GNSS Parameters

Position estimation uncertainties

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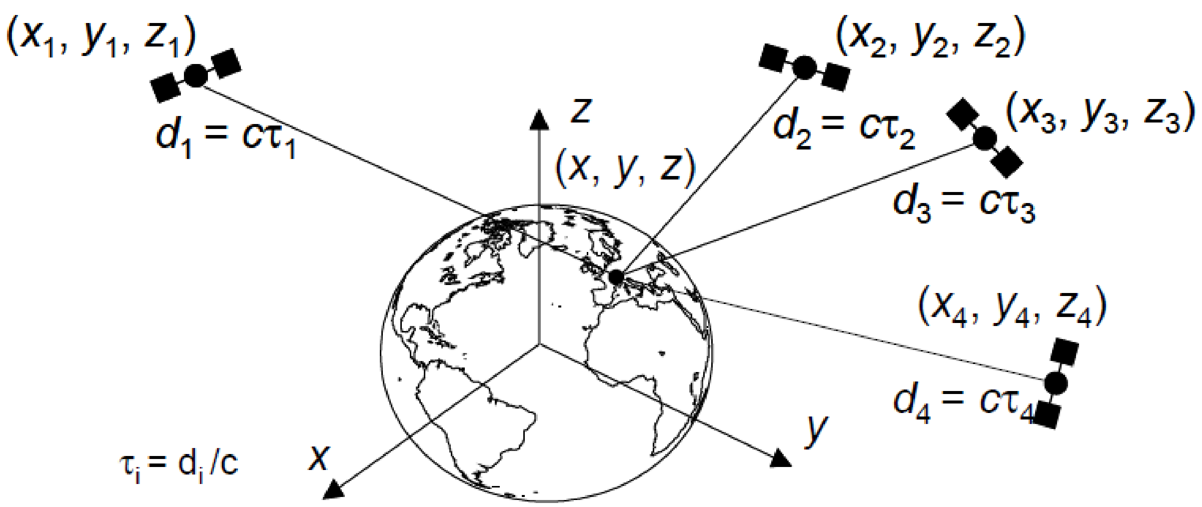
Contents

- Satellite systems in general
- Accuracy
- Position estimation error sources
- Position accuracy … uncertainty
- Availability of signal

…. Let us go back to satellite systems ..

How to find out a position?

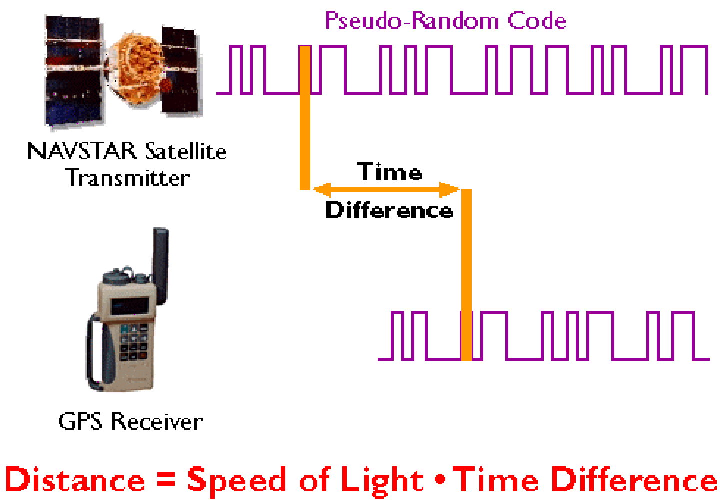
- calculated by precisely timed signals sent by satellites
- satellite <u>continually</u> transmits messages that include
  - the <u>time the message</u> was transmitted
  - <u>satellite position at time</u> of message transmission

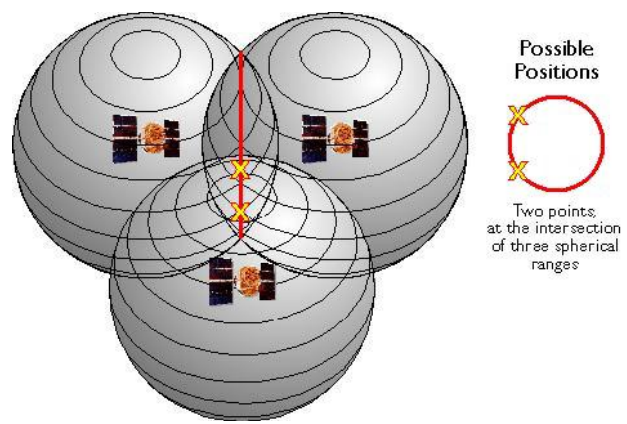


(data source: [1])

How to find out a position?

- GPS receivers calculate distance as a function of the <u>difference in time</u> of broadcast and reception of a GPS signal.
- **= trilateration**, positions are calculated as a function of distances from known locations (constellation).





(illustration source: [1])

Where are the satellites?

System	GPS	GLONASS	COMPASS	Galileo
Political entity	United States	Russia	China	European Union
Coding	CDMA	FDMA/CDMA	CDMA	CDMA
Orbital height	**20,180 km**	**19,130 km**	**21,150 km**	**23,220 km**
Period	(11 h 58 m)	(11 h 16 m)	(12 h 38 m)	(14 h 5 m)
Evolution / day	2	17/8	(36/19)	17/10
Number of satellites	At least 24. (now 31)	**29**, including 23 operational 2 on maintenance 3 reserve 1 on tests	5 geostationary orbit (GEO) satellites, 30 medium Earth orbit (MEO) satellites	4 test bed satellites in orbit, 22 operational satellites budgeted
Frequency	1.57542 GHz (L1 signal) 1.2276 GHz (L2 signal)	Around 1.602 GHz (SP) Around 1.246 GHz (SP)	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)	1.164–1.215 GHz (E5a and E5b) 1.260–1.300 GHz (E6) 1.559–1.592 GHz (E2-L1-E11)
Status	Operational	Operational, CDMA in preparation	15 satellites operational, 20 additional satellites planned	In preparation

(data source: [11])

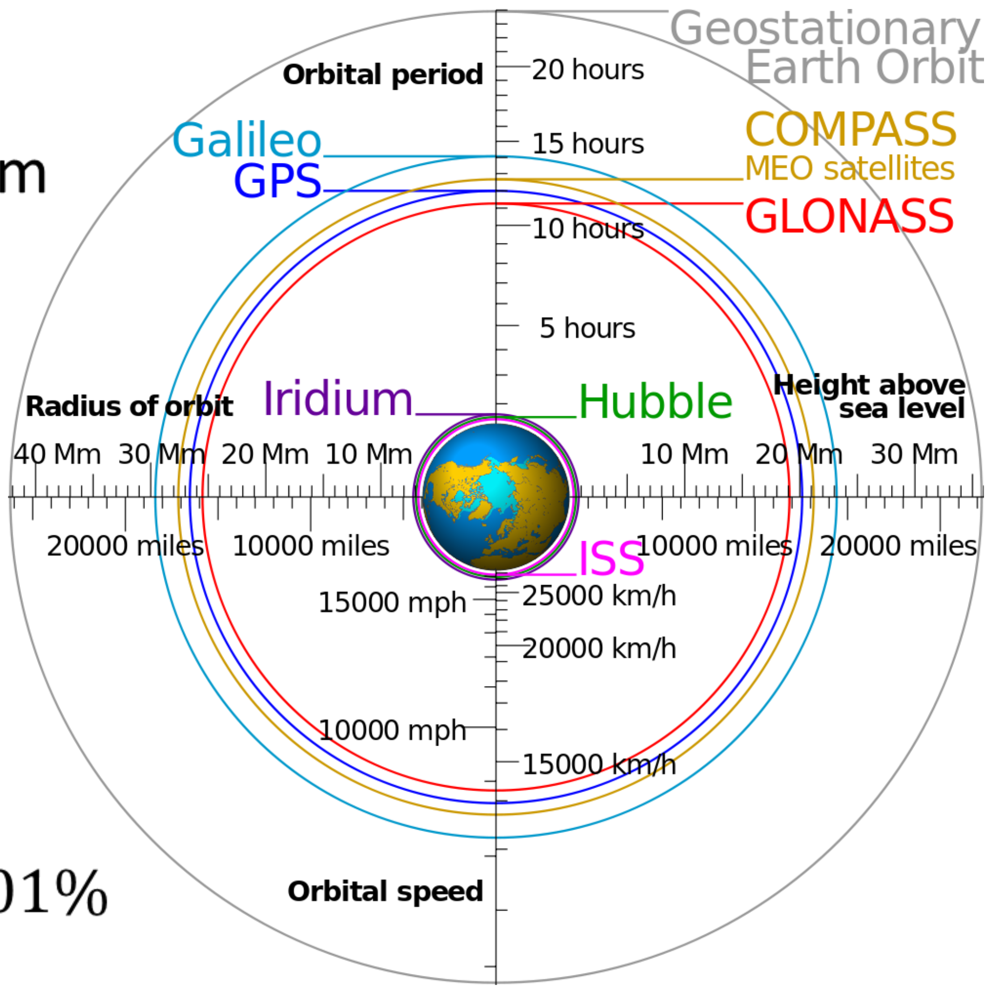
Where are the satellites?

- ISS ~ 400 km
- Hubble ~ 500 – 600 km
- GNSS ~ 20 000 km
- GEO ~ 36 000 km

Far, isn't it?

$$\sigma = \frac{0{,}020\ km}{20\ 000\ km} = 0{,}0001\%$$

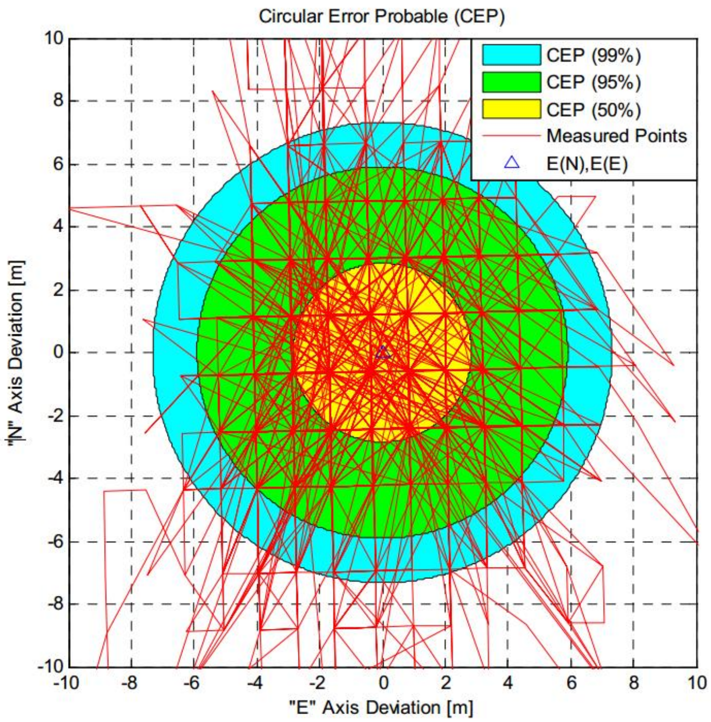
Accurate?



(illustration source: [11])

What is position accuracy? $(x \pm \Delta x)$

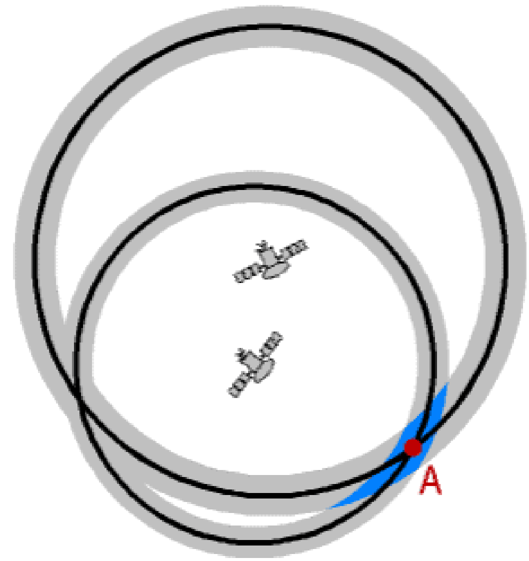
- Accuracy is expressed as a statistical value (a probability that estimated position lies within certain limits). For example CEP, one-sigma, etc.
- Measurement position accuracy in the horizontal plain (2D) is possible to express by the Circular Error Probable (CEP) as the circle radius with 50% realization errors



(illustration source: [2])

Sources of positioning errors

- Space segment
  - Clock errors
- Control segment
  - Ephemeris errors
- User segment
  - Ionosphere disturbances
  - Troposphere disturbances
  - Signal reflection and multipath
  - Receiver Noise
  - Visibility of Satellites
  - **Other**



$\sum * \mathrm{DOP}$

Geometry of satellites

(illustration source: [5])

1. Satellite clock – stability

- The atomic clocks on board SV are extremely accurate.
- Has effect on frequency of generated carrier waves and pseudo random codes.
- Error caused by clock instability should not be greater than 6,5 meters for 95 % of time with PPS
- Example: 1 microsecond difference between receiver and transmitter clock makes approximately **300m**

- For an ensemble of 14 clocks (in view), the clock error is expected to be **1.1 meters** after a 4-hour period

1. Satellite clock – stability

- Performance in terms of stability of various clock

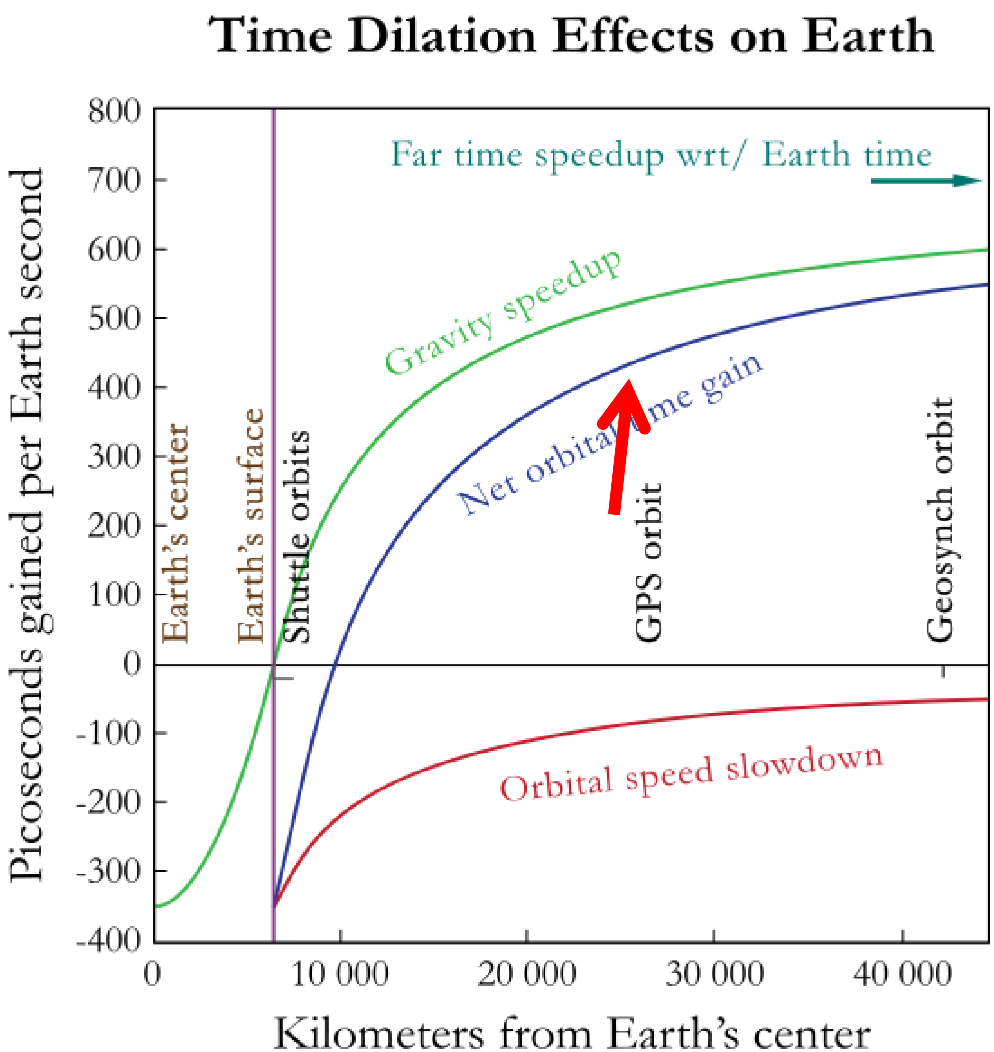
	Daily time difference	Equivalent in terms of distance accuracy
Quartz watch	One second	300 000 km
Temperature-controlled quartz oscillator (as used in GPS receivers)	10 milliseconds	3 000 km
Thermostatted quartz oscillator	0.1 millisecond (10^{-4}s)	30 km
Ultra-stable oscillator	Several microseconds (10^{-6}s)	300 m
Atomic clock (as used on GPS or Galileo satellites)	Ten nanoseconds (10^{-8}s)	3 m
Atomic clock from ACES/PHARAO scientific project	Ten picoseconds (10^{-11}s)	3 mm

(data source: [9])

1a. Satellite clock - Relativistic effect

Time effects

- time <u>runs slower</u> during very fast movements
- time moves <u>the faster weaker</u> the field of gravitation is
- Shift of time to the observer on earth is +38 ms/day = an total error of approximately 10 km per day.

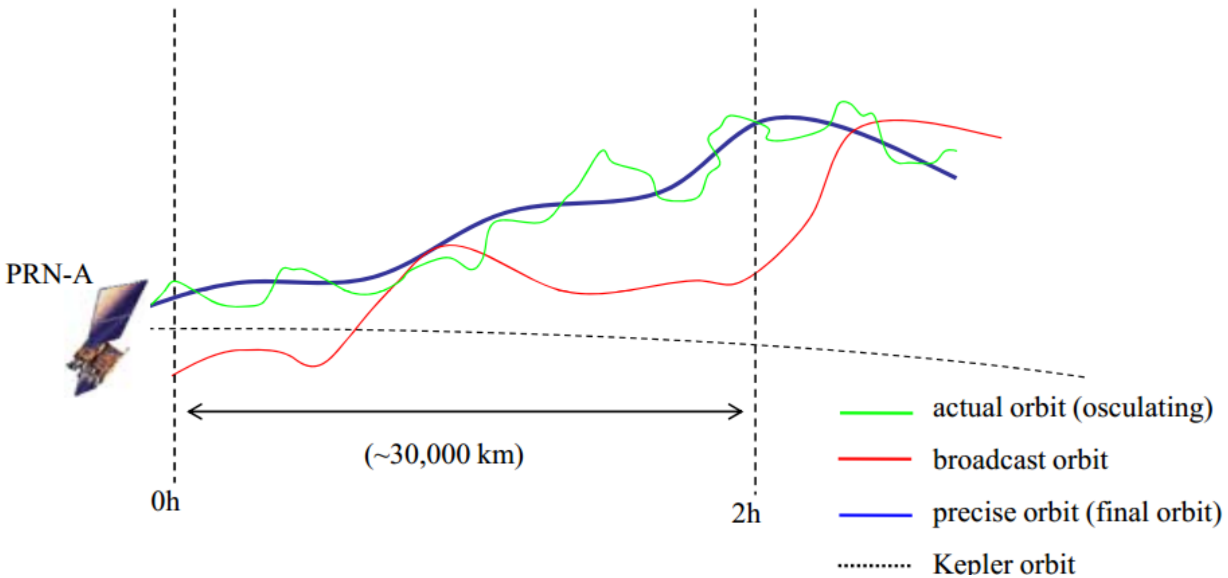


(illustration source: [11])

2. Ephemeris errors

- These are errors in the satellite's reported position against its actual position.
  - Broadcast orbit: based on pseuodorange (~ 2 m)
  - Final precise orbit: based on phase observables (~ 0.05 m)

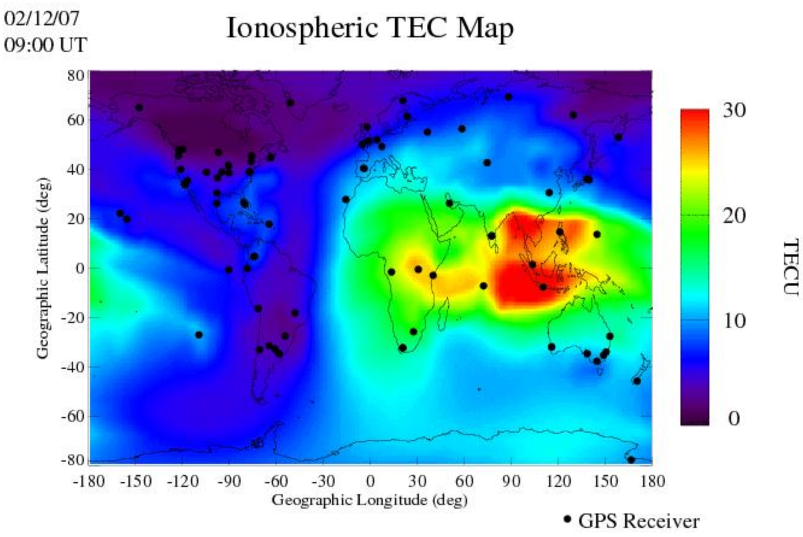
Note: the figure below is much exaggerated for explanation



(illustration source: [11])

3. Ionosphere disturbances

- A major source of range error for GPS positioning
  - In the region between 70 km and 1000 km
  - Formed by the UV ionizing radiation from the Sun
  - weekly ionized plasma, or gas, which can affect radio wave propagation in various ways
  - Change rapidly in absolute value & difficult to model

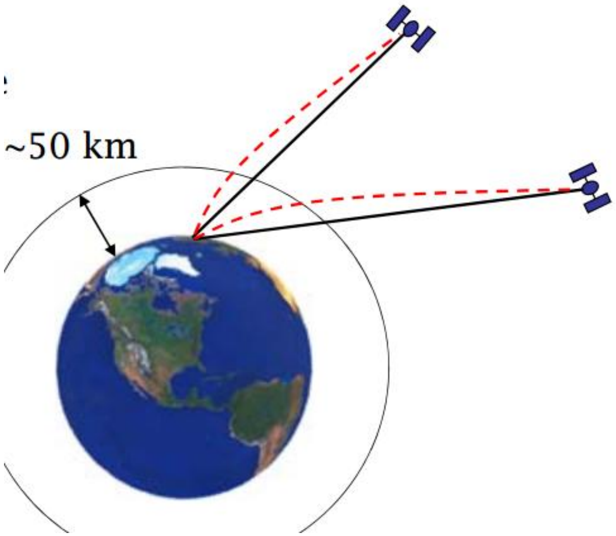


- GPS system has a built in <u>model that accounts</u> for an average amount of these disturbances. (compensated ~5 m, L1+L2)

(illustration source: [11])

4. Troposphere disturbances

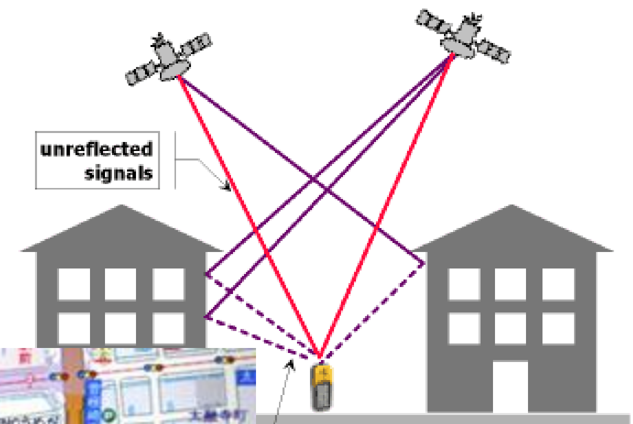
- Important source of range error for GPS positioning
  - Consist of dry gases (N_2, O_2, Ar, etc.) & water vapor
  - Non-dispersive medium for frequencies up to 15GHz
  - The phase and group velocities on both L1 & L2 are equally delayed
  - Tropospheric delay is a function of the refractive index & height
  - Refractive index is dependent on the local temperature, pressure, and relative humidity



  - complicated models, (wet and dry delay, ~0,5 m)

5. Signal reflection and multipath

- signal hits and is reflected off objects like tall buildings, rocks etc. This causes the signal to be delayed before it reaches the receiver.
- The resulting error typically lies in the range of a few meters (significant in urban environment)



By High precision GPS reciever module with speed and gyro input

By standalone GPS reciever

(illustration source: [5,6])

6. Receiver issues

Only 8 for the globe!

Quality of the receiver

- Model calculations – provided constants with limited precision – Ionospheric model constants, etc.
- Round up errors – during correlation calculation
- Antennae issues – small inadequate reception antenna causes loss of a signal

Map and positioning quality

- WGS-84's precision is limited to its significant numbers, namely XXX° XX.XXX'. = it is around 2m (in latitude), longitude lines get closer together as you go towards the poles, so the distance is COS(lat)*6ft.

UERE: User Equivalent Range Errors

- The errors of the GPS system are summarized in the following table. The individual values are <u>no constant values</u>, but are subject to variances. All numbers are <u>approximative values</u>.

Ionospheric effects	± 5 metres
Shifts in the satellite orbits	± 2.5 meter
Clock errors of the satellites' clocks	± 2 meter
Multipath effect	± 1 meter
Tropospheric effects	± 0.5 meter
Calculation and rounding errors	± 1 meter

± 12 m

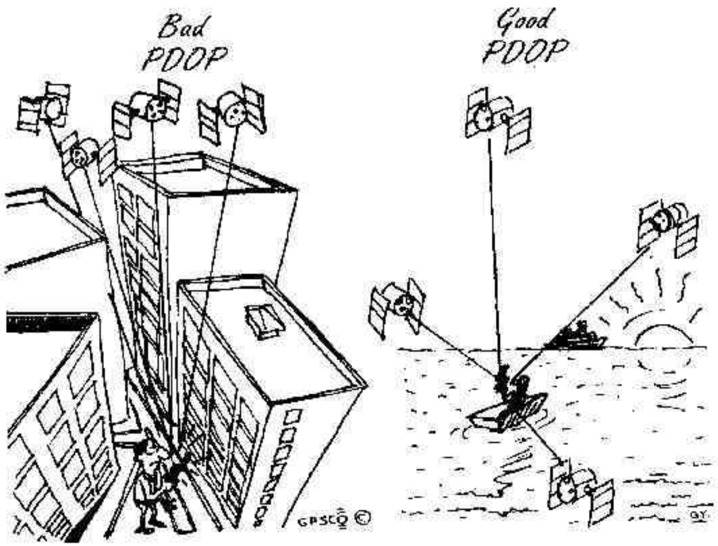
Is that all?

$$UERE = \sqrt{5^2 + 2{,}5^2 + 2^2 + 1^2 + 0{,}5^2 + 1^2} = 6{,}1m$$

(data source: [5])

Position Dilution of precision (PDOP)

- when satellites are clustered close together in the sky
- PDOP is a factor that **multiplies the uncertainty associated with User Equivalent Range Errors**
- Lowest PDOP encountered in practice is about 2
- Total uncertainty:
  Accuracy = UERE x DOP
- *Always relative to circle of probability – CEP, values are different for 50 % or 90 % radius*



Example: Standard error model - L1 C/A

sqr(alpha) Probability Notation

sqr(alpha)	Probability	Notation
1.00	*39.4%*	*1-sigma or standard ellipse*
1.18	*50.0%*	*Circular Error Probable (CEP)*

Error source	One-sigma error, m Bias	Random	Total	DGPS
Ephemeris data	2.1	0.0	2.1	0.0
Satellite clock	2.0	0.7	2.1	0.0
Ionosphere	4.0	0.5	4.0	0.4
Troposphere	0.5	0.5	0.7	0.2
Multipath	1.0	1.0	1.4	1.4
Receiver measurement	0.5	0.2	0.5	0.5
User equivalent range error (UERE), rms*	5.1	1.4	5.3	1.6
Filtered UERE, rms	5.1	0.4	5.1	1.5
Vertical one-sigma errors--VDOP= 2.5			**12.8**	**3.9**
Horizontal one-sigma errors--HDOP= 2.0			**10.2**	**3.1**

(data source: [8])

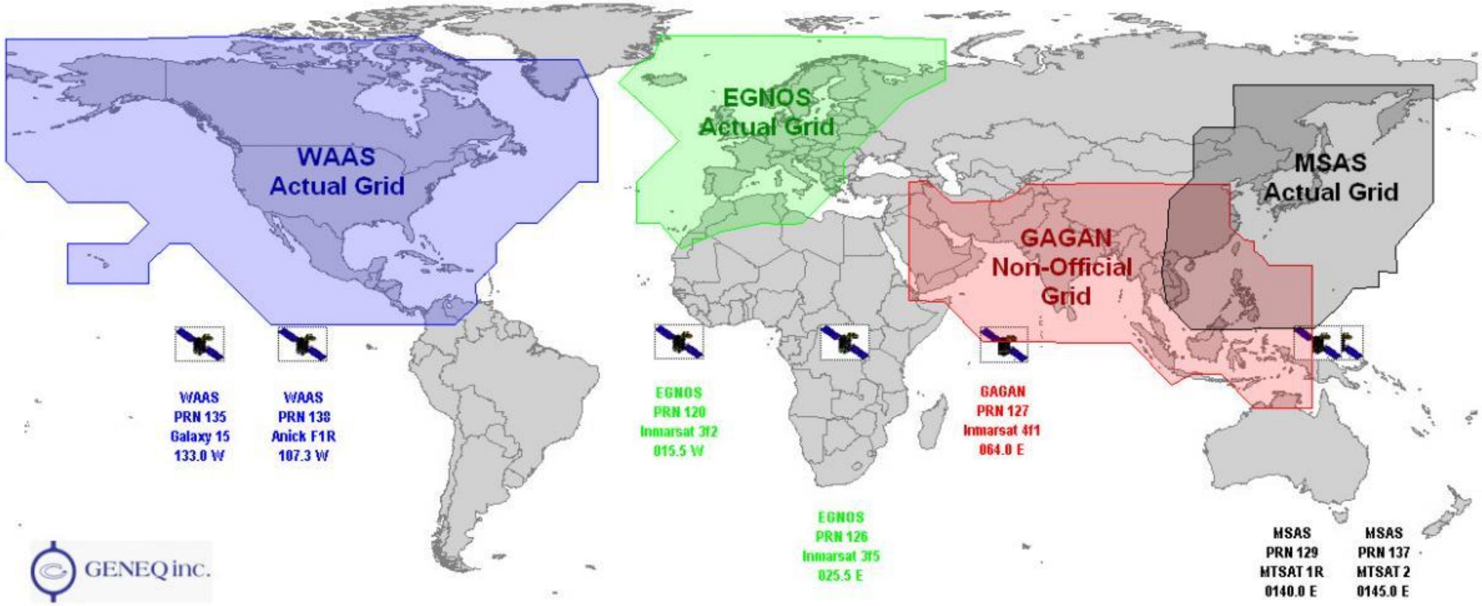
ERROR ELIMINATION

GNSS augmentation

- Improving the navigation system's attributes, such as
  - accuracy, reliability, and availability,
- through the integration of external information into the calculation process by providing
  1. additional information about sources of error (such as clock drift, ephemeris, or Ionospheric delay),
  2. direct measurements of how much the signal was off in the past, or
  3. additional vehicle information (inertial sensors), or
  4. combination of the above.

Satellite-based augmentation system (SBAS)

- Provides additional information about sources of error (<u>clock drift, ephemeris, or Ionospheric delay</u>)
- Measured at multiple ground stations and uploaded onto satellite to broadcast to users



(illustration source: [10])

GPS EGNOS comparison

- Summary of GPS-EGNOS errors: typical orders of magnitude

Error type	GPS	EGNOS
Orbit and clock synchronisation	1 m	0,5 m
Tropospheric error	0,25 m	0,25 m
Ionosphéric error	2 m	0,3 m
Receiver noise	0,5 m	0,5 m
Multipath	0,2 m	0,2 m
UERE (quadratic sum of errors - 1 σ)	2,31 m	0,83 m
HDOP (function of geometry of visible satellites)	1,1 m	1,1 m
Horizontal positioning accuracy error (1 σ) = UERE x HDOP	2,54 m	0,92 m
Horizontal positioning accuracy error (2 σ, 95 %)	5,08 m	1,84 m

(data source: [9])

GNSS needs to be maintained …

- **2009: United States Government Accountability Office GAO-09-325** (only 3 new satellite launches since then)

DON'T take your satnav for granted. Existing satellites are ageing, and replacements are behind schedule and over budget, according to a report from the US Government Accountability Office (GAO).

Satnavs and other GPS devices calculate their position by comparing time signals from at least four satellites. To keep that many within range at all times requires a fleet of at least 24. For now there are 31 operating, but 13 of them are more than four years past their design lifetime.

The first replacement "block IIF" satellites are not due to launch till November, three years behind schedule, and the GAO predicts a 20 per cent chance that the fleet will drop below 24 at times in 2011 and 2012. That wouldn't cause GPS to shut down, but its accuracy would drop unpredictably.

Plans by the US air force for the next generation of improved "block IIIA" satellites could also fall behind. The GAO calculates that if they slip by just two years, there is a 90 per cent chance that the fleet will drop below 24 in 2018."

(source: [12])

Good luck with GNSS Applications

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Resources

1. https://www.e-education.psu.edu/natureofgeoinfo/c5_p6.html
2. http://elth.ucv.ro/fisiere/anale/2006/6_1.pdf
3. http://www.glonass-ianc.rsa.ru/en/
4. http://www.path.cz
5. http://www.kowoma.de/en/gps/errors.htm
6. http://www.furuno.com/en/business_product/gps/case/case_field2.html
7. http://earthmeasurement.com/GPS_accuracy.html
8. http://www.edu-observatory.org/gps/gps_accuracy.html
9. http://ec.europa.eu/enterprise/policies/satnav/egnos/files/brochures-leaflets/egnos-user-guide_en.pdf
10. http://www.elisanet.fi/master.navigator/InfoEGNOS_WAAS.htm
11. http://en.wikipedia.org/wiki/Satellite_navigation
12. http://www.gao.gov/new.items/d09325.pdf