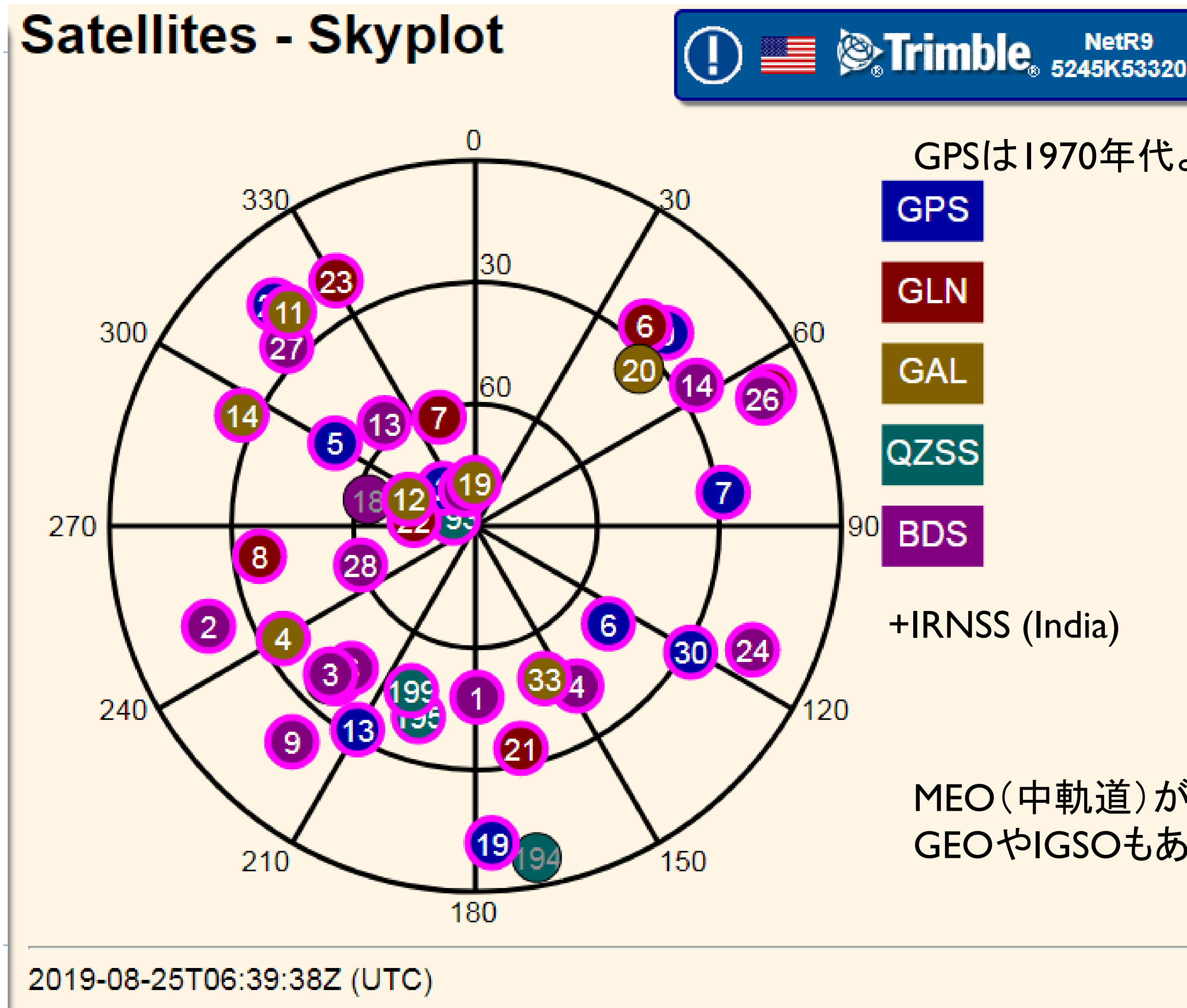
Contents

Basic 1

Basic2

79問の確認用のGoogleフォームでの4択問題があります
70問以上正解してください

Why do we call “GNSS” not “GPS” ?



GPSは1970年代より開発された

+IRNSS (India)

MEO（中軌道）が多く、中には
GEOやIGSOもある

Position

NetR9
5245K533

Position:

Lat:	35° 39' 58.79617" N
Lon:	139° 47' 31.91111" E
Hgt:	61.115 [m]
Type:	Autonomous
Datum:	WGS-84

Velocity:

East:	0.00 [m/s]
North:	0.00 [m/s]
Up:	0.00 [m/s]

Position Solution Detail:

Position Dimension:	3D
Augmentation:	GPS+GLN+GAL+BDS+QZSS
Height Mode:	Normal
Correction Controls:	Off

Satellites Used:39

GPS(9):	2, 5, 6, 7, 9, 13, 19, 29, 30
GLONASS(7):	6, 7, 8, 16, 21, 22, 23
Galileo(6):	4, 11, 12, 14, 19, 33
BeiDou(14):	1, 2, 3, 4, 6, 8, 9, 13, 14, 16, 24, 26, 27, 28
QZSS(3):	193, 195, 199

Satellites Tracked:40

GPS (9):	2, 5, 6, 7, 9, 13, 19, 29, 30
GLONASS (7):	6, 7, 8, 16, 21, 22, 23
Galileo (7):	4, 11, 12, 14, 19, 20, 33
BeiDou (14):	1, 2, 3, 4, 6, 8, 9, 13, 14, 16, 24, 26, 27, 28
QZSS (3):	193, 195, 199

Receiver Clock:

GPS Week:	2068
GPS Seconds:	24038
Offset:	0.00000 [msec]
Drift:	0.00000 [ppm]

Multi-System Clock Offsets:

Master Clock System:	GPS
GLONASS Offset:	-29.6 [ns]
Galileo Offset:	-5.4 [ns]
BeiDou Offset:	-13.4 [ns]

Dilutions of Precision:

PDOP:	0.8
HDOP:	0.4
VDOP:	0.7
TDOP:	0.5

Error Estimates(1σ):

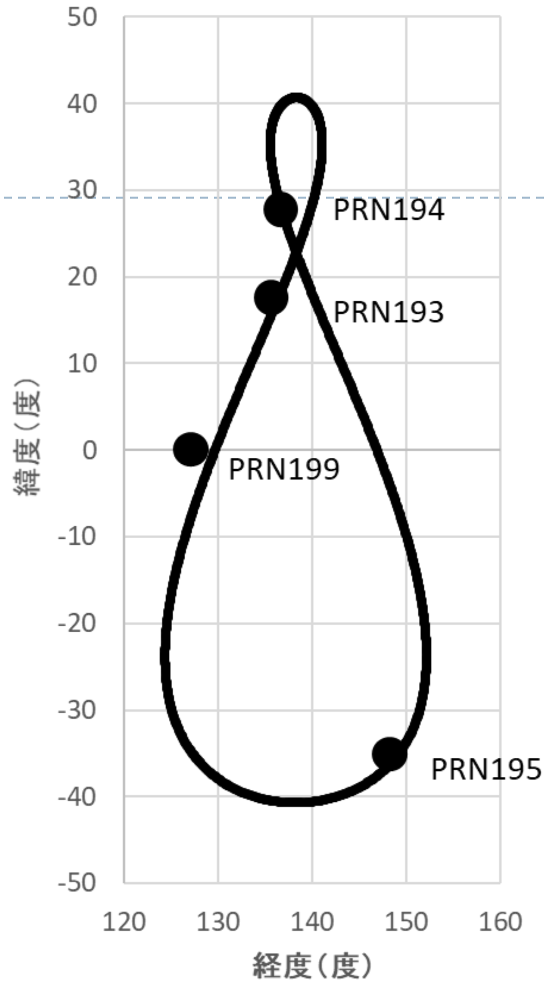
East:	0.268 [m]
North:	0.274 [m]
Up:	0.580 [m]
Semi Major Axis:	0.275 [m]
Semi Minor Axis:	0.268 [m]
Orientation:	167.7°

PVT

Position

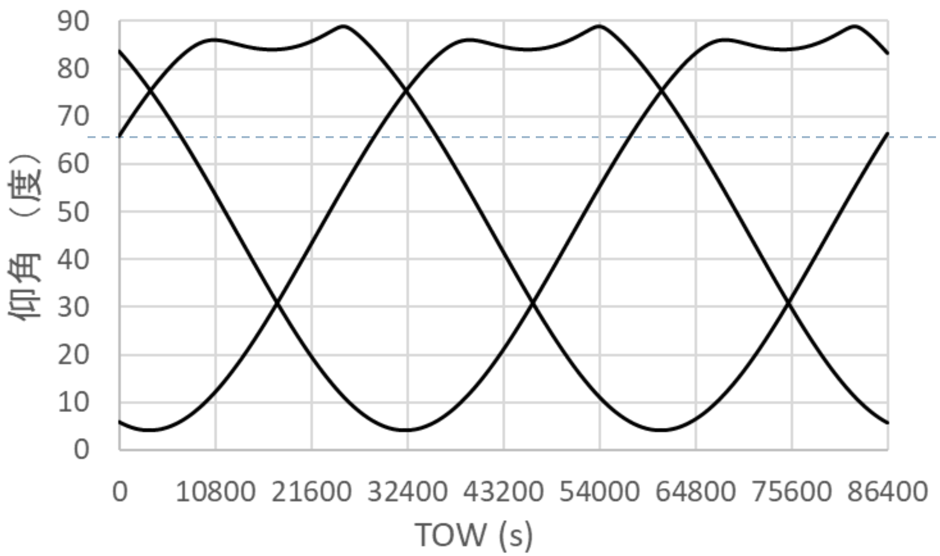
Velocity

Time

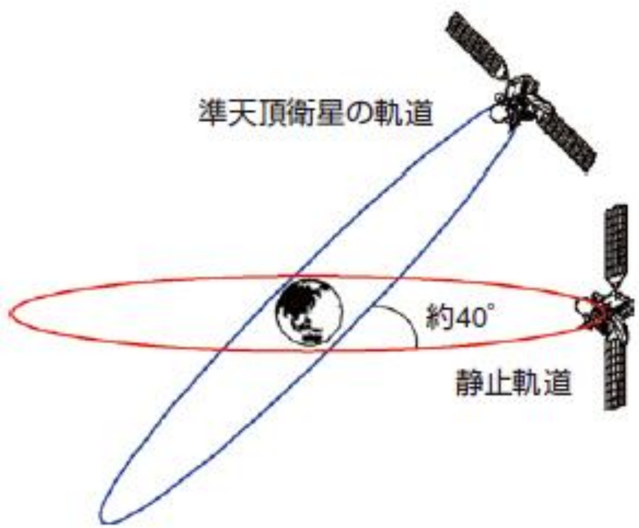


日本の準天頂衛星はGPSと同様の信号を放送
→測位補完
L1-C/A, (L1C), L2C, L5 + LEX (L6)
L6信号は異なり、補正データ等を放送
→測位補強
＋災害危機情報も送信（気象庁ベース）

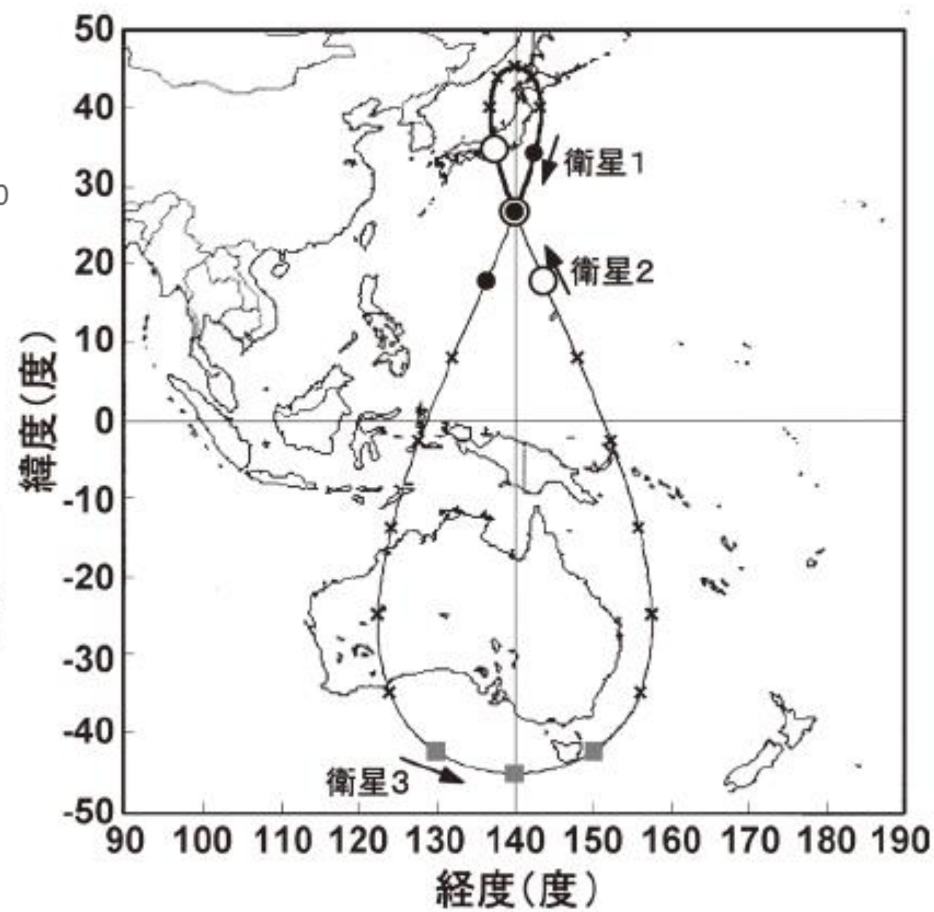
都市	札幌	仙台	東京	名古屋	大阪	福岡	沖縄
平均衛星数（4機）	3.3	3.5	3.6	3.6	3.6	3.6	4.0
平均衛星数（7機）	6.1	6.3	6.4	6.5	6.5	6.5	7.0



東京で最低でも約75度以上



準天頂衛星の軌道



準天頂衛星が地球に対して描く軌跡

位置を推定するための技術

- 衛星測位の前（Transit、ドップラ測位、ロラン）
- 衛星測位→開けた場所でスマホでも数m（世界中）→アンテナをよくすると改善。測位衛星は衛星位置と測距用のコードを送信するだけ
- Wifi、UWB、Radar、RFID…
- 電波航法（ILSやMLS）
- 他にも様々の方法があるが、昔からある技術はINS（inertial navigation system）

- INSでは、加速度と角速度を積分することで、移動体の姿勢を位置を推定する。初期位置は与える必要がある

船と飛行機の位置情報

- AIS

[MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic]

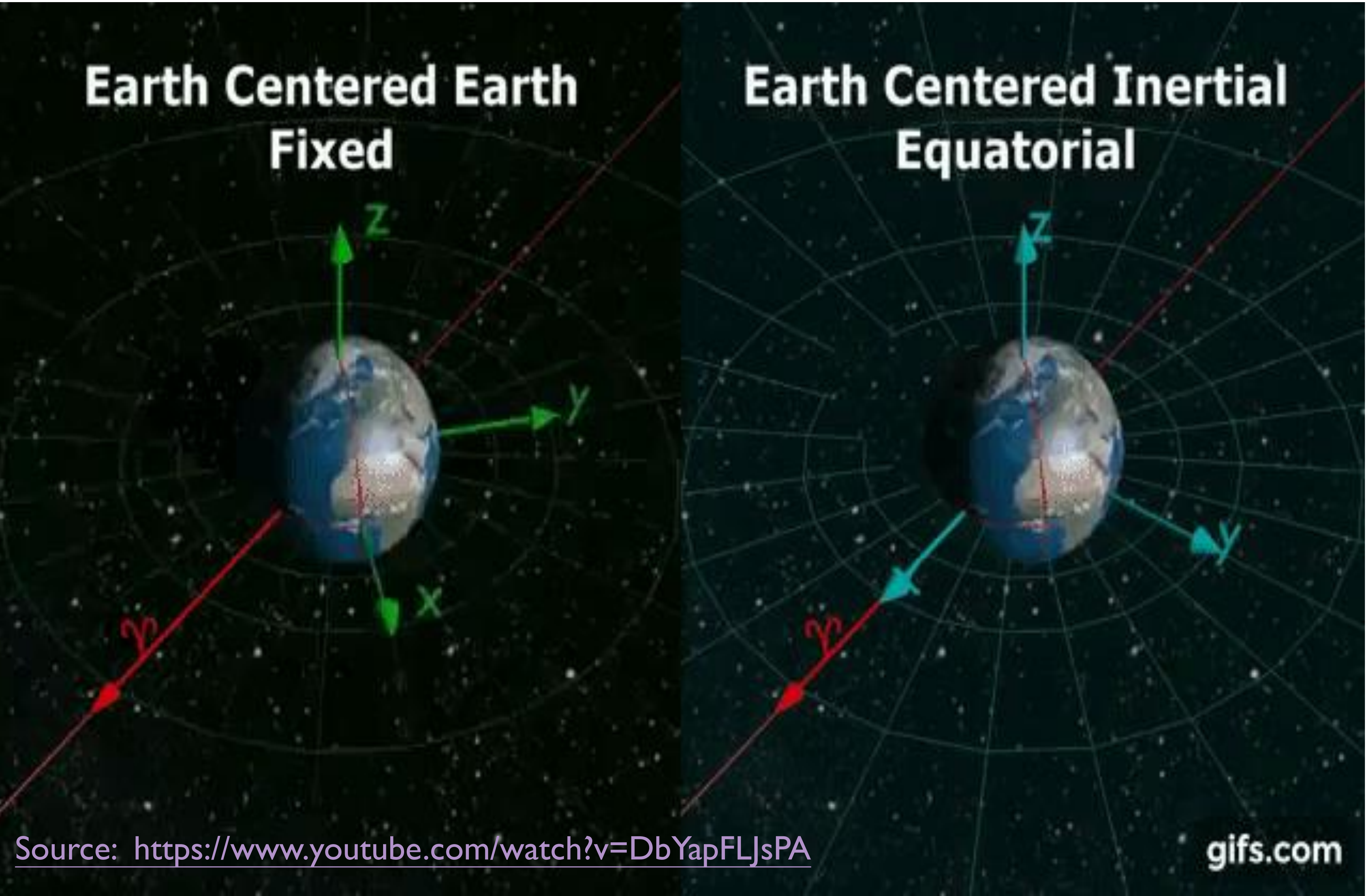
- Flight Radar

[Flightradar24: Live Flight Tracker - Real-Time Flight Tracker Map]

Coordinate systems

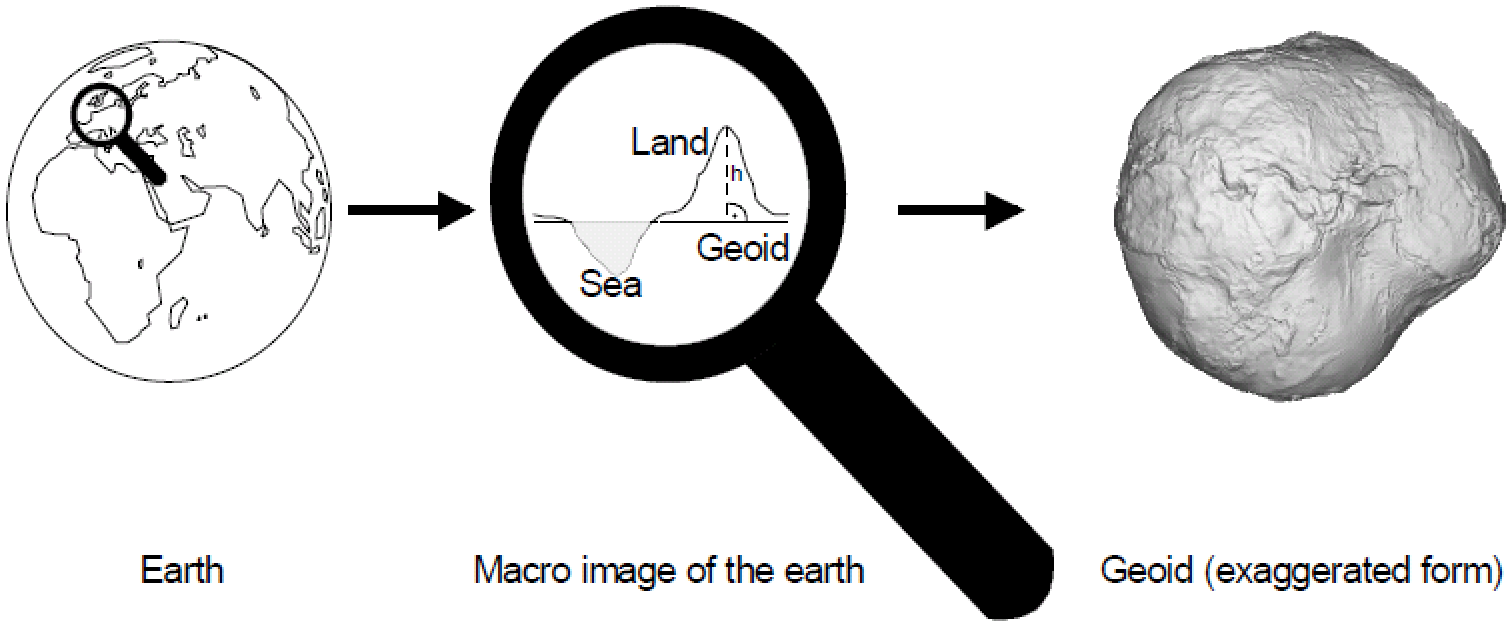
- A significant problem to overcome when using a GNSS system is the fact that there are a great number of different coordinate systems worldwide.
- As a result, the position measured and calculated does not always correspond with one's supposed position.
- In order to understand how GNSS systems function, it is necessary to examine some of the basics of geodesy.

A Demonstration of ECI and ECEF Coordinate System



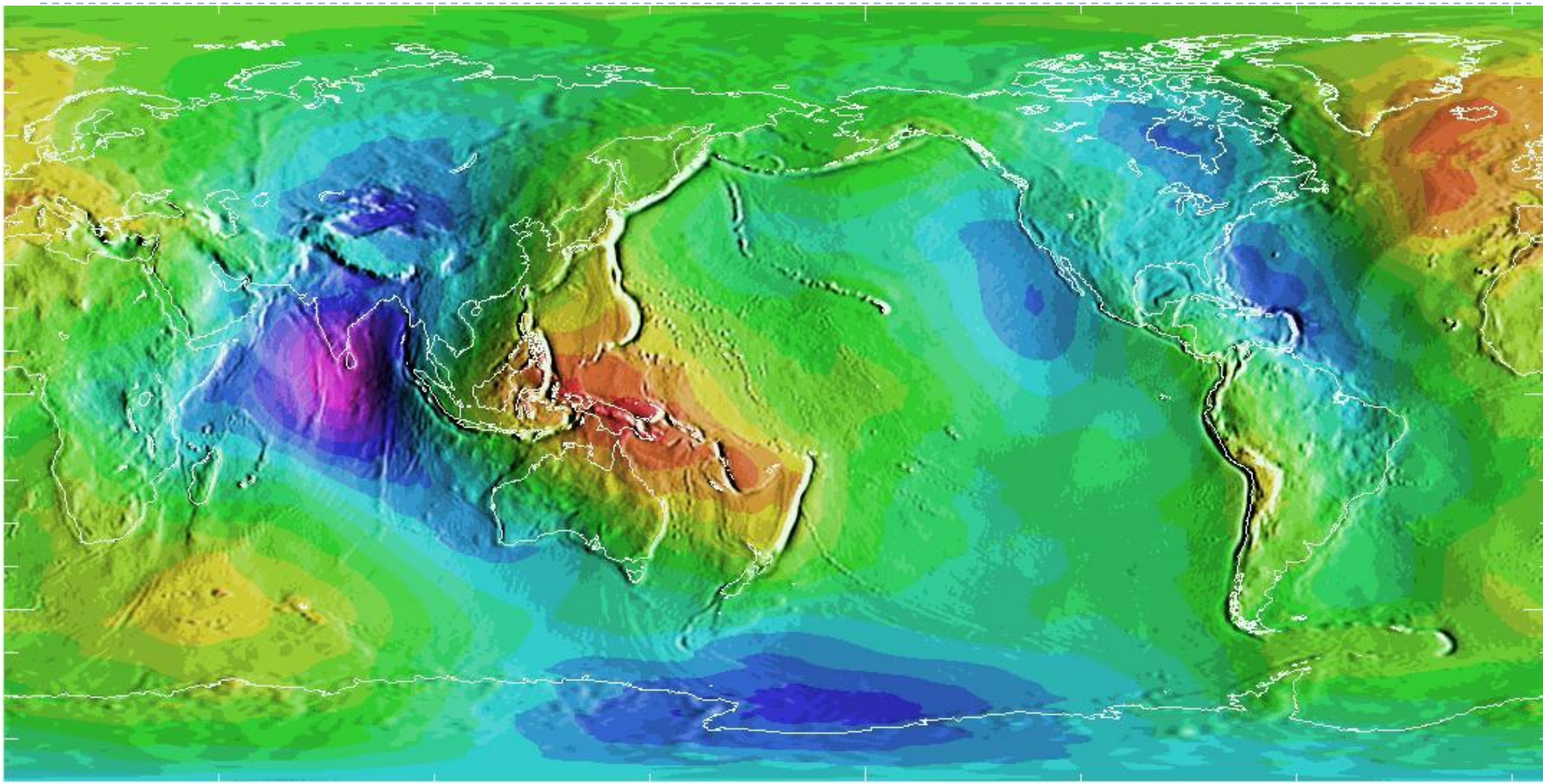
Source: https://www.youtube.com/watch?v=DbYapFLJsPA

What is Geoid ?



- The Geoid represents the true shape of the earth; defined as the surface, where the mean sea level is zero. However, a Geoid is a difficult shape to manipulate when conducting calculations.

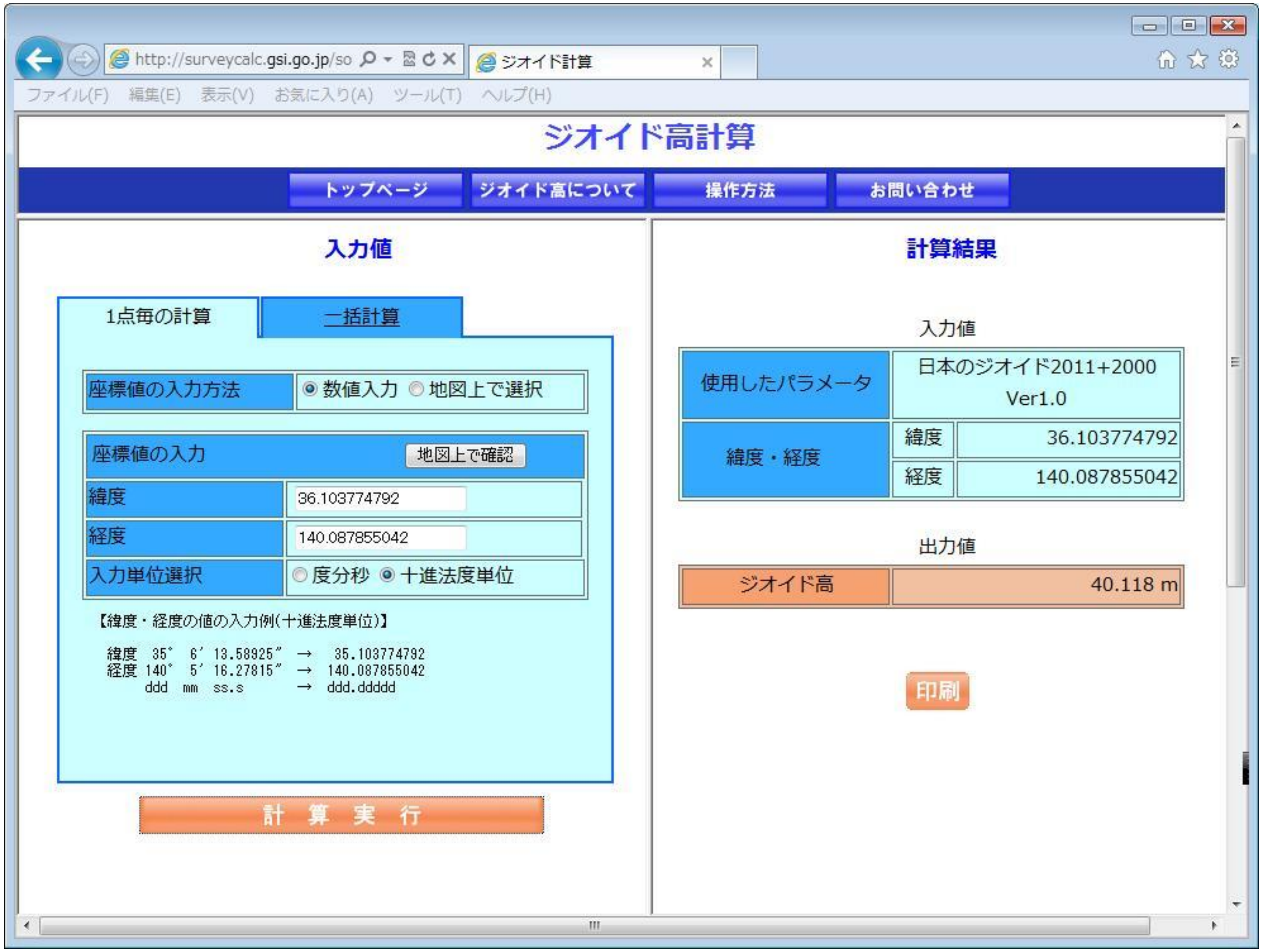
World Geoid



http://principles.ou.edu/earth_figure_gravity/geoid/

Color Scale, Upper (Red) : 85.4 meters and higher;
Color Scale, Lower (Magenta) :-107.0 meters and lower

Geoid Height in Japan

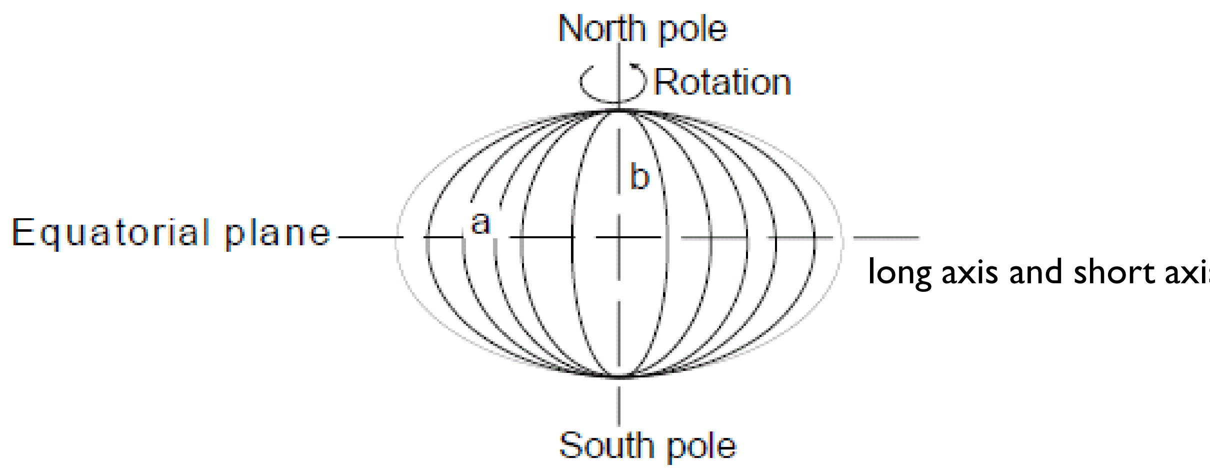


- TUMSAT
  - 36.41 m
- Narita
  - 35.24 m
- Mt. Fuji
  - 42.50 m
- Osaka
  - 37.45 m

https://vldb.gsi.go.jp/sokuchi/surveycalc/geoid/calcgh/calcframe.html

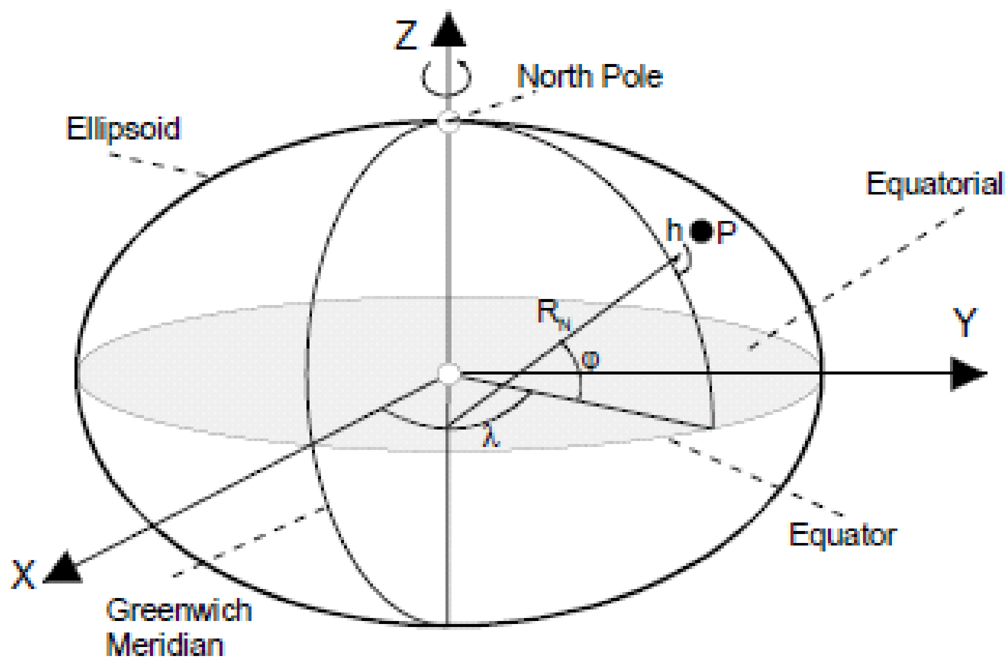
What is Ellipsoid ?

$$f = \frac{a - b}{a}$$



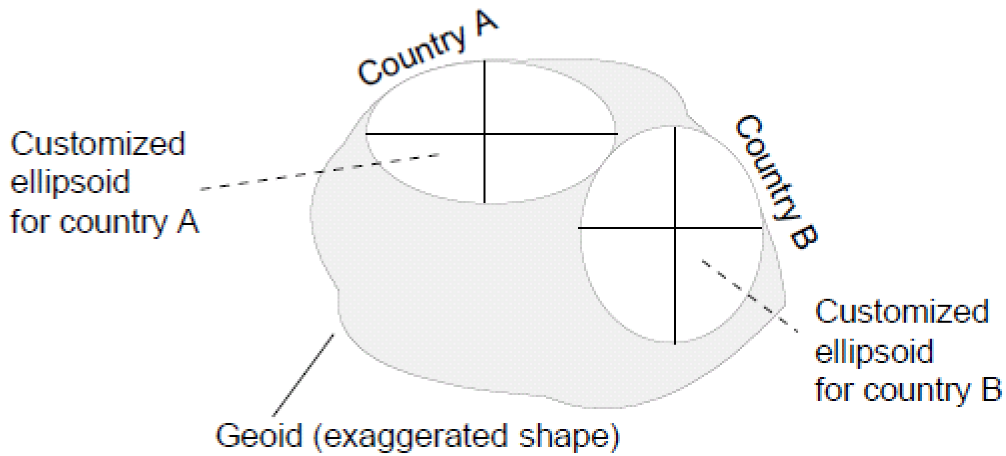
- A simpler, more definable shape is needed when carrying out daily surveying operations. Such a substitute surface is known as an ellipsoid. A spheroid is obtained like the above figure.

Ellipsoidal Coordinates

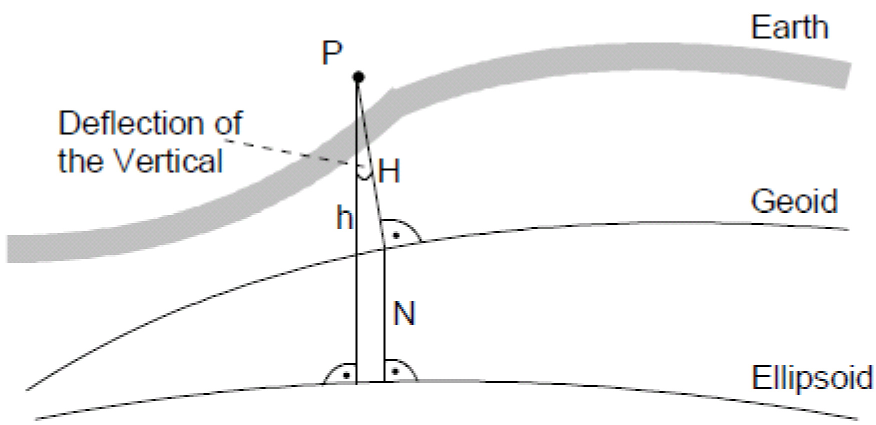


Ellipsoidal coordinates (Φ, λ, h), rather than Cartesian coordinates (X, Y, Z) are generally used for further processing. Φ corresponds to latitude, λ corresponds to longitude and h to the Ellipsoidal height.

Datum, map reference system



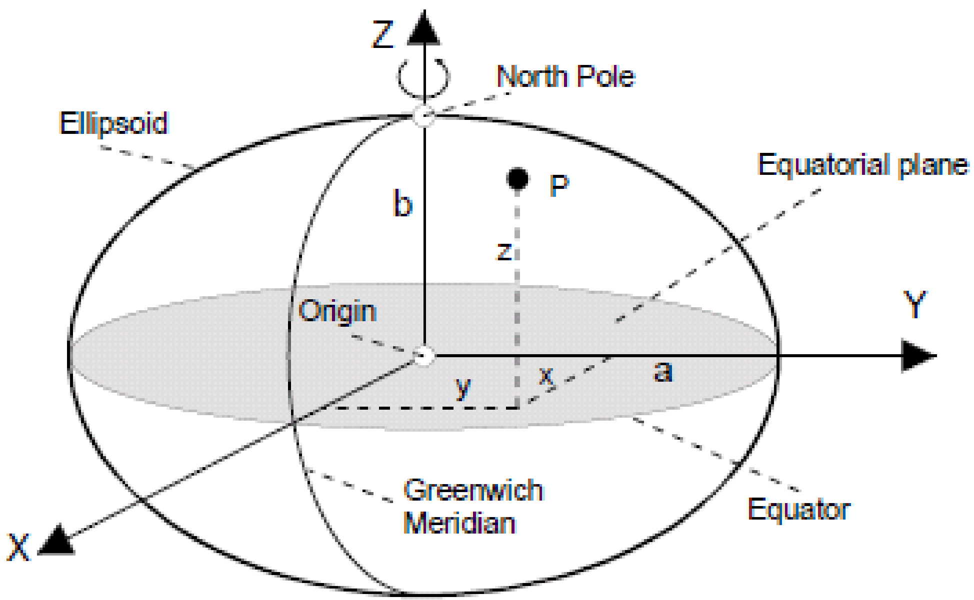
Each country has developed its own customized non-geocentric ellipsoid as a reference surface for carrying out surveying operations.



An ellipsoid is well suited for describing the positional coordinates of a point in degrees of longitude and latitude.

Ellipisodal Height = Undulation (H) + Geoid Height (N)

Worldwide reference ellipsoid WGS-84 (World Geodetic System 1984)



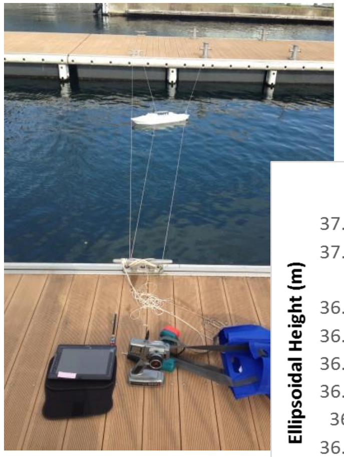
Parameter of WGS-84 Reference Ellipsoids		
Semi major axis a (m)	Semi minor axis b (m)	Flattening (1: ....)
6,378,137.00	6,356,752.31	298,257223563

- **GPS adopts this WGS-84 as a coordinate system.**
- The WGS-84 coordinate system is geocentrically positioned with respect to the center of the Earth. Such a system is called ECEF (Earth Centered, Earth Fixed)
- The WGS-84 is a three-dimensional, right-handed, Cartesian coordinate system.

Ellipsoidal Height (GPS)
= Geoid Height + Orthometric Height

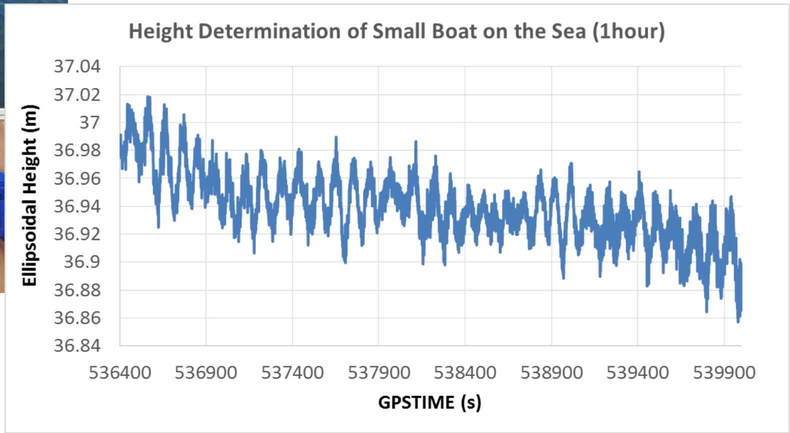
24m

Geoid = 36m (MSL)
GPS Height = 60m



セミナーを実施する建物は
第4実験棟の5階：標高24m程度

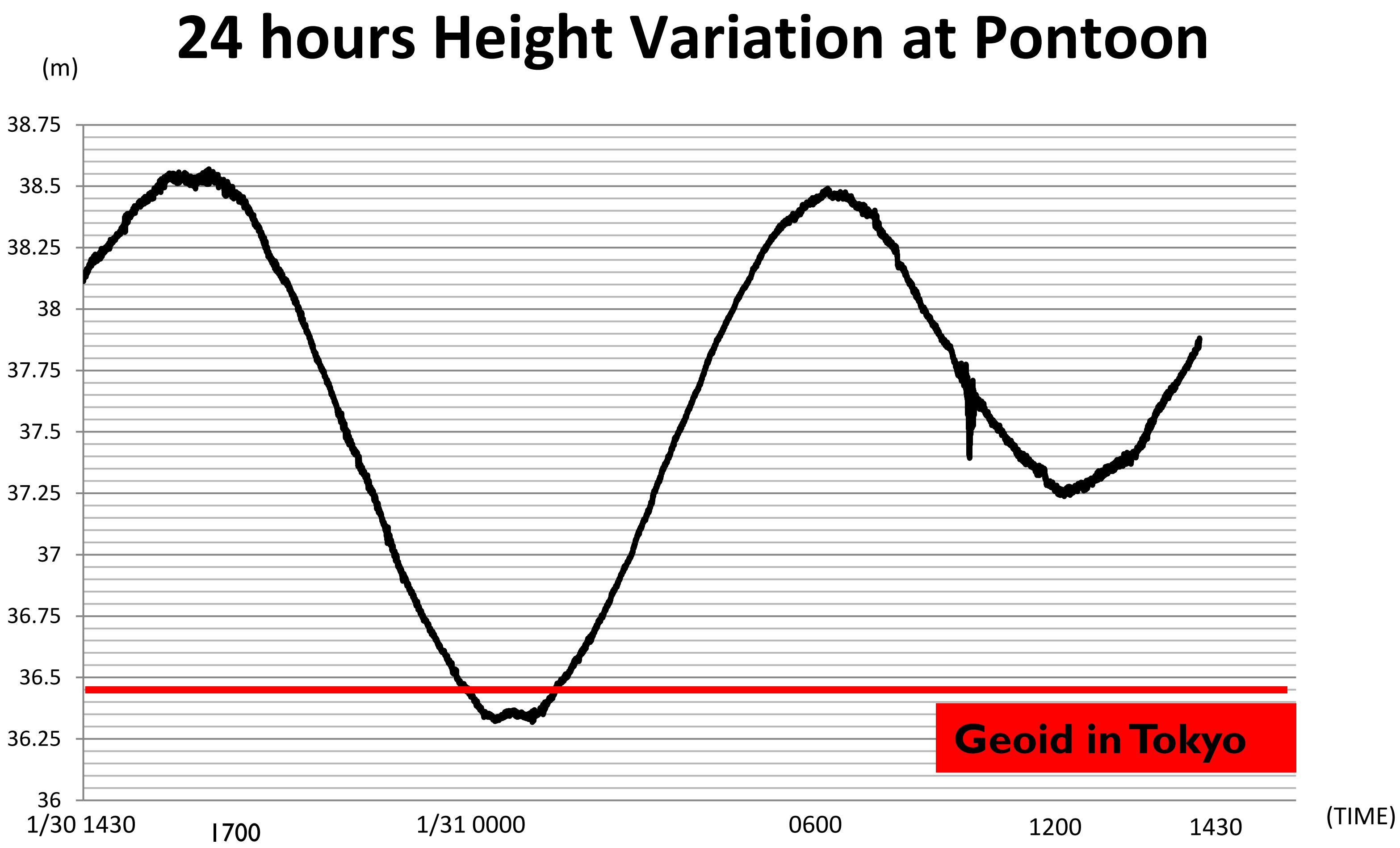
36m



WGS84 Ellipsoid

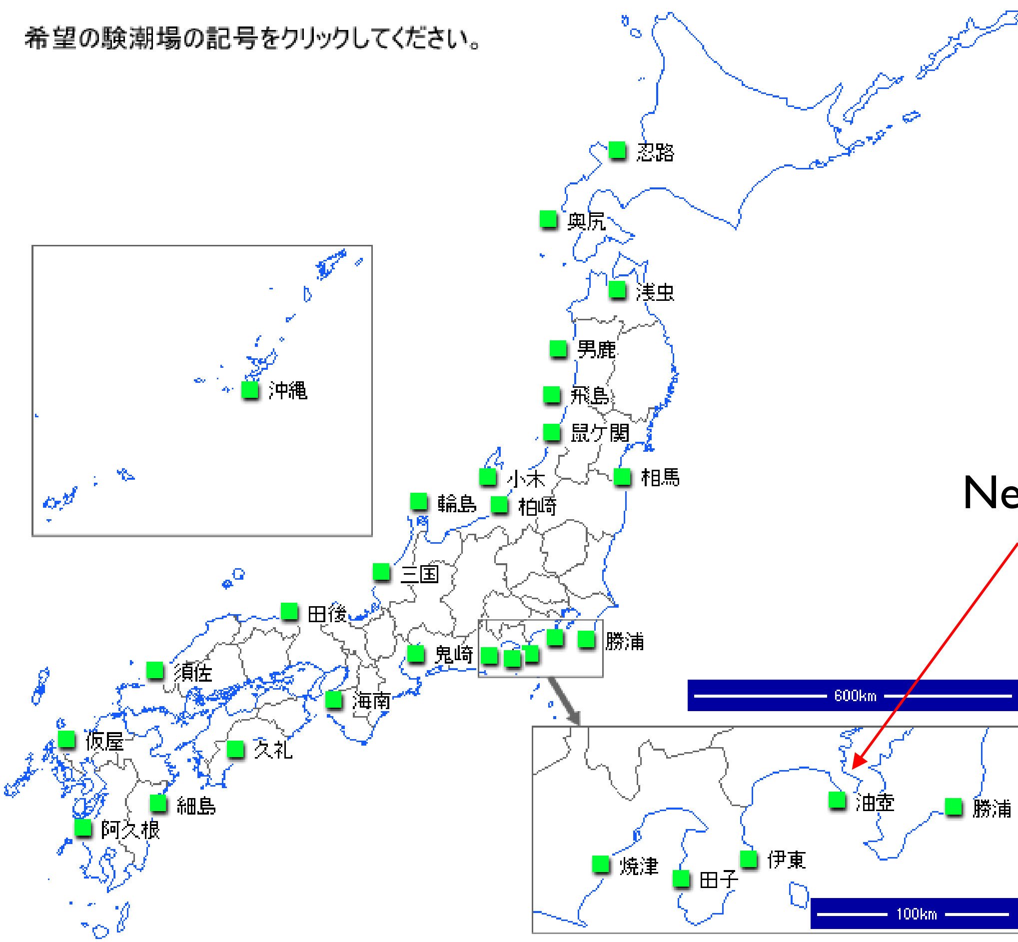
Tide Observation

RTK at Pontoon



Geoid was not the average of the tide variation here…

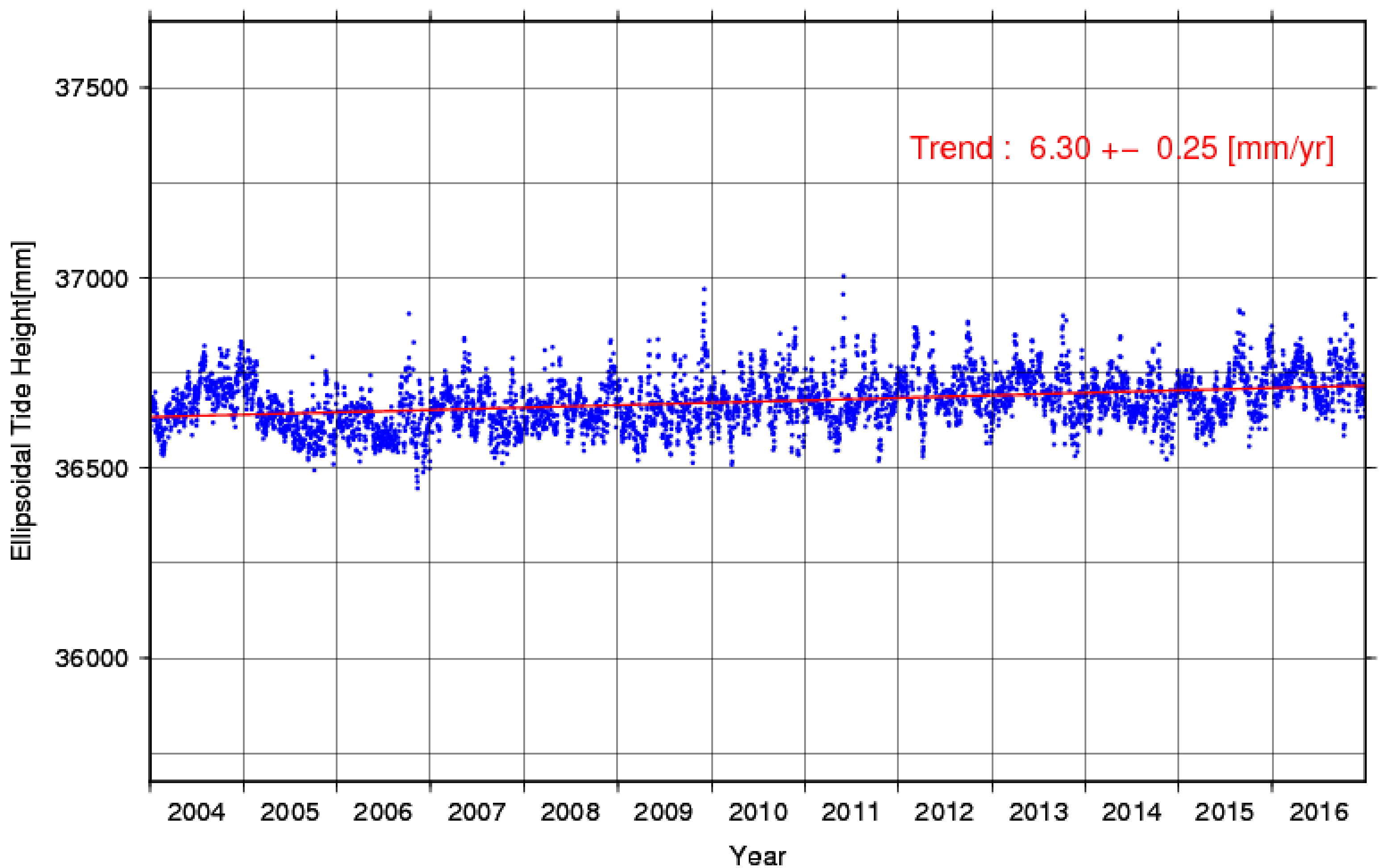
Average ocean level over 10 years



Next slide

Provided by Geospatial Information Authority of Japan

Trend – 01_Aburatsubo



Provided by Geospatial Information Authority of Japan

How about GLO, GAL, BeiDou ?

- Each navigation system uses the different coordinates system, but the coordinates for Galileo and BeiDou are quite similar to WGS84.
- GLONASS adopts PZ-90.02. We need to consider the difference if we combine GPS and GLONASS.

Quiz

- Calculate the distance (mm level) between the following two surveyed positions.

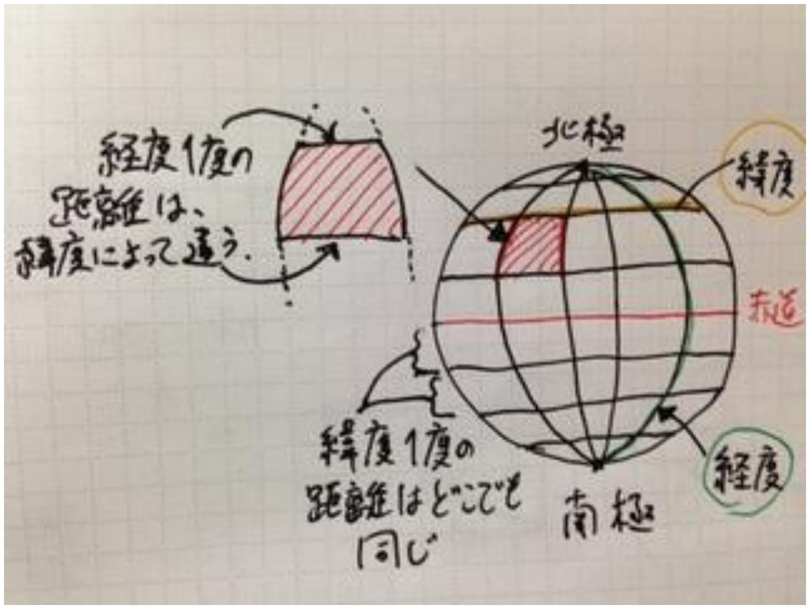
#1 35.6662474, 139.7923025

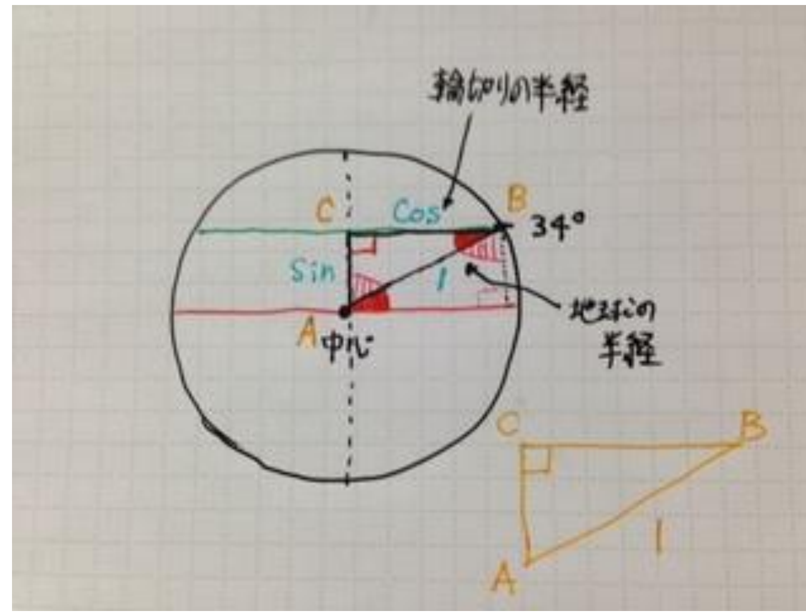
#2 35.6662475, 139.7923025

seventh decimal place

http://vldb.gsi.go.jp/sokuchi/surveycalc/surveycalc/bl2stf.html

Distance per degree of longitude





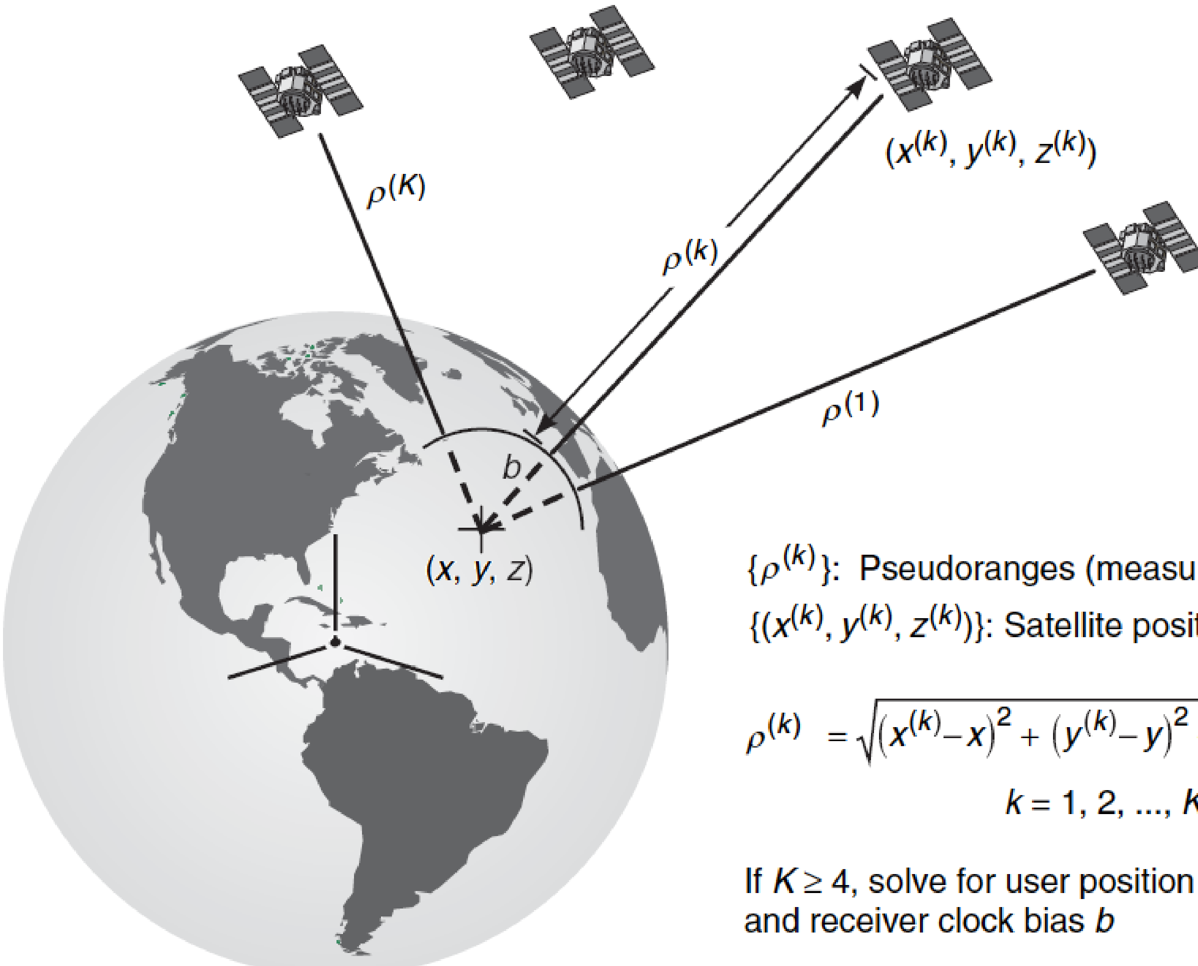
Place	Distance (very roughly)
Equator	111 km
Tokyo	91 km
Hokkaido	80 km
Siberia	38 km

Satellite Position Estimation

- Two critical things in GNSS. Satellite position and range measurement.
- There are two methods in the satellite position estimation. One is based on **almanac (1km accuracy)** data. The another one is based on **ephemeris (1m accuracy)** data. These are the parameters to estimate satellite position.
- Speed of GPS satellite is about 4 km/s.

これらエフェメリスの情報は測位衛自身から放送され、それをデコードする。
その際に位相追尾が必要なので、それなりの受信環境が必要。
AGPSでは、この情報を携帯回線で受信でき、すぐに測位できる

Satellite position and Range



$\{\rho^{(k)}\}$: Pseudoranges (measurements)

$\{(x^{(k)}, y^{(k)}, z^{(k)})\}$: Satellite positions (known)

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

$$k = 1, 2, \ldots, K$$

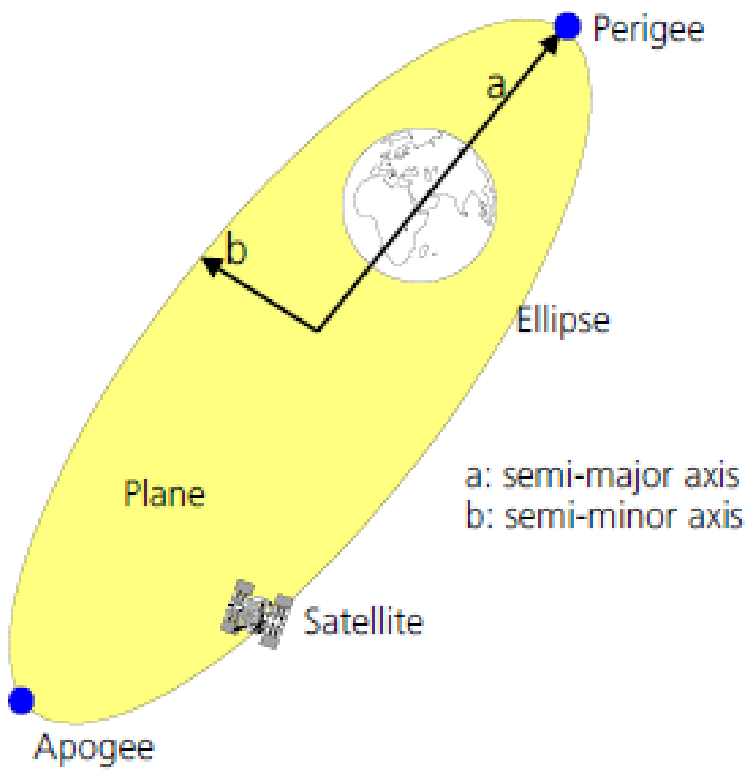
If $K \geq 4$, solve for user position (x, y, z), and receiver clock bias b

Keplerian Elements

- Epoch (time)

- Semi-major Axis (km)
- Eccentricity
- Inclination (radian)
- RAAN (Right Ascension of Ascending Node) (radian)
- Argument of Perigee (radian)
- Mean Anomaly (radian)

Kepler’s first law



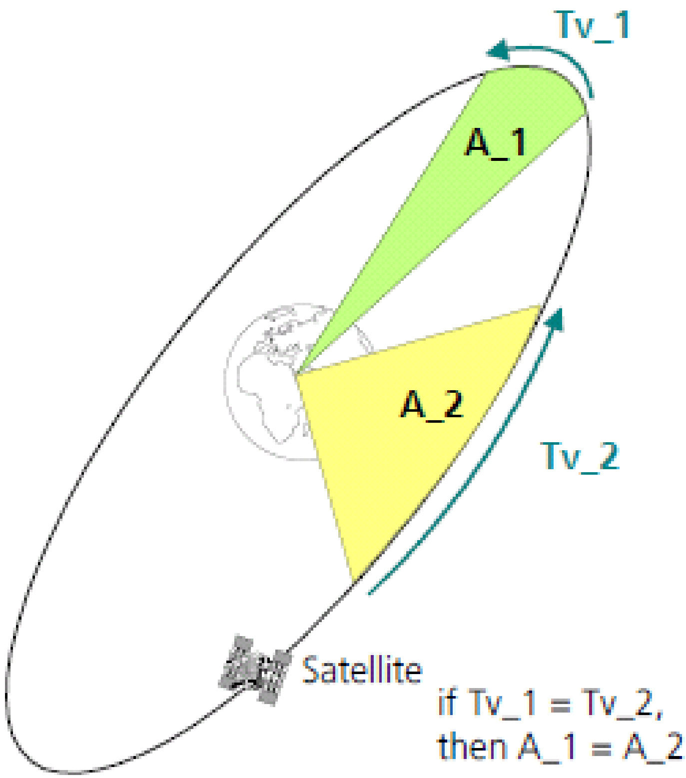
- The Apogee expresses the furthest point of an elliptical orbit from the canter of the Earth.
- The Perigee is the closest point of the orbital ellipse to the Earth.

Semi-major axis and Eccentricity

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

① ②

Kepler's second law



- The second law states that: "A line joining a planet and the sun sweeps out equal areas during equal intervals of time"
- For satellites this means left figure.

Kepler's third law

$\frac{P^2}{a^3}$ is constant for all planets.

P = orbital Period, a = semi-major axis of the orbital ellipse

$$h = \sqrt[3]{3{,}9860042 \bullet 10^{14}\,\frac{m^3}{s^2} \bullet \left(\frac{P}{2\pi}\right)^2} - R_e \qquad [m]$$

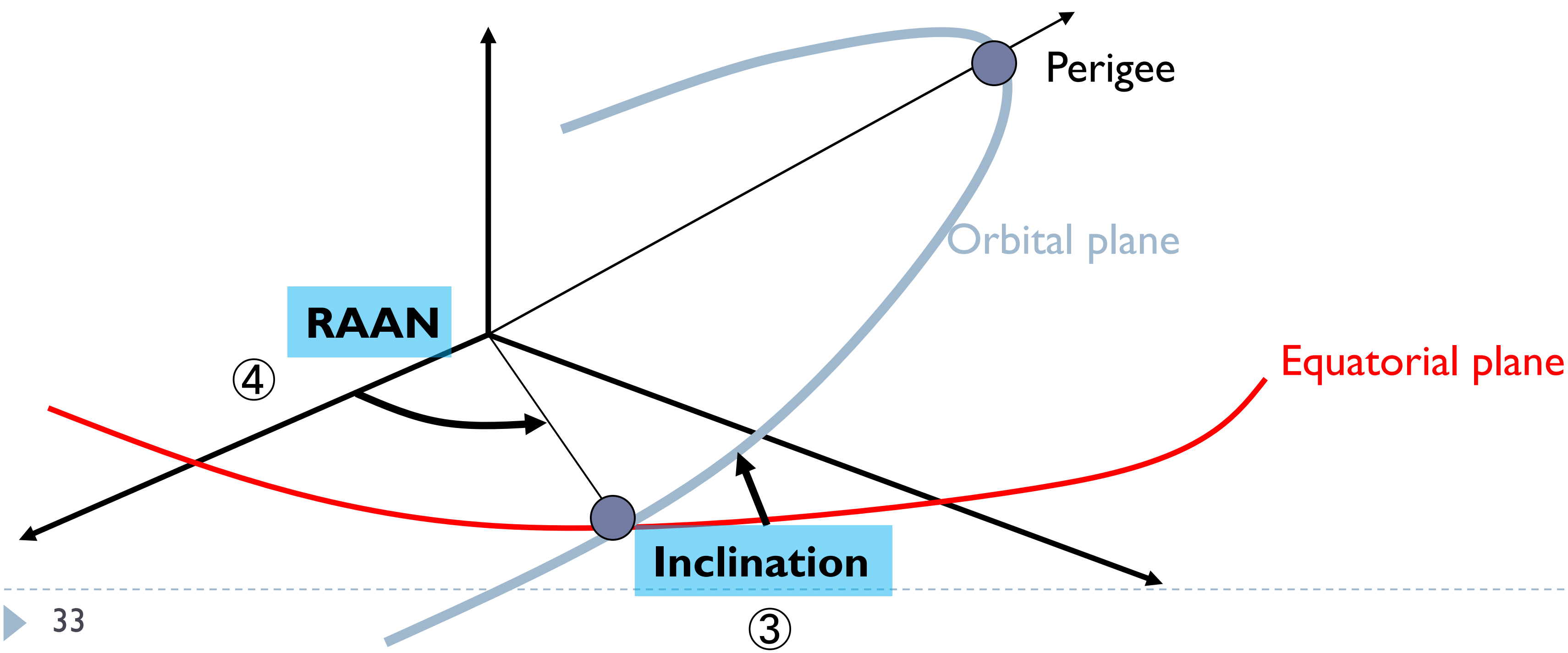
R_e: Radius of the Earth (6378.137km)

P: orbital period of the satellite around the Earth

- This law states that the squares of the orbital periods of planets are directly proportional to the cubes of the semi-major axis of the orbits.

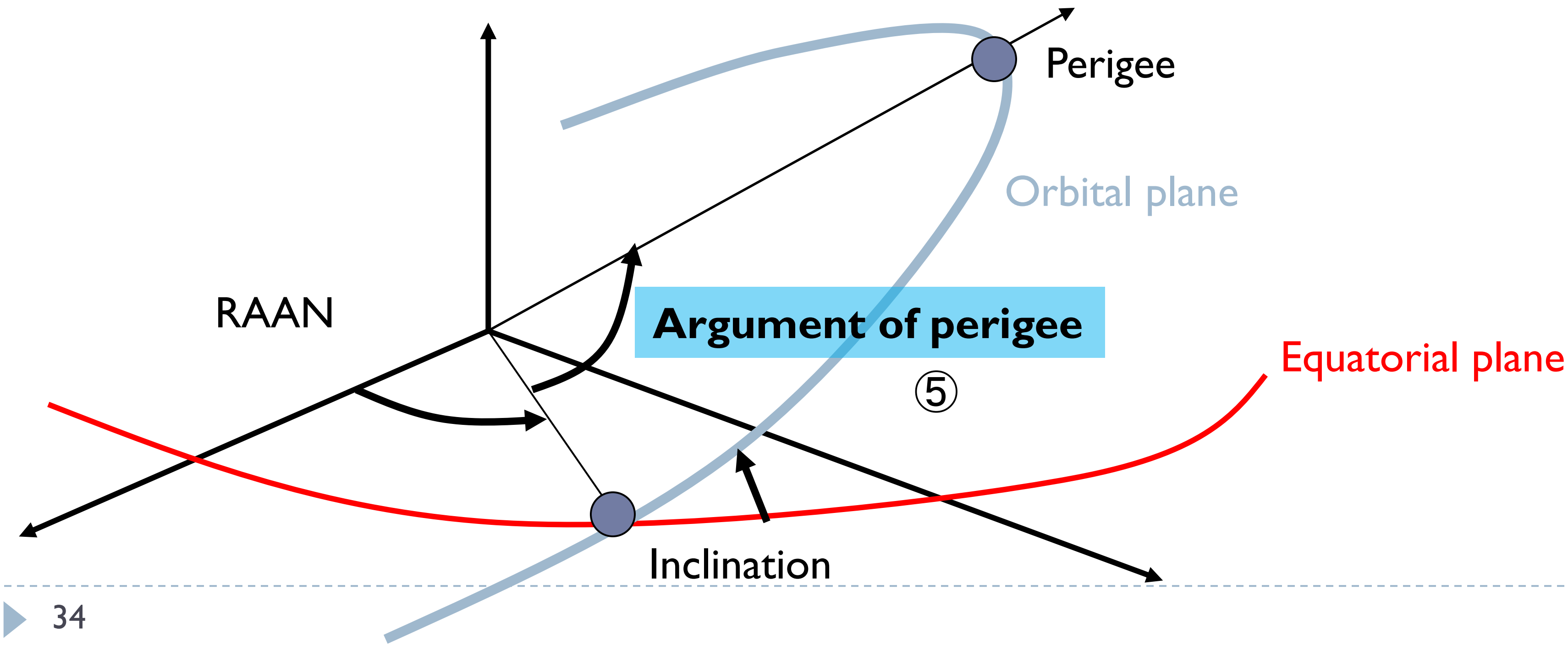
Orbital Plane

- **Inclination** : the angle between orbital plane and equatorial plane
- **Right Ascension of Ascending Node** : the geocentric R.A. of a satellite as it intersects the Earth's equatorial plane traveling northward (ascending)



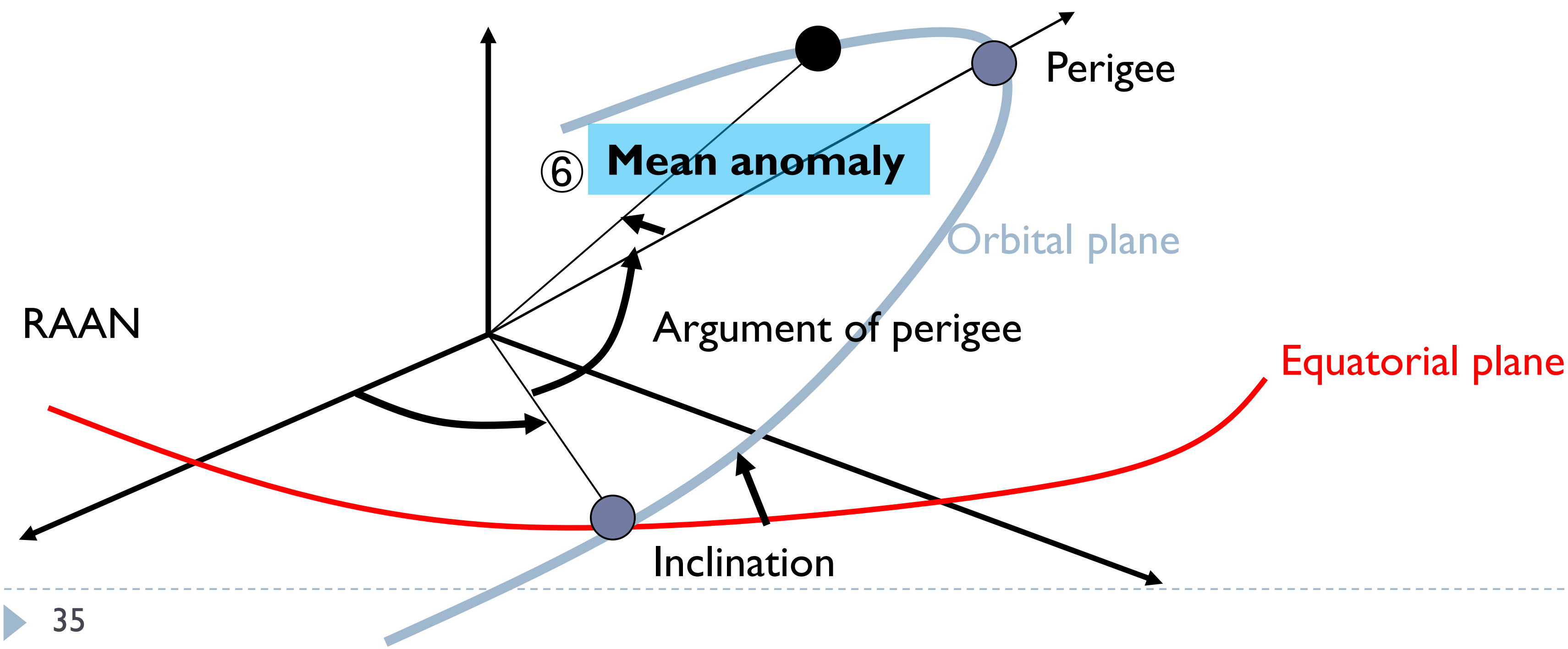
Direction of a semi-major axis

- **Argument of Perigee** : the angle between the perigee and the orbit's RAAN



Satellite position on orbital plane

- Mean anomaly : relating position and time for a body moving in a orbital plane



Almanac

```
******** Week 424 almanac for PRN-01 ********
ID:                           01
Health:                       000
Eccentricity:                 0.6912231445E-002
Time of Applicability(s):     405504.0000
Orbital Inclination(rad):     0.9911766052
Rate of Right Ascen(r/s):    -0.7417838788E-008
SQRT(A)  (m 1/2):             5153.549316
Right Ascen at Week(rad):    -0.1640348434E+000
Argument of Perigee(rad):    -1.812852621
Mean Anom(rad):              -0.1197433472E+000
Af0(s):                       0.1583099365E-003
Af1(s/s):                     0.3637978807E-011
week:                         424
```

- The current Almanac/Ephemeris Data can be viewed over the internet.
- <u>Accuracy</u>

  <u>Almanac: 100-1000m 1week</u>

  <u>Ephemeris: 1-2m 2hours</u>

Ephemeris

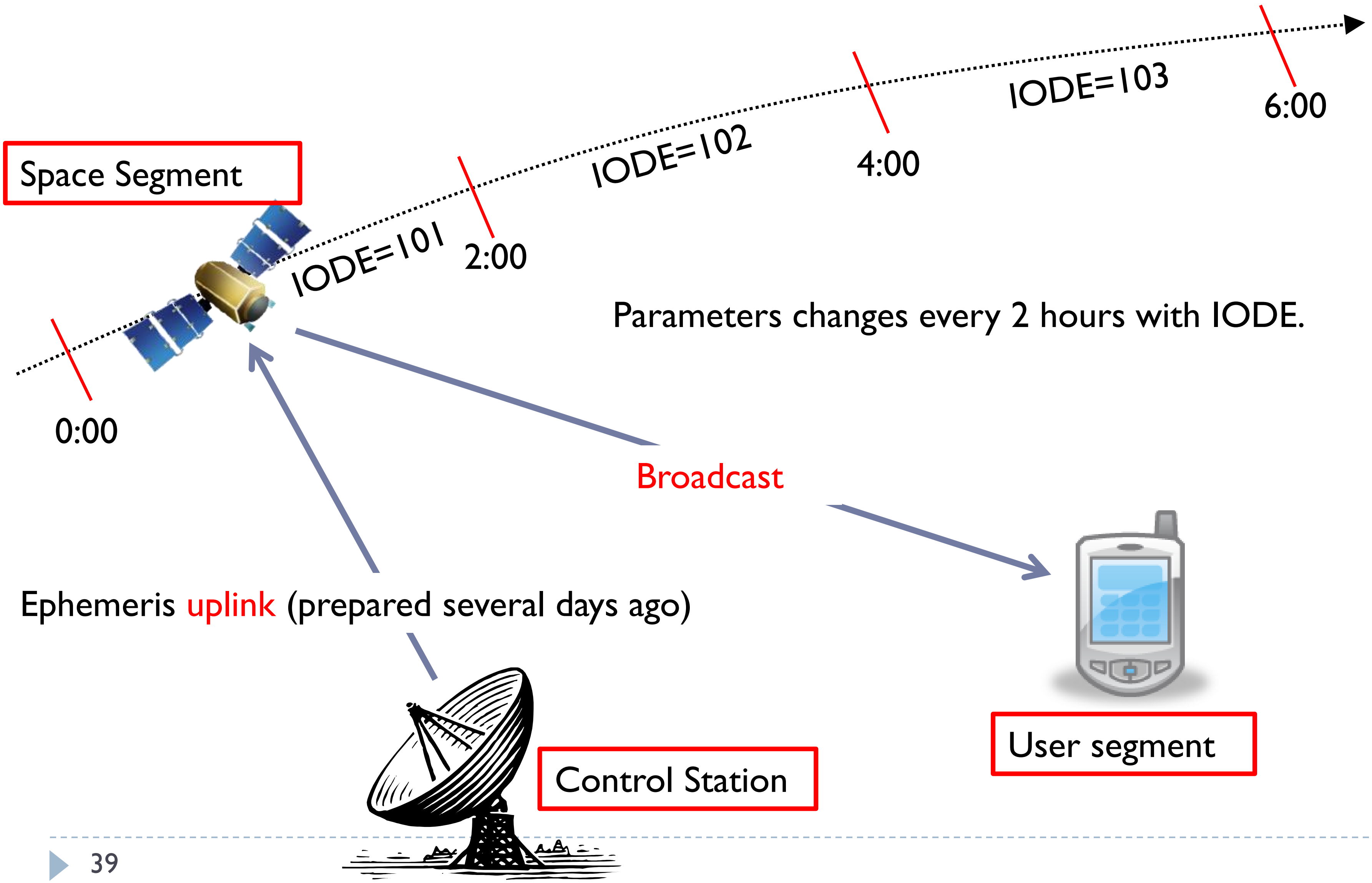
- All receivers positioning engine uses Ephemeris. Almanac is used for rough estimation(ELE/AZI).
- Ephemeris = Almanac + Perturbation
- 16 coefficients
- Calculating satellite position based on several equations shown in ICD(interface control document) is very simple.
- Accuracy : 1-2m, 2 hours life for GPS

Perturbation

- **Perturbation** is the complex motion of a massive body subject to forces other than the gravitational attraction of a single other massive body.

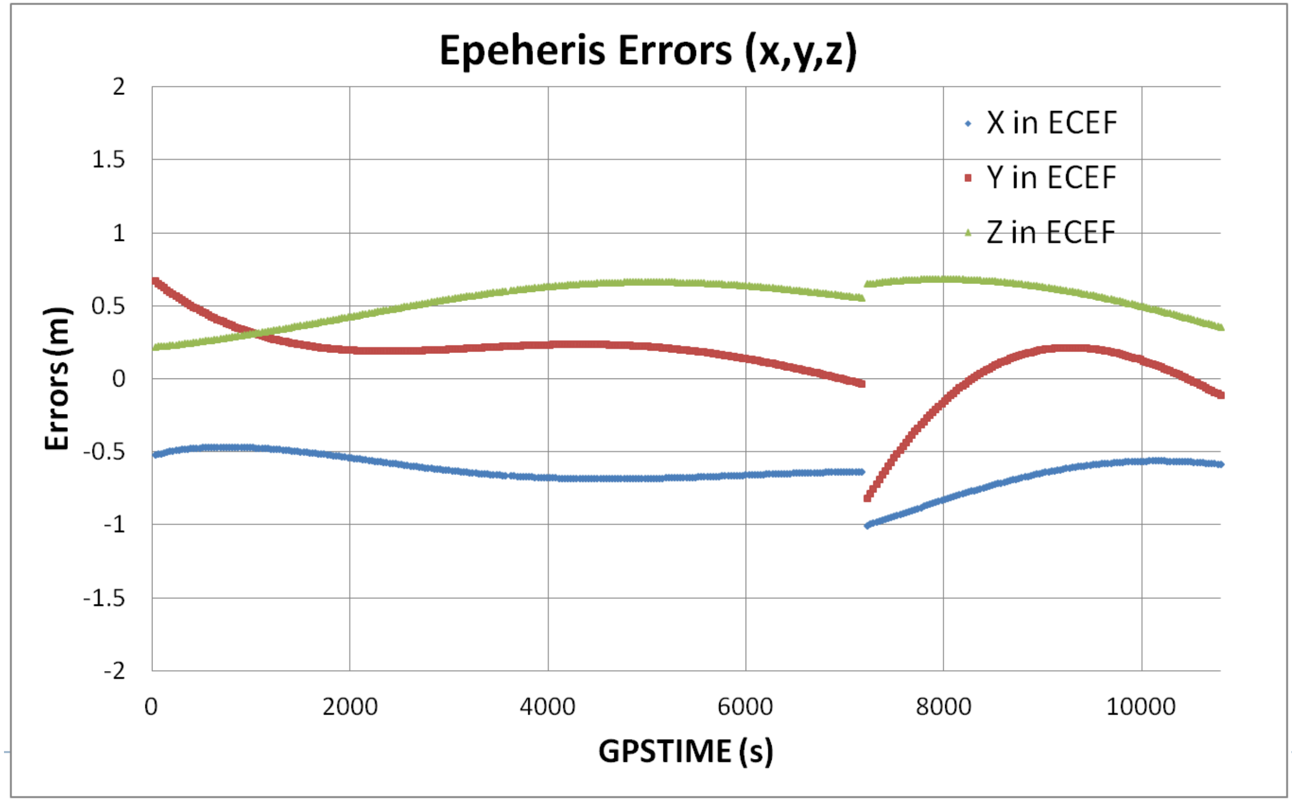
1. Non-spherical gravitational potential of earth
2. Resistance from atmosphere
3. Attraction from sun and moon
4. Solar radiation pressure

Image of using Ephemeris

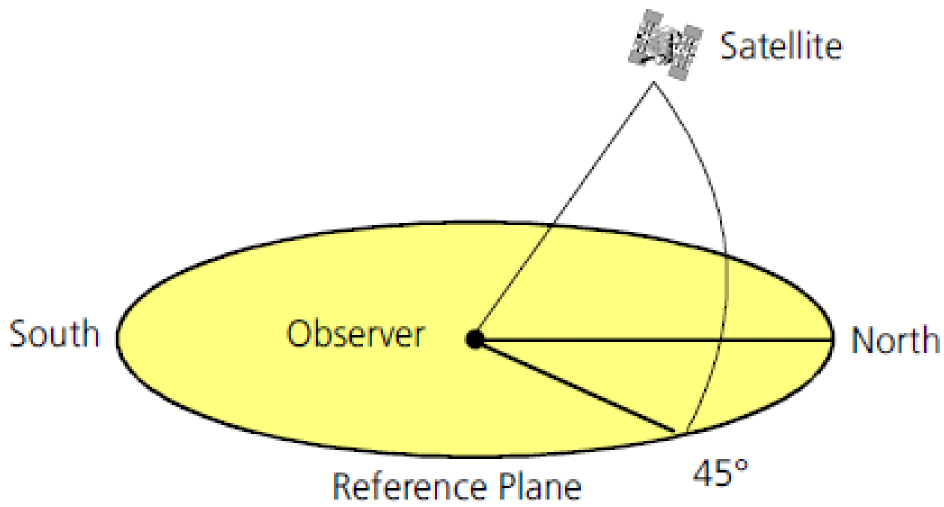


Real Ephemeris Errors
(based on precise orbit data)

- Precise orbit data (-1cm) also can be obtained over the internet (IGS http://www.igs.org/).



Elevation, Azimuth



- The **Elevation** describes the angle of a satellite relative to the horizontal plane.
- The **Azimuth** is the angle between the satellite and true North.

Receiver Status - Position

Trimble NetR9 5245K53320

Position:

Lat: 35° 39' 58.82248" N
Lon: 139° 47' 31.92186" E
Hgt: 58.733 [m]
Type: Autonomous
Datum: WGS-84

Velocity:

East: -0.01 [m/s]
North: 0.00 [m/s]
Up: -0.02 [m/s]

Position Solution Detail:

Position Dimension: 3D
Augmentation: GPS+GLN+GAL+BDS+QZSS
Height Mode: Normal
Correction Controls: Off

Satellites Used:34

GPS(11): 1, 3, 7, 8, 10, 11, 16, 22, 27, 28, 30
GLONASS(8): 5, 6, 7, 10, 11, 12, 21, 22
Galileo(5): 11, 12, 18, 19, 24
BeiDou(9): 1, 2, 3, 4, 7, 8, 10, 12, 13
QZSS(1): 193

Satellites Tracked:36

GPS (11): 1, 3, 7, 8, 10, 11, 16, 22, 27, 28, 30
GLONASS (8): 5, 6, 7, 10, 11, 12, 21, 22
Galileo (6): 11, 12, 18, 19, 20, 24
BeiDou (9): 1, 2, 3, 4, 7, 8, 10, 12, 13
QZSS (2): 193, 194

Receiver Clock:

GPS Week: 1962
GPS Seconds: 265539
Offset: -0.01435 [msec]
Drift: -0.43858 [ppm]

Multi-System Clock Offsets:

Master Clock System: GPS
GLONASS Offset: -10.9 [ns]
Galileo Offset: -1.5 [ns]
BeiDou Offset: -50.4 [ns]
GLONASS Drift: -0.023 [ns/s]
Galileo Drift: 0.027 [ns/s]
BeiDou Drift: 0.033 [ns/s]

Dilutions of Precision:

PDOP: 0.9
HDOP: 0.5
VDOP: 0.8
TDOP: 0.5

Error Estimates(1σ):

East: 0.435 [m]
North: 0.526 [m]
Up: 1.003 [m]
Semi Major Axis: 0.540 [m]
Semi Minor Axis: 0.418 [m]
Orientation: 20.4°

How to read the receiver status

2017-08-16T01:45:21Z (UTC)

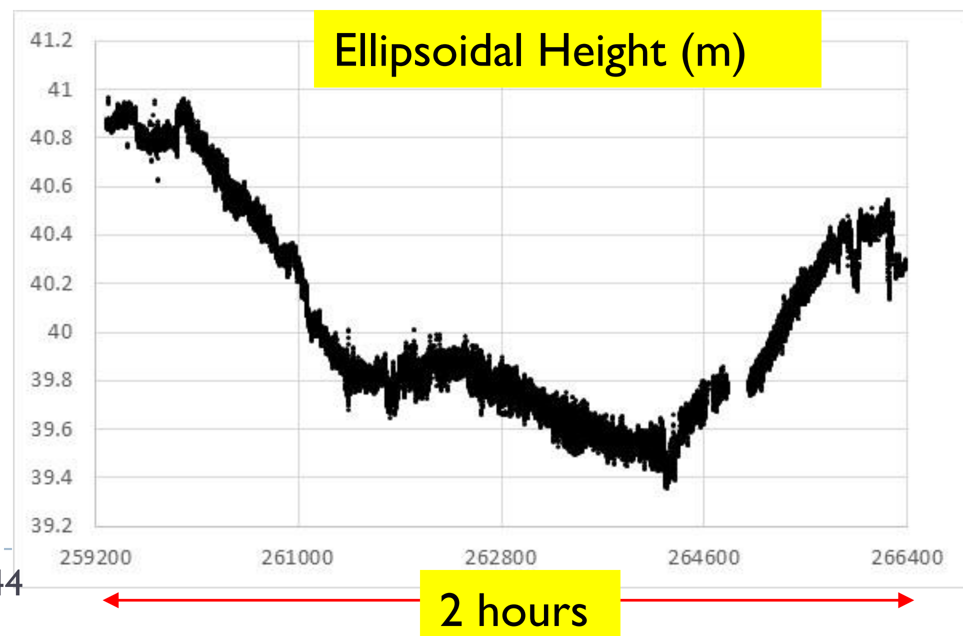
How to get satellite positions

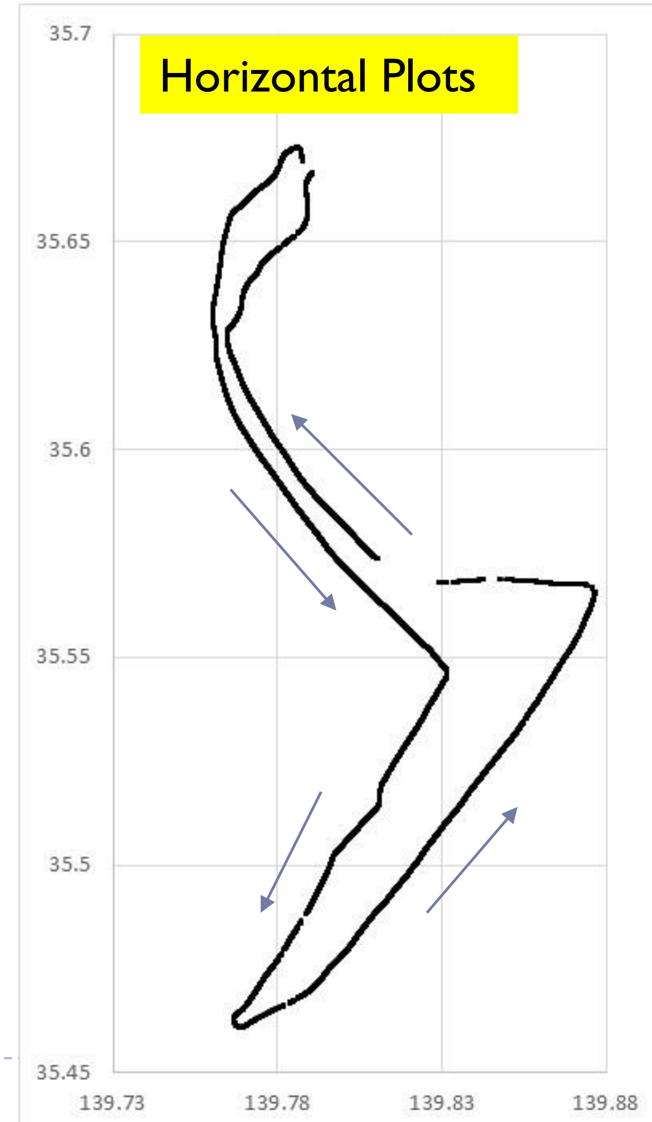
- GNSS View
- Almanac
- TLE

Quiz

Two figures are RTK results of small ship (Yayoi).
You can see the height variation.
Please tell me why there was the variation
in altitude direction.

2013/12/4 9:00-11:00





Why we learn measurements and errors ?

- Needless to say, "position, velocity and time" are important for users.
- The ability to improve final performance of the above outputs strongly depends on how can we estimate or possibly mitigate measurements errors.
- Measurements errors strongly depends on the environment and receiver performance.

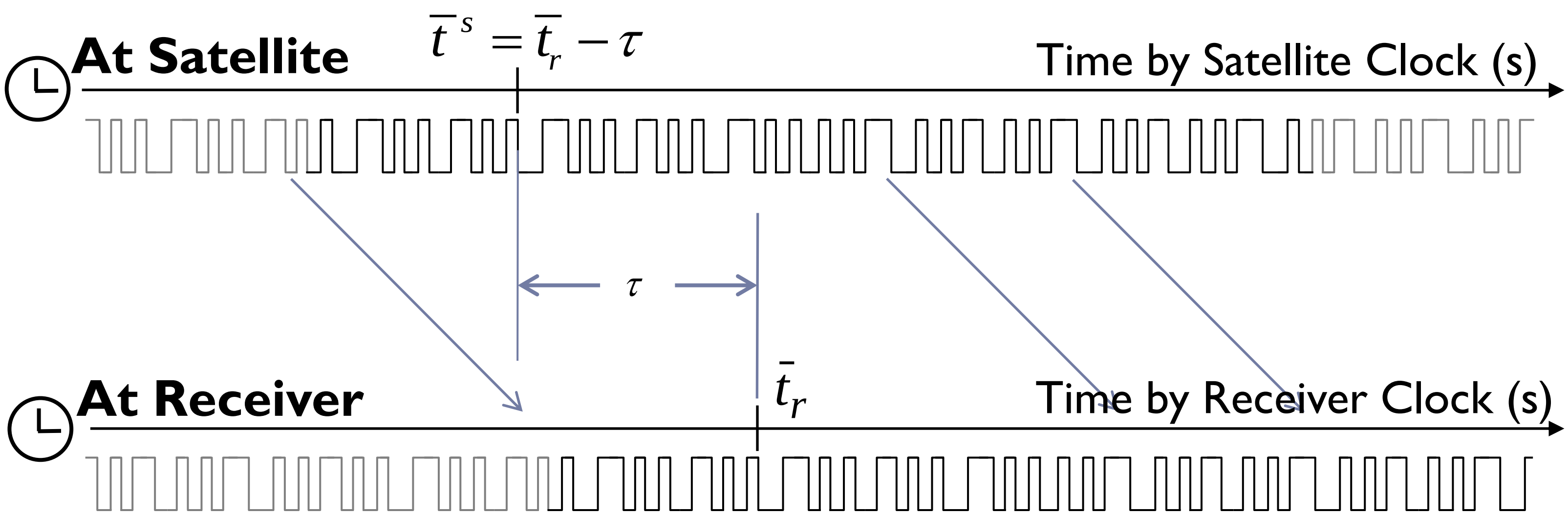
Pseudo-range (Code-phase)

Definition:

$$P_r^s \equiv c\tau = c(\bar{t}_r - \bar{t}^s)$$

(m)

The pseudo-range (PR) is the distance from the receiver antenna to the satellite antenna including receiver and satellite clock offsets (and other biases, such as atmospheric delays) *(RINEX 2.10)*



GPS/QZSS/GALILEO/QZSS→CDMA（code division multiple access）
GLONASS→FDMA（frequency division multiple access）

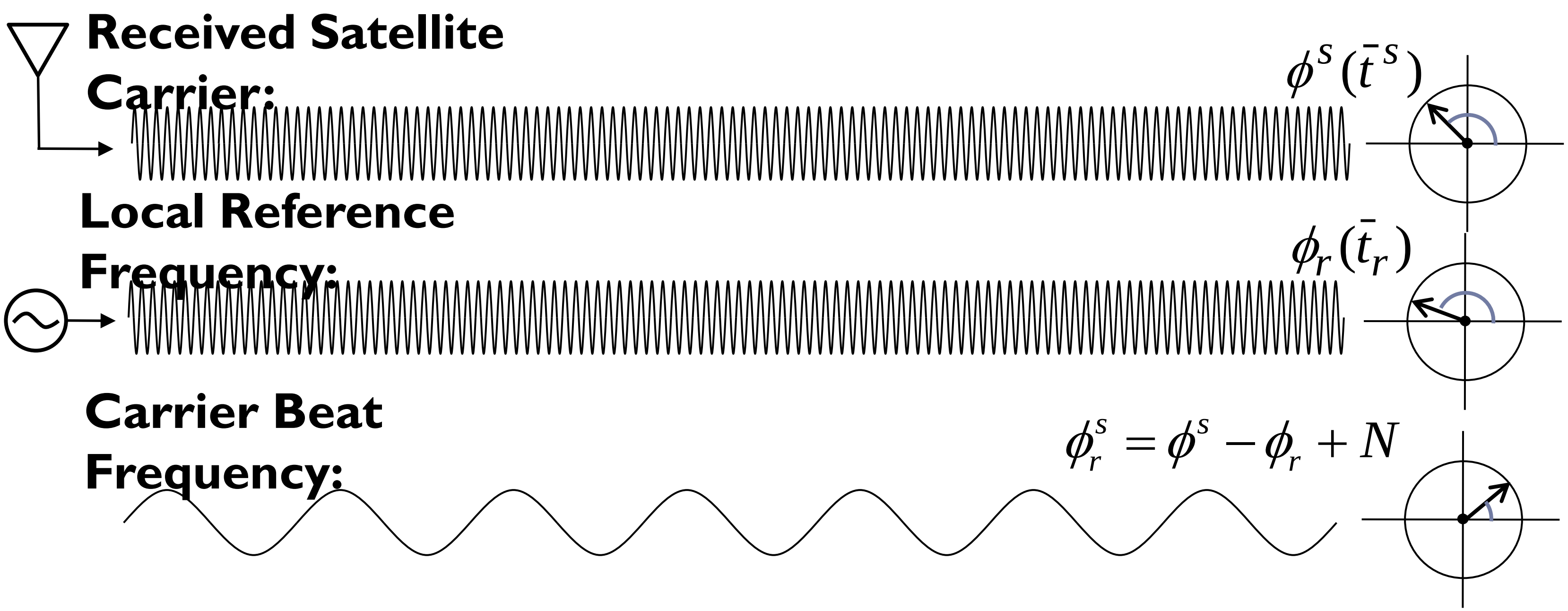
Carrier-Phase

Definition:

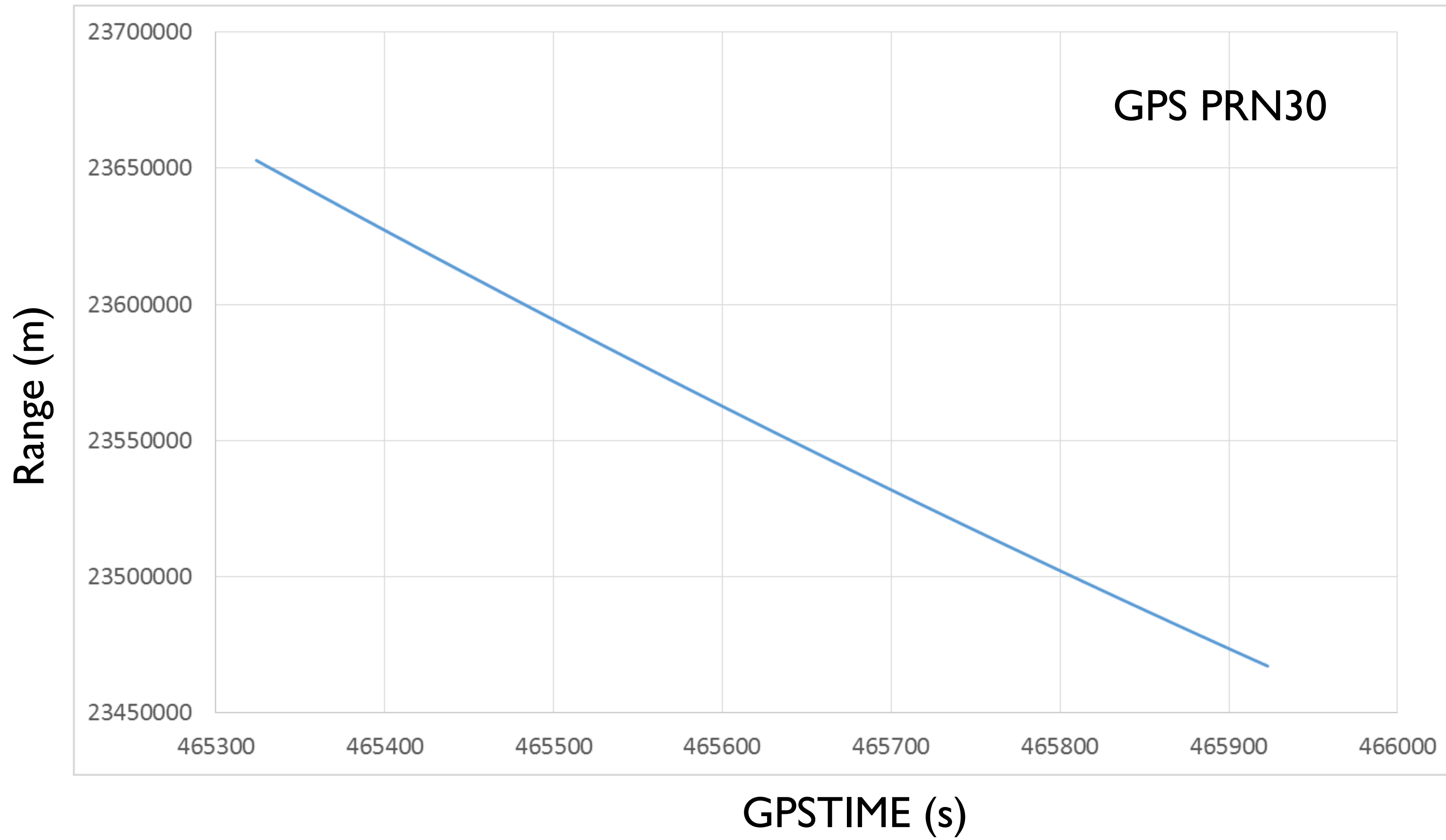
$$\phi_r^s = \phi^s - \phi_r + N$$

(cycle)

... actually being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency. *(RINEX 2.10)*



Real Pseudo-range Measurements



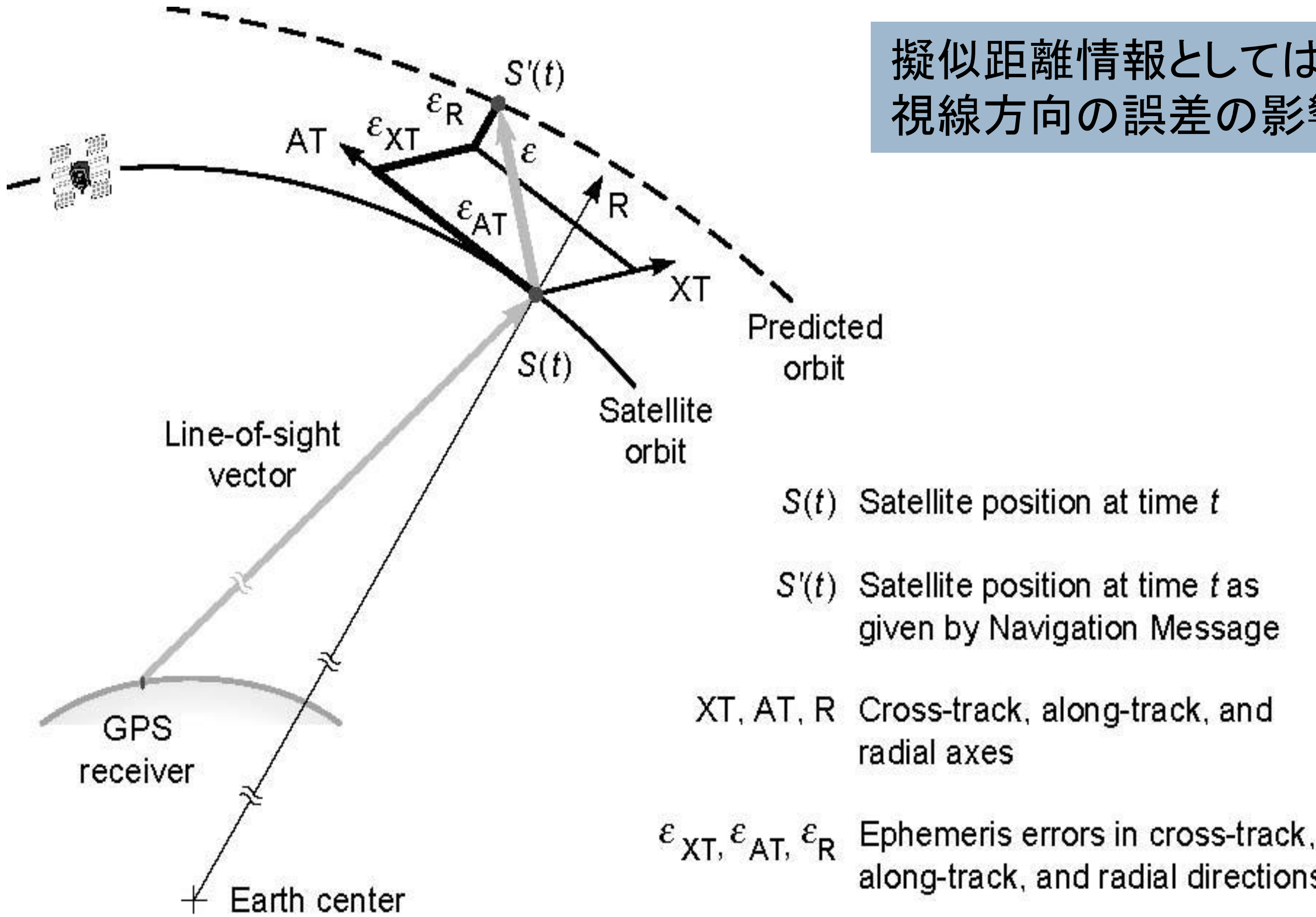
-186km / 10min → -309m / sec

Code vs Carrier-Based Positioning

	Standard Positioning (code-based)	**Precise Positioning (carrier-based)**
Observables	Pseudorange (Code)	**Carrier-Phase + Pseudorange**
Receiver Noise	30 cm	3 mm
Multipath	30 cm - 30 m	1 - 3 cm
Sensitivity	High (<20dBHz)	Low (>35dBHz)
Discontinuity	No Slip	Cycle-Slip
Ambiguity	-	Estimated/Resolved
Receiver	Low-Cost (~$100)	**Expensive (~$10,000)**
Accuracy (RMS)	3 m (H), 5 m (V) (Single) 1 m (H), 2 m (V) (DGPS)	**5 mm (H), 1 cm (V) (Static) 1 cm (H), 2 cm (V) (RTK)**
Application	Navigation, Timing, SAR,...	Survey, Mapping, ...

Control Segment Errors

擬似距離情報としては、
視線方向の誤差の影響が大きい



Satellite clock and ephemeris errors

Ephemeris/ Clock	Accuracy (RMS)	Real-time	Update	Sample
Navigation	**1m/5ns**	○	**2hour**	
Ultra-Rapid (predicted half)	0.05m/3ns	○	4/day	15 min
Ultra-Rapid (observed half)	0.03m/150ps	3-9 hours	4/day	15 min
Rapid	0.025m/75ps	17-41 hours	1/day	15/5 min
Final	0.025m/75ps	12-18 days	1/week	15/5 min

IGS site (2009)

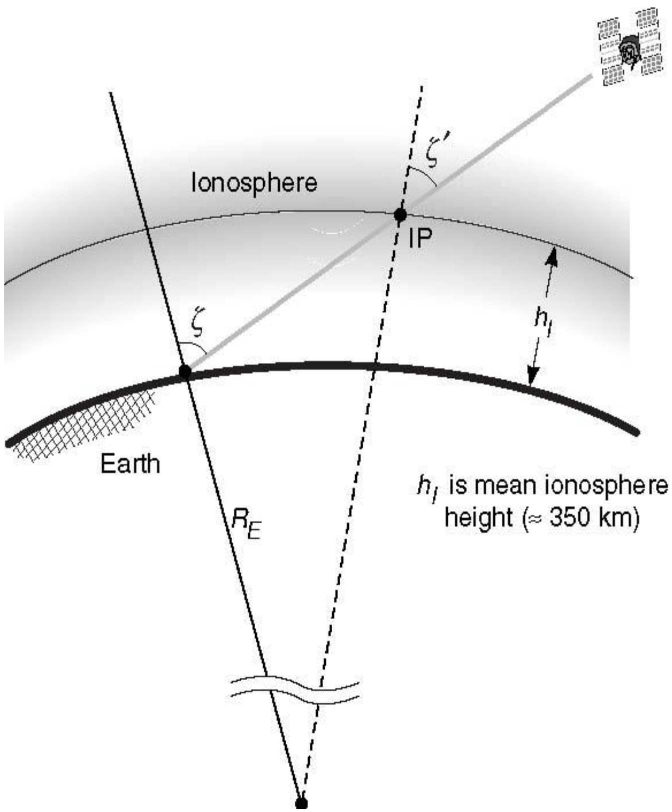
Precise Ephemeris

- Precise ephemeris is based on actual tracking data that are **post-processed** to obtain the more accurate satellite positions.
- Commonly, precise ephemeris is available **at a later date, i.e. not in real time**.
- The accuracy is **at centimeter level (< 2 cm)**.

For example:
IGS network

http://www.igs.org/network

Ionospheric delay

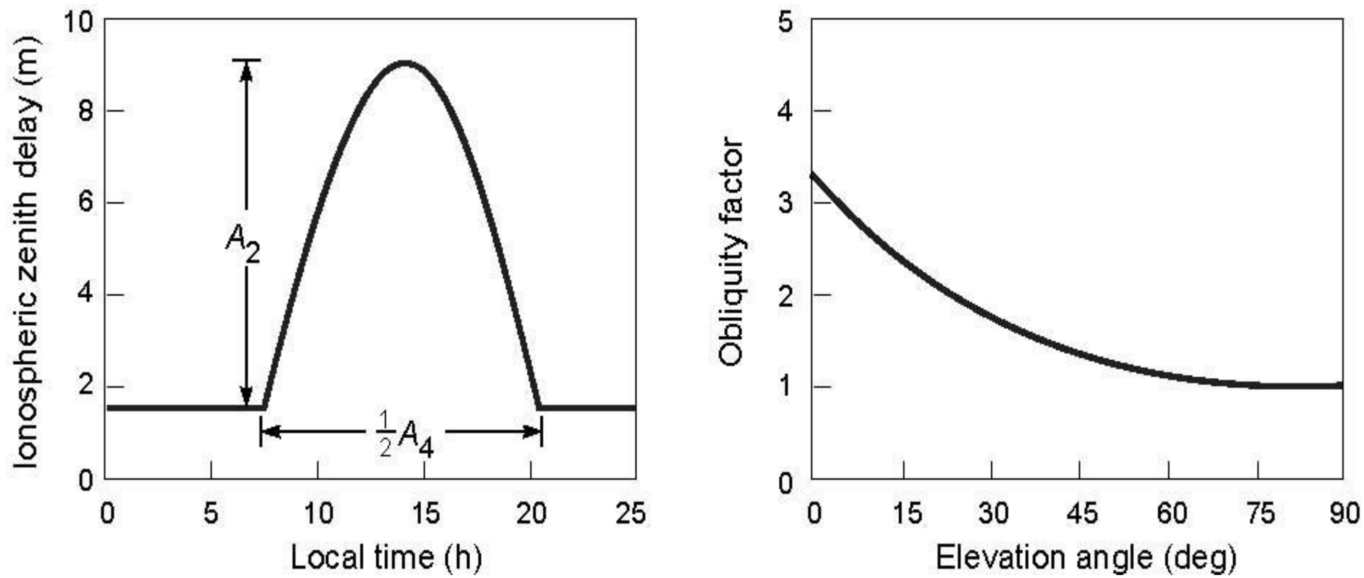


The ionosphere is a region of ionized gases. The state of the ionosphere is determined primarily by the intensity of the solar activity.

The speed of propagation of radio signals in The ionosphere depends on the number of free electron in the path of a signal, defined as the total electron content (TEC): the number of electrons in a tube of 1 m^2 cross section extending from the receiver to the satellite.

The increased path length is accounted for in terms of a multiplier of the zenith delay. The multiplier is called **Obliquity Factor**.

Broadcast Model



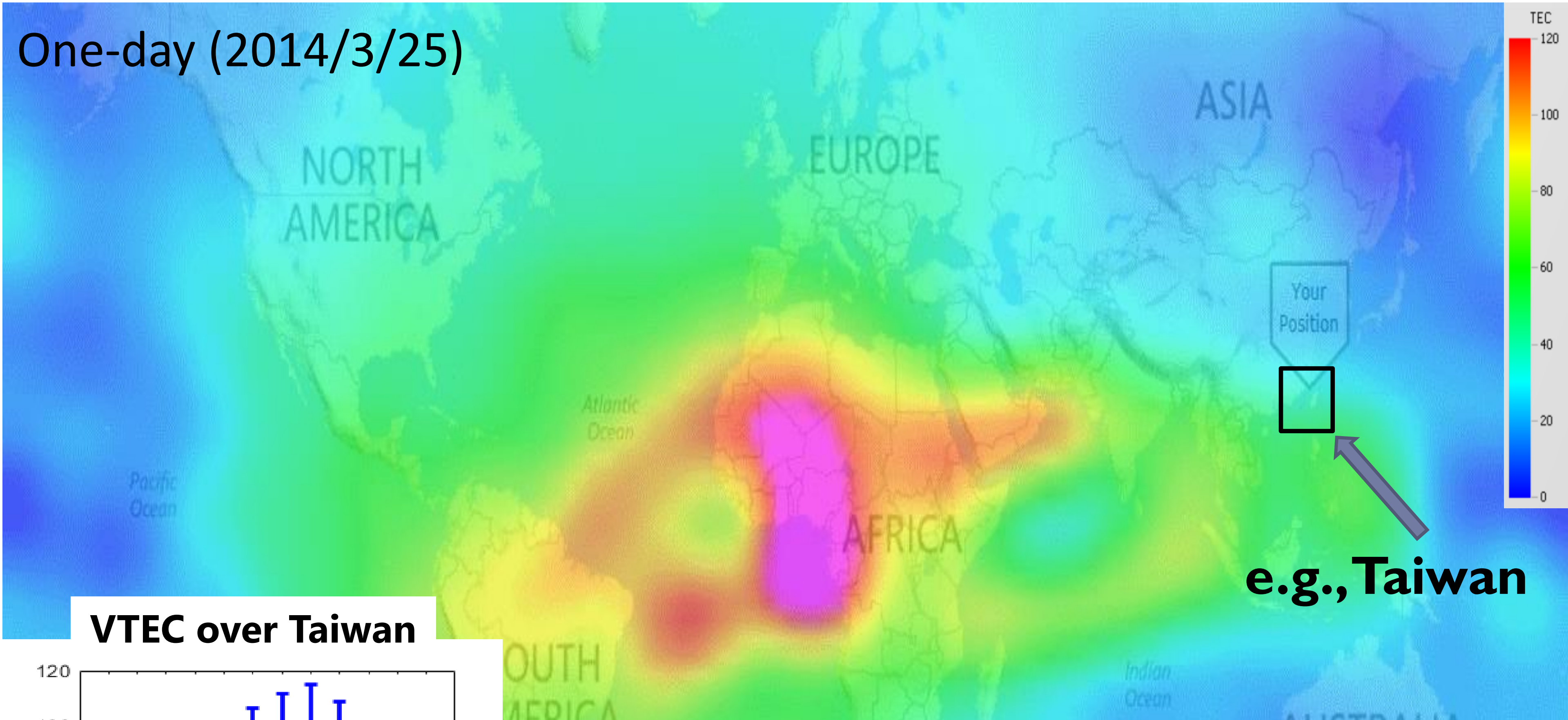
The Klobuchar ionospheric model. Parameter values A2 and A4 are selected by the Control Segment to reflect the prevailing ionospheric conditions and are broadcast by the satellites.

For Galileo, **NeQuick model** will be used to estimate ionospheric errors.

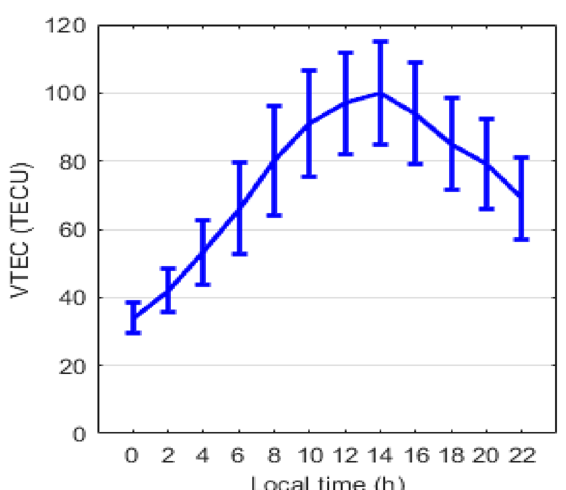
Worldwide VTEC

トリンブルHP

One-day (2014/3/25)



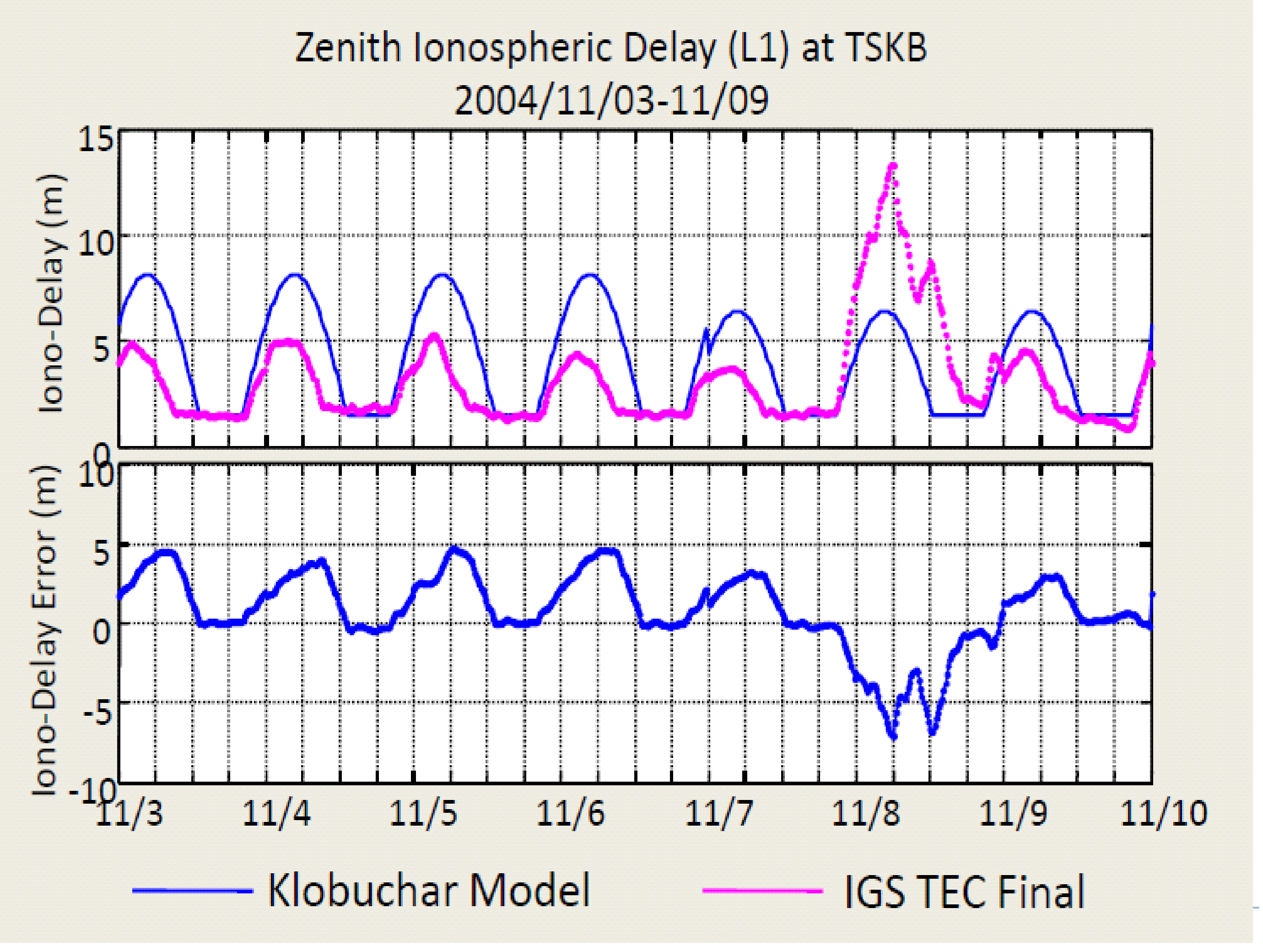
VTEC over Taiwan



1. VTEC changes with time and locations.

2. The mid-low latitude regions (range of equatorial anomaly) will suffer the largest ion. errors in the world near and after noon !!!!

Accuracy evaluation of Klobuchar model based estimates



Tropospheric delay

- The GPS signals are also reflected by the lower part of the earth's atmosphere composed of **gases and water vapor.**

- The speed of propagation of GPS signals in the troposphere is lower than that in free space and, therefore, the apparent range to a satellite appears longer, typically by **2.5-25 m** depending on the satellite elevation angle.

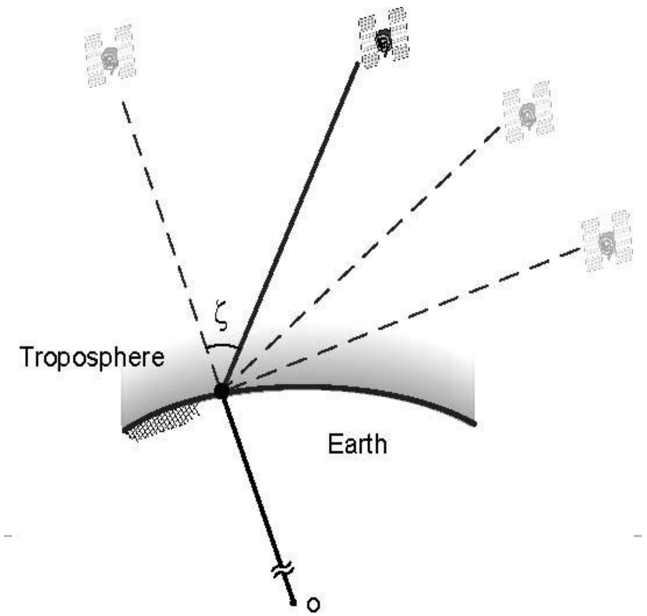
- Water vapor density caries with the local weather and can change quickly. Fortunately, **most of the tropospheric delay is due to the more predictable dry atmosphere**.

測定する場所の標高に注意が必要

Tropospheric models

- **Saastamoinen model** was derived using gas laws and simplifying assumptions regarding changes in temperature and water vapor with altitude.

- **Hopfield model** is based on a relationship between dry refractivity at height h to that at the surface. It was derived empirically on the basis of extensive measurements.



Obliquity factor is defined same as ionosphere, but the value is different because the height is different.

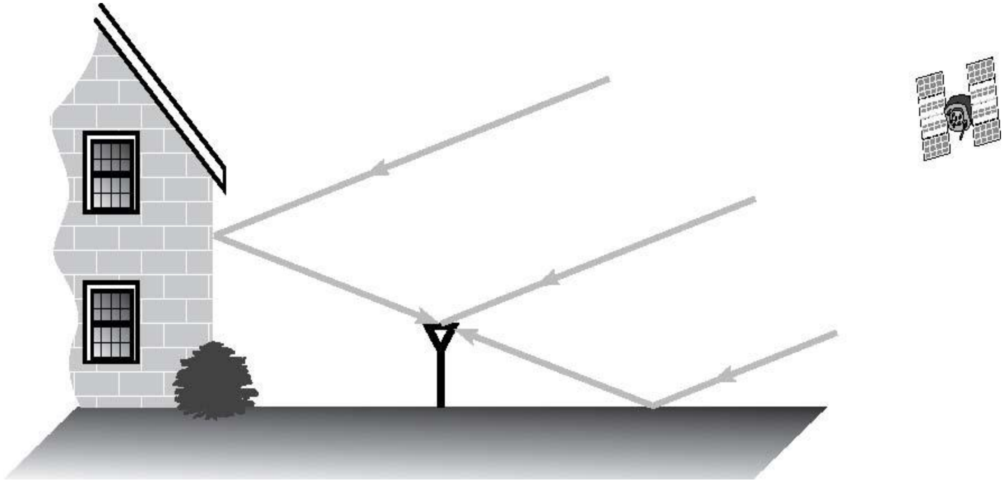
30 degrees : 2
15 degrees : 4
10 degrees : 6
5 degrees : 10

Measurement Errors
(Receiver Noise and Multipath)

- Multipath refers to the phenomenon of a signal reaching an antenna via two or more paths.

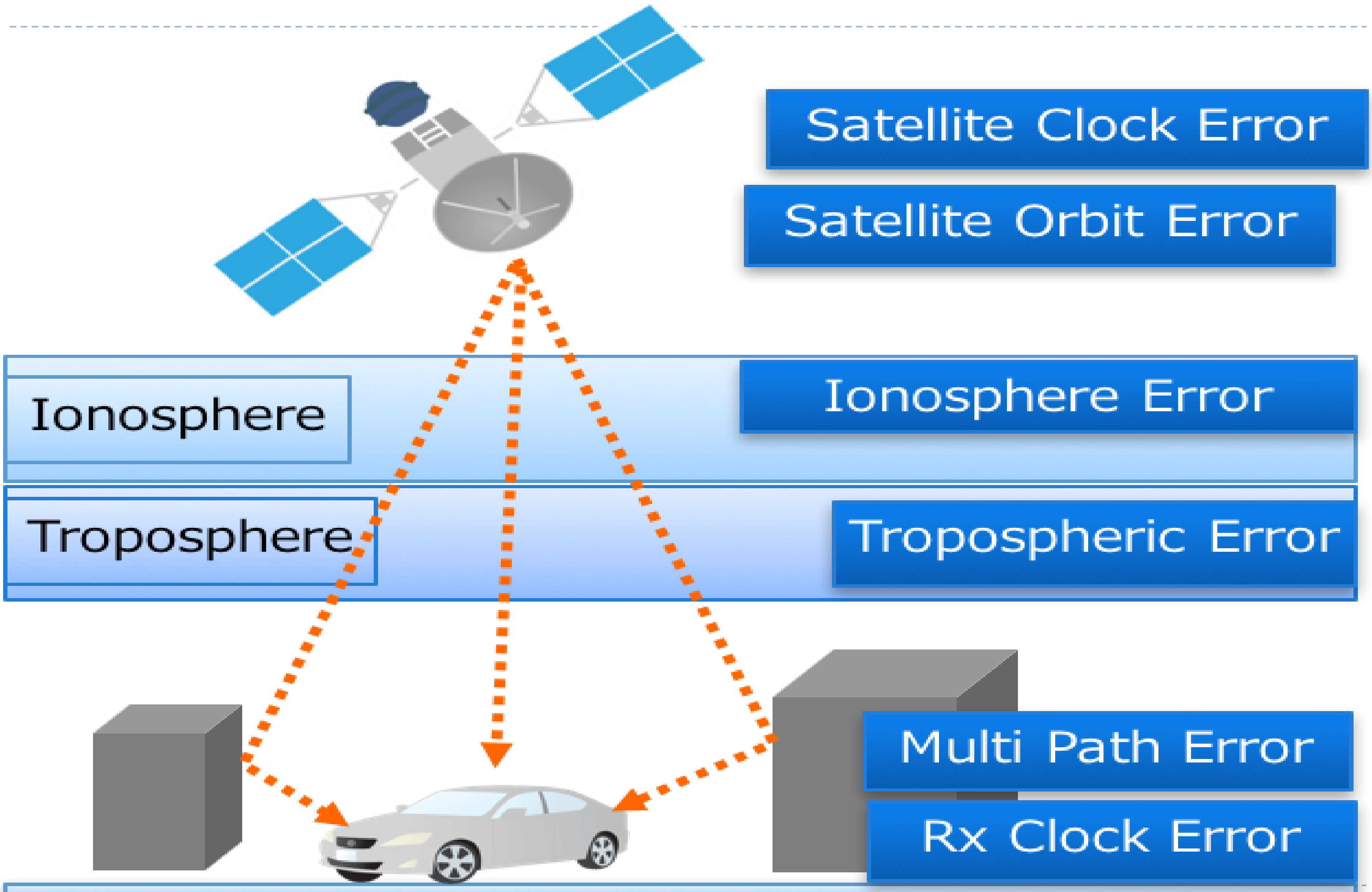
- The range measurement error due to multipath depends on the strength of the reflected signal and the delay between direct and reflected signals.

- Mitigation of multipath errors : Antenna or Receiver



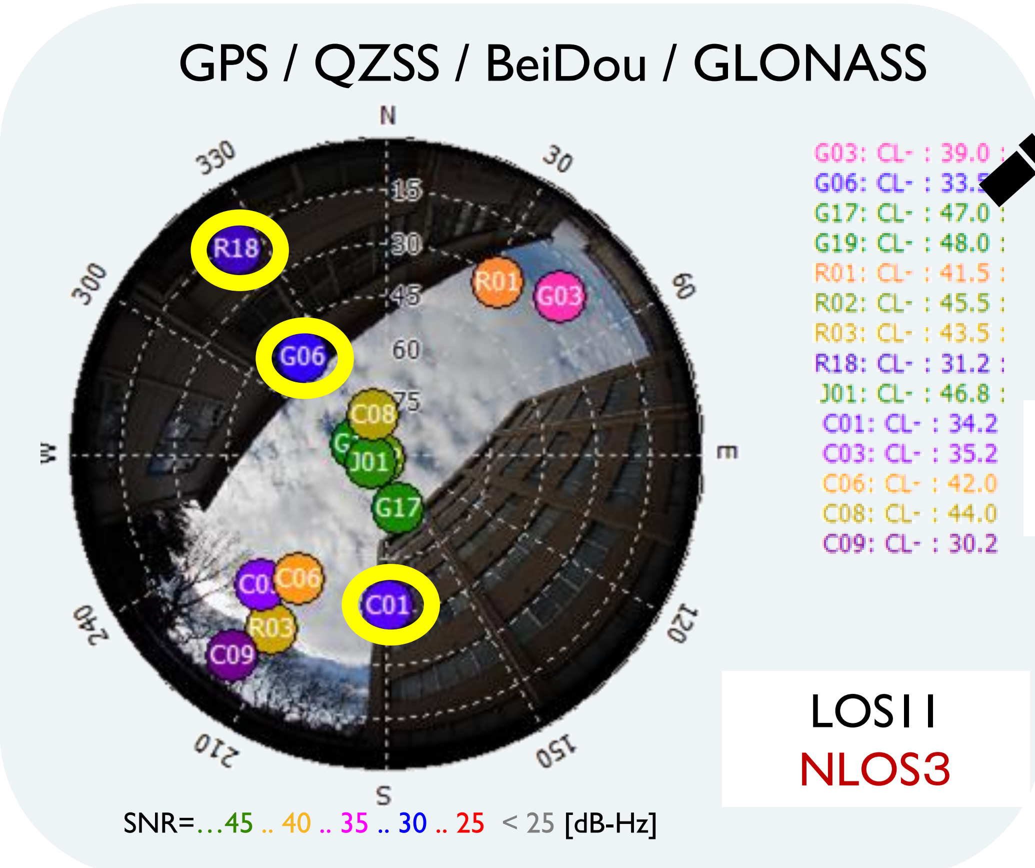
遅延距離が20-30mを
超えると、マルチパスの
影響を低減できる
→コリレータベース
→L5信号

Error Sources on the GNSS measurements



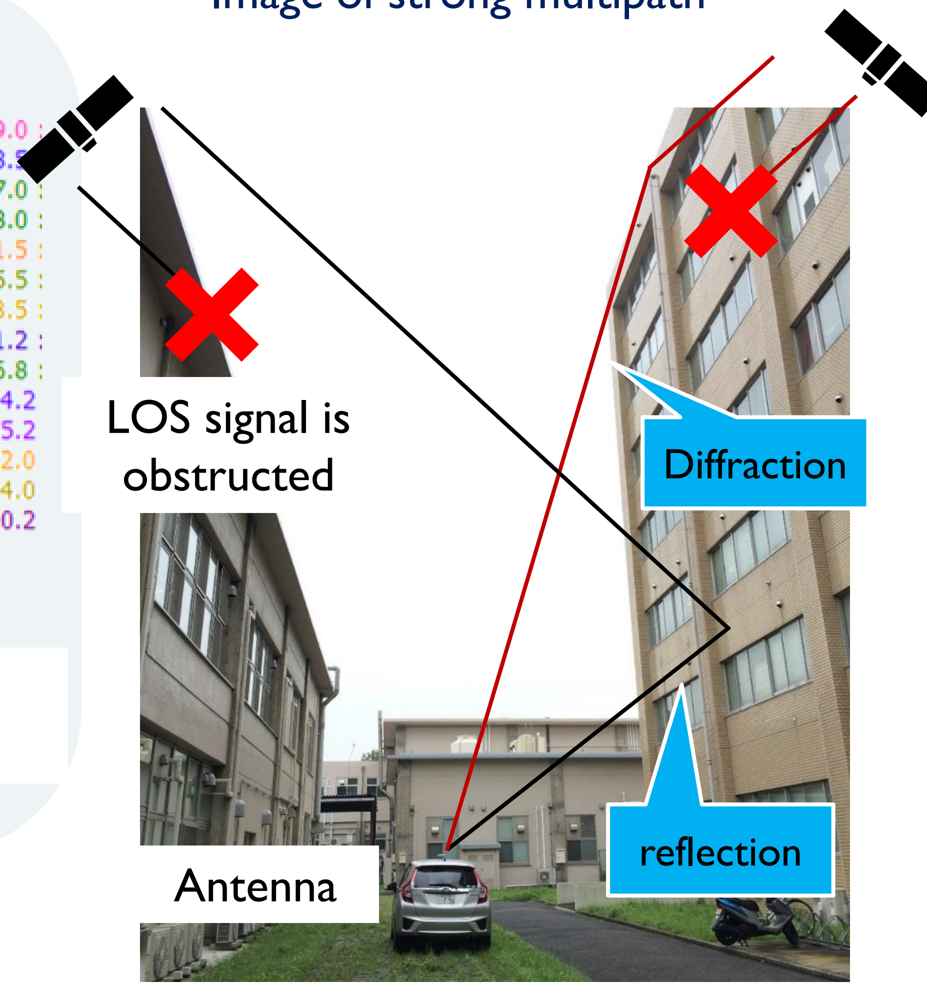
Source: (https://www.kke.co.jp/en/solution/casestudy/gpsstudio-kaiyodai.html)

Multipath Error

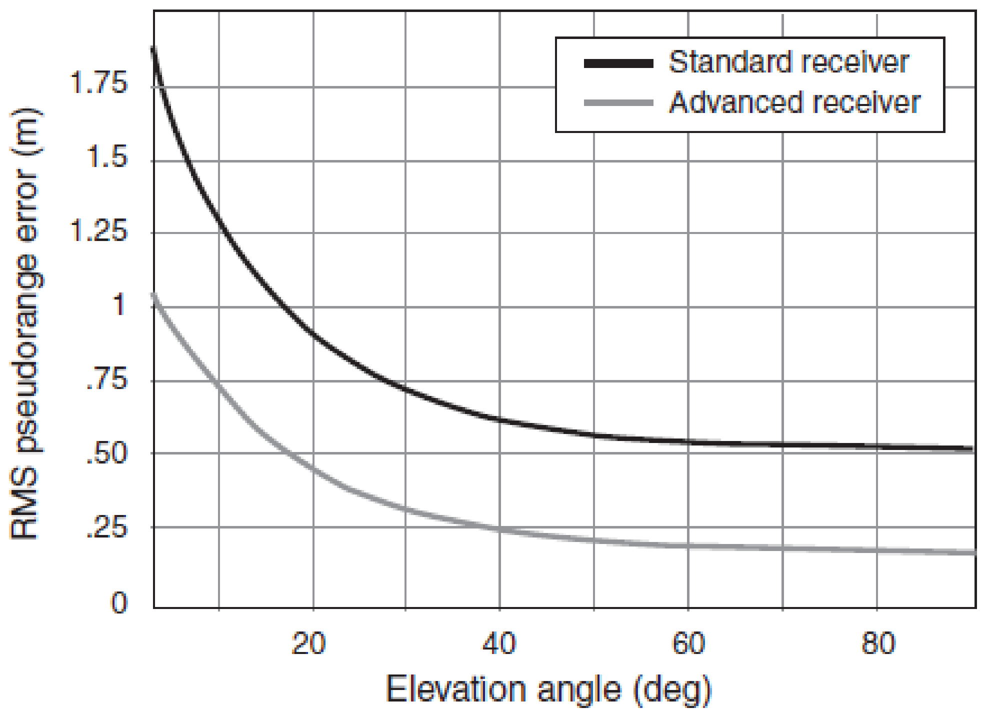


LOS : line of sight
NLOS : non line of sight

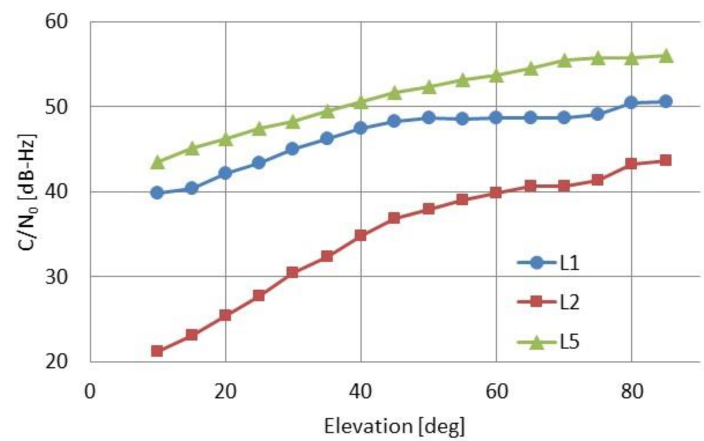
Image of strong multipath



Pseudo-range errors depends on C/N_0



You can change Elevation angle to signal strength

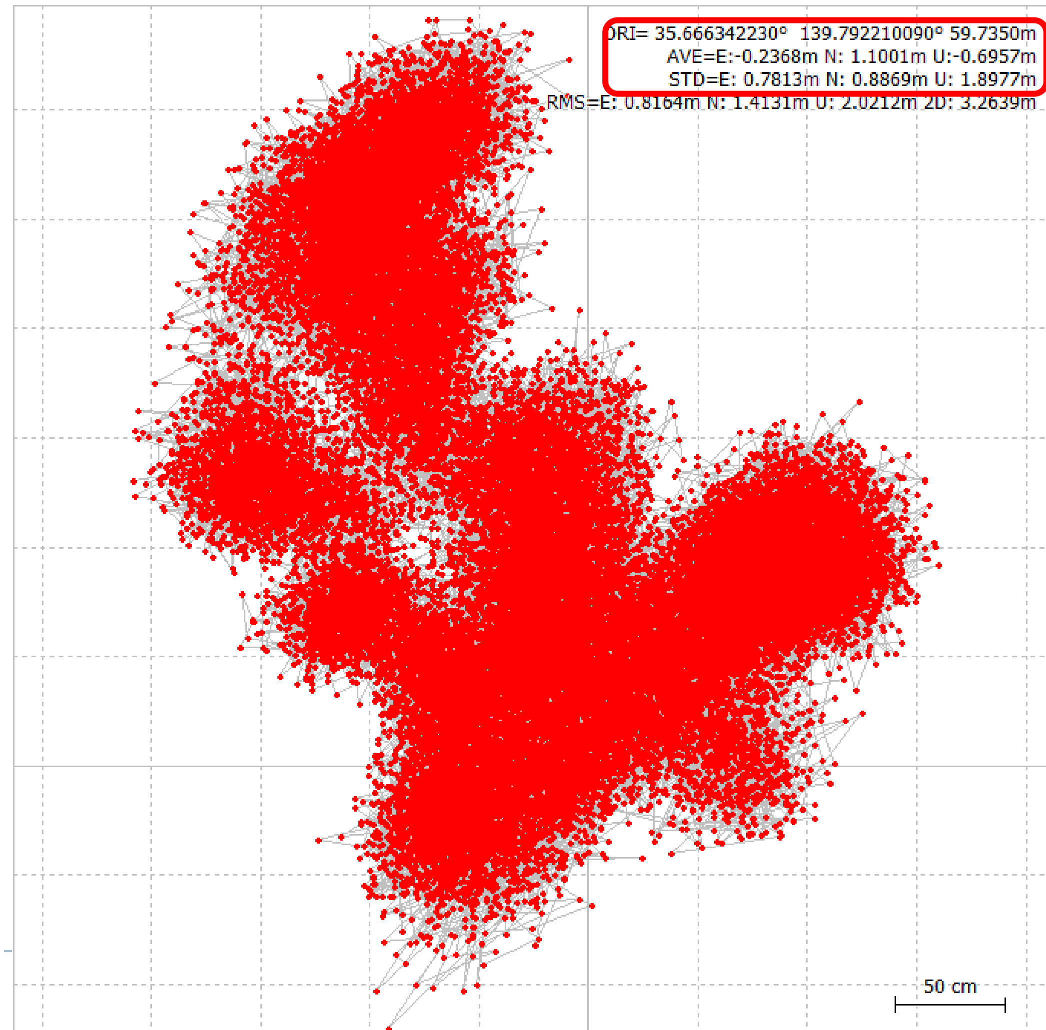


C/N_0 and Elevation

受信信号は非常に微弱
-160dBW(-130dBm)程度
dBW=10log(受信電力)

Single point positioning using pseudo-range

12h, rooftop, our building



GPS Measurement Errors

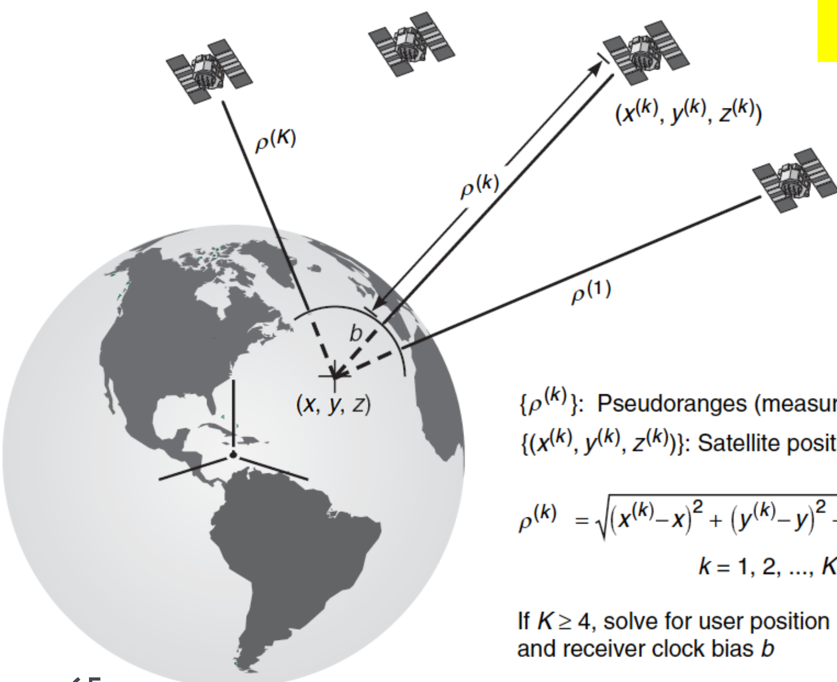
Source	Potential error size	Error mitigation using single point positioning
Satellite clock model	2 m (rms)	→
Satellite ephemeris prediction	2 m (rms) along the LOS	→
Ionospheric delay	2-10 m (zenith) Obliquity factor 3 at 5°	1-5 m (single-freq.) within 1m (dual-freq.)
Tropospheric delay	2.3-2.5m (zenith) Obliquity factor 10 at 5°	0.1-1 m
Multipath (open sky)	Code : 0.5-1 m Carrier : 0.5-1 cm	→
Receiver Noise	Code : 0.25-0.5 m (rms) Carrier : 1-2 mm (rms)	→

Positioning Performance of GNSS

Positioning Performance =

<u>Measurements Accuracy</u> × <u>DOP</u>

Ephemeris errors should be considered…



$\{\rho^{(k)}\}$: Pseudoranges (measurements)

$\{(x^{(k)}, y^{(k)}, z^{(k)})\}$: Satellite positions (known)

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

$$k = 1, 2, \ldots, K$$

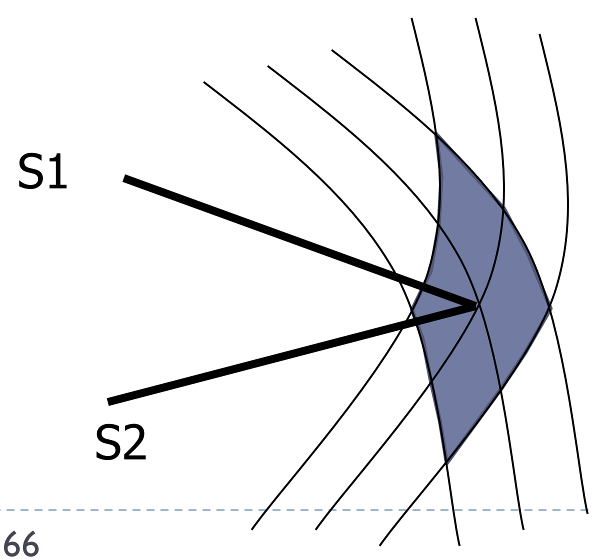
If $K \geq 4$, solve for user position (x, y, z), and receiver clock bias b

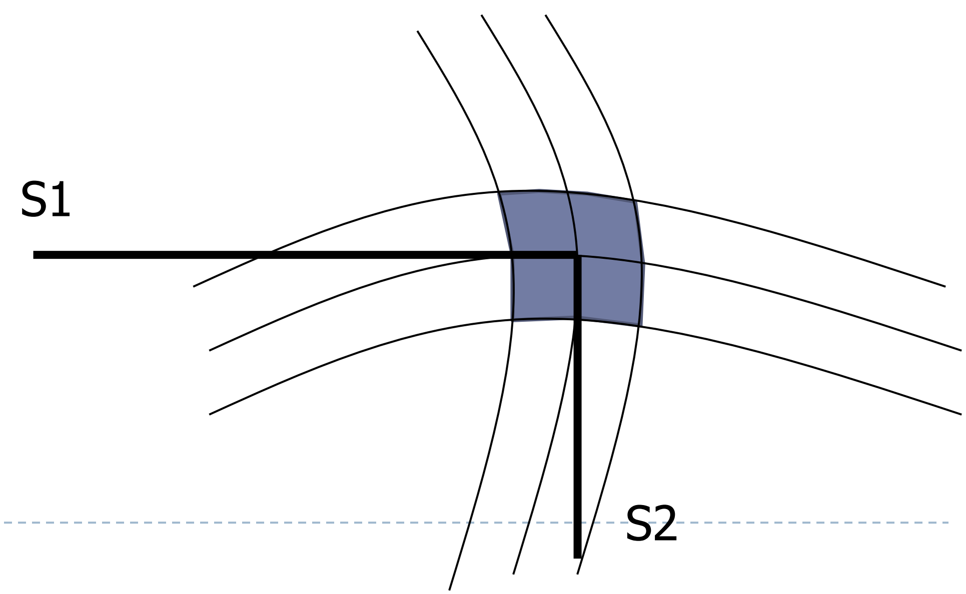
Horizontal accuracy =
Measurements accuracy × HDOP

What is DOP ?

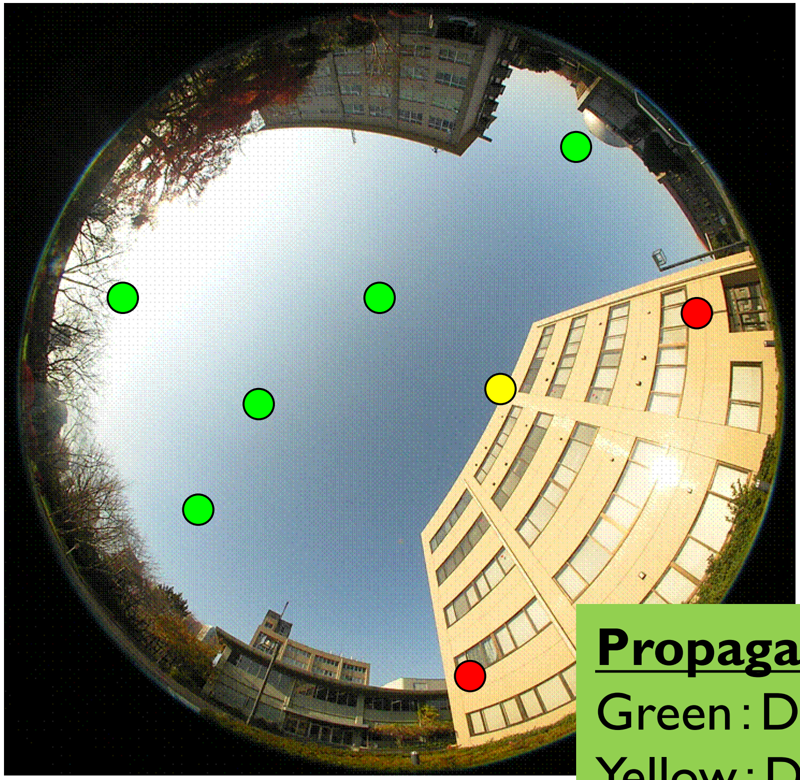
(dilution of precision : DOP)

- If the measurements errors are zero, the calculated user position is true.
- However, if the measurements include some errors, the accuracy depends on measurement errors as well as the geometry of satellites (=DOP).

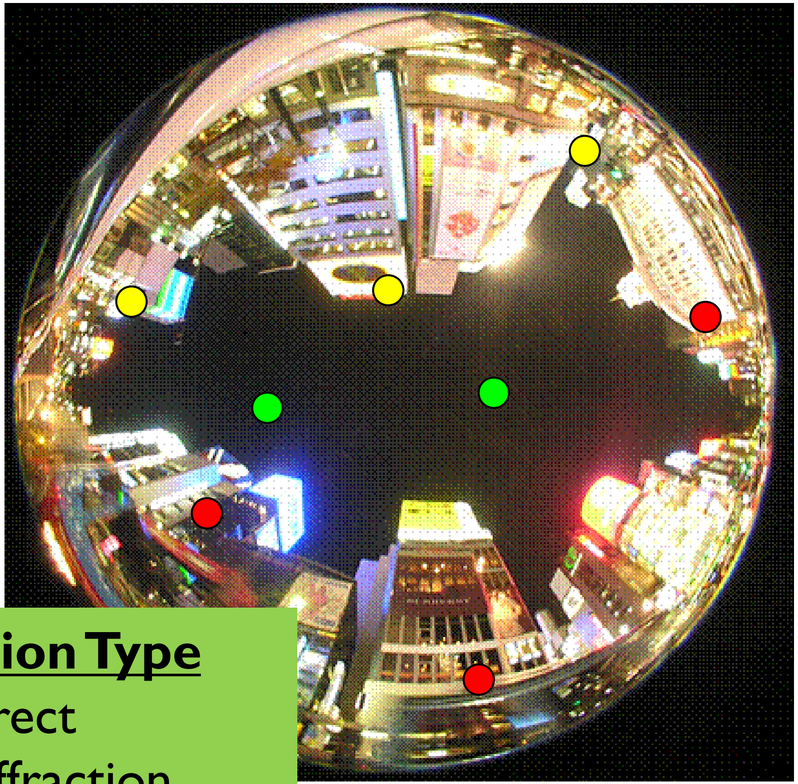




Sky Views in two different places
(same constellation but different performance)



Kaiyodai



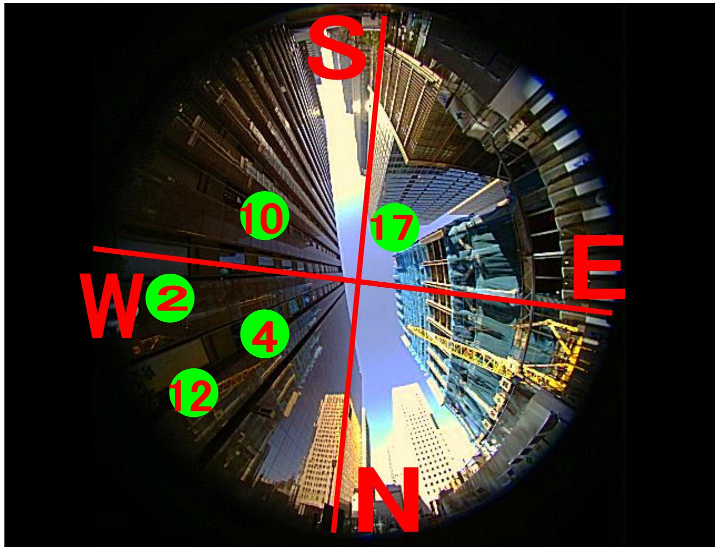
Ginza

<u>Propagation Type</u>

Green : Direct
Yellow : Diffraction
Red : Masking +Reflection

Quiz

- If you are in the very narrow street near the high-rise buildings, what position errors will you see ?



Please ignore the green number.

RTKNAVI demonstration