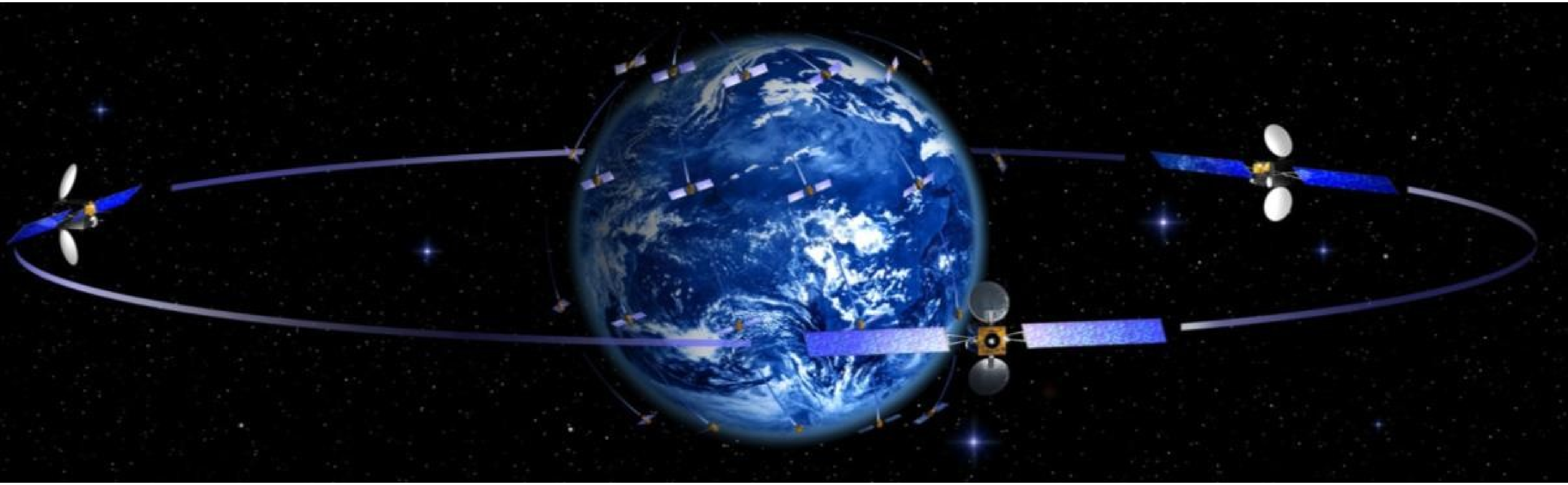
Satellite positioning – GNSS technologies



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Credits for some images & parts of the text: Heidi Kuusniemi, Laura Ruotsalainen, Zahidul Bhuiyan, FGI/NLS

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Learning objectives

- GNSS (Global Navigation Satellite System)
  - Applications
  - Constellations: GPS, Galileo, GLONASS, Beidou, QZSS
- GPS architecture and system

- Multi-sensor data input
- Position determination
- Error sources

Formulae!

- GNSS performance
- GNSS shortcomings
- Practicals for coding (formats, libs, links)

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Why is satellite-based positioning needed?

- With satellite-based positioning one can acquire Position, Velocity and Time (PVT) with

  1) global coverage

  2) very good accuracy

  3) integrity

- The current global market of applications and services of positioning systems is estimated to be more than 3 billion US dollars and it is expected to grow

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GNSS applications

Applications can be summarized into 5 broad categories:

- Location = determining a basic position (e.g., emergency calls)
- Navigation = getting from one location to another (e.g., car navigation)
- Tracking = monitoring the movement of people and things (e.g., fleet management, workforce management, lost child/pet tracking)
- Mapping = creating maps of the world
- Timing = bringing precise timing to the world

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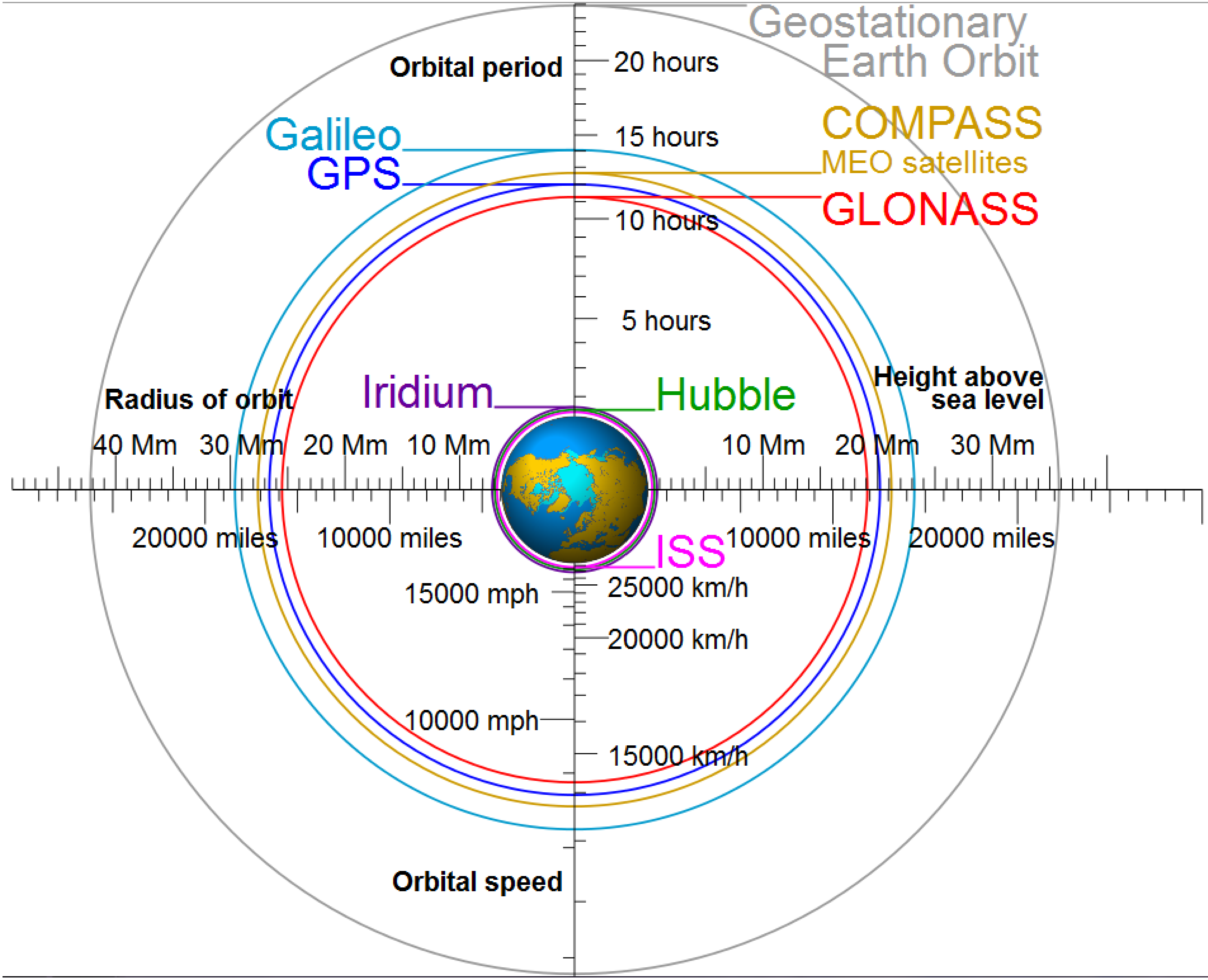
Galileo services

- 1998: European Union decides to develop its own satellite navigation system, called ”Galileo”
- Galileo satellite-only services
  - Open Service (OS): free for everyone; mass market applications, simple positioning
  - Safety of Life (SoL): for professional applications; integrity; authentication of signal
  - Commercial Service (CS): for maritime, aviation and train applications; (encrypted); high accuracy; guaranteed service
  - Public Regulated Service (PRS): encrypted; government-regulated; integrity; continuous availability
  - Support to Search and Rescue service (SAR): humanitarian purpose; near real time; precise; return link feasible
- Other Galileo-related services: Galileo locally assisted services (use some local elements to improve performance, e.g., differential encoding, more carriers, additional pilot tones), Galileo combined services (combination with other navigation or communication systems).

GNSS constellations

- Global:
  - GPS: Global Positioning System (USA)
  - Galileo: (European Union)
  - GLONASS: (Russian Federation)
  - Beidou: (China)
- Regional:
  - QZSS: Quasi-Zenith Satellite System (Japan)
  - IRNSS: Indian Regional Navigational Satellite System (India)


Geostationary Earth Orbit
Orbital period
20 hours
15 hours
10 hours
5 hours
COMPASS
MEO satellites
Galileo
GPS
GLONASS
Iridium
Hubble
ISS
Radius of orbit
Height above sea level
40 Mm
30 Mm
20 Mm
10 Mm
10 Mm
20 Mm
30 Mm
20000 miles
10000 miles
10000 miles
20000 miles
15000 mph
25000 km/h
20000 km/h
10000 mph
15000 km/h
Orbital speed

GNSS system architecture

- All GNSS systems are based on the same architecture (3-segment architecture):
- Space segment: satellites
- Control segment: monitoring, controlling and uploading stations => a heavy ground infrastructure required in order to deliver the right signals with the right parameters to the users.
- User segment: user community/GNSS receivers
- The number of satellites and monitor stations differ according to the GNSS system (GPS, Glonass, Galileo, BeiDou,...)

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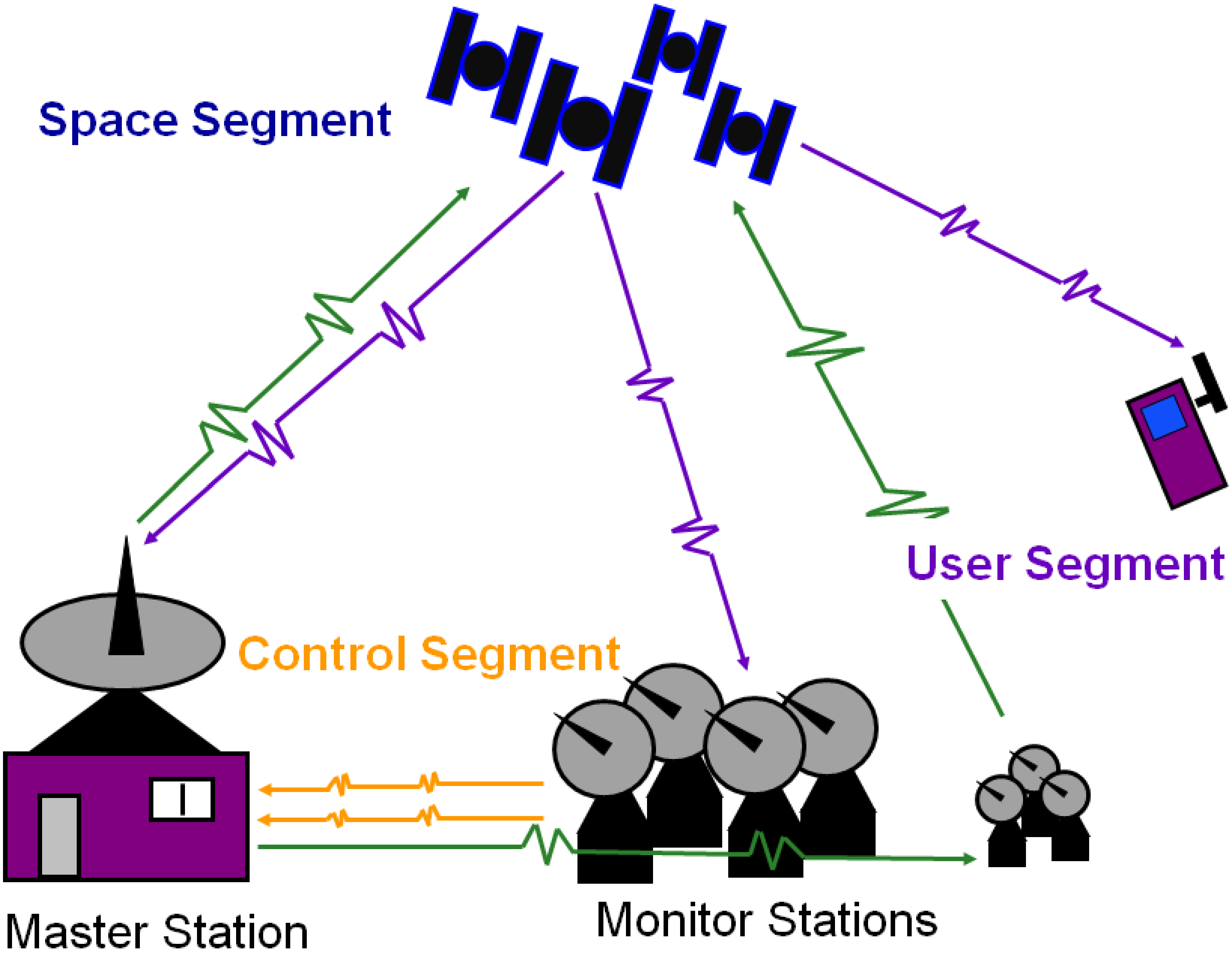

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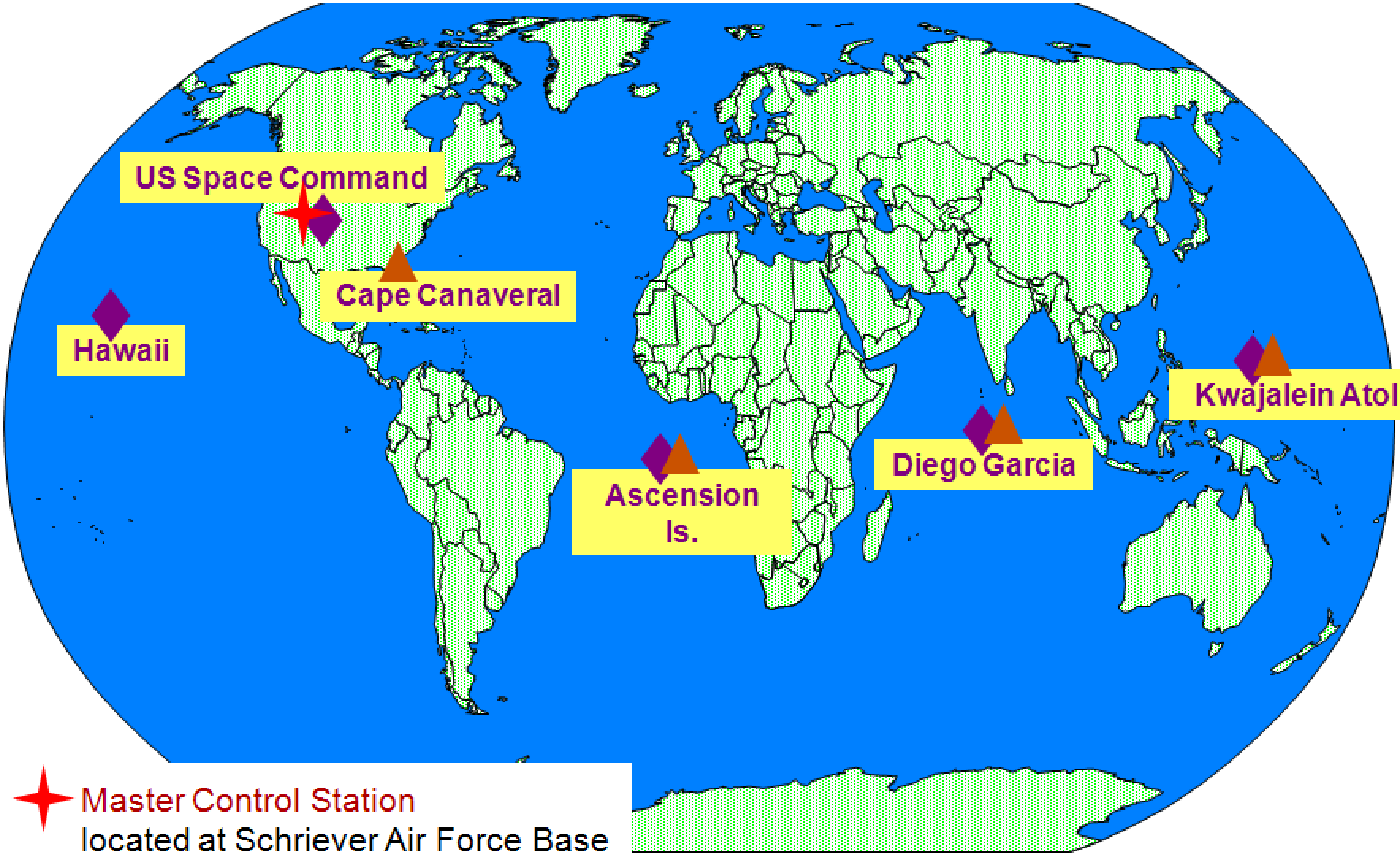
GPS architecture

- Navstar GPS was devised by the US Department of Defense for various applications (initially for military use only, later on also for civilian applications), such as fleet management, navigation, etc.
- It has 3 segments:
- Satellite constellation (Space segment): Currently 32 satellites (originally 24), positioned in 6 Earth-centered orbital planes; they provide the ranging signals and navigation data messages to the user equipment.
- Ground control network (Ground segment): 1 Master Control Station (MCS), 3 uploading stations, and 11 monitor (surveillance) stations; this segment tracks and maintains the satellite constellation by monitoring satellite health and signal integrity, and maintaining satellite orbit configuration.
- User equipment (User equipment): It receives signals from the satellite constellations and computes user Position, Velocity and Time (PVT).



✦ Master Control Station
located at Schriever Air Force Base

◆ Monitor Station

▲ Ground Antenna

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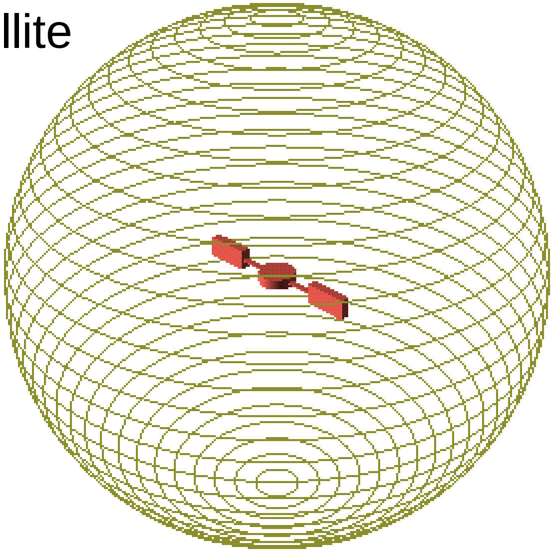
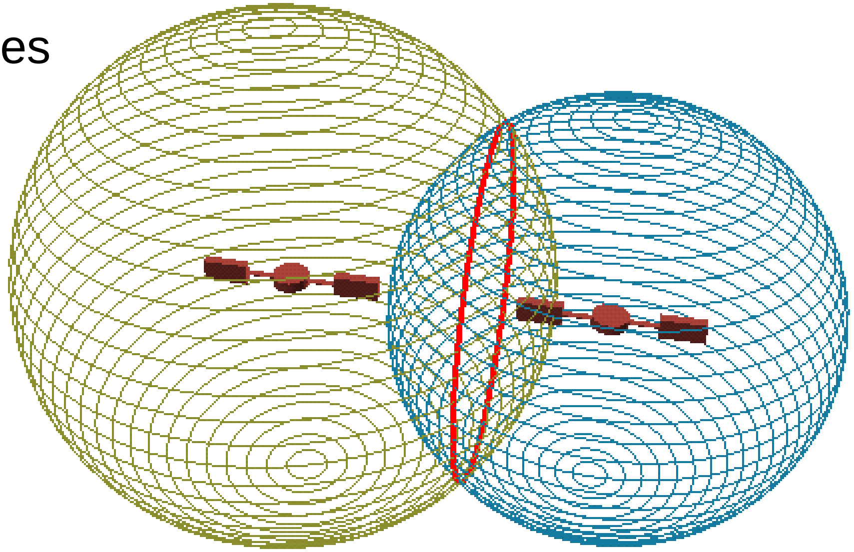
Positioning overview (1)
3D trilateration

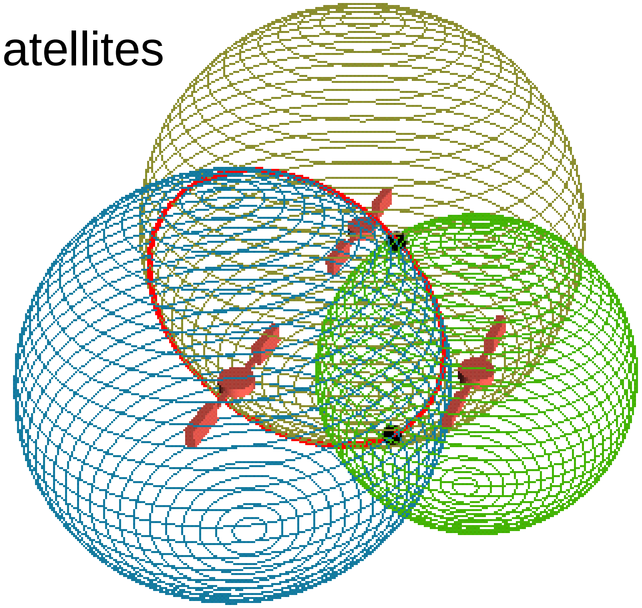
1 Satellite



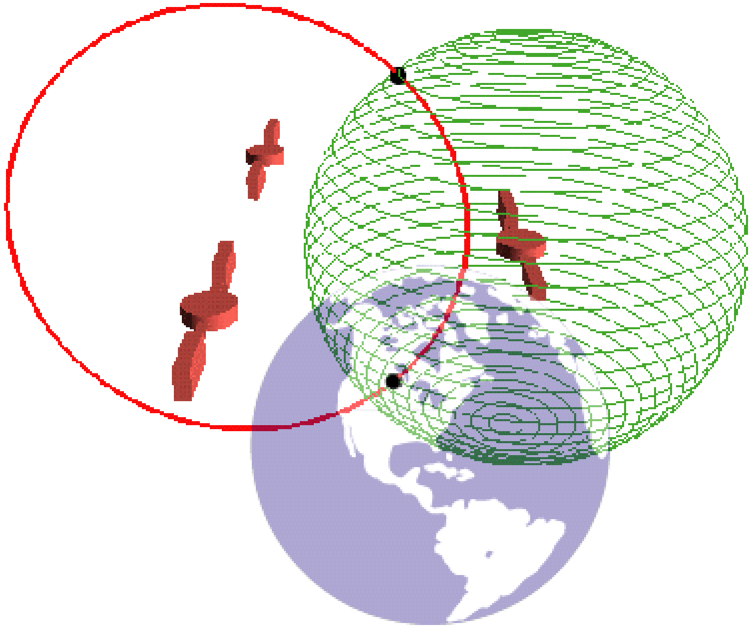
2 Satellites



3 Satellites



Zoom in



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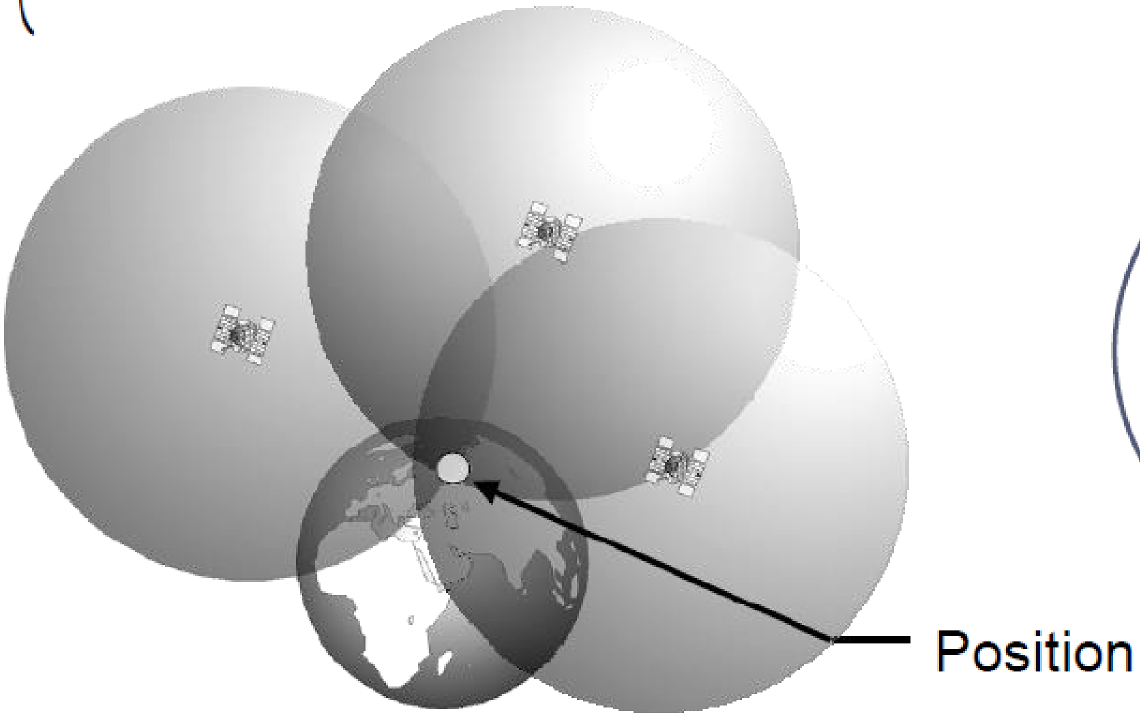
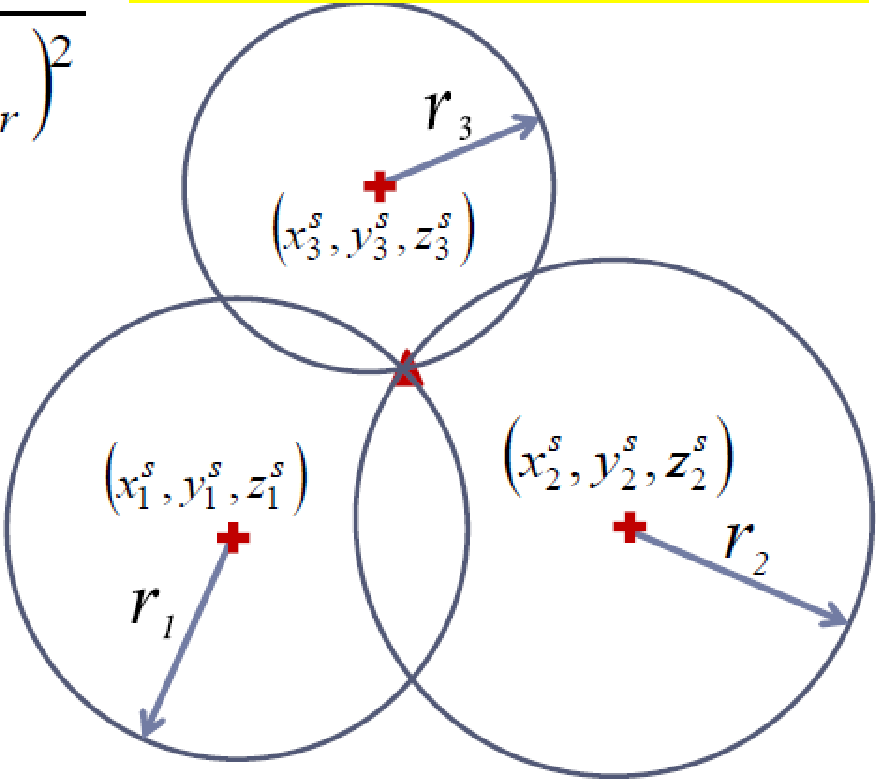
Positioning overview (2)

$$
\begin{cases}
r_1 = \sqrt{\left(x_1^s - x_r\right)^2 + \left(y_1^s - y_r\right)^2 + \left(z_1^s - z_r\right)^2} \\
r_2 = \sqrt{\left(x_2^s - x_r\right)^2 + \left(y_2^s - y_r\right)^2 + \left(z_2^s - z_r\right)^2} \\
r_3 = \sqrt{\left(x_3^s - x_r\right)^2 + \left(y_3^s - y_r\right)^2 + \left(z_3^s - z_r\right)^2}
\end{cases}
$$

Finding (x_r, y_r, z_r) so that the three equations stand, when r and (x^s, y^s, z^s) are known





▲ User position(x_r, y_r, z_r)

N satellites are sending data, how?

- CDMA (Code-division multiple access)
  - several transmitters can send information simultaneously over a single communication channel. A band of frequencies is shared.
- FDMA (Frequency division multiple access)
  - FDMA gives users an individual allocation of one or several frequency bands, or channels.
- TDMA (Time-division multiple access)
  - users transmit in rapid succession, one after the other, each using their own time slot, provided by central command.

Data transmission speed is not affected by this choice!

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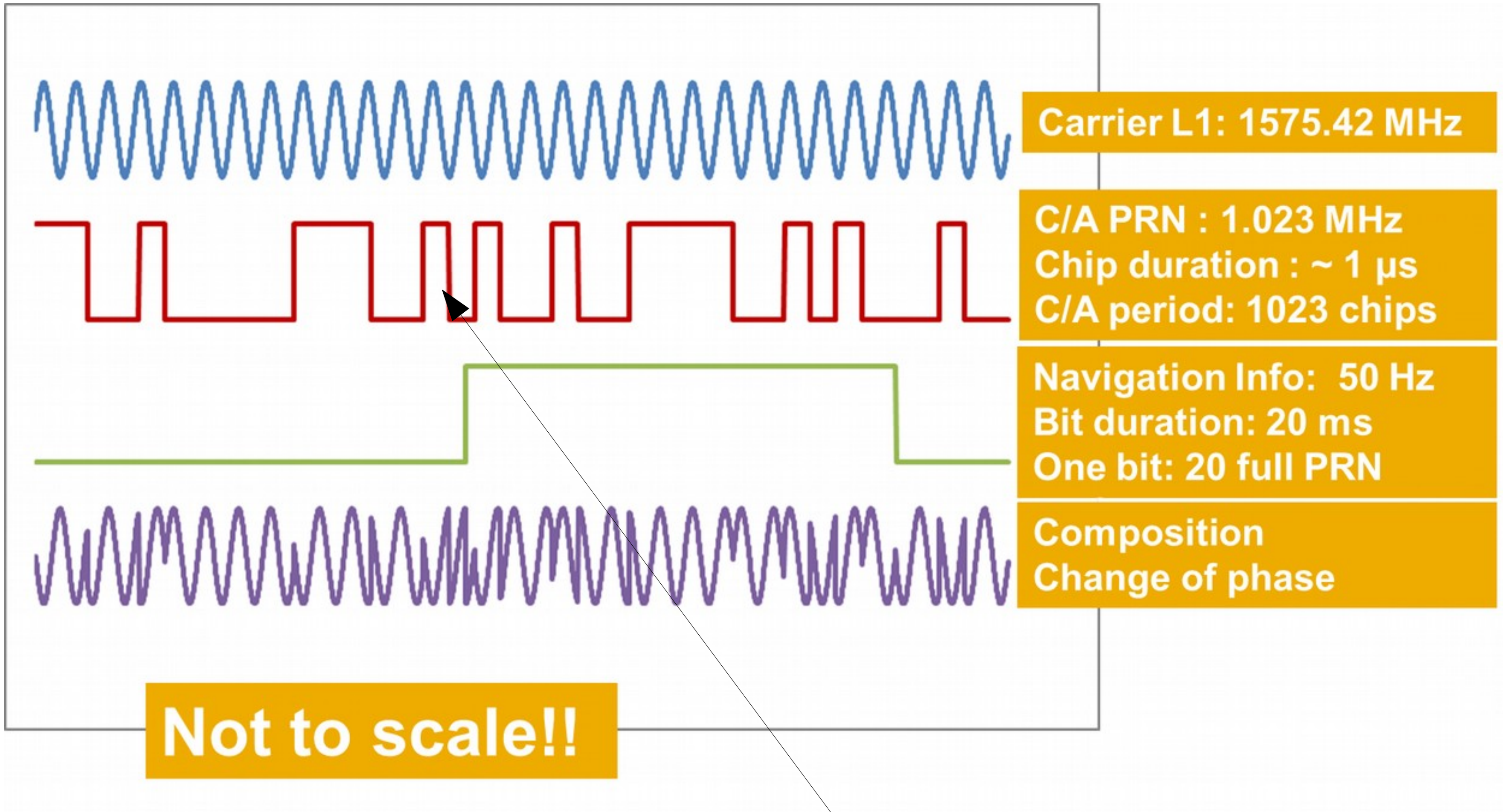
Structure of GPS signal (1)



Pseudo-Random Noise (PRN) sequence

Each satellite has its own
code in CDMA!

http://www.navipedia.net/index.php/GNSS_signal

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Structure of GPS signal (2)

- Carrier: Radio frequency sinusoidal signal at a given frequency.
- Ranging code: Sequences of 0s and 1s (zeroes and ones), which allow the receiver to determine the travel time of radio signal from satellite to receiver. They are called Pseudo-Random Noise (PRN) sequences or PRN codes.
- Navigation data: A binary-coded message providing information on the satellite ephemeris (Keplerian elements or satellite position and velocity), clock bias parameters, almanac (with a reduced accuracy ephemeris data set), satellite health status, and other complementary information.

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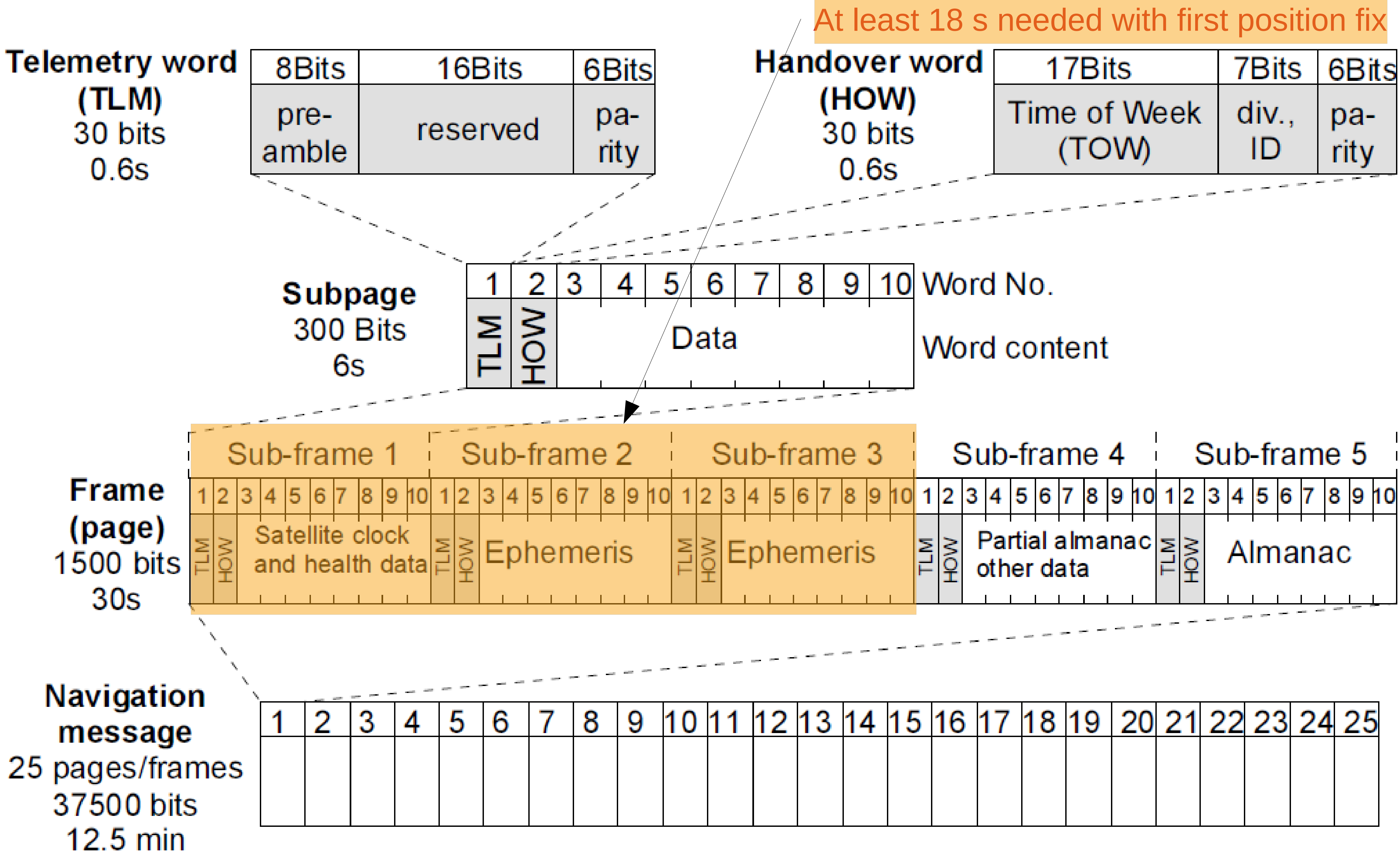
Structure of GPS signal (3)

At least 18 s needed with first position fix



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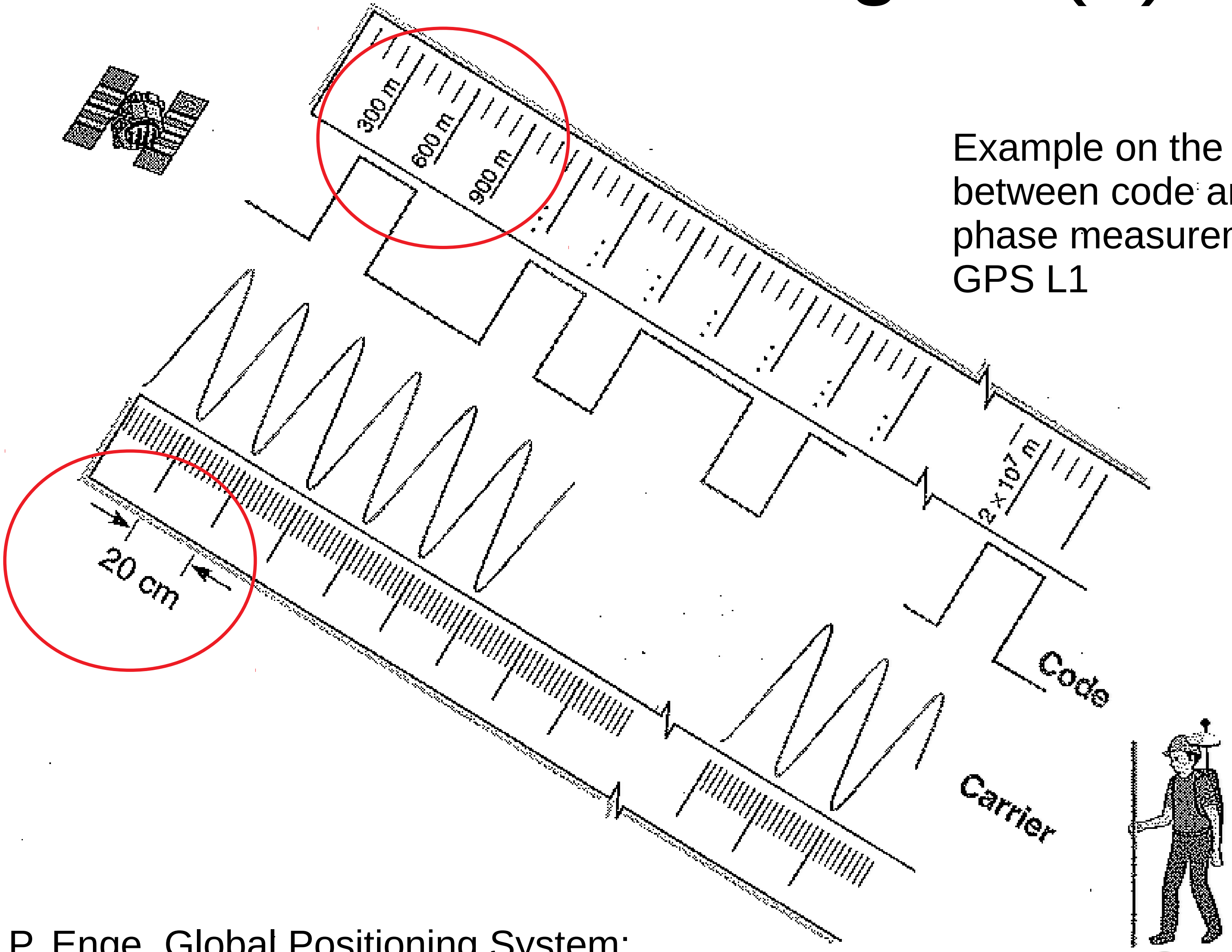
Structure of GPS signal (4)



Example on the difference between code and carrier phase measurements on GPS L1

Source:
P. Misra, P. Enge, Global Positioning System; Signals, Measurements, and Performance, 2006, 569 s.

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Signal strength (dB, C/$N_{0,}$ SNR)

- deciBel (dB) is a logarithmic unit of signal measurement that expresses the magnitude of a physical quantity relative to a specified or implied reference level
- dB is dimensionless and is used for signal power comparison e.g. signal amplification, attenuation or Signal-to-Noise-Ratio (SNR) computation
- Signal power is typically measured in dBW

$$dBW = 10 \cdot \log_{10}\left(\frac{P}{1W}\right)$$

- CDMA: GNSS signal strength is below noise level!
  - Can only be acquired by using code correlation!

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Relationship between SNR and C/N_0

- Carrier-to-Noise-density ratio C/N_0 is a measure of the analog part, but it is also widely used to analyze the baseband performance
  - Typical values in an L1 C/A code receiver, C/N0 ~ 37 to 45dB-Hz
- Signal-to-Noise-Ratio (SNR) is a measure of the digital part, and therefore, we need a mapping between the two terms:
- The SNR (in dB) at a certain point of the baseband domain where the bandwidth is B_W can be written as:

$$SNR = (C/N_0) - 10\log_{10}(B_W)$$

- B_W is not the front-end receiver bandwidth, but the bandwidth of the particular point considered in the analysis
- For example, if the analysis is done after 1 ms processing that is at a B_W of 1 kHz, the relationship becomes:

$$SNR = (C/N_0) - 30$$

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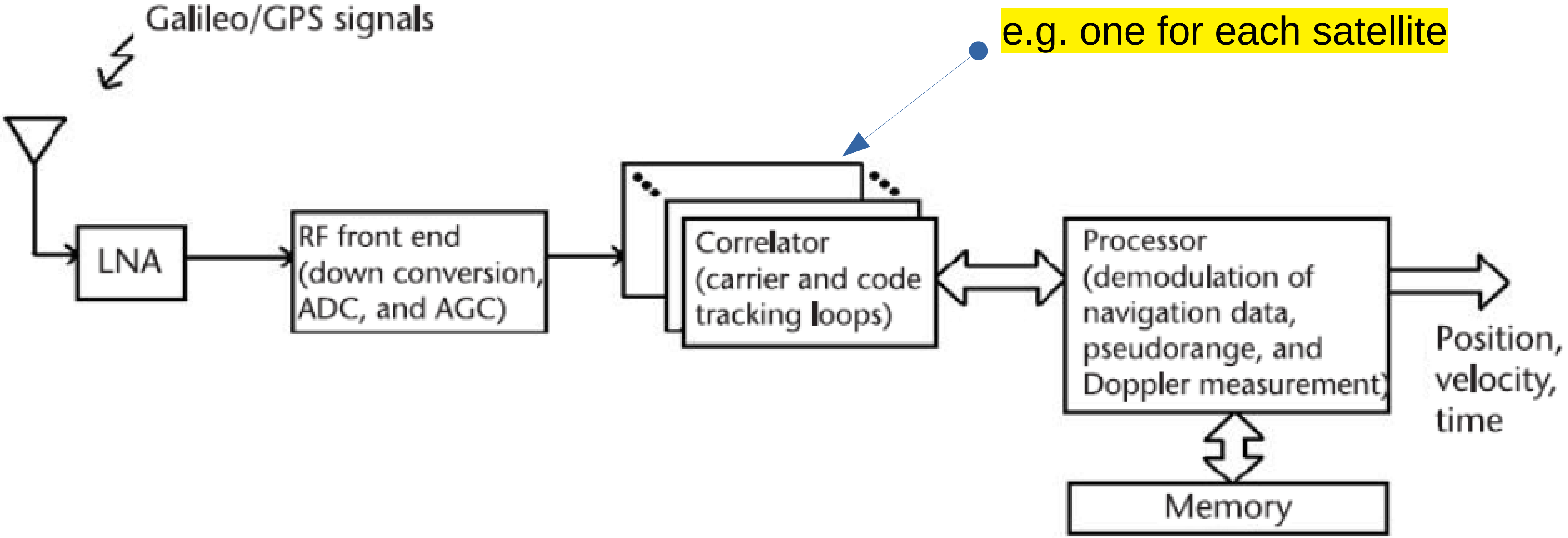
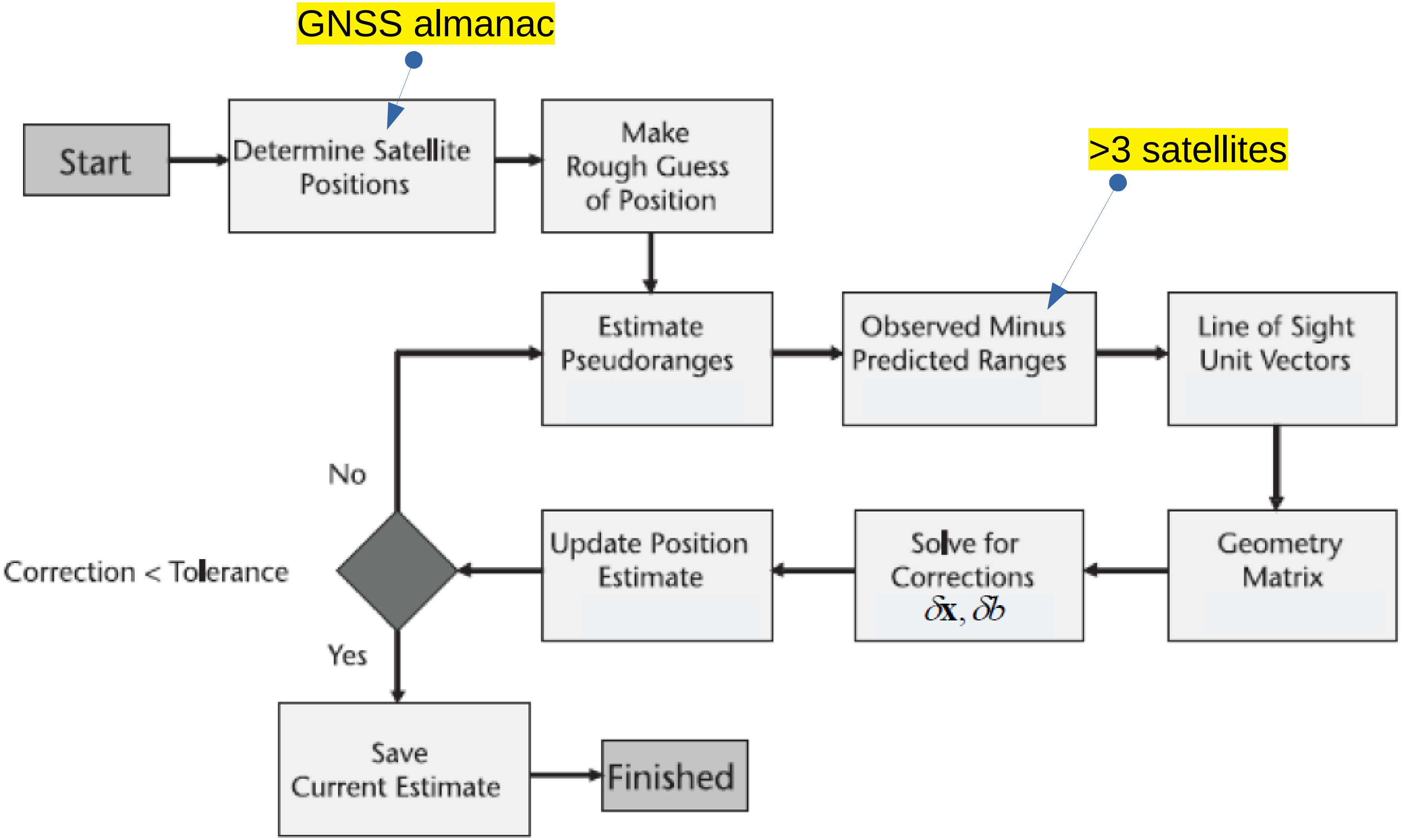
GNSS Receiver (1)



e.g. one for each satellite

- GNSS signals are normally received through the use of a right-hand circularly polarized (RHCP) antenna and amplified using a low-noise amplifier (LNA), which essentially determines the receiver's noise figure
- The RF signals are down-converted, typically in a number of stages, to an intermediate frequency (IF), sufficiently high in frequency to support the signal bandwidth
- After down-conversion, the signal is digitized by an analog-to-digital converter (ADC), with automatic gain control (AGC), and the digital IF is then passed to the receiver's correlator channels
- In the correlator channels, the carrier signal and code sequence are removed from the signal by correlating the received signal with locally generated replicas

GNSS Receiver (2)



GNSS almanac

>3 satellites

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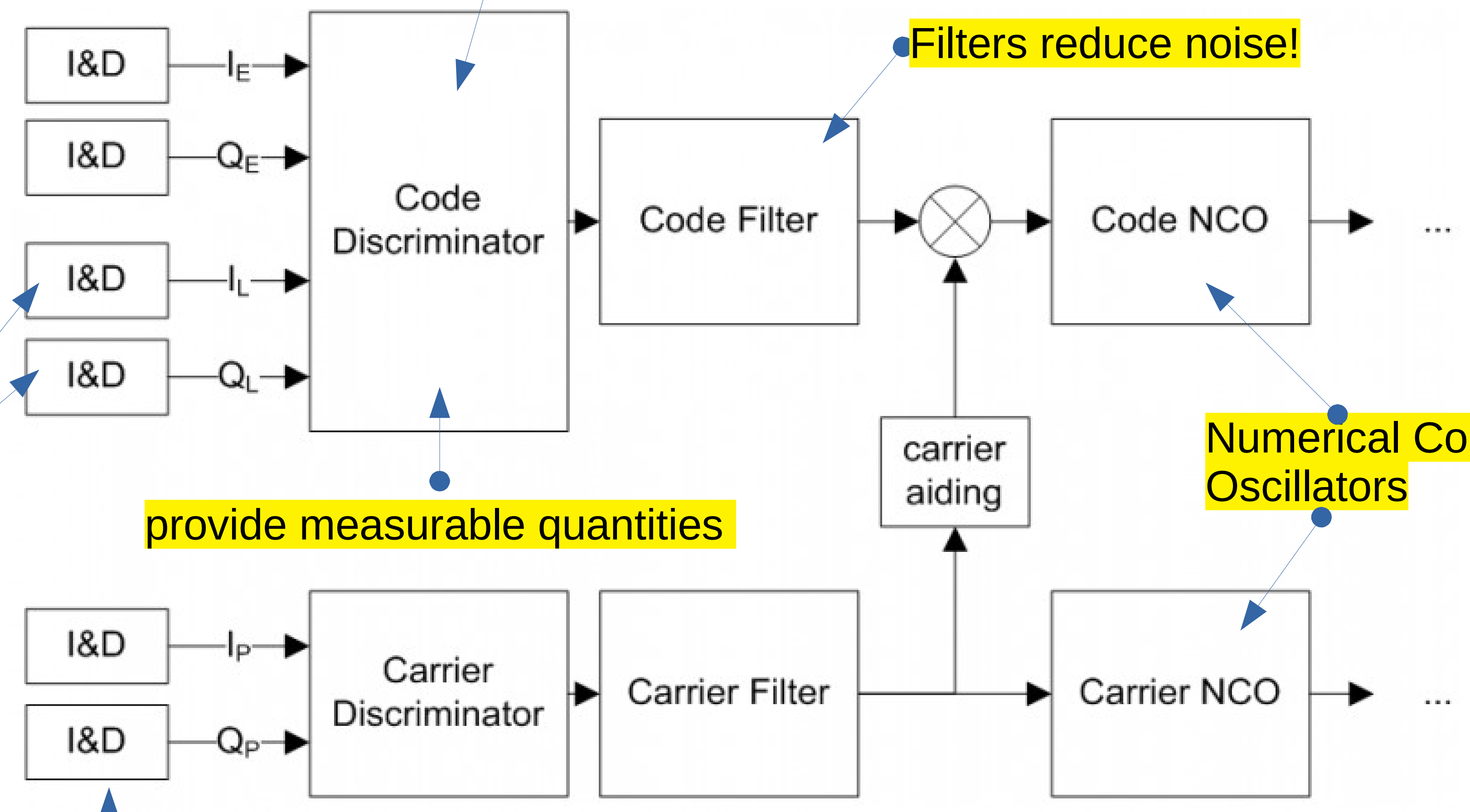
GNSS Receiver (3): Code and carrier tracking loops



shift the signal by one bit and try again, until it's found (1023 bit periods, ~1 Hz)

Filters reduce noise!

different PRN code for each satellite

provide measurable quantities

Numerical Control Oscillators

Integrate & Dump

Basic block diagram of the tracking loops.

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GNSS Receiver (4)

- Multiple correlator channels are required
  - +/- 10kHz, therefore requiring searching about 40 different frequency shifts
  - different PRN code for each satellite (N=20-30)
    - Length of each PRN is 30s (essentials in ~18s)
- shift the signal by one bit and try again, until it's found (1023 bit periods, ~1 Hz)

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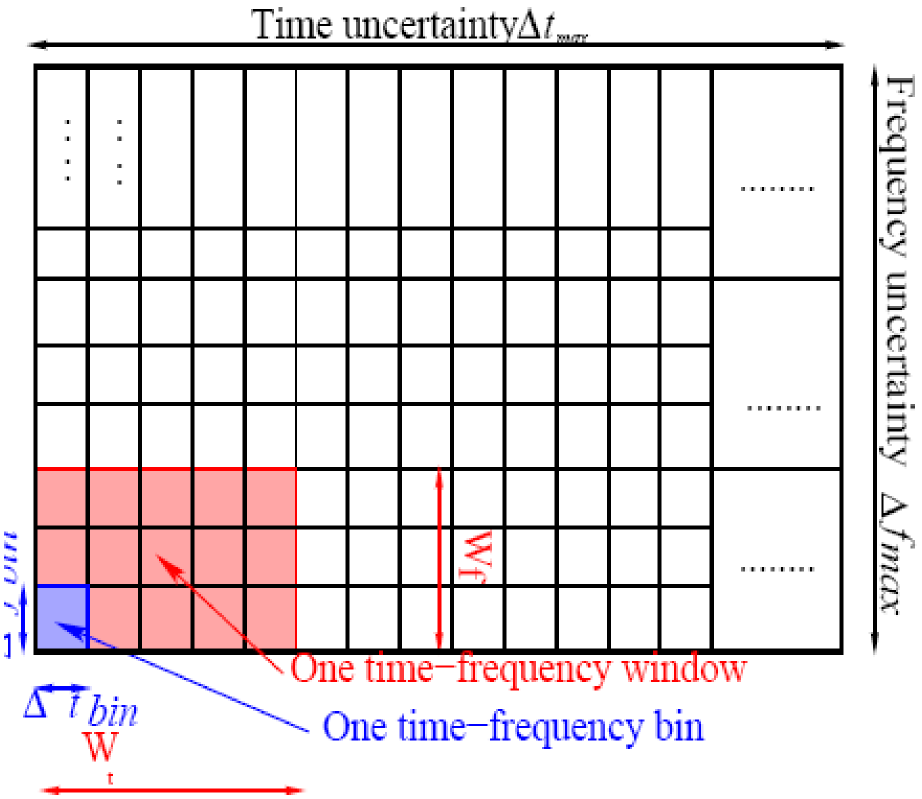
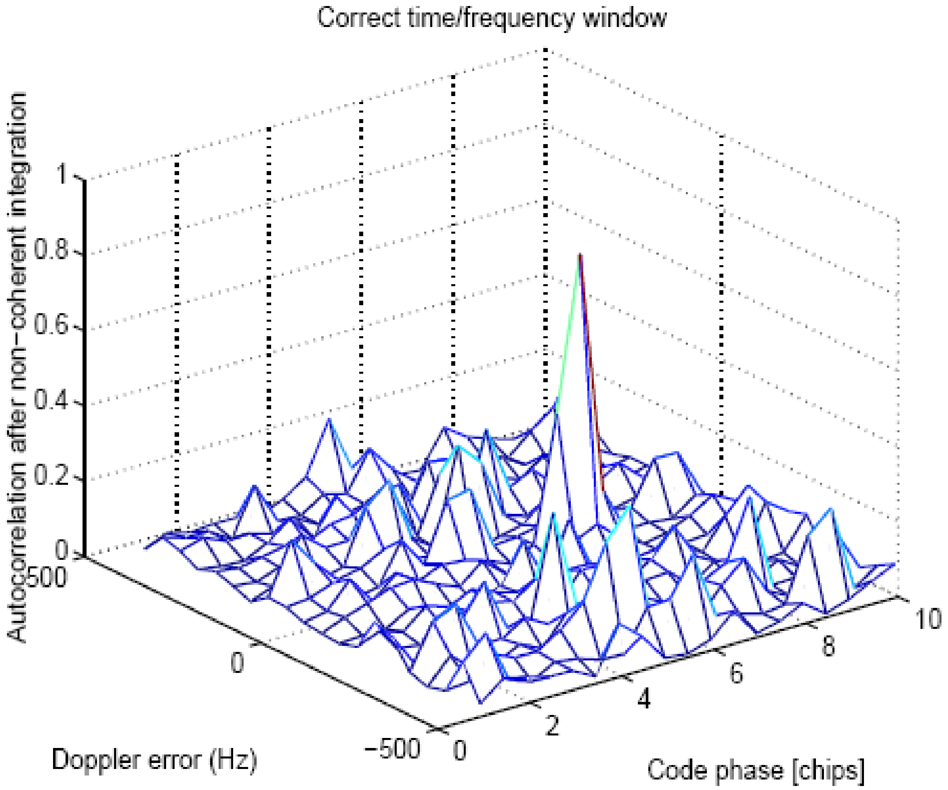
GNSS Receiver (5):
Search for time-frequency





One correlation output forms a time-frequency bin. Several bins form a time-frequency window. The whole search space = time-frequency uncertainty window.

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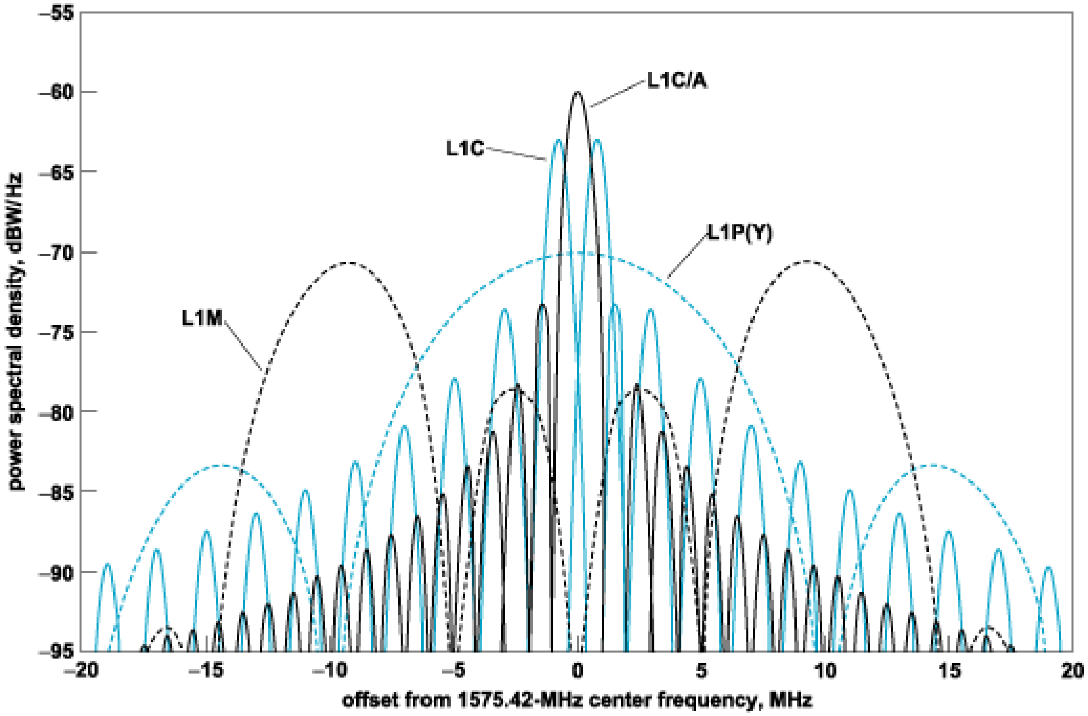
GNSS Receiver (6): Frequency offset in tracking



Power spectral densities of GPS L1 signals

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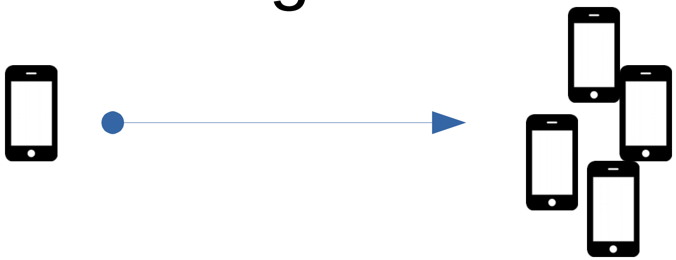
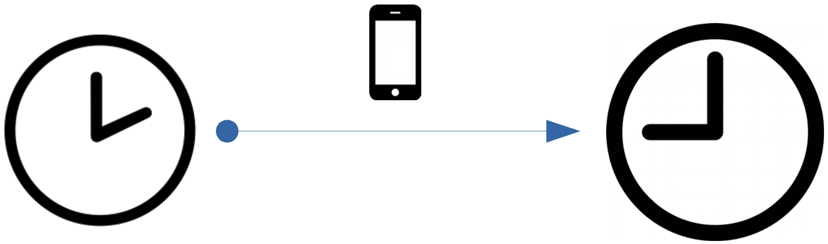
Wake up questions (1)

- Can a bad antenna / receiver (e.g. smartphone) position estimate be mitigated?
  - by increasing the amount of receivers?



  - By increasing the length of time series obtained from one receiver?



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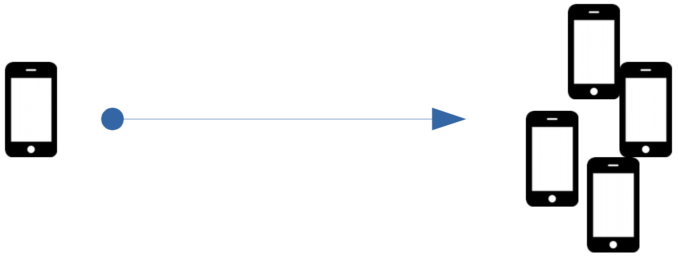
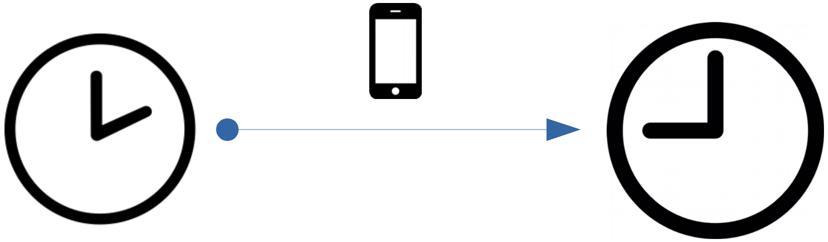
Wake up questions (2)

- Problem with bad receivers:
  - Signal to noise ratio is bad
  - Phase lock in carrier tracking loop does not hold
  - Tracking fails. Back to square one (acquisition)



Maybe, if N is large



Maybe, if receiver is in static mode and there are no bias (multipath, atmosphere)

http://www.navipedia.net/index.php/Phase_Lock_Loop_(PLL)

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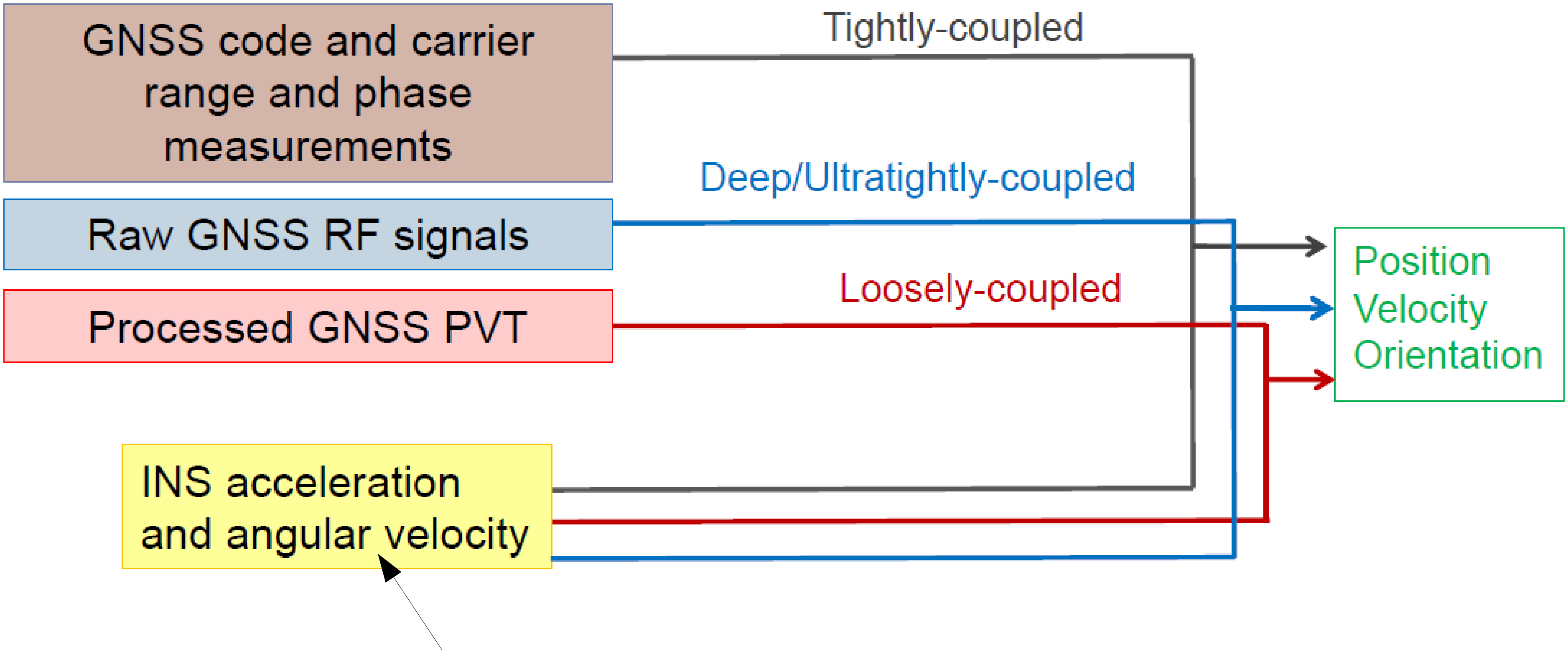
How can roboticists use GNSS?

- Combine the GNSS data with other sensor data
  - Integration architectures



GNSS code and carrier range and phase measurements

Raw GNSS RF signals

Processed GNSS PVT

INS acceleration and angular velocity

Tightly-coupled

Deep/Ultratightly-coupled

Loosely-coupled

Position
Velocity
Orientation

And other data as well

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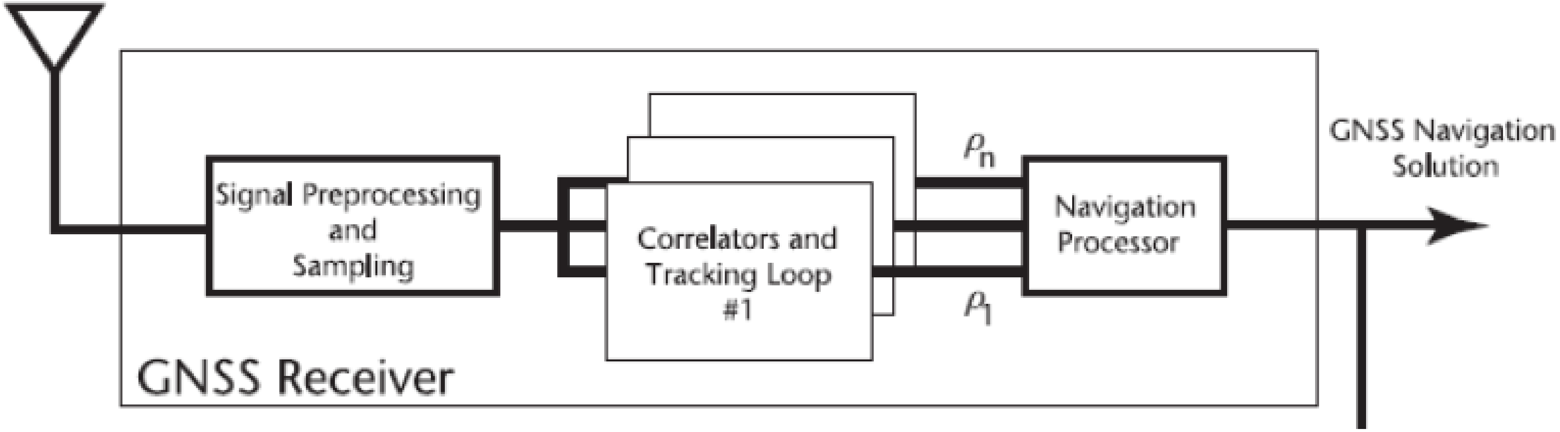
GNSS integration (1)



- Loosely coupled
- GNSS receiver = black box
  - Obtain PVT (position, velocity, time)
- So what?
  - Obtain perturbed forest trajectory (the other lecture)

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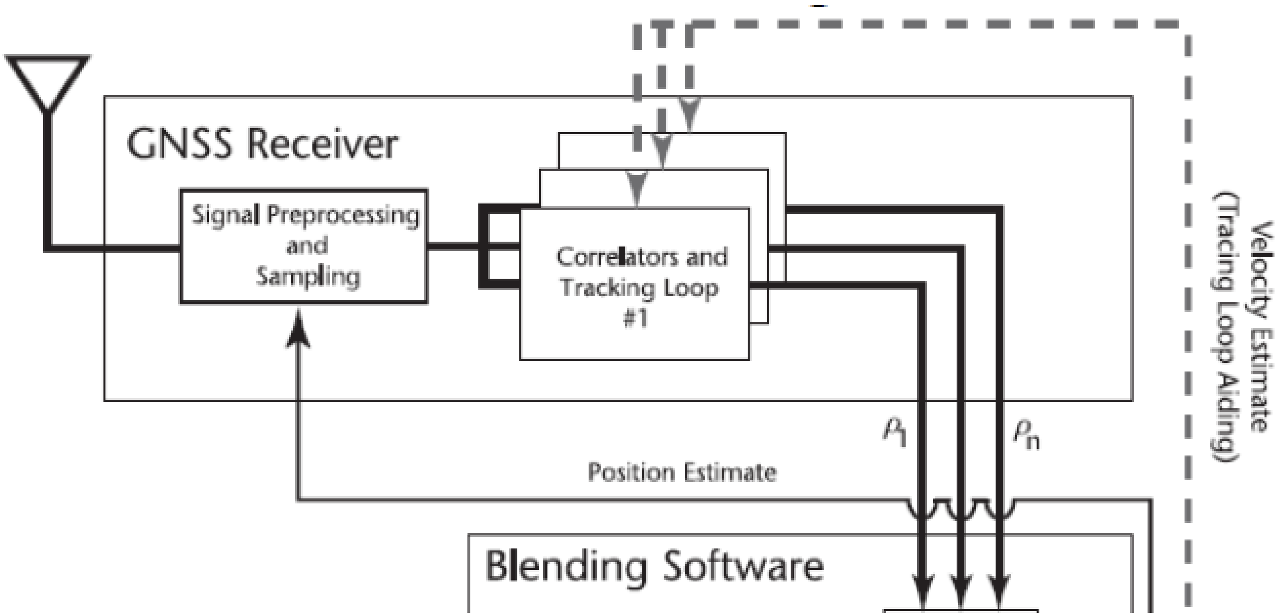
GNSS integration (2)

- Tightly coupled
- Provide position & velocity estimates to GNSS tracking loop
- Obtain pseudo-ranges to fuse with other data
  - works with less than 4 satellites!



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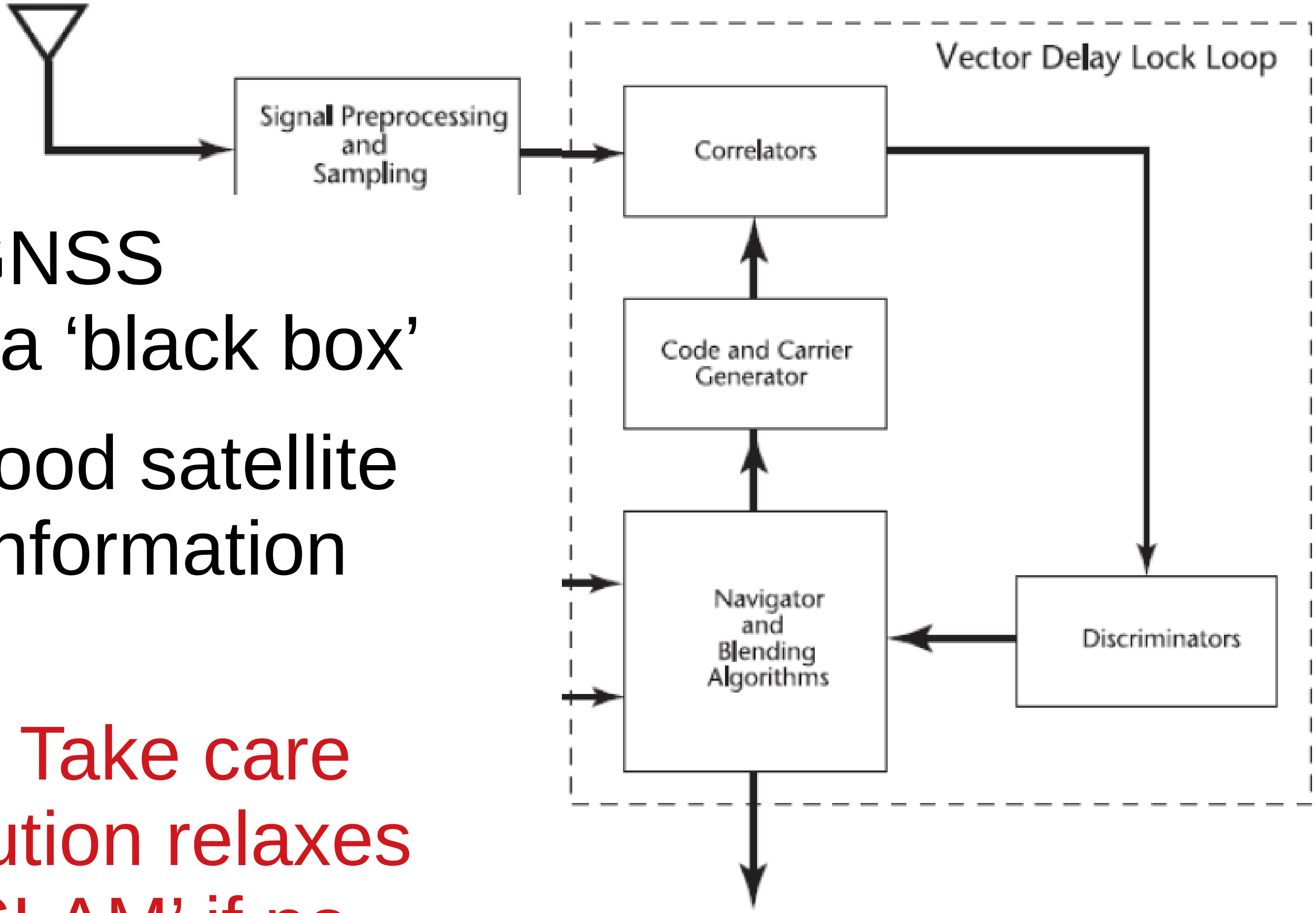
GNSS integration (3)

- Deep coupled
- Don’t use GNSS receiver as a ‘black box’
- Even one good satellite signal has information value
- Roboticists: Take care that the solution relaxes to ‘normal SLAM’ if no satellites are visible



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Signal Acquisition & Tracking: Briefly

- Code shift and Doppler frequency acquisition are needed for reliable performance of any CDMA system (Code-division multiple access)
- The code synchronization task is typically split into:
  - coarse synchronization (or acquisition stage) and
  - fine synchronization (or tracking stage).
- Acquisition is used to get a rough timing estimate, say within +/-0.5 chips in case of GPS L1 C/A signal
- Tracking means finding and maintaining fine synchronization
- Signal tracking is much easier given the initial acquisition
- Signal acquisition, however, is usually considered as one of the most challenging tasks in any spread spectrum system
- Signal acquisition is usually a one-shot estimate. On the contrary, signal tracking is performed in a continuous fashion

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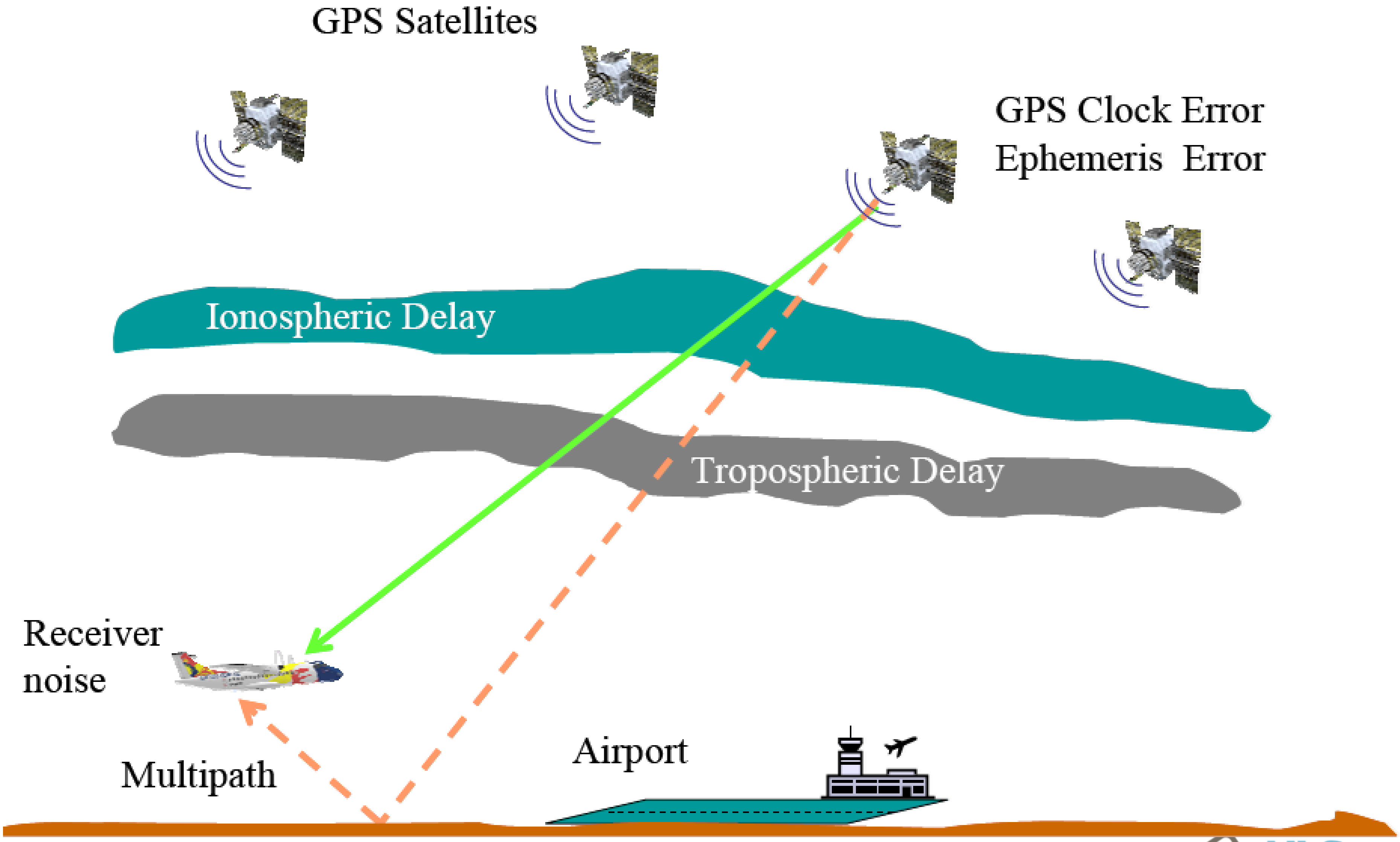
GNSS error sources (1)



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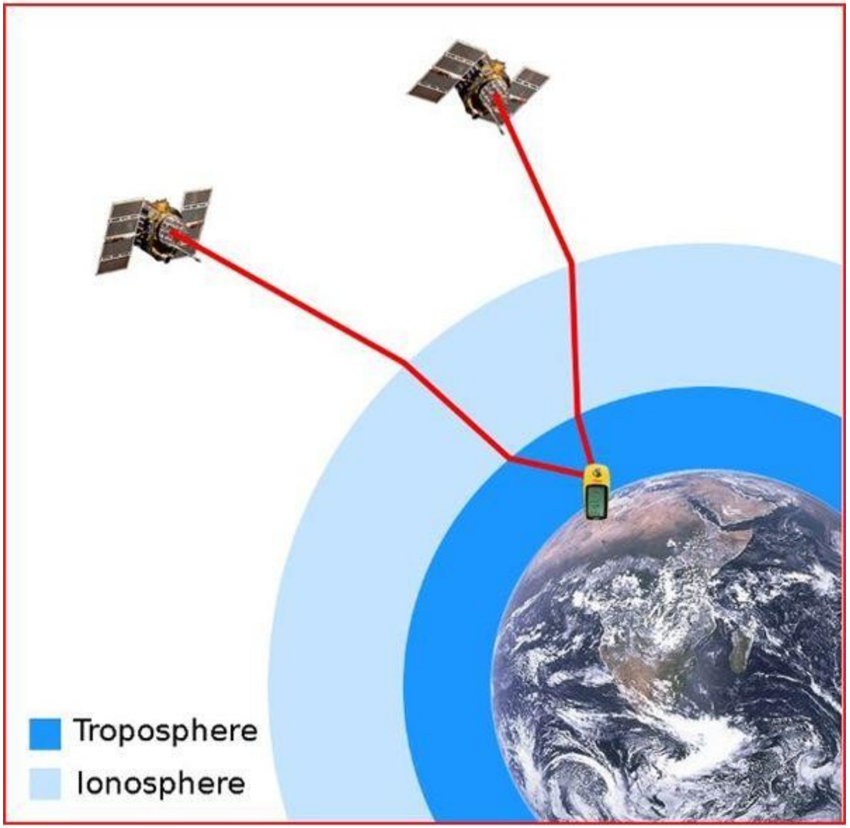
GNSS error sources (2)
GPS Error budget

- Standard error model - L1 C/A (sources: Samuel J. Wormley http://edu-observatory.org/gps/, E. Kaplan and J. Hegarty: GPS Principles and Applications, 2 nd edition, 2006)

Error source	One sigma error, m
Ephemeris data	1.1 – 2.1
Satellite clock	1.1 – 2.1
Ionosphere	4.0 – 7.0
Troposphere	0.2 – 0.7
Multipath	0.2 – 1.4
Receiver measurement	0.1 – 0.5



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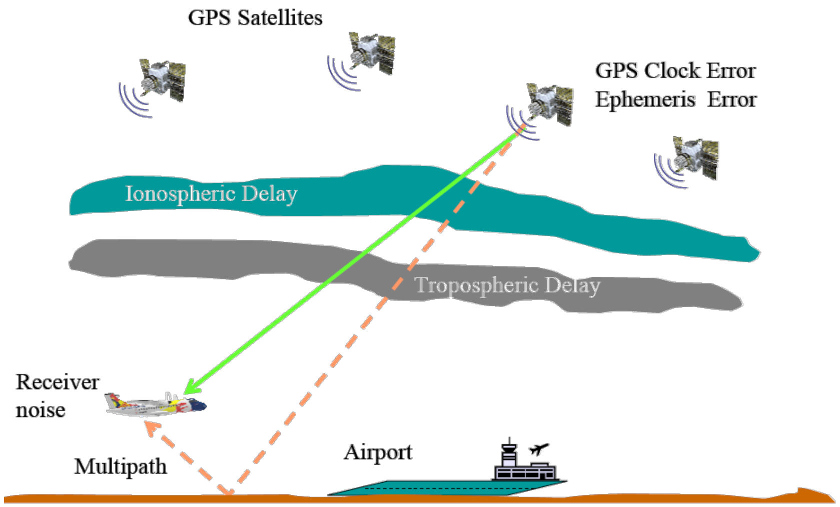
GNSS error sources (3)
Pseudo-range ρ computation (code)

- Satellite k related errors:
  - Satellite clock offset, δt^k
  - Ephemeris errors, r^k
- Atmospheric related errors:
  - Ionospheric delays, I^k
  - Tropospheric delays, T^k
- Receiver u and its surrounding:
  - Receiver noise, ε_u
  - Multipath, M_u



Speed of light c

$$\rho^k = \sqrt{(x_u - x^k)^2 + (y_u - y^k)^2 + (z_u - z^k)^2}$$

$$\hat{\rho}^k = \rho^k + c[\delta t_u - \delta t^k] + I^k + T^k + \epsilon_u + M_u$$

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GNSS error sources (4)
Ionospheric delay

- The ionosphere is ionized by solar radiation during each day.
  - The propagation speed of the GNSS electromagnetic signals in the ionosphere depends on its electron density
- By combining measurements made at different frequencies, the pseudorange errors due to the ionosphere on frequency L1 is

$$I_{f_1}^{k} = \frac{f_2^2}{(f_1^2 - f_2^2)}(\rho_{f_2}^{k} - \rho_{f_1}^{k})$$

Pseudorange measurements at L1 and L2 for satellite k

Carrier frequencies at L1 and L2

$$\hat{\rho}^{k} = \rho^{k} + c[\delta t_u - \delta t^{k}] + I^{k} + T^{k} + \epsilon_u + M_u$$

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GNSS error sources (5)
Tropospheric delay

- Radio signal delay due to refraction
  - Troposphere (<50km) contains over 95% of the atmospheric mass
- Hydrostatic part: dry gas component N_{dry}
  - Nitrogen and oxygen
  - Easy to correct with reference stations
- Hydrodynamic part: wet component N_{wet}
  - Water vapor
  - Changes w.r.t. time and location

$$T=\int N_{dry}+N_{wet}\,dl$$

$$\hat{\rho}^k=\rho^k+c[\delta t_u-\delta t^k]+I^k+T^k+\epsilon_u+M_u$$

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GNSS error sources (6)
Receiver error

- Antenna
- Receiver chip
- Software issues: e.g.
    - duty cycling in smartphones
    - software optimization for multi-GNSS

$$\hat{\rho}^k = \rho^k + c[\delta t_u - \delta t^k] + I^k + T^k + \epsilon_u + M_u$$

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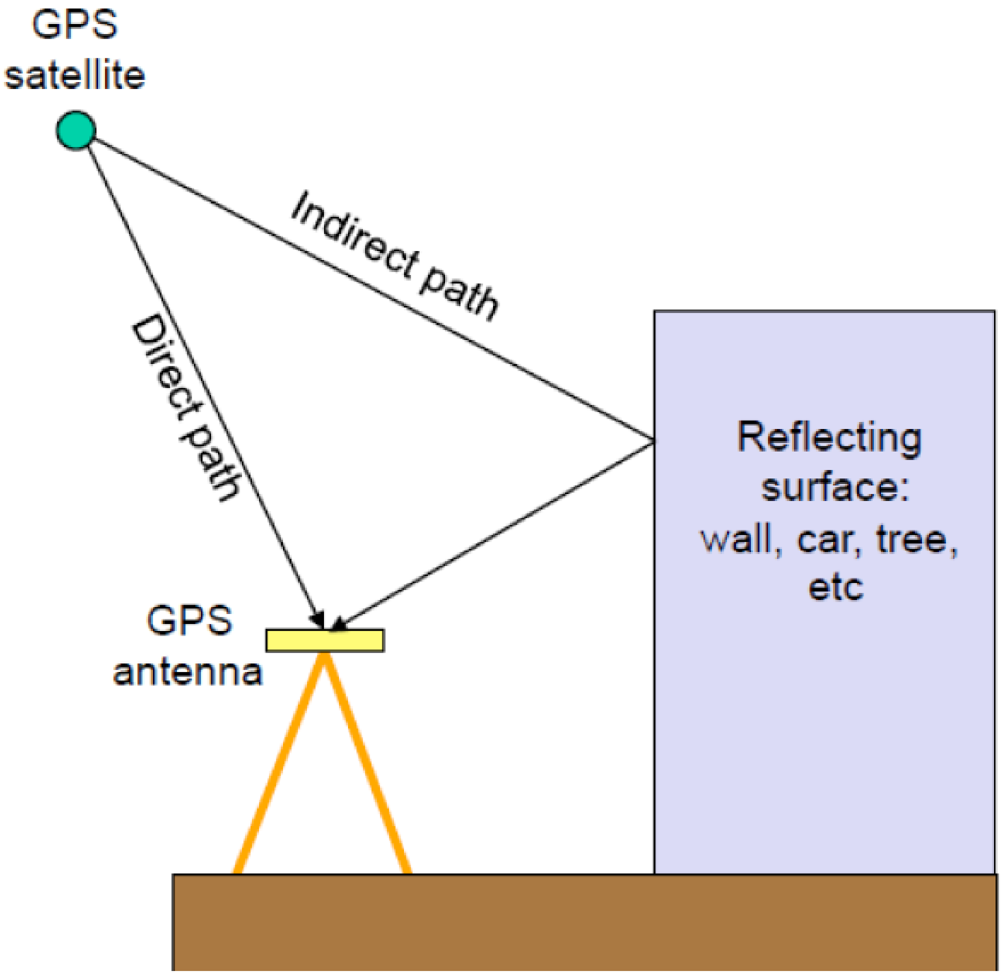
GNSS error sources (7)
Multi-path error

- A GPS signal may be reflected by surfaces near the receiver => measurements include both direct and reflected signals
- Urban & forest & water bodies
- Mitigation example: retain only the first ‘signal’, i.e. correlation peak



Source: E. Calais, GPS Geodesy, Purdue University, 2009.

$$\hat{\rho}^k = \rho^k + c[\delta t_u - \delta t^k] + I^k + T^k + \epsilon_u + \boxed{M_u}$$

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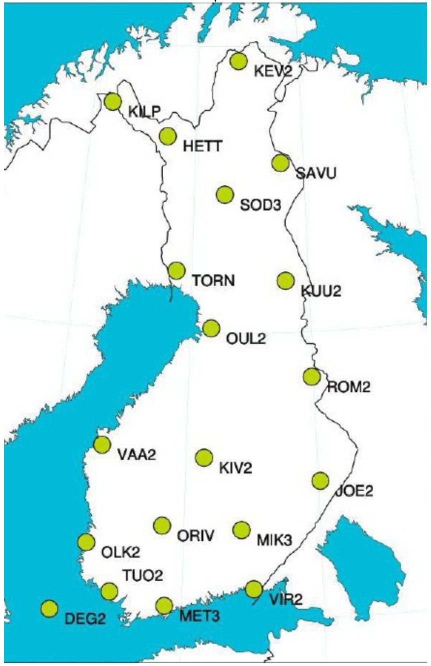
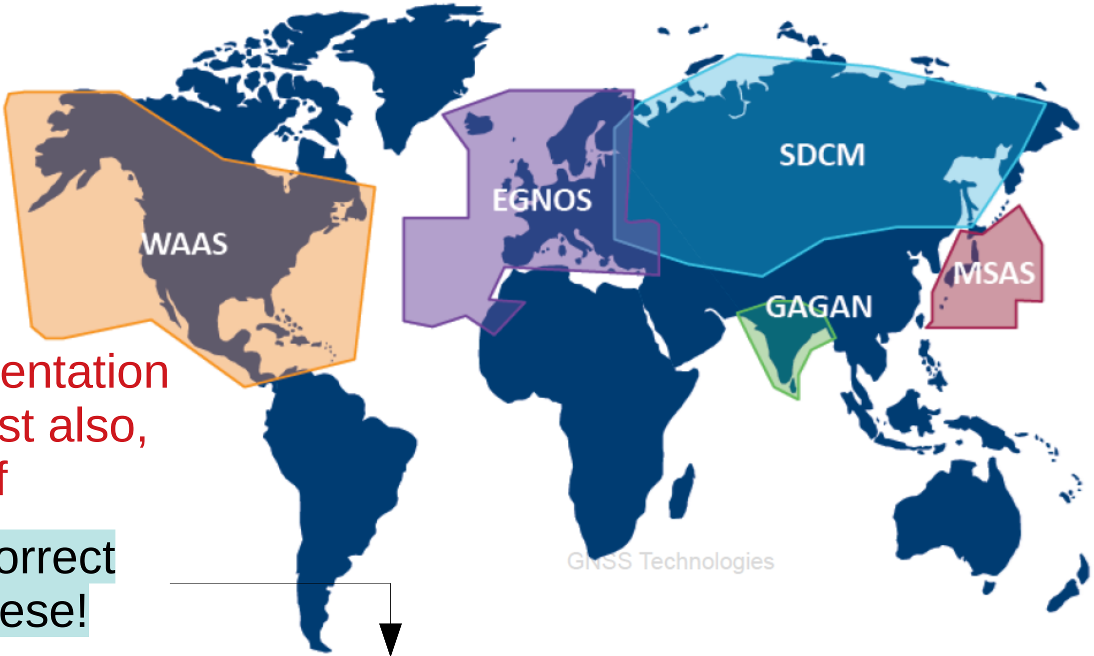
GNSS Augmentation services (1)

- Augmentation systems provide atmospheric corrections to GNSS receivers via external data
- EGNOS (European Geostationary Navigation Overlay Service)
- Ground stations at known locations





Other augmentation systems exist also, e.g. FinnRef

Correct these!

$$\hat{\rho}^k = \rho^k + c[\delta t_u - \delta t^k] + \boxed{I^k + T^k} + \epsilon_u + M_u$$

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GNSS Augmentation services (2)
Differential GNSS

- Several techniques exist
- DGPS: use pre-estimated terms
  - Range: up to 300 km from base station
  - Use base station pseudoranges R_0

$$\Delta_{GPS}^{k}=R_0^k-\hat{\rho}^{k}$$

$$\hat{R}_0^{\,k}=R_0^k+c[\delta t_0-\delta t^k]+I^k+T^k$$

$$\hat{\rho}^{\,k}=\rho^k+c[\delta t_u-\delta t^k]+I^k+T^k+\epsilon_u+M_u$$

- Real-time kinematics (RTK)
  - Range: 10 or 20 km from base station
  - Real time communication channel is needed between the GNSS receiver and the base station
  - Focused on fixing signal phase ambiguities

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GNSS Augmentation services (3)

- EUREF Permanent GNSS Network http://www.epncb.oma.be/
- Metsähovi station: MET300FIN
- Virtual Reference Stations (VRS) can be created for research purposes @ NLS paikannuspalvelu@maanmittauslaitos.fi

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GNSS Augmentation services (4)

- How to get and use the data yourself?
- EUREF → Network&Data
    - → Daily&Hourly (RINEX - files)
    - → Real-time (needs registration)
    - → Proposed stations, 8 new Finnish stations
        - RINEX - files
- Free of charge
- Fps-service for hourly data
    - 2h computation time

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GNSS Augmentation services (5) Metsähovi MET3 base station

2. Site Location Information

City or Town : Kirkkonummi

Country : Finland

Tectonic Plate : EURASIAN

Approximate Position (ITRF)

X coordinate (m) : 2892583.9749

Y coordinate (m) : 1311799.5635

Z coordinate (m) : 5512619.8547

Latitude (N is +) : +601302.84

Longitude (E is +) : +0242340.20

Elevation (m,ellips.) : 79.2

Additional Information : Coordinates are in epoch 2016-11-16.

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GNSS Augmentation services (6) RINEX and SP3 standard

- Receiver Independent Exchange format (RINEX)
- Description of RINEX standard can be found at ftp://igscb.jpl.nasa.gov/igscb/data/format/rinex2.txt
- The RINEX standard is an ASCII format that is used internationally to exchange GPS data and broadcast ephemeris information
- Recent additions to the format also include metrological and ionospheric data records
- Precise orbit information in the form of tabulation of the positions of the satellites (usually at 15 minute intervals) is provided in the SP3 format (3rd version of Satellite Position format)
- Latest version SP3c contains clock information for the satellites as well
    - These can be used for point positioning at a few millimeters several days after real-time

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Final overview (1)
GNSS accuracy

- Accuracies obtainable:
  - 10 m Navigation; code measurement; one receiver
  - 1 m DGPS; code measurement + base station
  - 0.1 m RTK; phase observations + base station
  - 0.01 m Static positioning; phase observations, network of base stations, post processing
  - 0.001m Permanent stations; time series
- Issues affecting GNSS accuracy:
  - Receiver technology used
  - Location and environment of the antenna

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Final overview (2)
Positioning performance metrics

- Accuracy: measure of the level of positioning error
- Integrity: measure of the trust that can be placed in the correctness of the information supplied by a navigation system
- Continuity: the probability that the specified system performance will be maintained for the duration of the operation, presuming that the system was available at the beginning of the operation
- Availability: fraction of time a navigation system is providing position fixes to the specified level of accuracy, integrity, and continuity

Final overview (3)
GNSS shortcomings

- Signal is susceptible to unintentional or malicious radio frequency interference (RFI) or jamming
- GNSS signals are typically too weak to be observable indoors
- Signal cannot provide an orientation solution easily, a feature that is indispensable in many vehicle navigation and guidance applications
- Positioning errors culminate at high velocities ◄
- GNSS and integrated navigation:
  - Inertial navigation systems (INSs) have been integrated with GNSSs with considerable success. This fusion between GNSSs and INSs is complementary: INS helps mitigate the shortcoming of the GNSS and vice versa. Other sensors are also commonly integrated with GNSS (e.g. other radio frequency (RF) signals, magnetometer, LIDAR, barometer).

Cf. static case position estimation is easy, will converge in 15-30 minutes

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More information

- RTKLIB: An Open Source Program Package for GNSS Positioning (C++)
  http://www.rtklib.com/
- Software receiver (fastgps)
  http://gnssapplications.org/chapter5.html
- Quality differences due to amount of GPS data used and ability to check the quality of the solutions and data
  http://igscb.jpl.nasa.gov/components/prods.html
- Plan your measurement campaigns or obtain reference data on visible satellites (all constellations)
  http://gnssmissionplanning.com/
- EUREF Permanent GNSS Network
  http://www.epncb.oma.be/

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