Impact on GNSS

Acknowledgements

Thanks to NASA, NOAA & ESA for most of the graphics

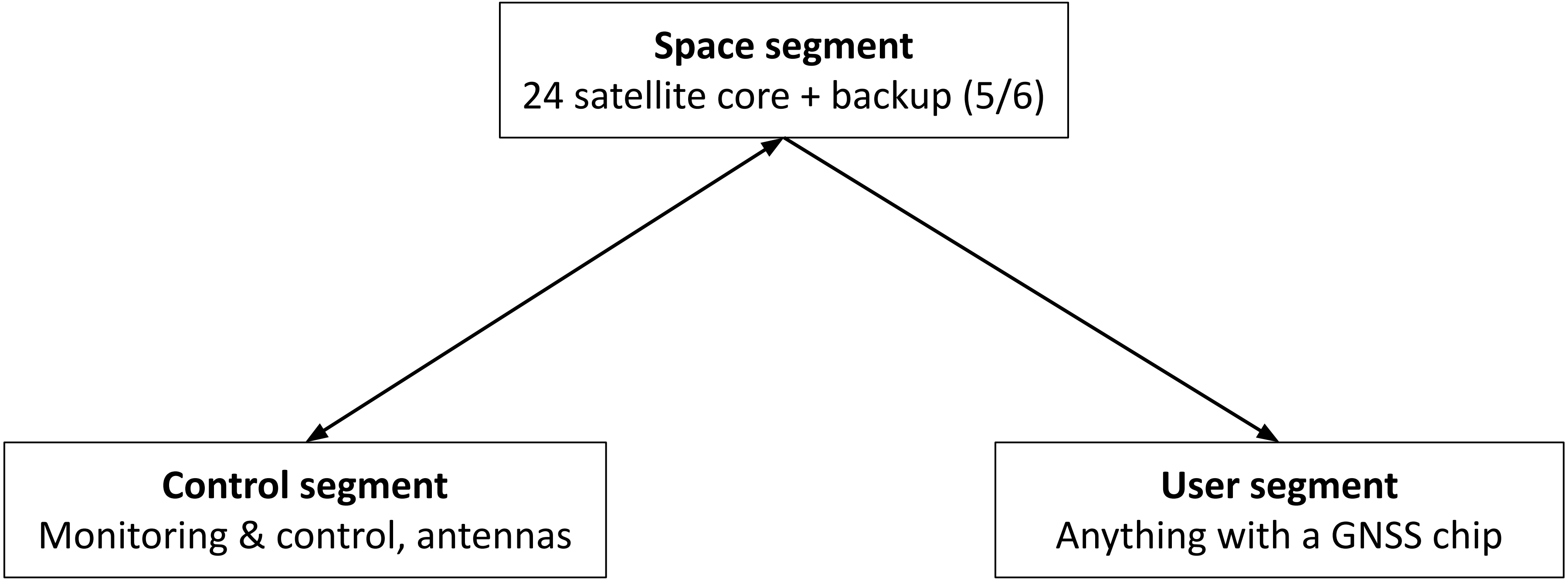
Thanks to WP van der Laan for the base slides

Image sources can be provided upon request

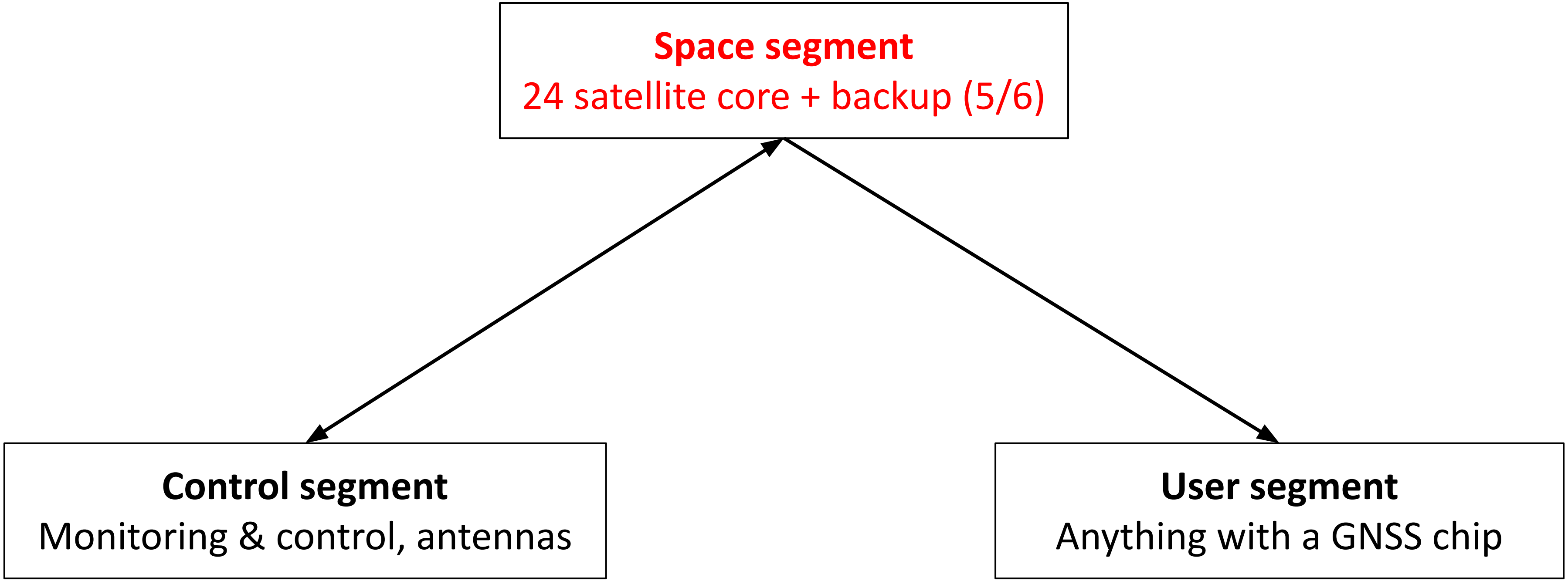
GPS/ GNSS

- GNSS: Global Navigation Satellite System
- GPS: Global Positioning System → GNSS of the US
- also:
    - Galileo → European GNSS service
    - GLONASS → Russian GNSS service
    - BeiDou → Chinese GNSS service
    - IRNSS → Indian GNSS service

GNSS link components

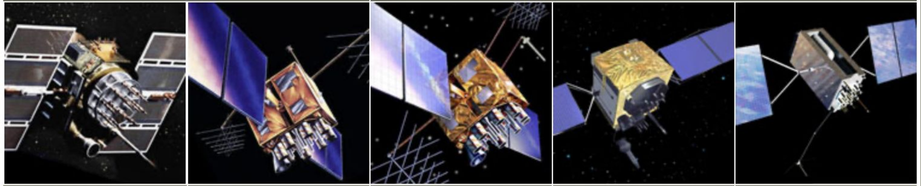


GNSS link components



GPS blocks and bands: civilian

- L1 C/A: at 1575MHz, the original GPS design
- L2C: L2 at 1227MHz signal for civic uses, to meet commercial needs, when combined with L1 C/A → dual frequency, allows ionospheric correction
- L5: at 1176MHz for safety-of-life high performance applications, reserved for aviation and safety services
- L1C: at 1575MHz, at the same band as the legacy L1 C/A, but with special modulation, allows international interoperability (GPS-Galileo), higher power level

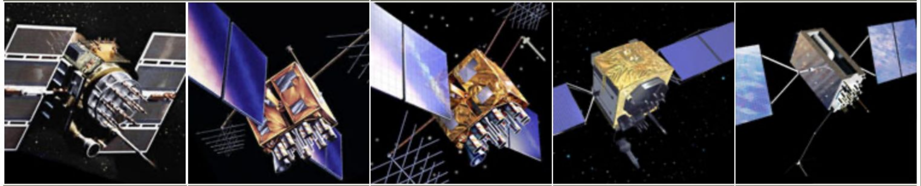


LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	6 operational	7 operational	12 operational	6 operational
▪ Coarse Acquisition (C/A) code on L1 frequency for civil users ▪ Precise P(Y) code on L1 & L2 frequencies for military users ▪ 7.5-year design lifespan ▪ Launched in 1990-1997 ▪ Last one decommissioned in 2019	▪ C/A code on L1 ▪ P(Y) code on L1 & L2 ▪ On-board clock monitoring ▪ 7.5-year design lifespan ▪ Launched in 1997-2004	▪ All legacy signals ▪ 2nd civil signal on L2 (L2C) *LEARN MORE* ▪ New military M code signals for enhanced jam resistance ▪ Flexible power levels for military signals ▪ 7.5-year design lifespan ▪ Launched in 2005-2009	▪ All Block IIR-M signals ▪ 3rd civil signal on L5 frequency (L5) *LEARN MORE* ▪ Advanced atomic clocks ▪ Improved accuracy, signal strength, and quality ▪ 12-year design lifespan ▪ Launched in 2010-2016	▪ All Block IIF signals ▪ 4th civil signal on L1 (L1C) *LEARN MORE* ▪ Enhanced signal reliability, accuracy, and integrity ▪ No Selective Availability *LEARN MORE* ▪ 15-year design lifespan ▪ IIIF: laser reflectors; search & rescue payload ▪ First launch in 2018

GPS blocks and bands: military

- P(Y) at L1 & L2: original precise code for military users
  - P: precision signal, in precision-code
  - Y: code used for anti-spoofing operation (P-code is modulated with W-code to produce Y-code, W-code is secret)

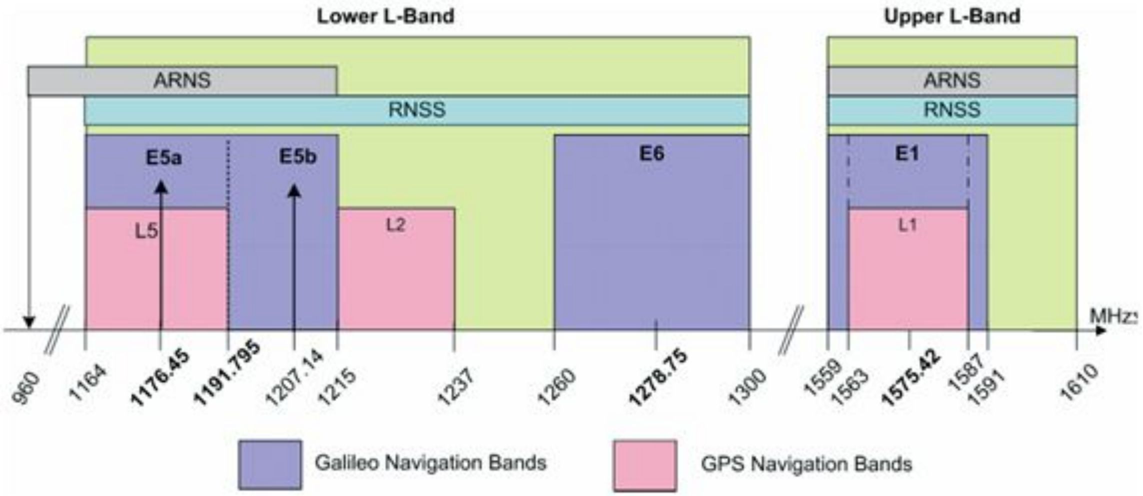
- M code for the military on L1 & L2: should be enhanced against spoofing and jamming while operating at a much higher power, to eventually replace P(Y)



LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	6 operational	7 operational	12 operational	6 operational
▪ Coarse Acquisition (C/A) code on L1 frequency for civil users ▪ Precise P(Y) code on L1 & L2 frequencies for military users ▪ 7.5-year design lifespan ▪ Launched in 1990-1997 ▪ Last one decommissioned in 2019	▪ C/A code on L1 ▪ P(Y) code on L1 & L2 ▪ On-board clock monitoring ▪ 7.5-year design lifespan ▪ Launched in 1997-2004	▪ All legacy signals ▪ 2nd civil signal on L2 (L2C) LEARN MORE ▪ New military M code signals for enhanced jam resistance ▪ Flexible power levels for military signals ▪ 7.5-year design lifespan ▪ Launched in 2005-2009	▪ All Block IIR-M signals ▪ 3rd civil signal on L5 frequency (L5) LEARN MORE ▪ Advanced atomic clocks ▪ Improved accuracy, signal strength, and quality ▪ 12-year design lifespan ▪ Launched in 2010-2016	▪ All Block IIF signals ▪ 4th civil signal on L1 (L1C) LEARN MORE ▪ Enhanced signal reliability, accuracy, and integrity ▪ No Selective Availability LEARN MORE ▪ 15-year design lifespan ▪ IIIF: laser reflectors; search & rescue payload ▪ First launch in 2018

Galileo bands

- transmit permanently E1, E5 and E6, E5 further divided
- the main bands in the allocated spectrum for Radio Navigation Satellite Services (RNSS)
- in addition, E5a, E5b and E1 bands are for Aeronautical Radio Navigation Services (ARNS), employed by civil aviation users and for safety-critical applications.



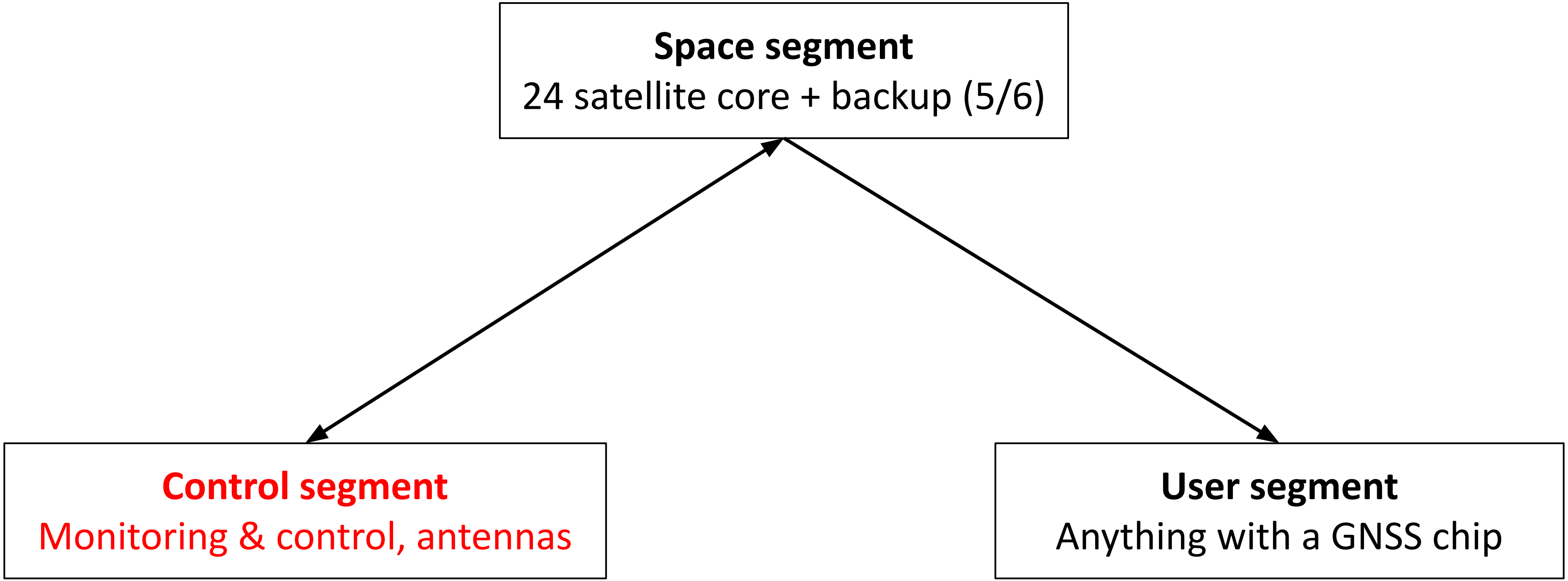
GNSS signals

- four satellites needed:
  - position (3x)
  - time

  → your GNSS signal is not only used for position determination, also for time synchronisation!

- thus also applications such as safe radio communication (frequency hopping, encryption, …)

GNSS link components



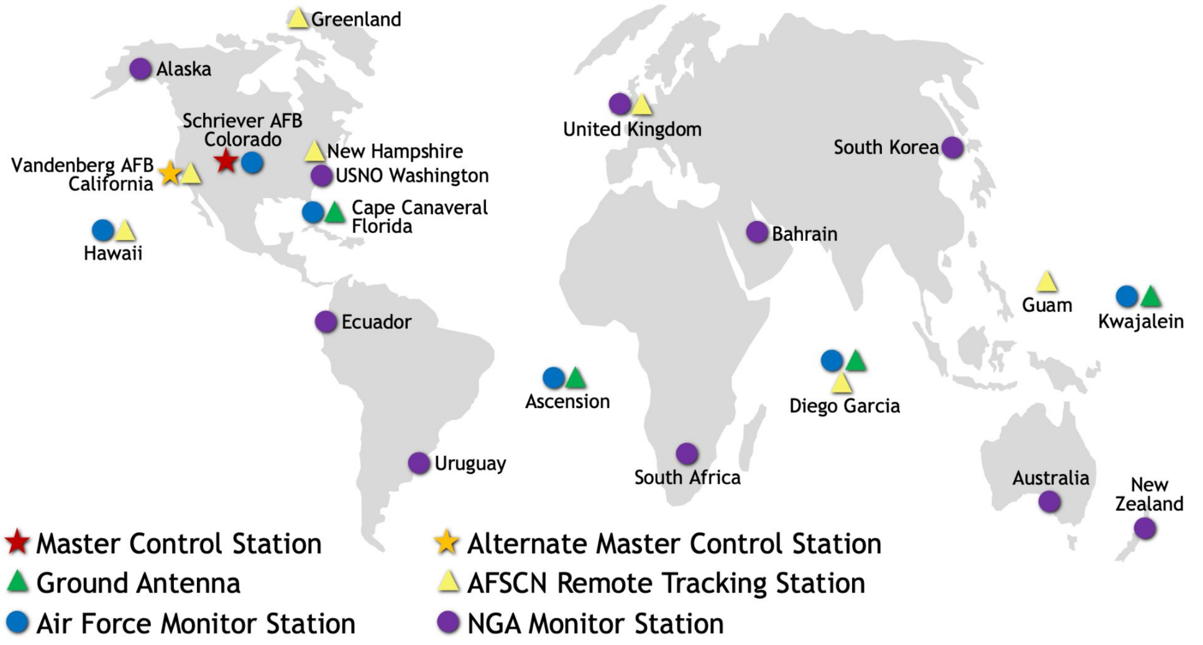
GPS control segment

- monitoring stations collect nav. signals/ carriers meas. and atmospheric data → send to master control

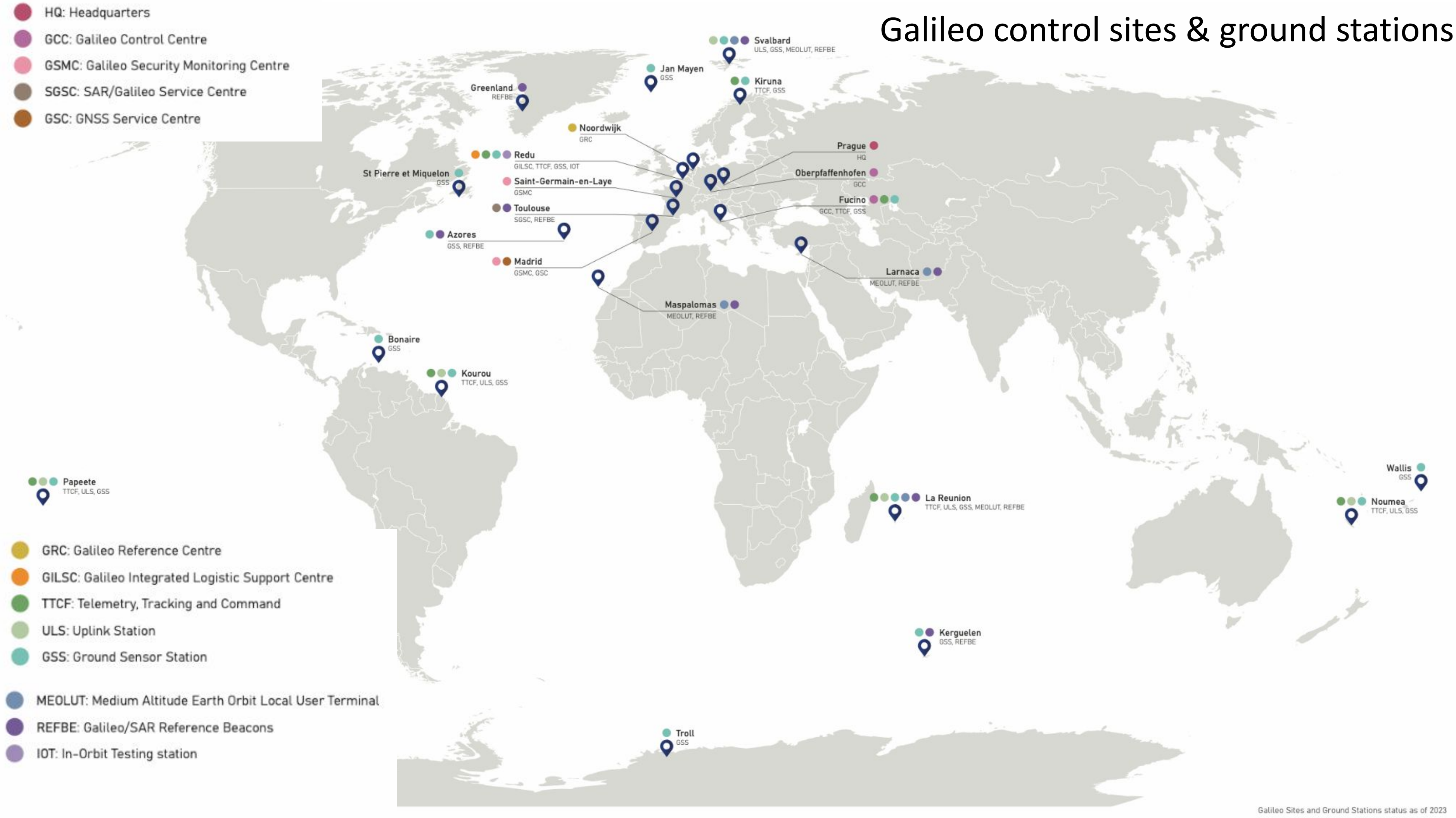
- master control computes satellite positions & needed corrections and maintenance → to ground antennas

- ground antennas upload commands and updates

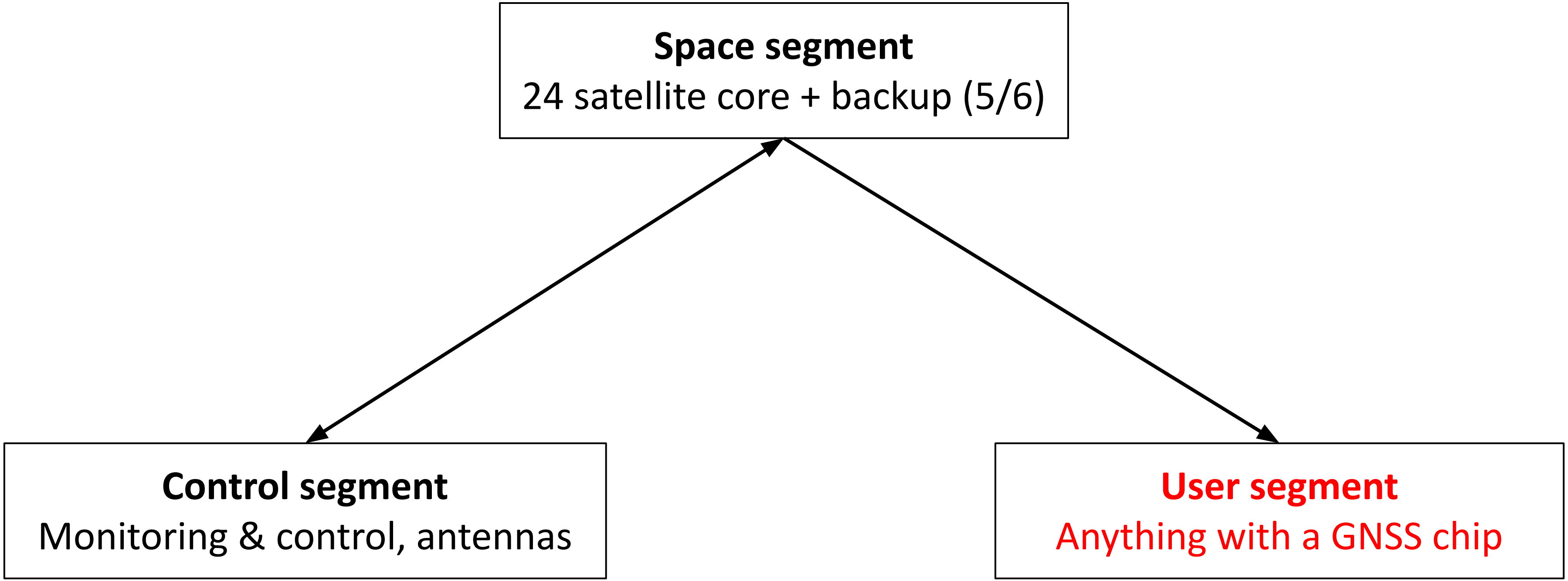
GPS control stations



Galileo control sites & ground stations



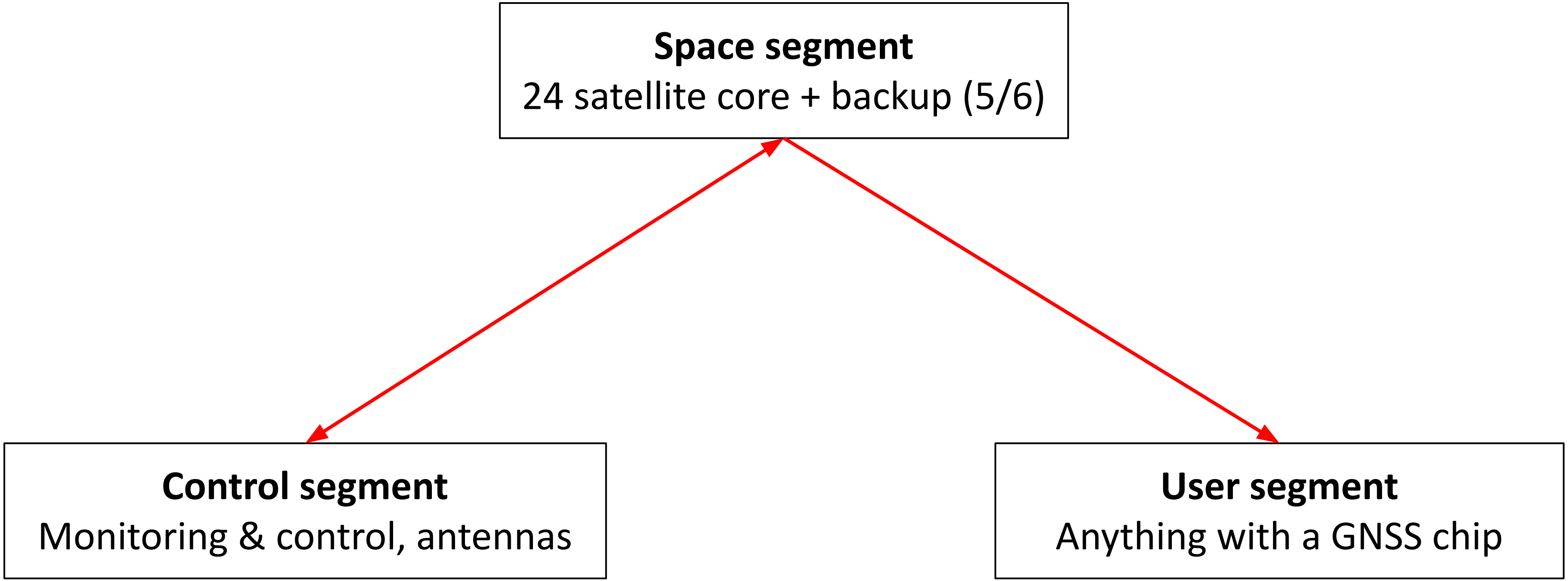
GNSS link components



GNSS uses

- Military:
  - Navigation
  - Search and rescue
  - Reconnaissance and map creation
  - Unmanned vehicles
  - Munitions guidance
  - …
- Civilian:
  - Autonomous cars
  - Precision farming
  - …

GNSS link components

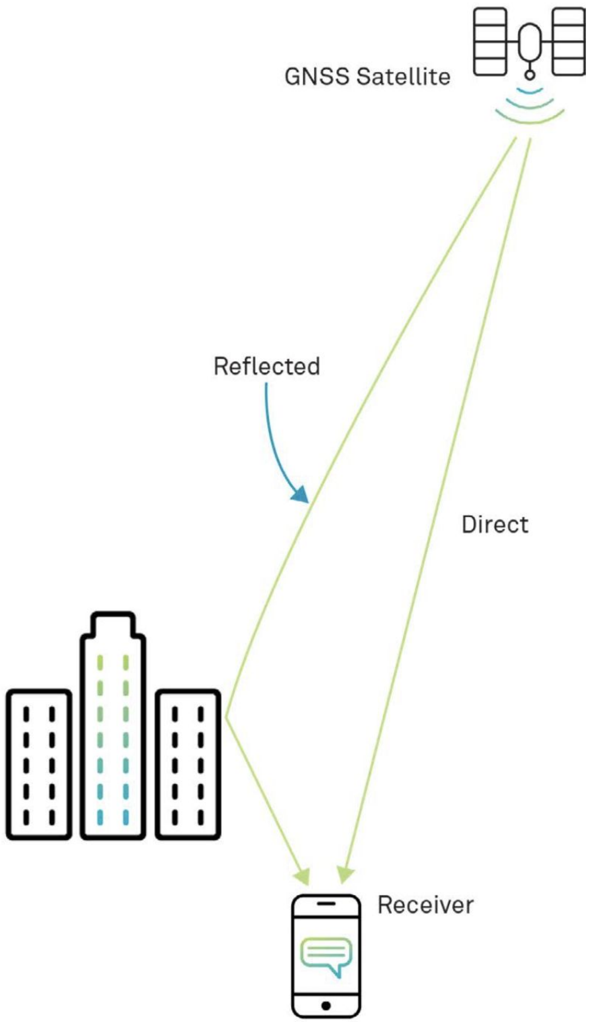


Error sources

- typical GNSS error estimates (novatel.com):

Contributing source	Error range
Satellite clocks	±2 m
Orbit errors	±2.5 m
Ionospheric error	±5 m
Tropospheric error	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

- even just 10ns offset in satellite clock → 3m error
- receiver noise depends highly on the receiver quality
- largest source → ionospheric errors

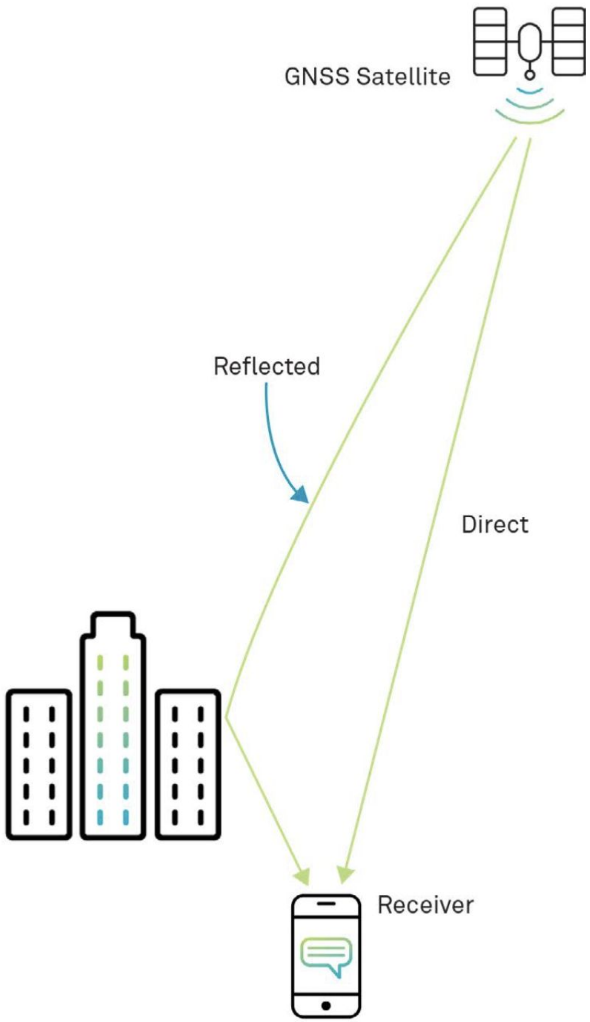


Error sources

- typical GNSS error estimates (novatel.com):

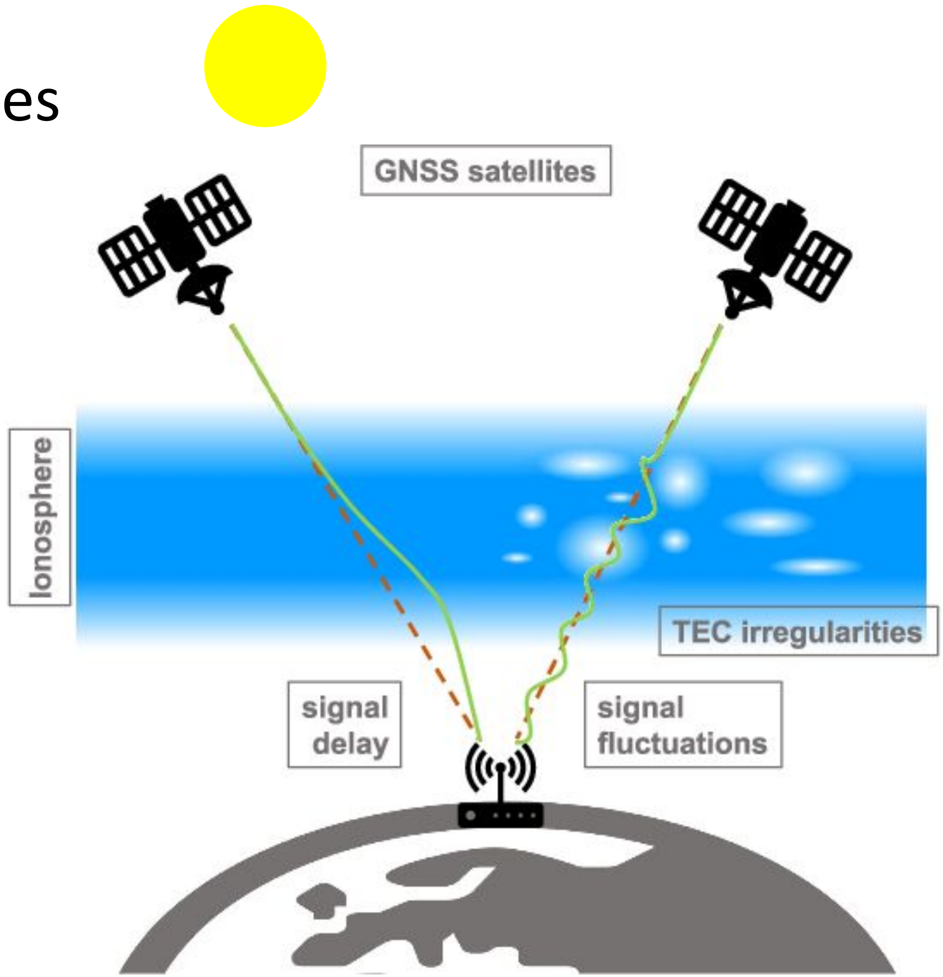
Contributing source	Error range
Satellite clocks	±2 m
Orbit errors	±2.5 m
Ionospheric error	±5 m
Tropospheric error	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

- even just 10ns offset in satellite clock → 3m error
- receiver noise depends highly on the receiver quality
- largest source → **ionospheric errors**



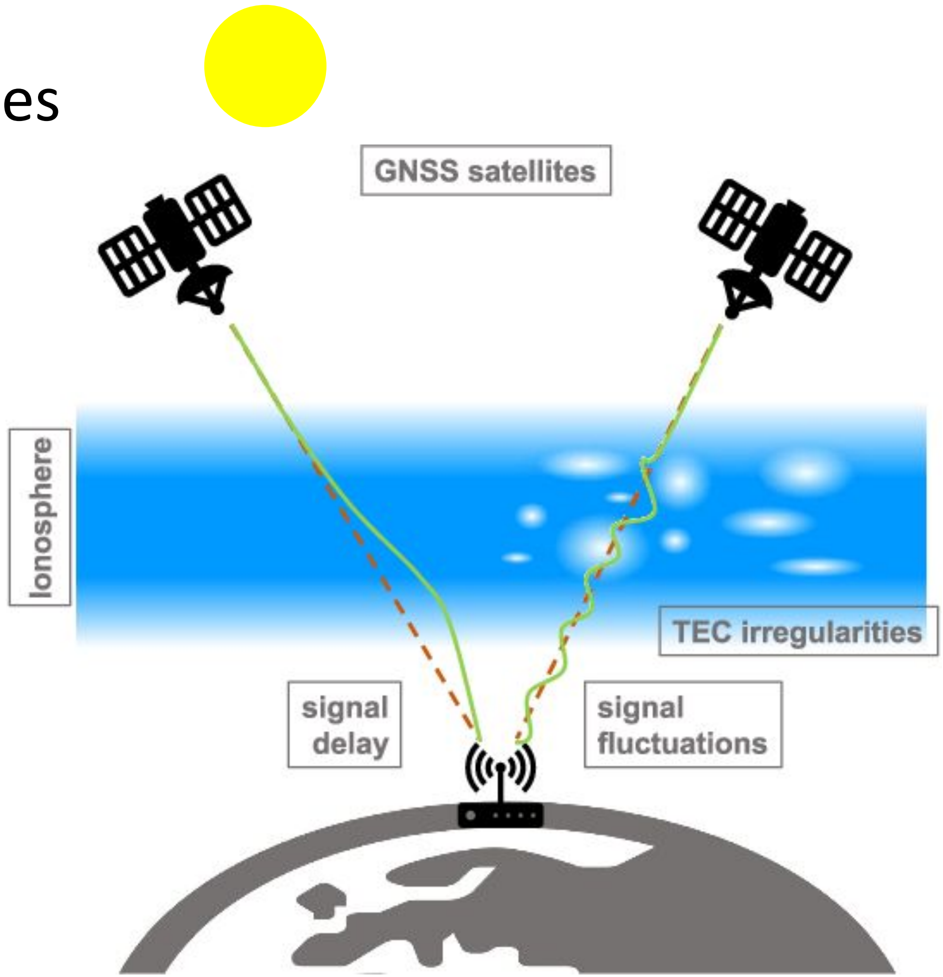
Space weather GNSS error sources

- connected to the ionosphere:
  - ionospheric delay
  - ionospheric scintillation
- direct blinding by a solar radio burst
- direct satellite damage



Space weather GNSS error sources

- connected to the ionosphere:
  - **ionospheric delay**
  - ionospheric scintillation
- direct blinding by a solar radio burst
- direct satellite damage



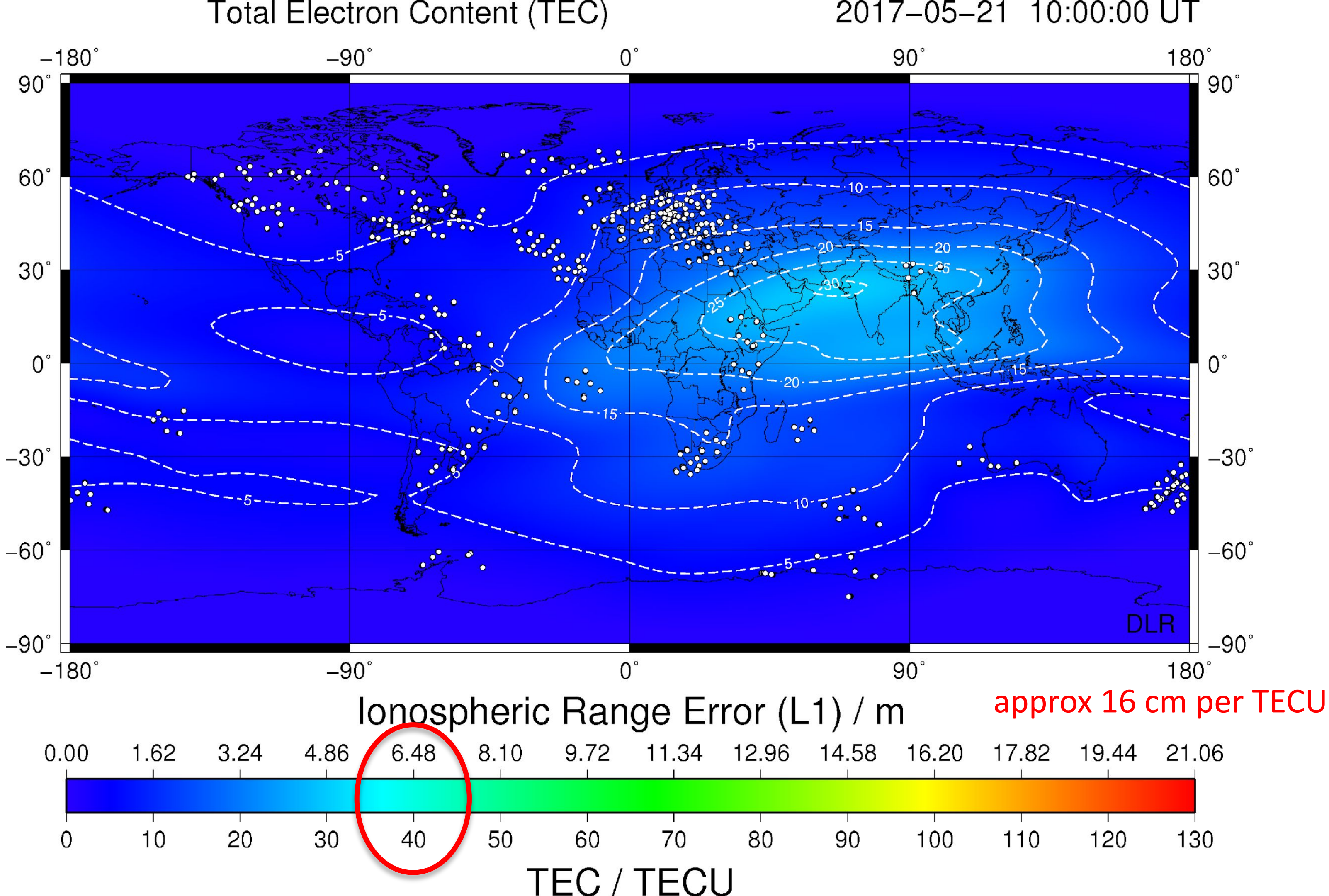
Ionospheric delay

- the first approximation: proportional to slant TEC (along LOS), where K~40.3 m^3/s^2

$$d_I \approx \frac{K}{f^2}\int n_e ds = \frac{K}{f^2} TEC^{slnt}$$

→ frequency dependent, can be removed via dual frequency measurements: but not all military products can afford dual frequency! (JDAMs, cheap drones)

- several models to compute slant TEC depending on the user's position and azimuths of the observed satellites:
    - Klobuchar model (can remove ~50% ionospheric error)
    - NeQuick model, 3D model offered to Galileo users, uses solar 10.7cm flux

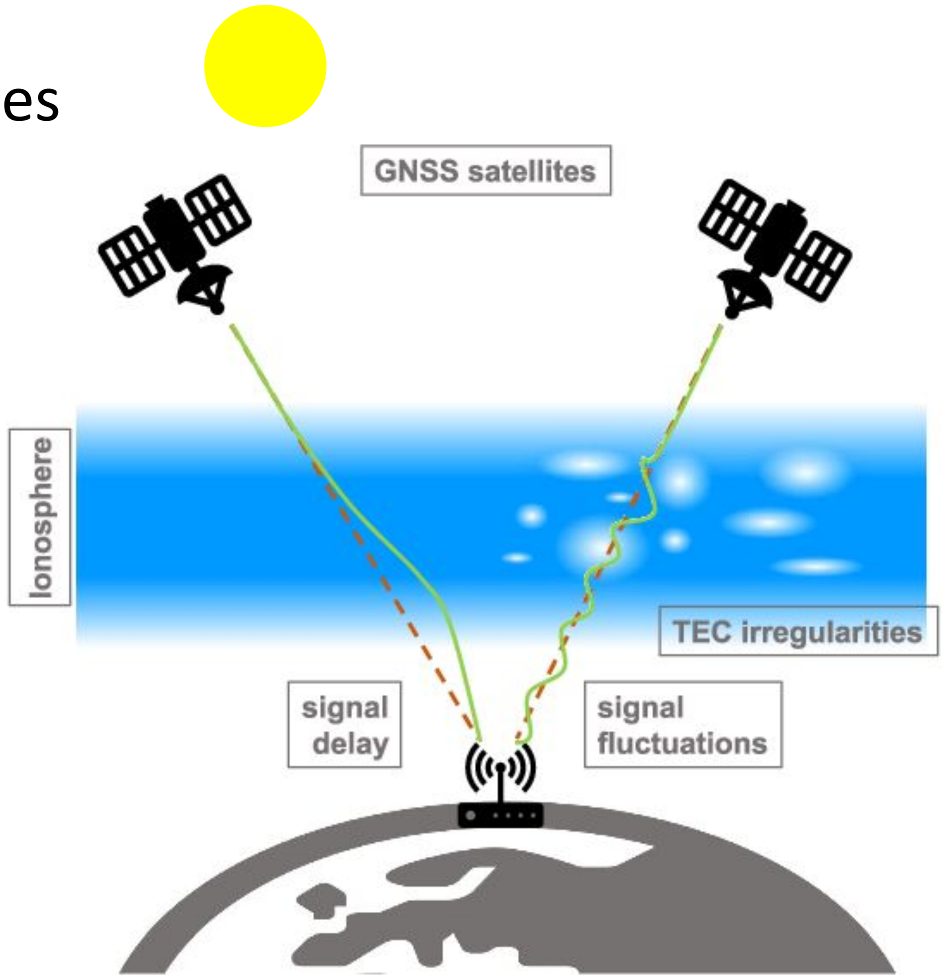

Total Electron Content (TEC)
2017−05−21 10:00:00 UT
DLR
Ionospheric Range Error (L1) / m
0.00 1.62 3.24 4.86 6.48 8.10 9.72 11.34 12.96 14.58 16.20 17.82 19.44 21.06
0 10 20 30 40 50 60 70 80 90 100 110 120 130
TEC / TECU
approx 16 cm per TECU

Space weather GNSS error sources

- connected to the ionosphere:
  - ionospheric delay
  - **ionospheric scintillation**

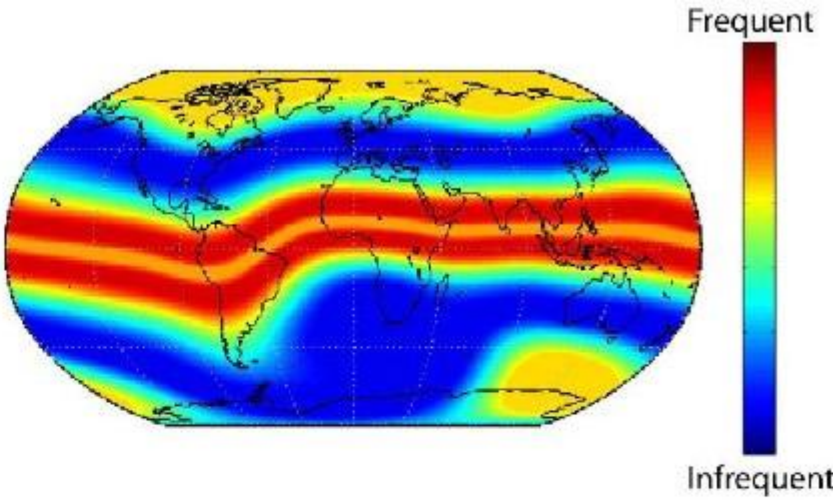
- direct blinding by a solar radio burst

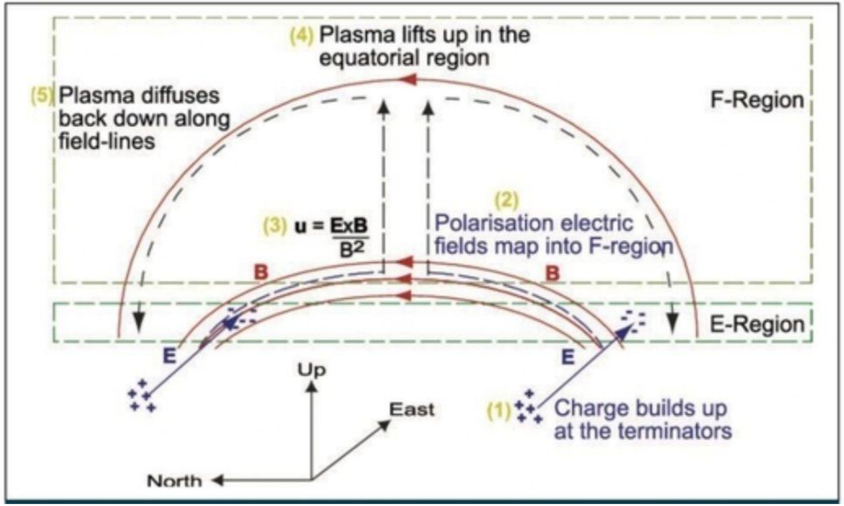
- direct satellite damage



Scintillation

- plasma irregularities cause signals passing through them to fluctuate in amplitude and phase → scintillation
- primarily in the polar regions & equator
- also very large gradients in TEC ionospheric delay → increase residual errors
- polar regions: aurora/ substorms
- equatorial regions: Appleton effect
    - newly charged particles → eastward directed electric field → upward particle transport





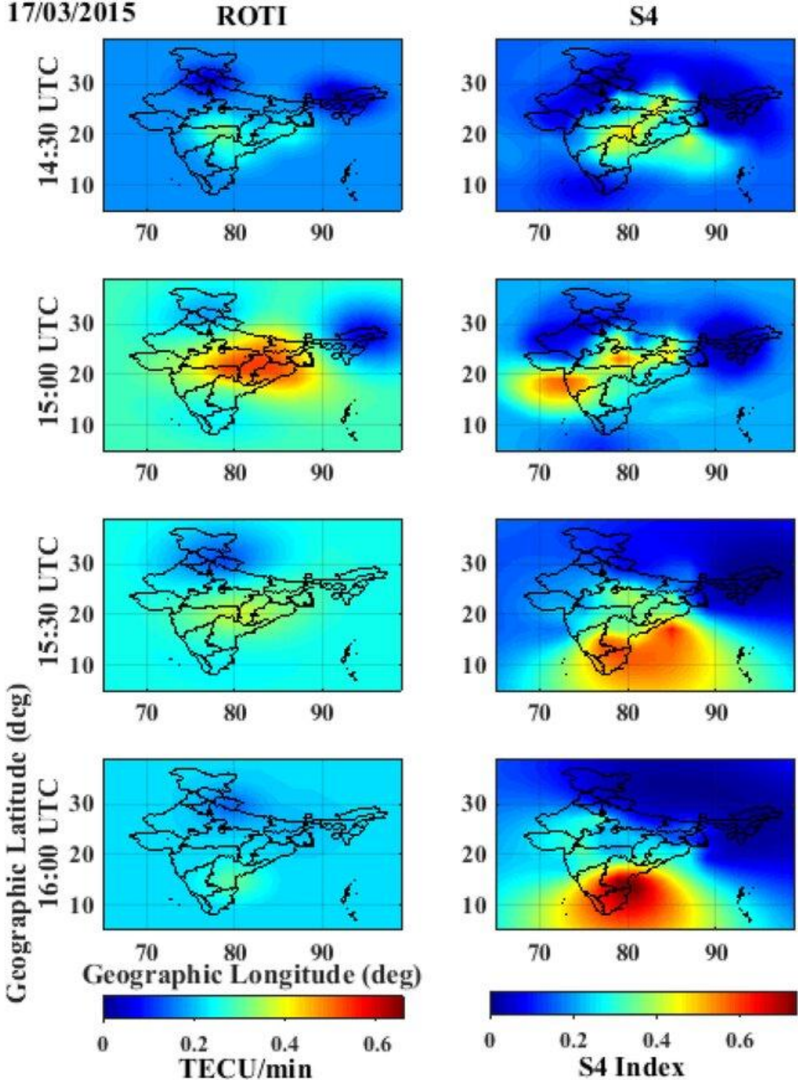
Scintillation

- S4 index: standard deviation of signal intensity to the average signal intensity

- σ: (phase) the standard deviation of the detrended carrier phase, averaged over a specific temporal window → usually 1 min: Phi60 index

- if no access to S4/Phi60, one may use the rate of change of TEC index, ROTI as a proxy to S4 (temporal ionospheric irregularities)

- in the equatorial zones often diurnal & seasonal variations



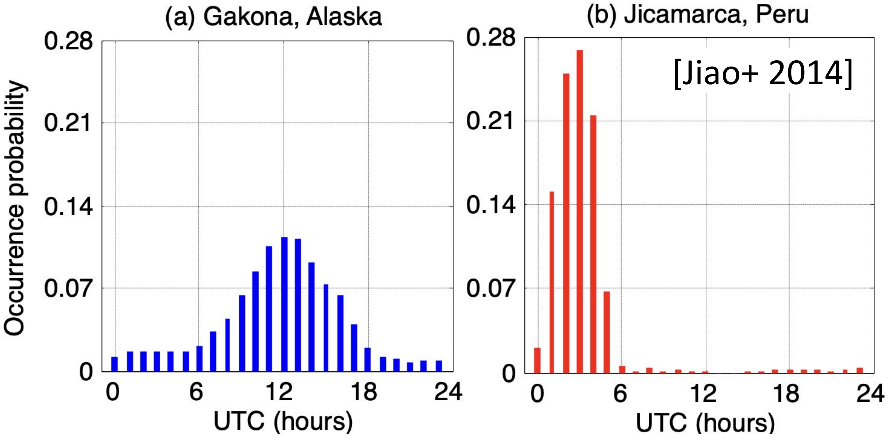
Scintillation

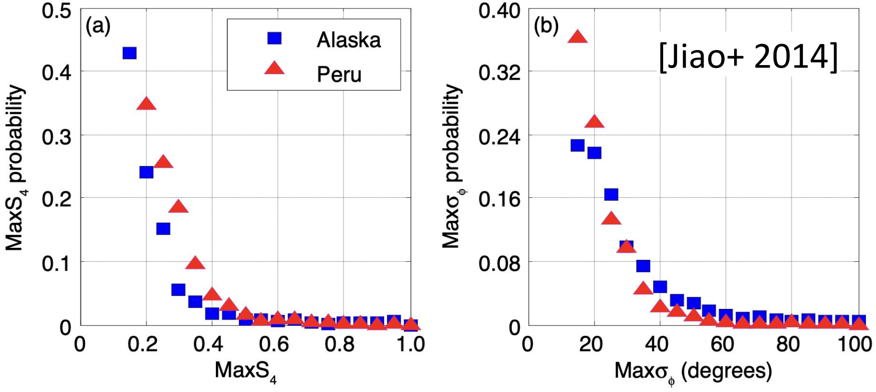
- different mechanisms & statistics in polar and equatorial regions

- polar regions:
  - moderate usually around midday
  - severe around midnight

- equatorial regions:
  - within the first six hours after sunset

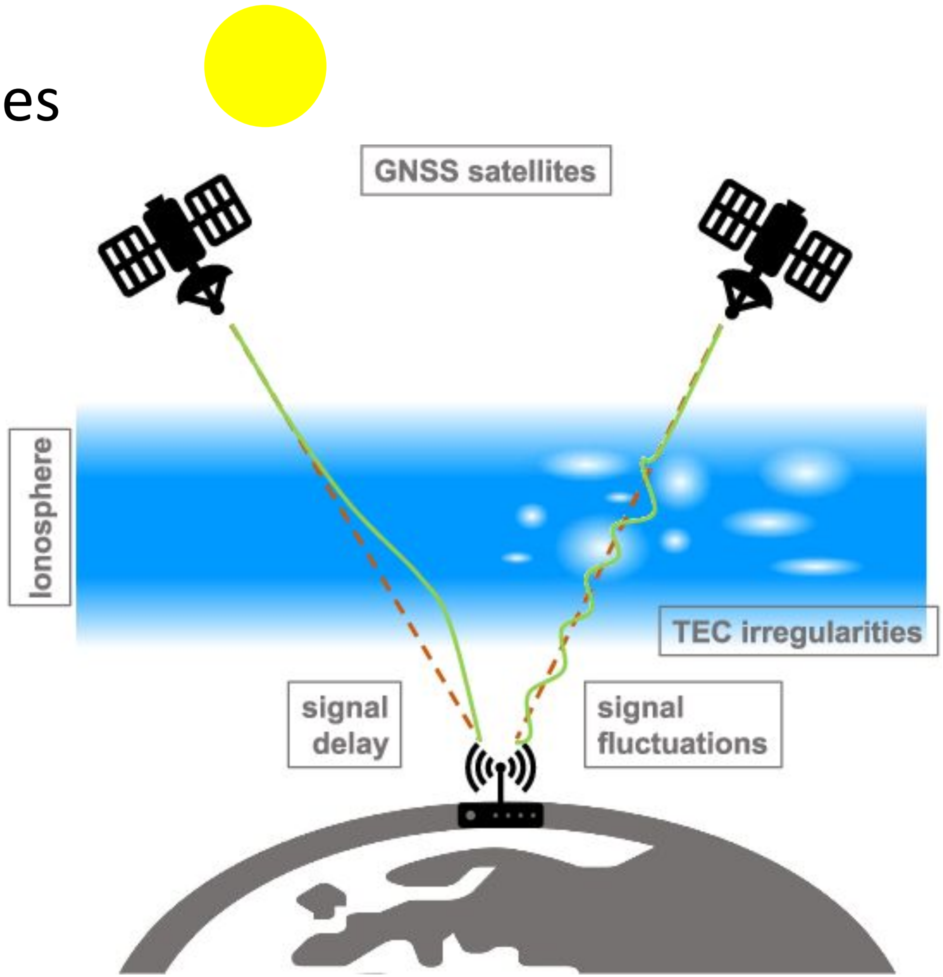
- occurrence statistics of the two similar
- difficult to establish thresholds (system-dependent)





Space weather GNSS error sources

- connected to the ionosphere:
  - ionospheric delay
  - ionospheric scintillation
- direct blinding by a **solar radio burst**
- direct satellite damage

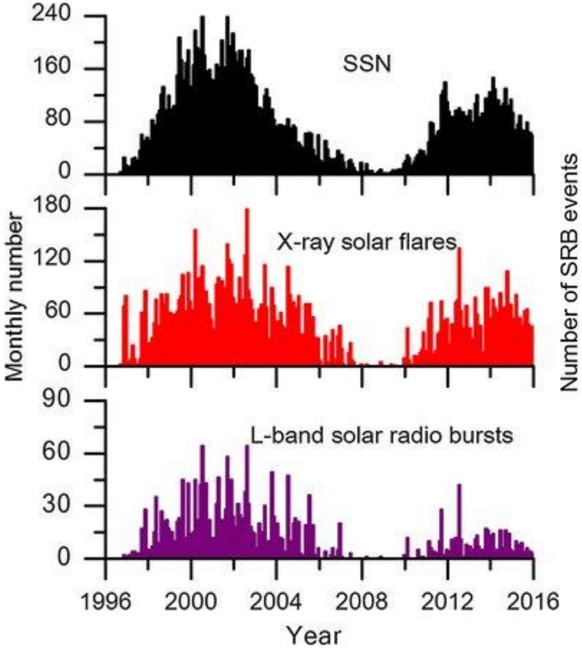


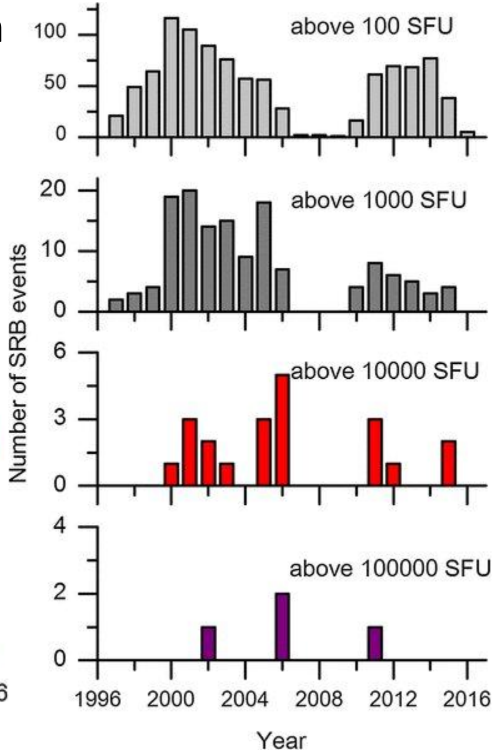
Solar radio bursts

- if SRB emissions match the GNSS frequency and antenna polarization pattern, interference signals acting as additional noise will compete with GNSS signals

- If the solar radio flux is sufficiently large, SRBs will reduce the SNR of the GNSS signals that impact accuracy, and might even cause a loss of lock

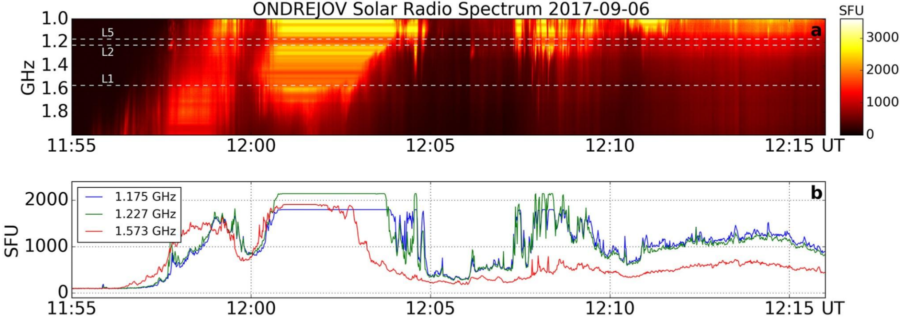
- statistics from Huang+ 2018

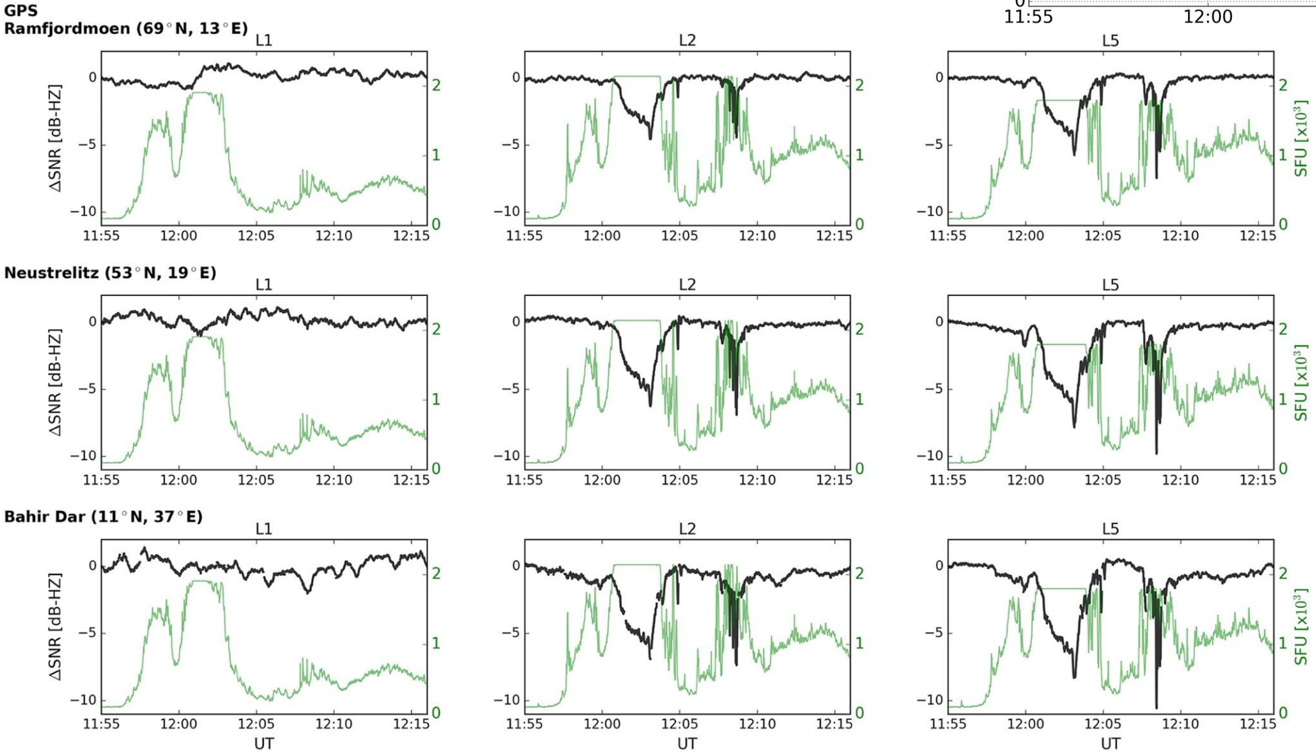




SRB of 2017 example, Sato+ 2019

L1 at 1575MHz, L2 at 1227MHz, L5 at 1176MHz

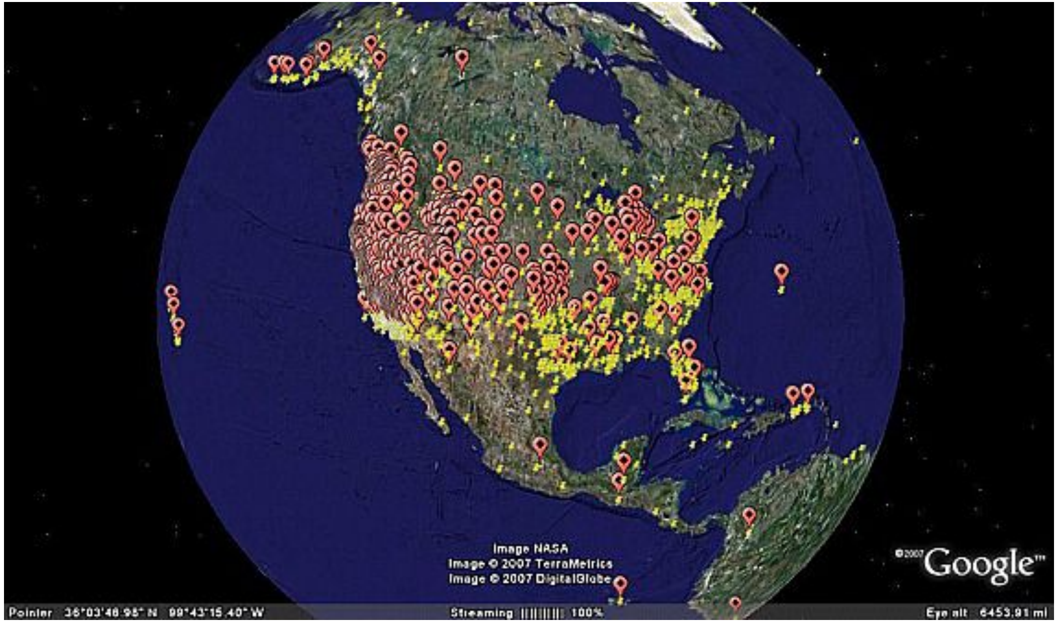


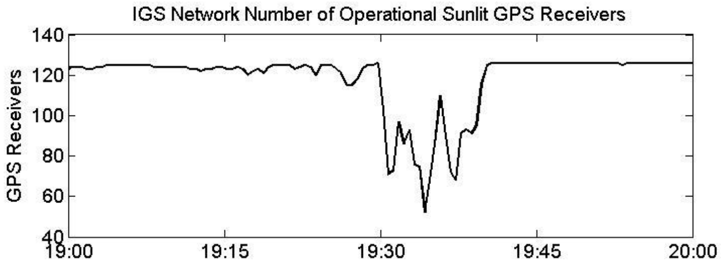


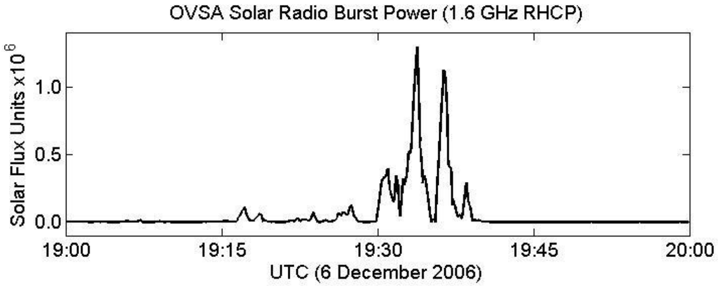
→ the impact can be location- and frequency- dependent

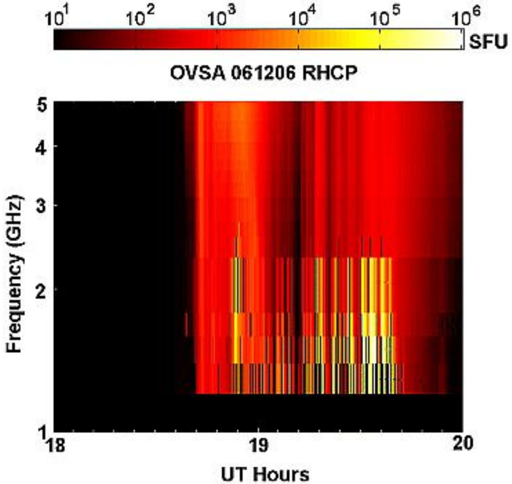
SRB on 6 Dec 2006

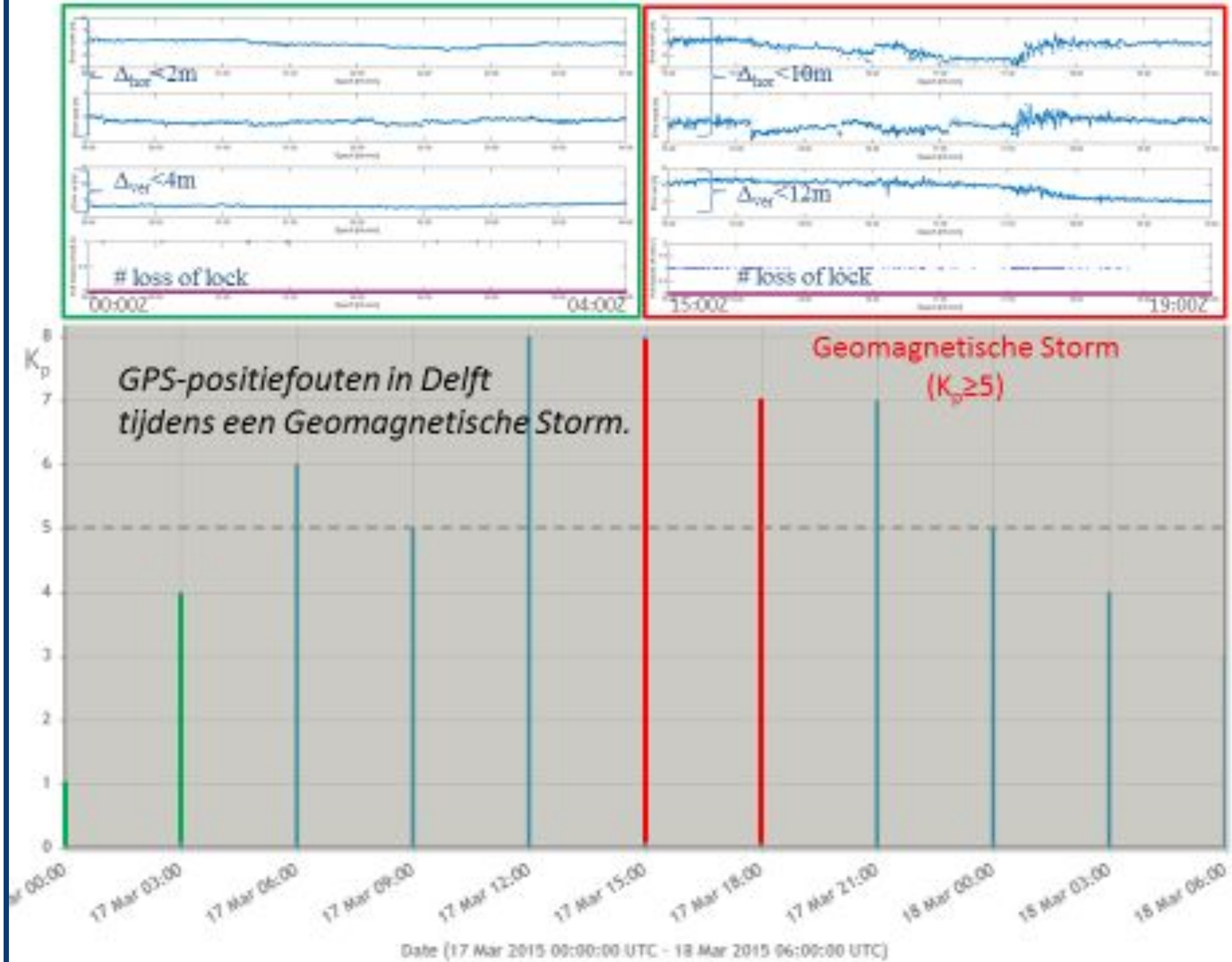
- yellow: all, red: affected











Δhor<2m
Δver<4m
loss of lock
00:00Z
04:00Z
Δhor<10m
Δver<12m
loss of lock
15:00Z
19:00Z
Kp
GPS-positiefouten in Delft
tijdens een Geomagnetische Storm.
Geomagnetische Storm
(Kp≥5)
17 Mar 03:00
17 Mar 06:00
17 Mar 09:00
17 Mar 12:00
17 Mar 15:00
17 Mar 18:00
17 Mar 21:00
18 Mar 00:00
18 Mar 03:00
18 Mar 06:00
Date (17 Mar 2015 00:00:00 UTC - 18 Mar 2015 06:00:00 UTC)

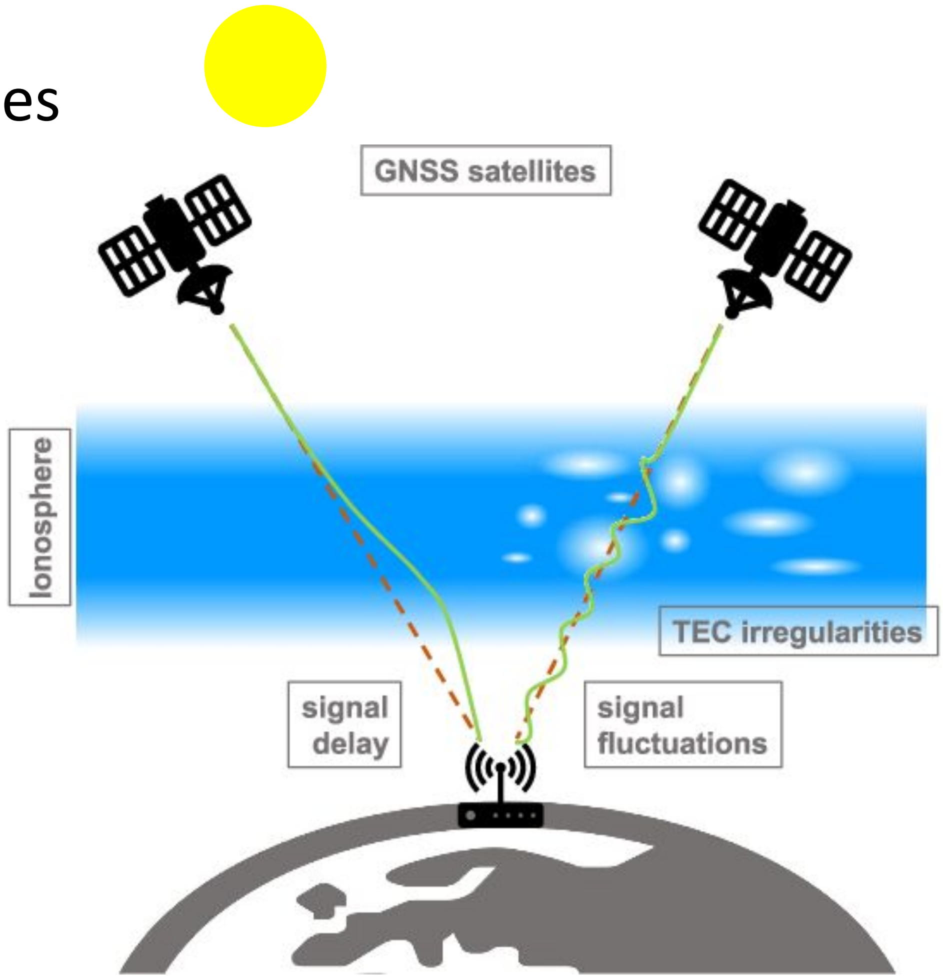
Space weather GNSS error sources

- connected to the ionosphere:
  - ionospheric delay
  - ionospheric scintillation

- direct blinding by a solar radio burst

- **direct satellite damage**

→ see the first application lecture

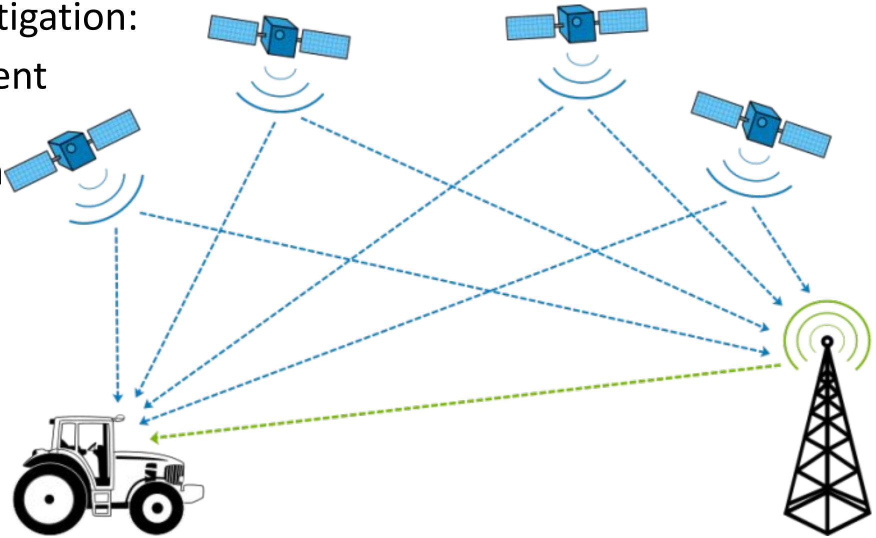


What can we do?

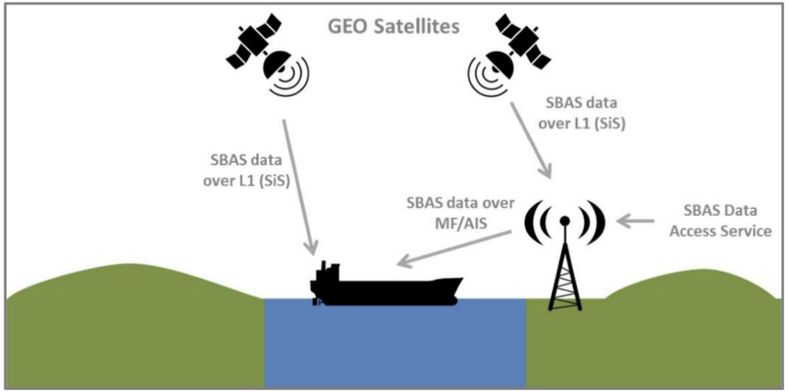
- **scintillation**: locking onto another satellite (different signal path), methods to reduce cycle slip
  → may be difficult in arctic areas (GPS coverage)

- **SRBs**: using different satellites or bands if possible

- **ionospheric delay**: several techniques to help mitigation:
  - dual frequency: since delay is freq. dependent
  - differential GPS (DGPS): using a “base” with a precisely known location, deriving GNSS errors from it for the “rover” nearby the location of which needs to be known
  - overlay services: next slide



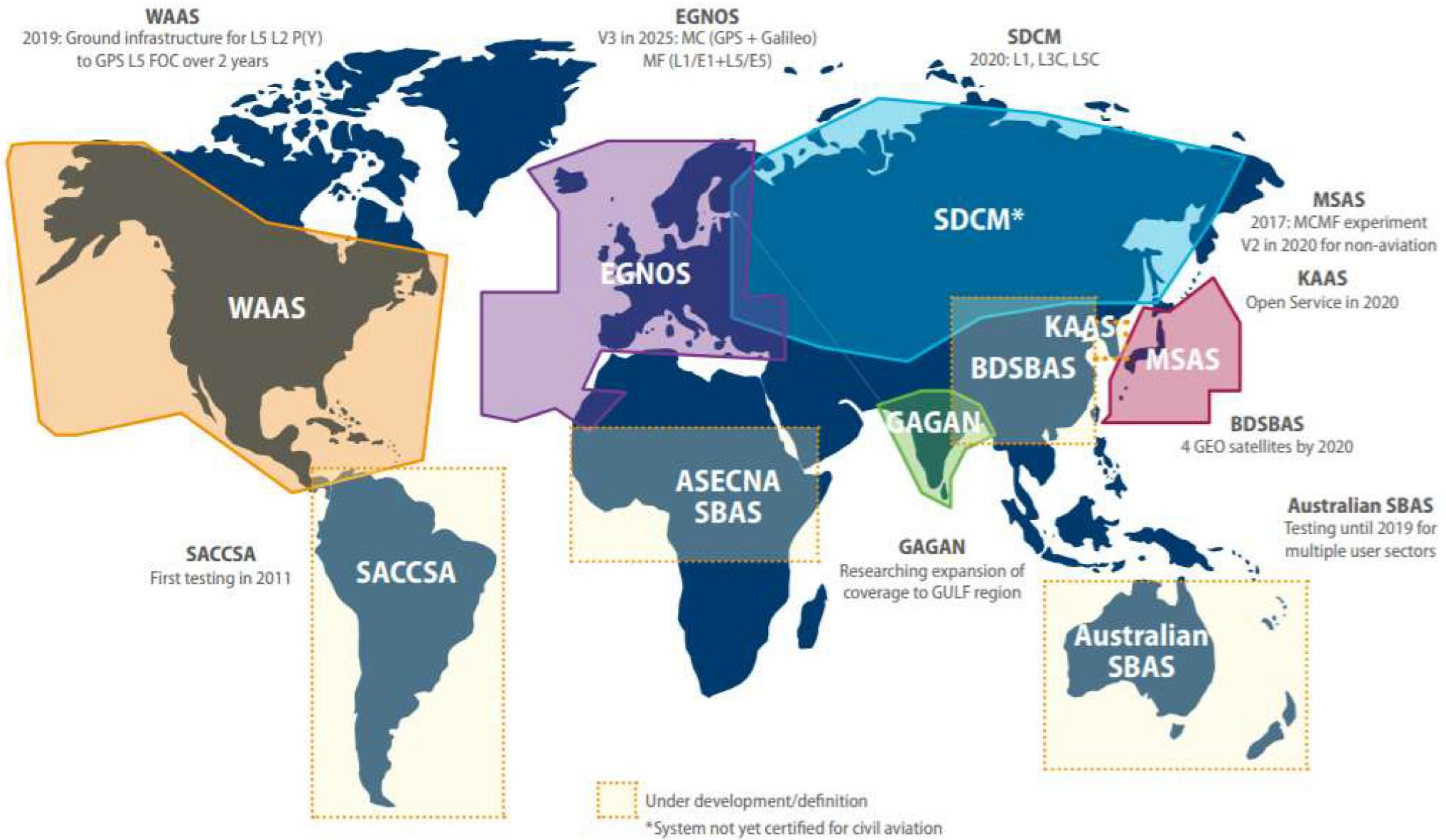
GBAS, SBAS & EGNOS



- **Ground Based Augmentation System, GBAS**
    - differential corrections and integrity monitoring
    - using as input data 3/4 GNSS signals
    - continually broadcast the corrections and integrity omnidirectionally up to 42km to the nearby airport for precision approaches and landing

- **Satellite-based Augmentation System, SBAS**
    - similar to GBAS, more general
    - corrections using accurately located reference stations deployed across a country, region or continent
    - e.g:
        - European Geostationary Navigation Overlay Service, EGNOS
        - Wide Area Reference Stations (US), WAAS
        - GPS-aided GEO augmented navigation (India), GAGAN

SBAS INDICATIVE SERVICE AREAS



To ask yourself

- What systems are using GNSS? What are they using it for?
- What kind of GNSS service do we have?
  - Single/ dual frequency? (Advanced systems vs cheap, light platforms)
  - Use of augmentation services?
- What will happen if GNSS falls off?
- Where are we operating these systems?
- What other means do we have to provide location/ time synchronisation?

Thank you for your attention! Questions?