Space-related activities in Poland

Future geodetic ESA missions: GENESIS, Moonlight, Galileo II

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25.09.2023, Institute of Geodesy and Geoinformatics, UPWr

Biography

- **University of Bern (Switzerland), Astronomical Institute, 2010-2015**

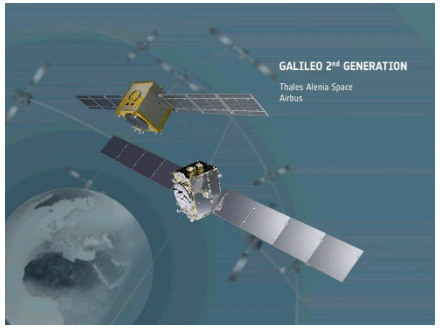
- **Wrocław University of Environmental and Life Sciences (Poland), Institute of Geodesy and Geoinformatics, since 2014**

- **European Space Agency, ESA GNSS Science Advisory Committee (France), since 2023**

Table of content

1. **GENESIS-1** - **an ESA mission for the co-location in space**

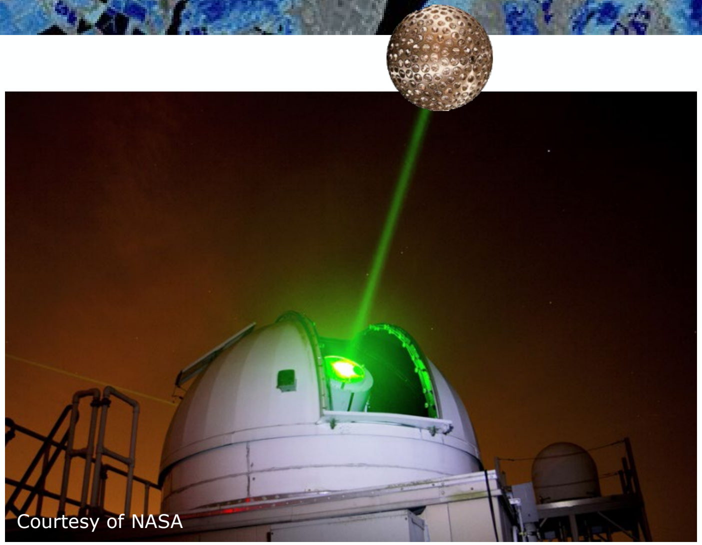
2. **Galileo I & II and its contribution to Geodesy**



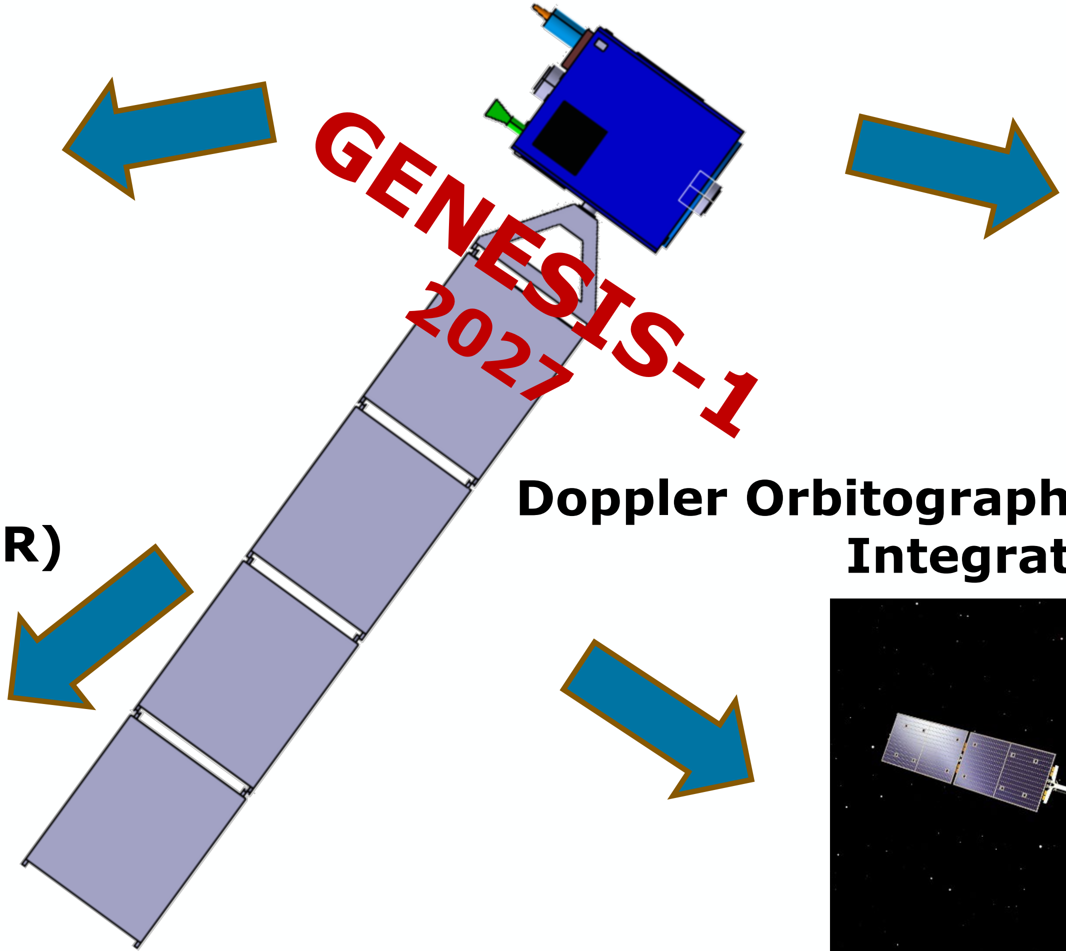
3. **Moonlight - „GPS on the Moon”**

GENESIS

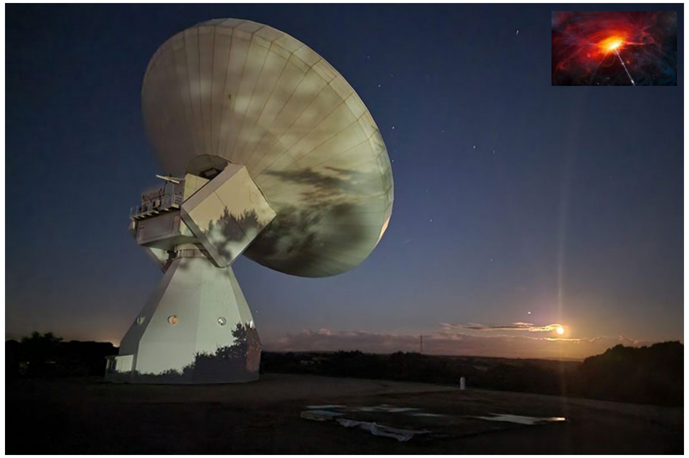
GENESIS


Courtesy of NASA

Satellite Laser Ranging (SLR)



Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)



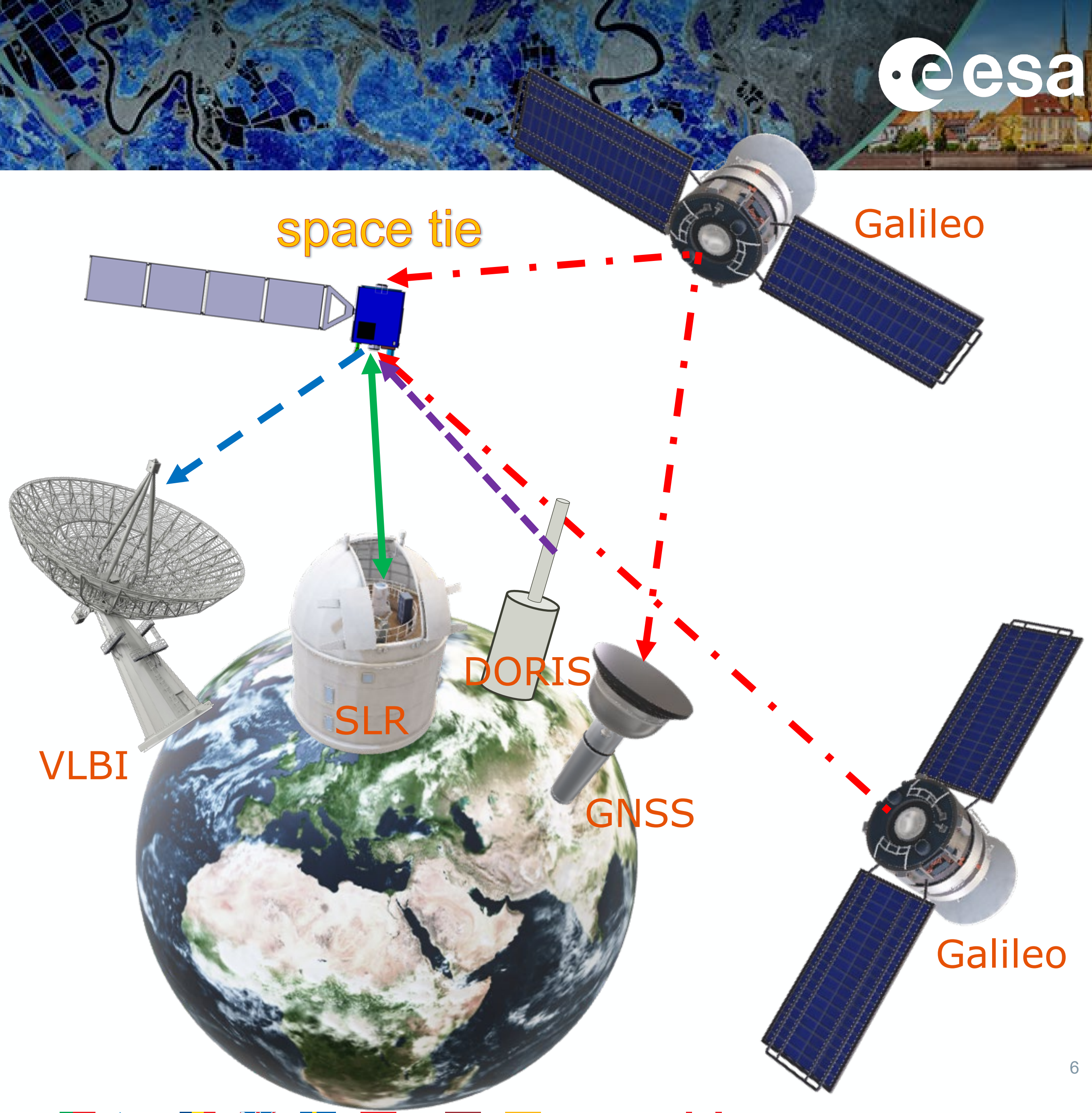
Very Long Baseline Interferometry (VLBI)

Global Navigation Satellite Systems (GNSS)

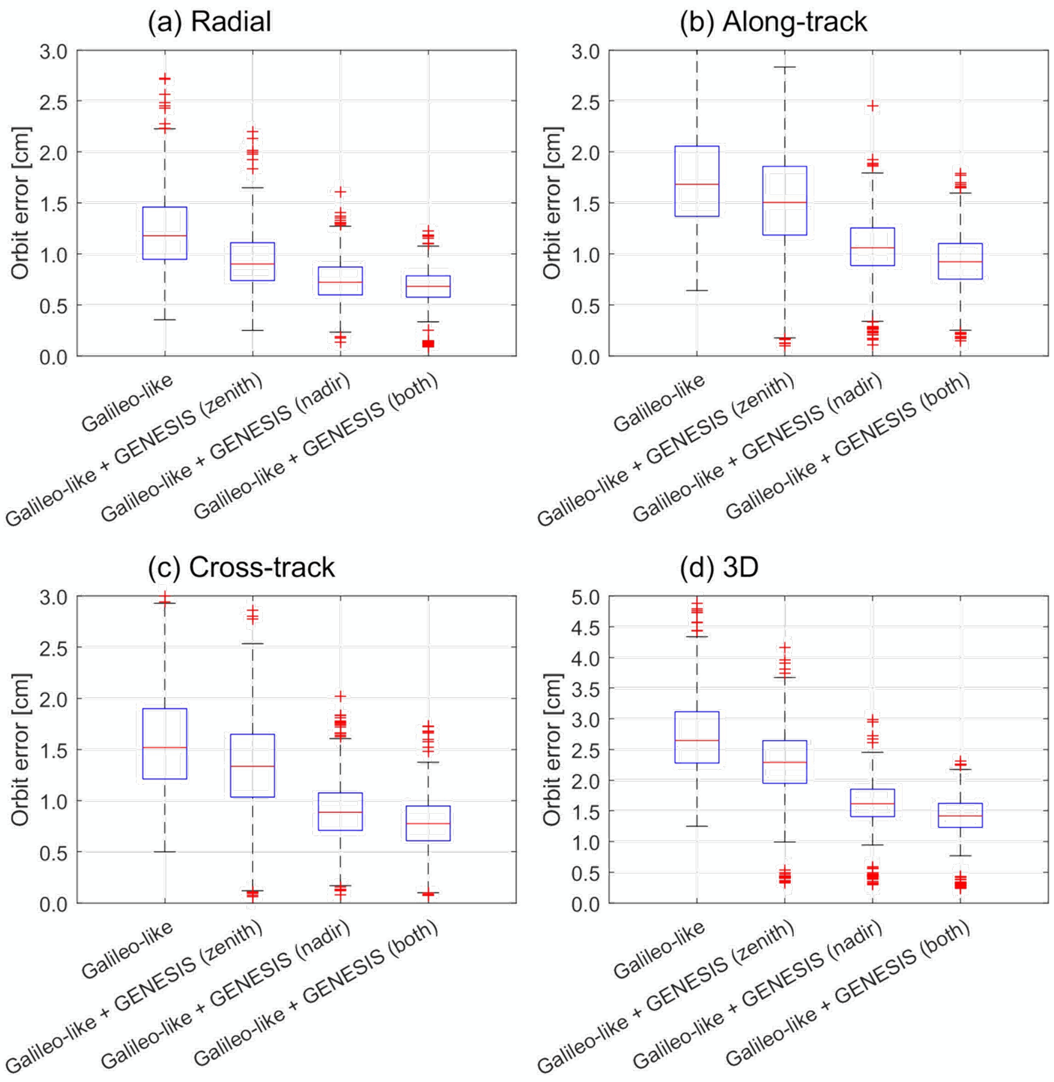
GENESIS

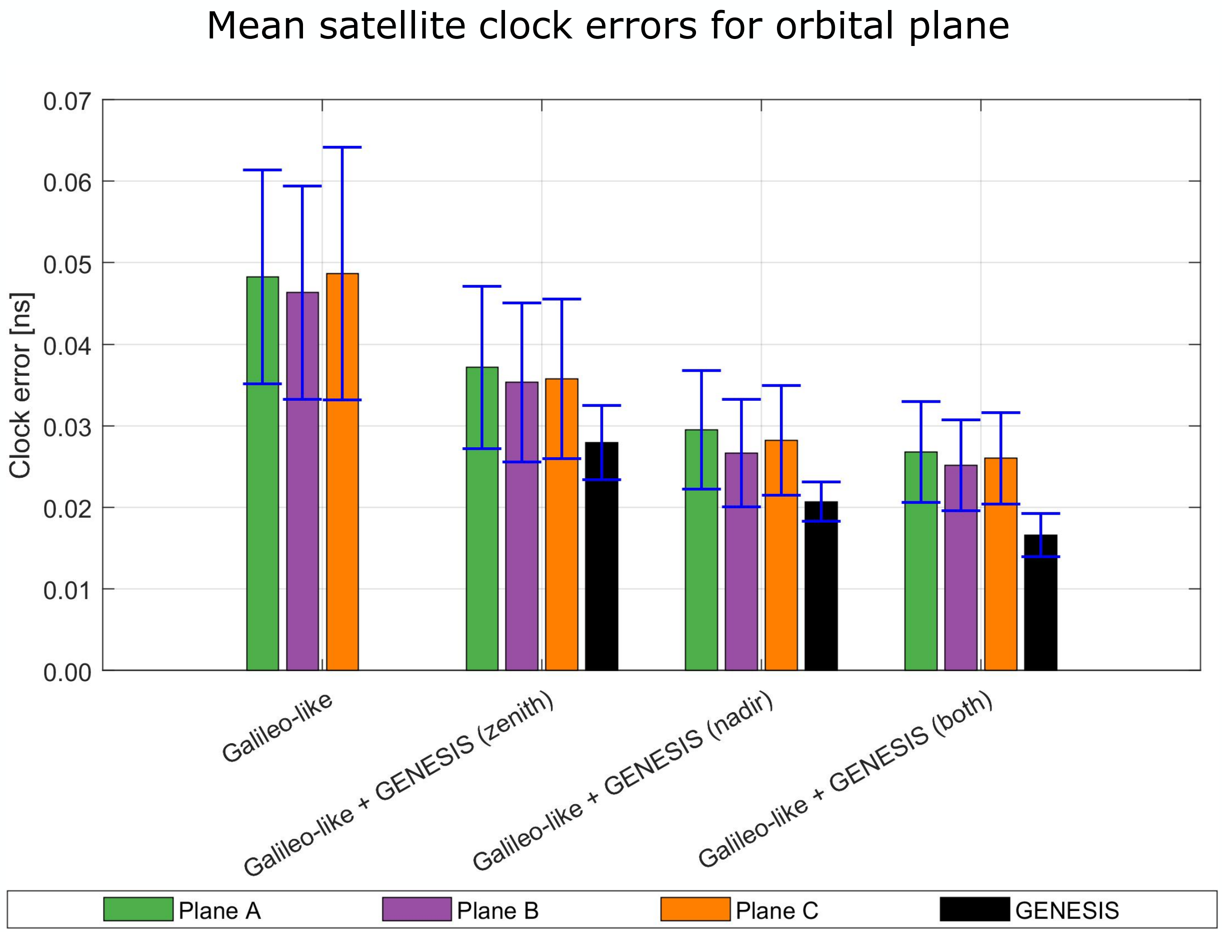
- To achieve the goals of the Global Geodetic Observing System (1 mm and 0.1 mm/y for the reference frame accuracy and stability) the better co-location of geodetic techqniques is needed:
  - Global Navigation Satellite System (GNSS),
  - Very Long Baseline Interferometry (VLBI),
  - Satellite Laser Ranging (SLR),
  - Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

Fundamental advantage of GENESIS-1 is complementary, highly accurate co-location of all four space geodetic techniques in space, on the same satellite platform.



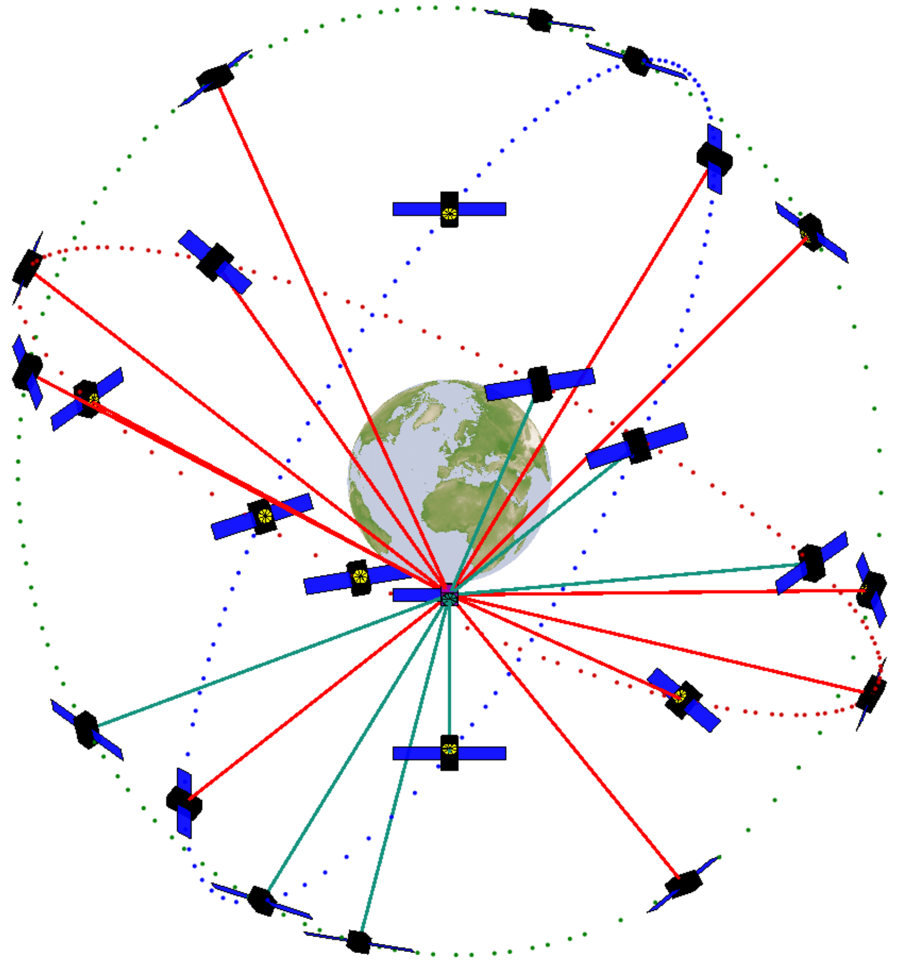
GENESIS – simulations for orbit and clocks



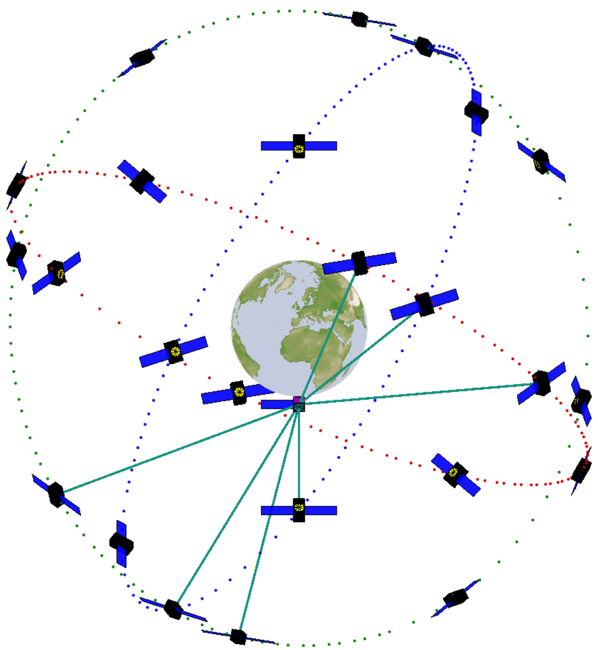


GENESIS GNSS Observations

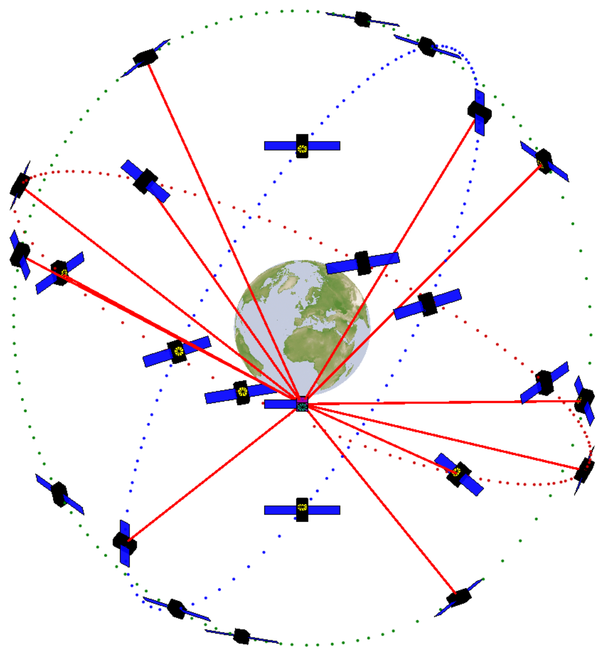
Observations from both antennas



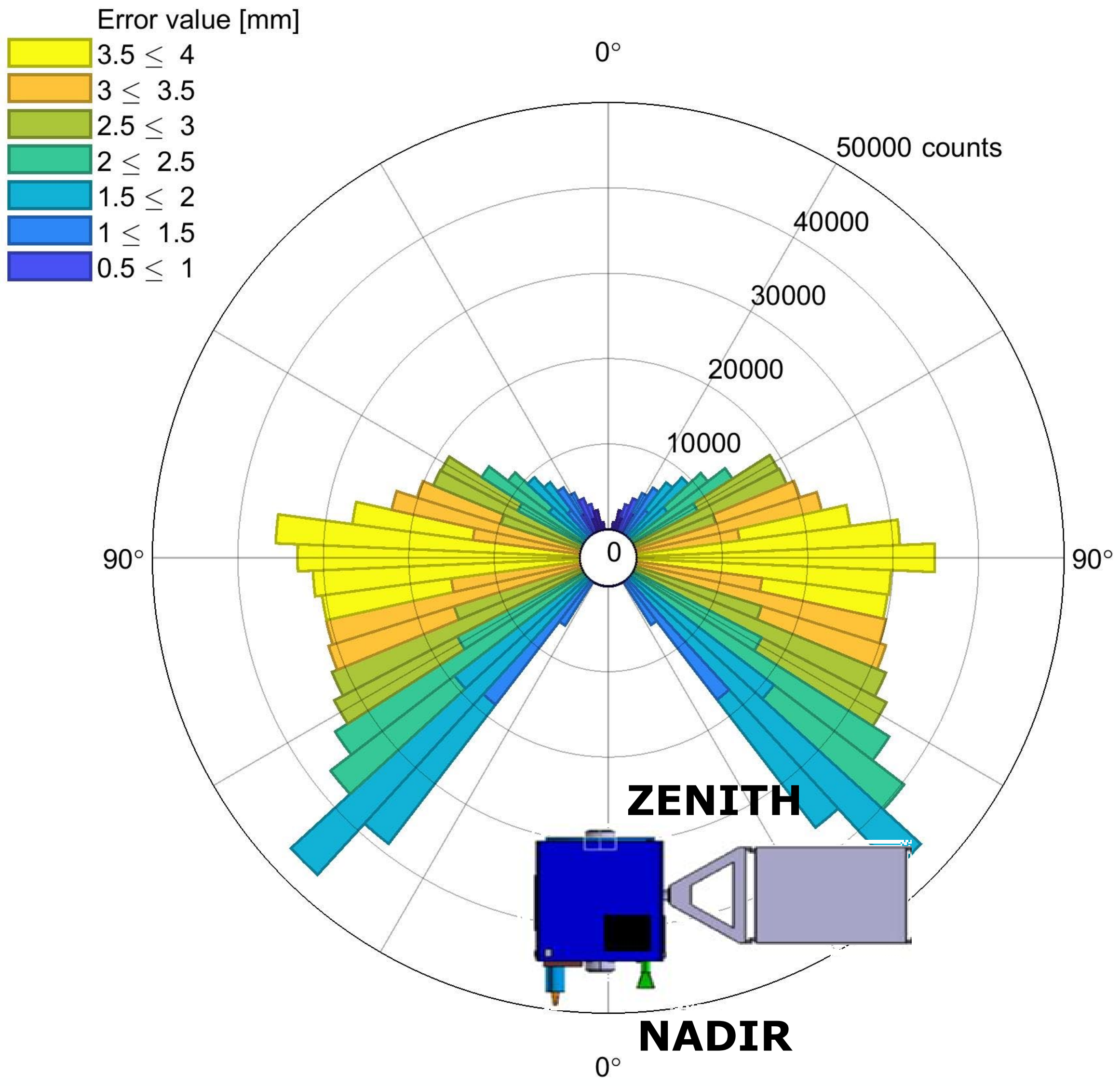
Observations from zenith antenna

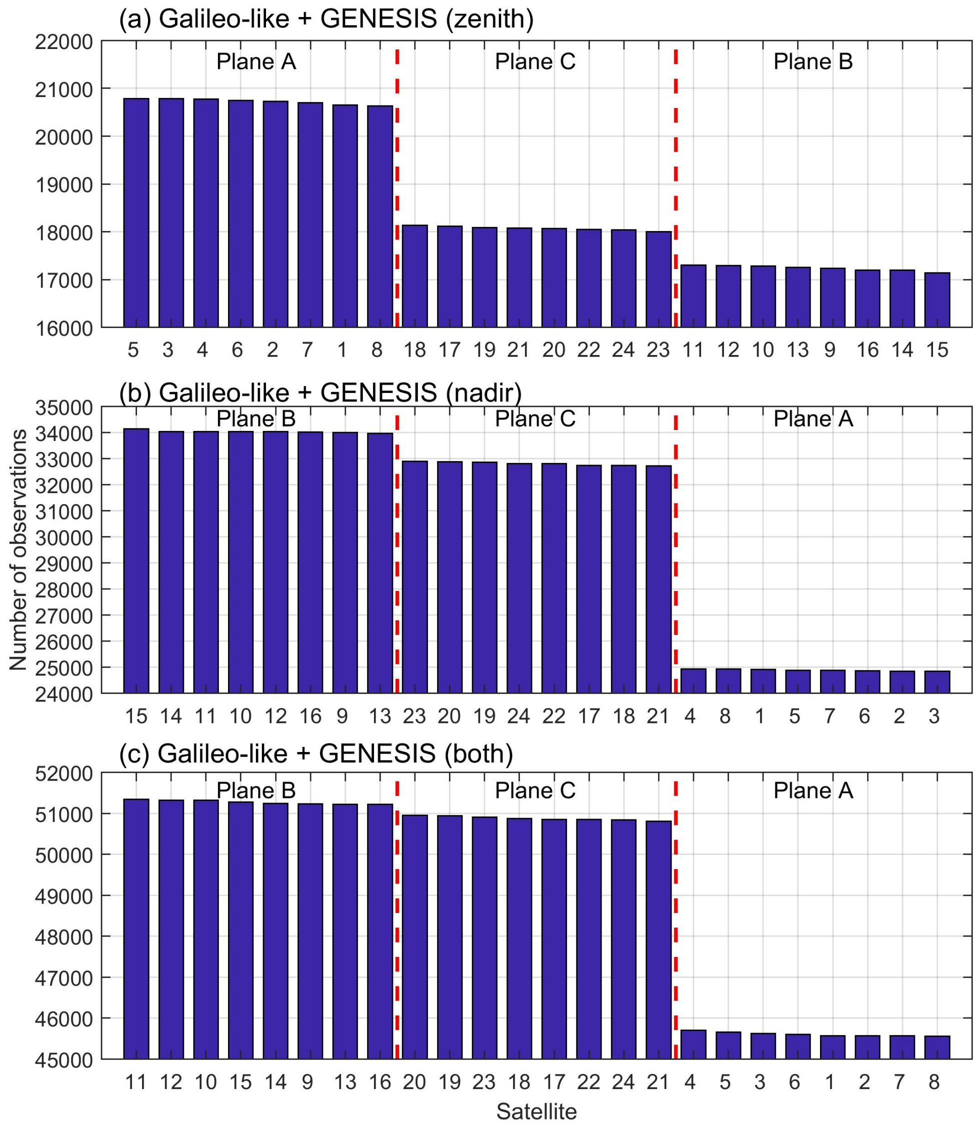


Observations from nadir antenna



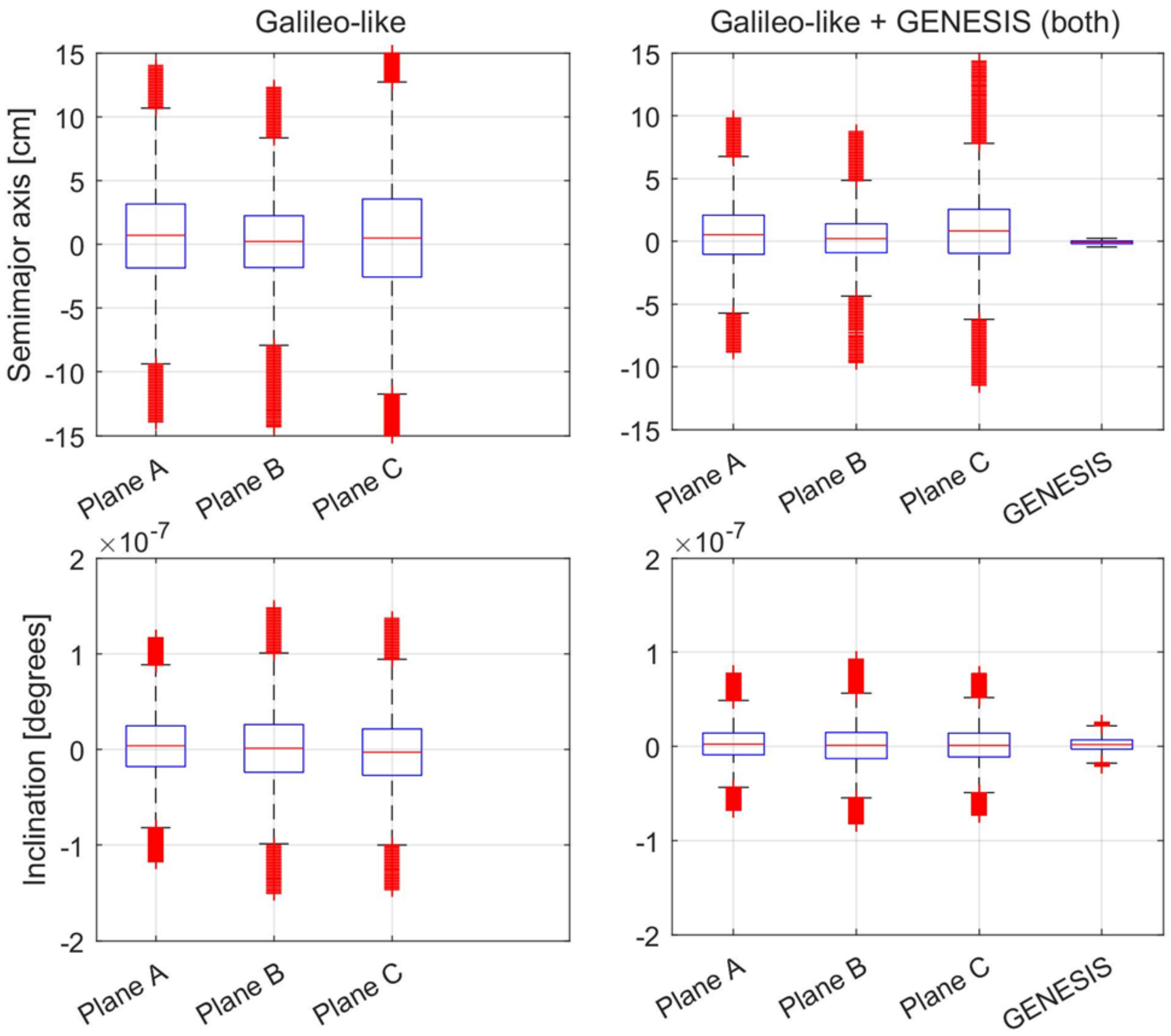
GENESIS antenna error pattern





Impact of GENESIS on Galileo orbit parameters

- GENESIS and Galileo joint orbit&clock determination improves Galileo orbits and satellite clocks. The radial orbit error of Galileo is improved from 14 mm (Galileo-only), 9 mm (Galileo+zenith), 8 mm (Galileo+nadir), to 7 mm (Galileo+zenith+nadir GENESIS observations).
- GENESIS nadir GNSS antenna has higher impact on the solution than zenith GNSS antenna despite providing data of lower quality.
- Although zenith and nadir GNSS antennas favor different orbital planes (plane A and place C, respectively) it does not substantially impact on the mean results for each orbital plane.



Galileo

Galileo & Geodesy

Terrestrial Reference Frames
- ITRF2020
- Geocenter coordinates
- GNSS-SLR co-location in space

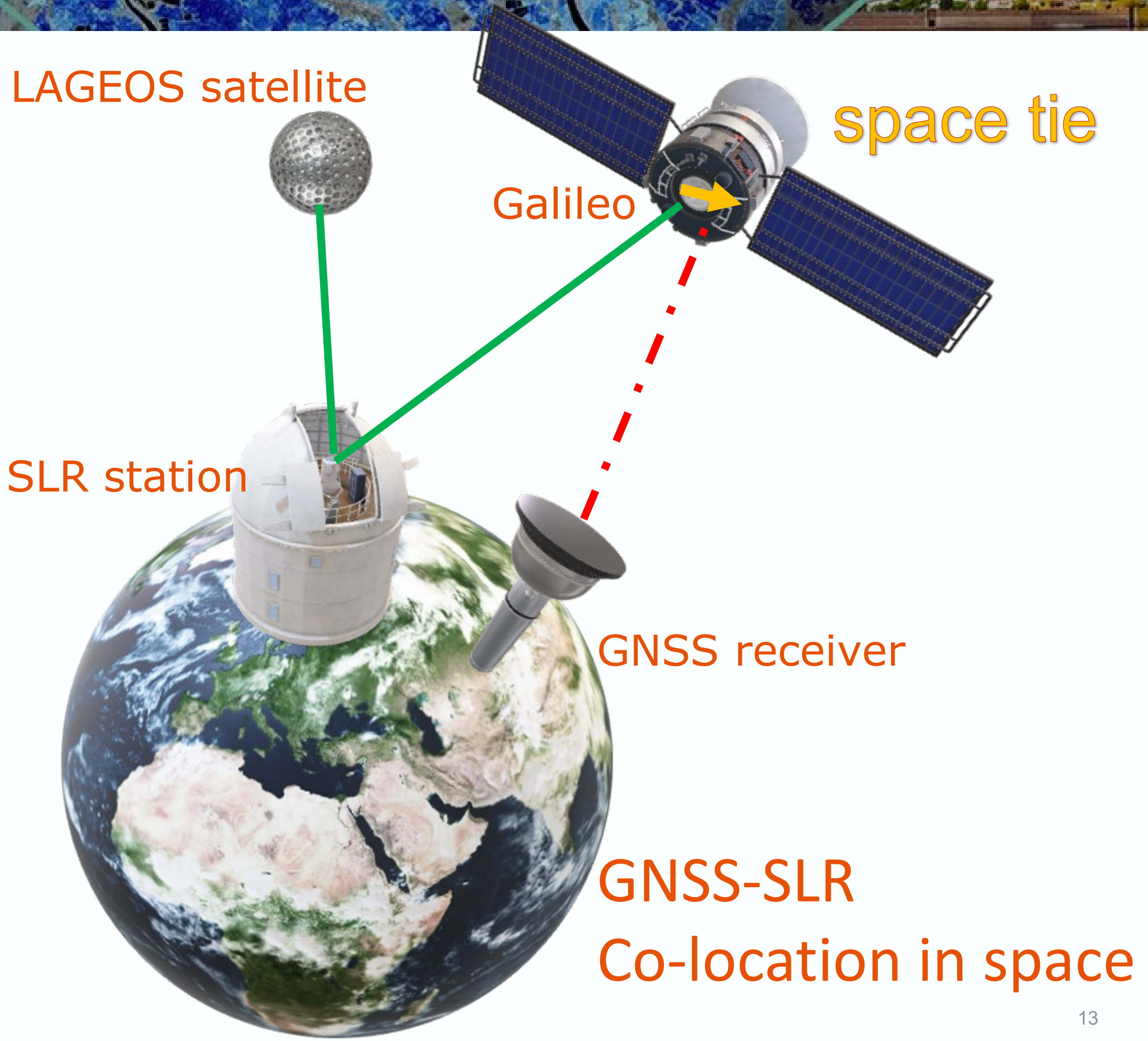
Earth Rotation Parameters
- X-pole, Y-pole: polar motion
- Length-of-day excess
- Sub-daily Earth rotation

Geodesy & Fundamental Physics
- Schwarzschild, de Sitter, Lense-Thirring
- Clock gravitational redshift
- Post-Newtonian parameter determination

Applications
- Station coordinates & time transfer
- Troposphere & ionosphere
- Real-time PPP, LEO orbits, etc.

Galileo & Geodesy

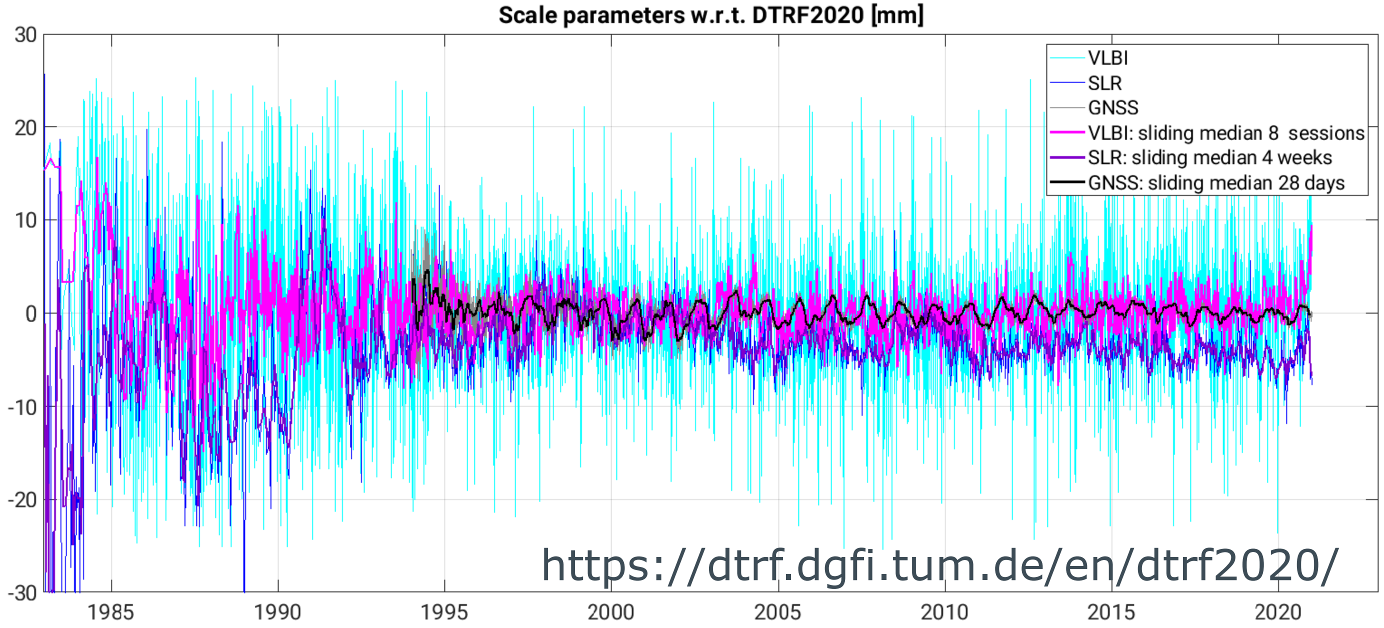
- **Satellite Laser Ranging** (SLR) retroreflectors onboard (as opposed to GPS)
- **Metadata** for Galileo allow for generation **a priori orbit models** (box-wing models)
- **Absolute antenna calibrations** provided for all satellites
- Weak resonance with Earth rotation (17:10) allow for the separation between **tidal signals** (diurnal, semi-diurnal, and terdiurnal), **orbital errors**, and **multipath** (impossible in the GPS system)
- High-quality atomic clocks

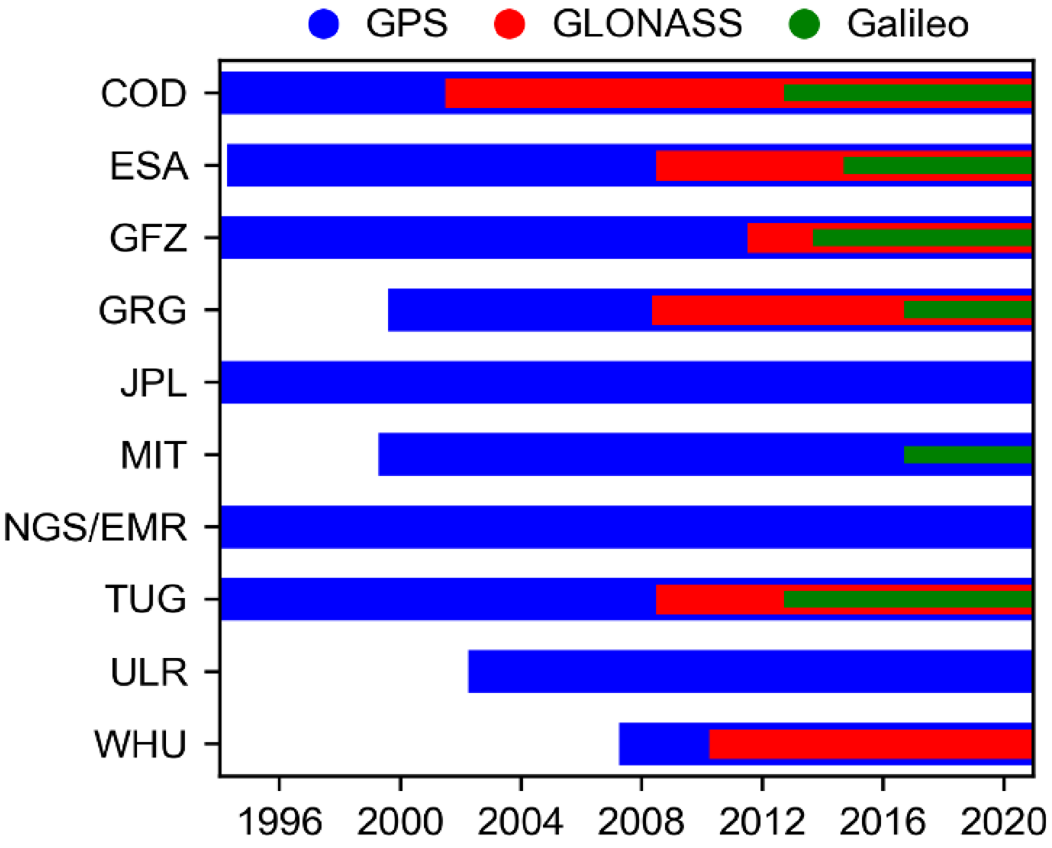


ITRF2020 – Galileo orbits

International Terrestrial Reference Frame ITRF2020 contains, for the first time,
GPS + GLONASS + Galileo observations.

Antenna calibrations for Galileo allow for the scale realization, however, the final scale of the reference frame (ITRF2020) was based on SLR+VLBI, whereas DTRF2020 (DGFI-TUM realization of ITRF) uses Galileo+VLBI.





Contribution of International GNSS Service (IGS) Analysis Centers to the ITRF2020 realization (the 3rd IGS reprocessing campaign).

SLR validation of Galileo orbits

Mean offsets of SLR residuals [mm]

	COD	ESA	GFZ	GRG	IGS	MIT	TUG	WHU
GAL-FOC	6.2	1.8	-6.9	35.3	13.3	15.2	29.8	
GAL-FOCe	8.1	2.1	-1.2	28.0	15.0	20.0	25.6	
GAL-IOV	-3.4	0.6	-10.2	14.0	-2.6	-0.1	-7.6	
GLO-K1B	3.2	14.0	24.1	10.8	13.9		11.6	21.6
GLO-M	-1.5	-1.3	-2.8	5.4	-1.1		-5.3	-0.3
GLO-M+	37.2	37.6	33.7	45.1	37.1		33.3	37.3

Standard dev. of SLR residuals [mm]

	COD	ESA	GFZ	GRG	IGS	MIT	TUG	WHU
GAL-FOC	17.9	13.2	23.0	15.8	13.7	17.7	13.6	
GAL-FOCe	17.6	14.1	17.6	16.6	13.4	16.6	14.7	
GAL-IOV	20.8	15.3	22.9	28.8	16.3	20.2	18.4	
GLO-K1B	17.8	18.5	21.4	20.7	17.2		17.0	26.4
GLO-M	22.1	19.1	27.9	23.9	20.3		23.1	28.5
GLO-M+	17.0	14.6	21.9	21.1	15.2		18.1	23.2

GAL FOC: 13 mm (ESA) 14 mm (IGS)
GAL FOCe: 14 mm (ESA) 13 mm (IGS)
GAL IOV: 15 mm (ESA) 16 mm (IGS)
GLO-M: 19 mm (ESA) 20 mm (IGS)
GLO-K1B: 17 mm (TUG) 17 mm (IGS)

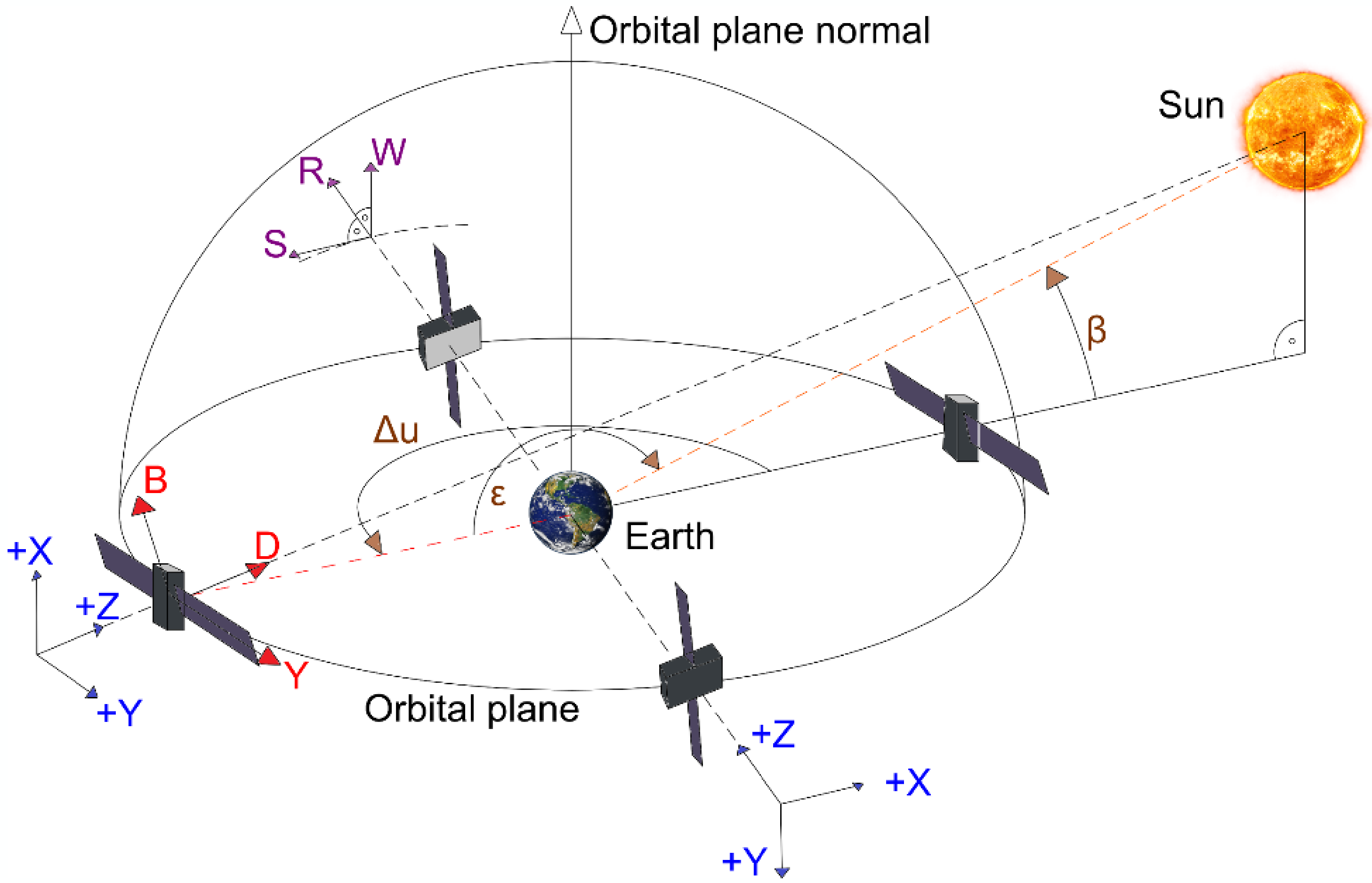
Orbit modeling issues - searching for patterns in SLR residuals (Galileo FOC)

SLR Validation of the combined orbits and individual ACs

Searching for patterns in SLR residuals in different
satellite-Sun-Earth geometry

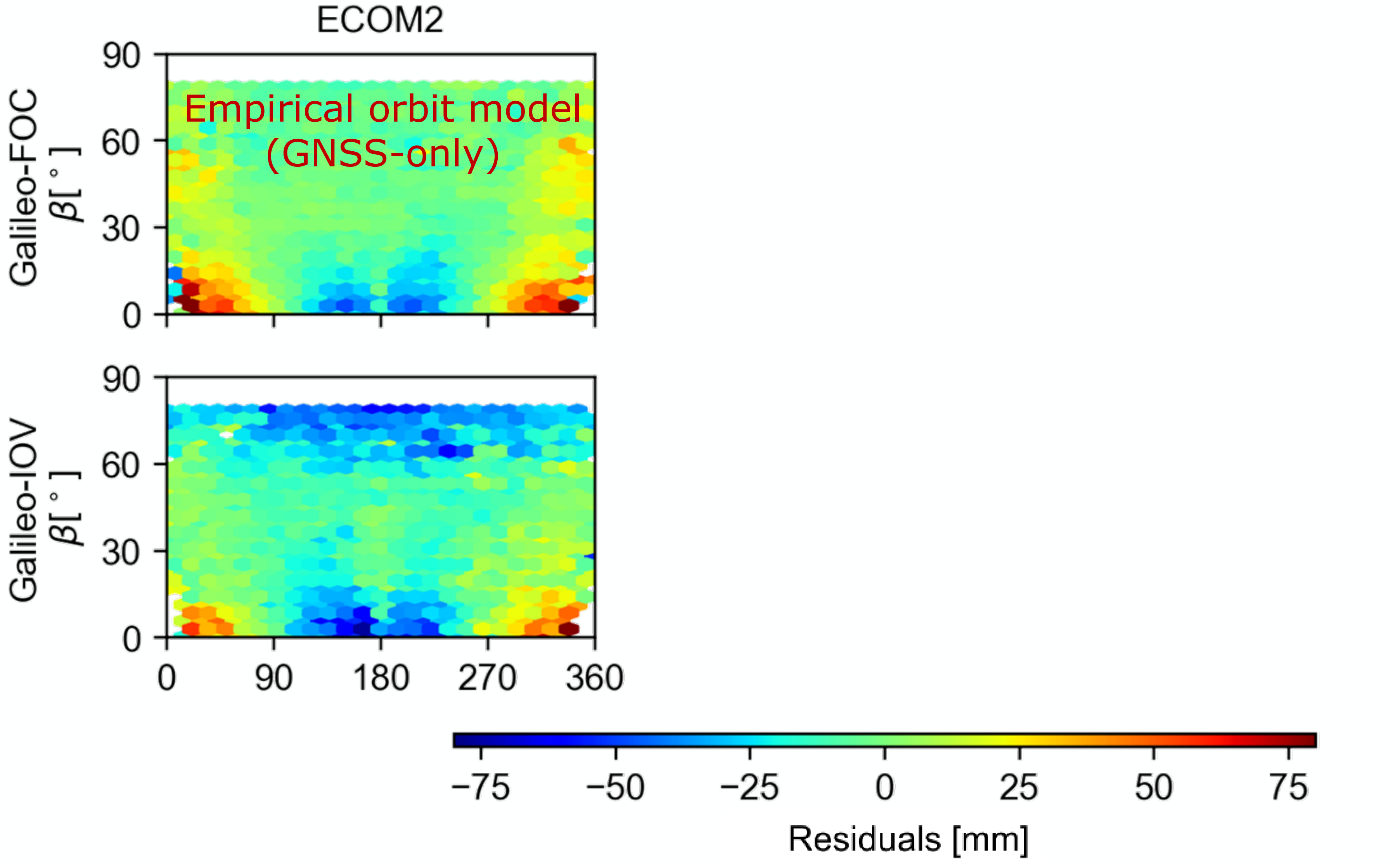
- SLR residuals as a function of β and argument of latitude of the satellite with respect to the argument of the latitude of the Sun (Δu),
- SLR residuals as a function of elongation angle (ε)

Possibilities to study SLR-related issues - Satellite signature effect

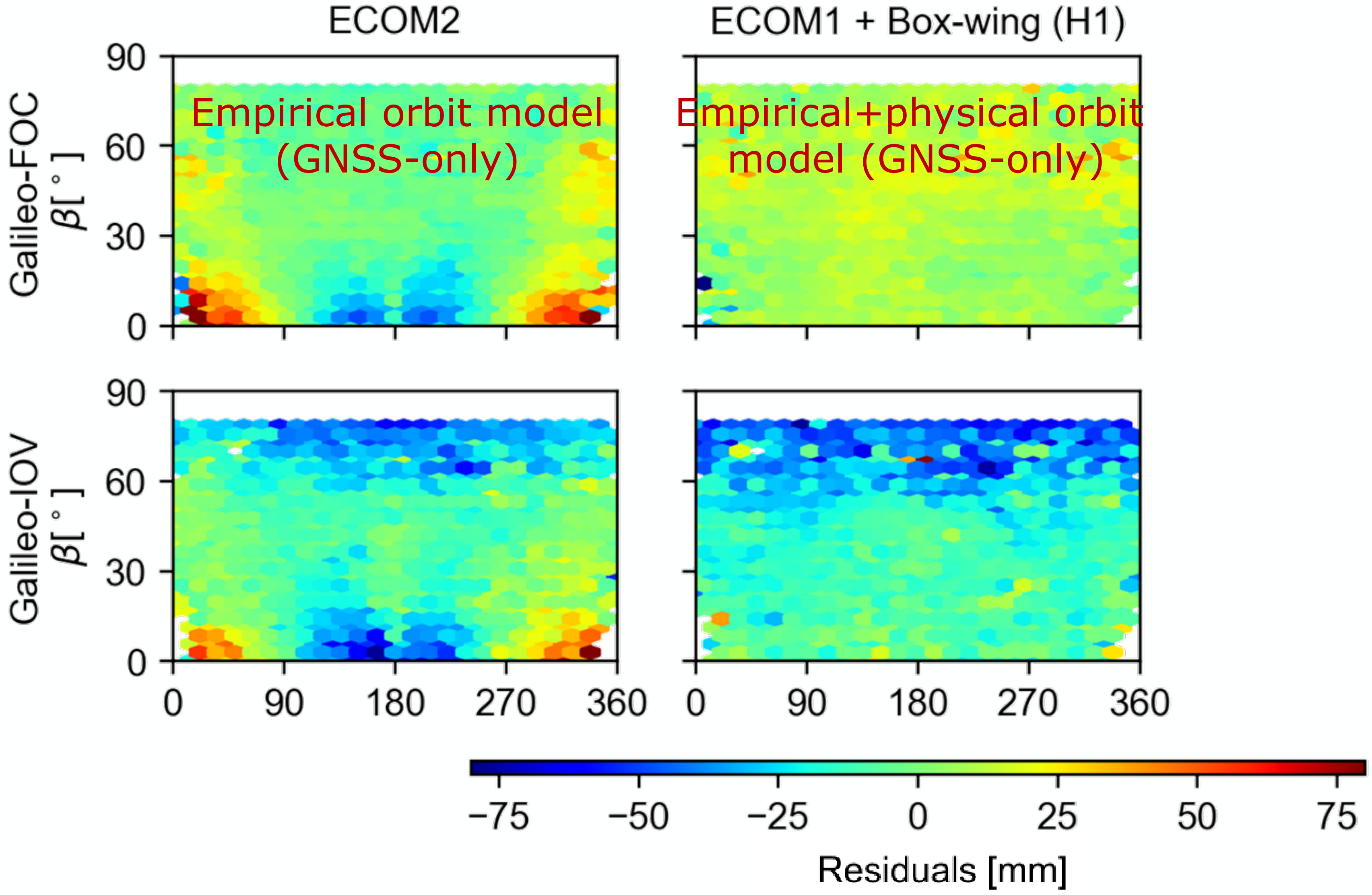


Satellite-Sun-Earth geometry

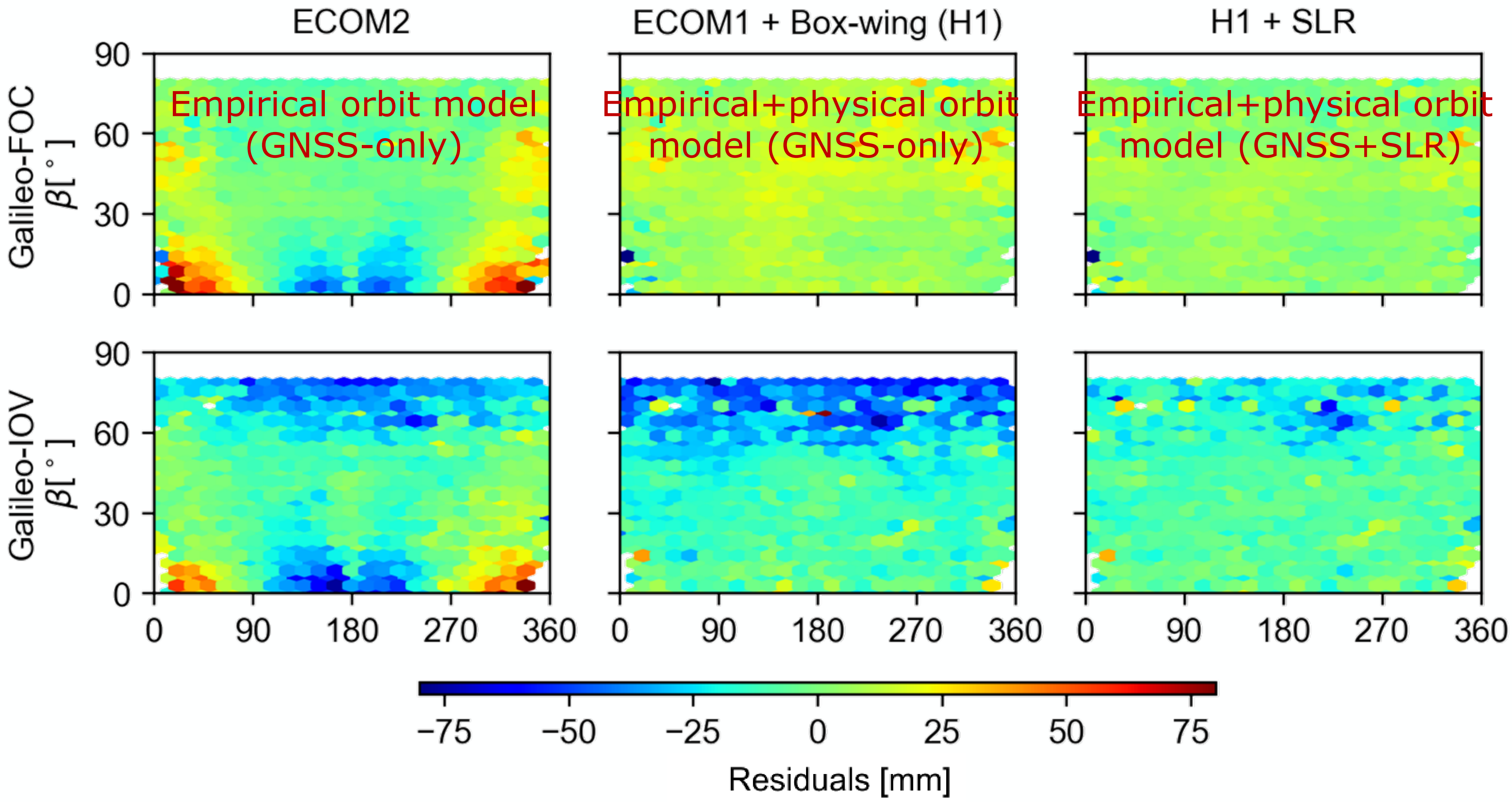
GNSS+SLR combinations – removing systematic patterns



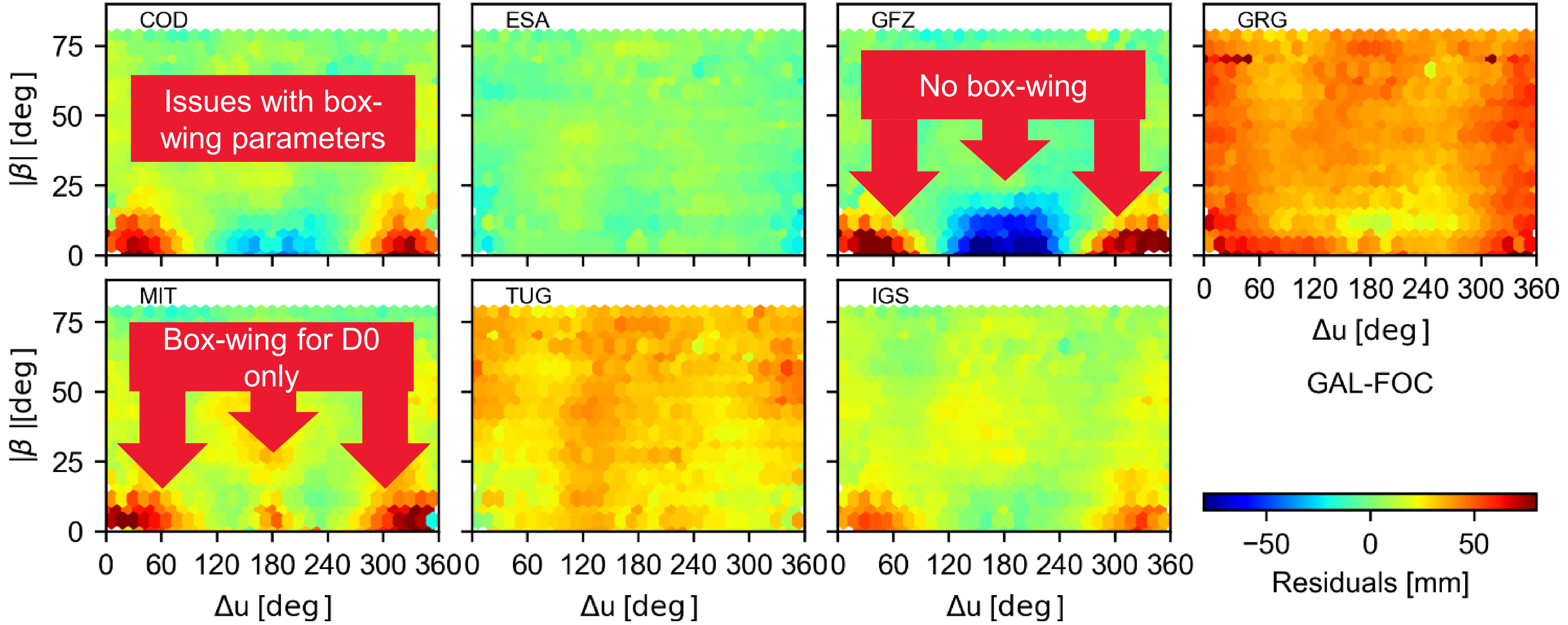
GNSS+SLR combinations – removing systematic patterns



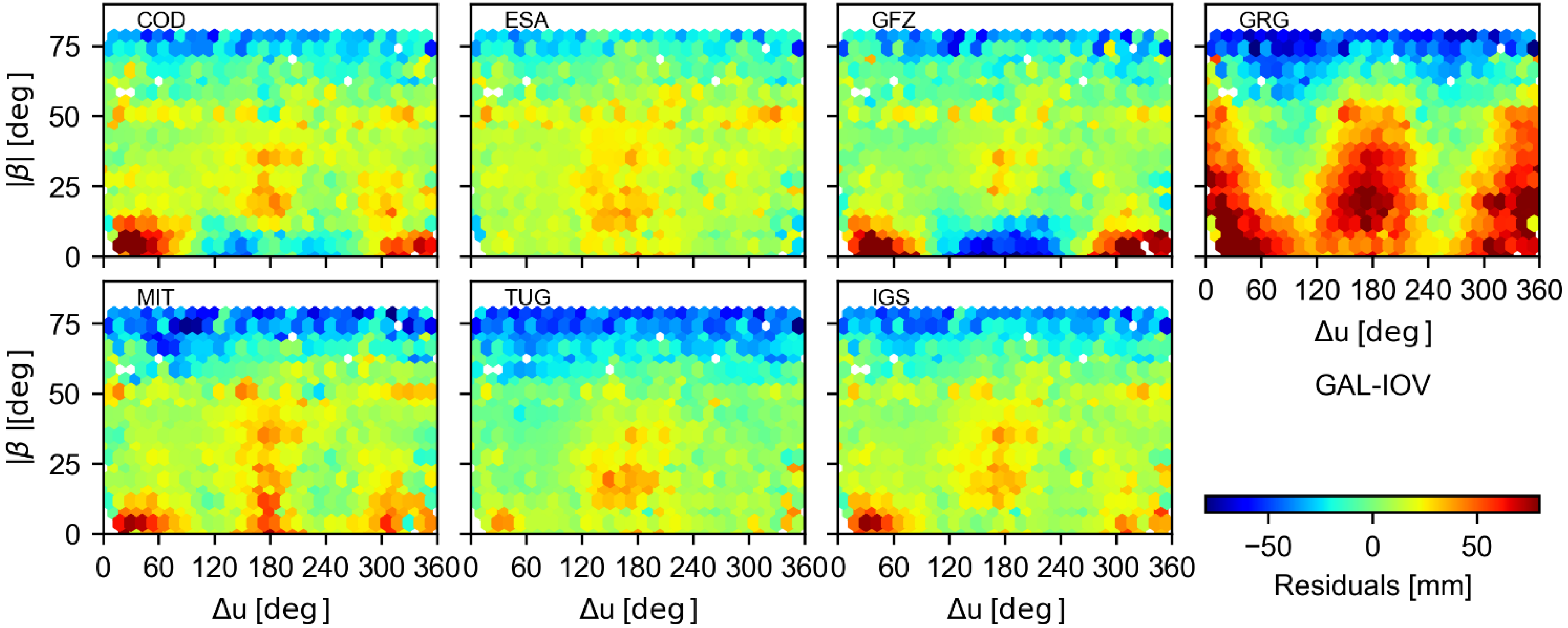
GNSS+SLR combinations – removing systematic patterns



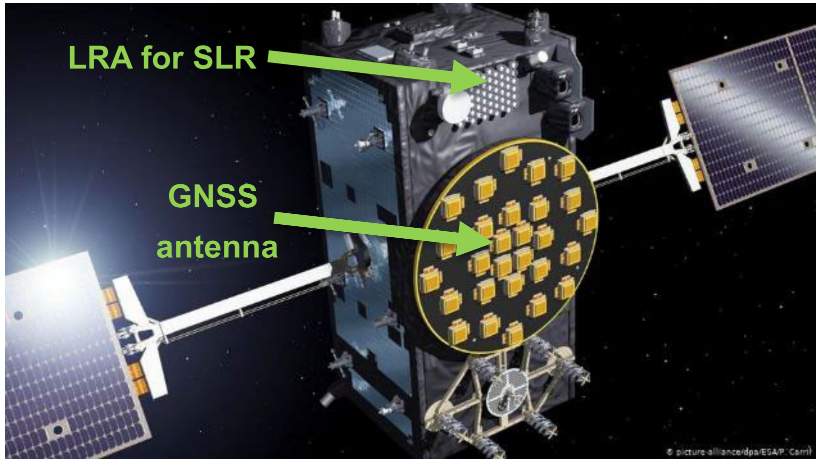
Orbit modeling issues - searching for patterns in SLR residuals (Galileo FOC)

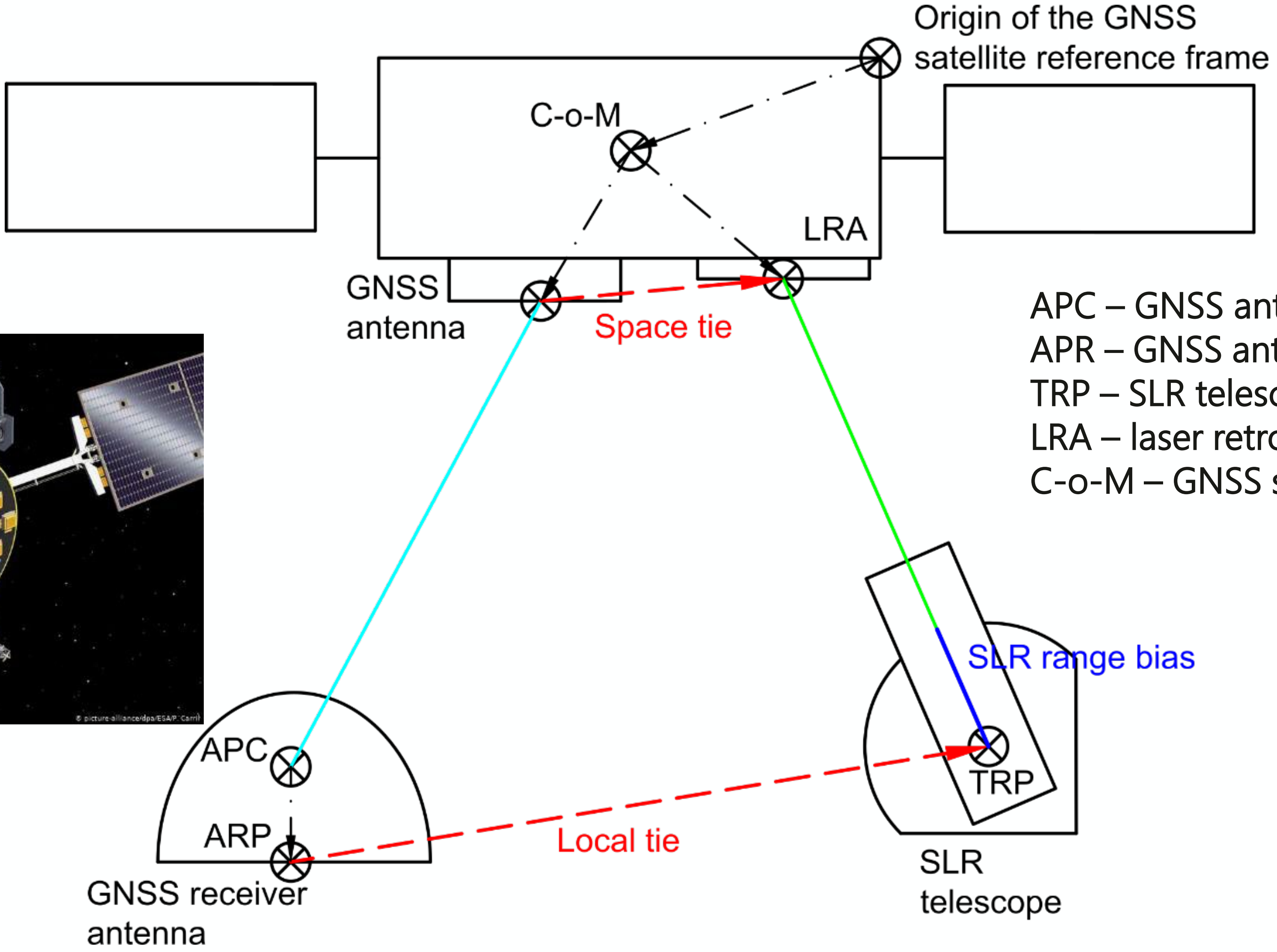


Orbit modeling issues - searching for patterns in SLR residuals (Galileo IOV)



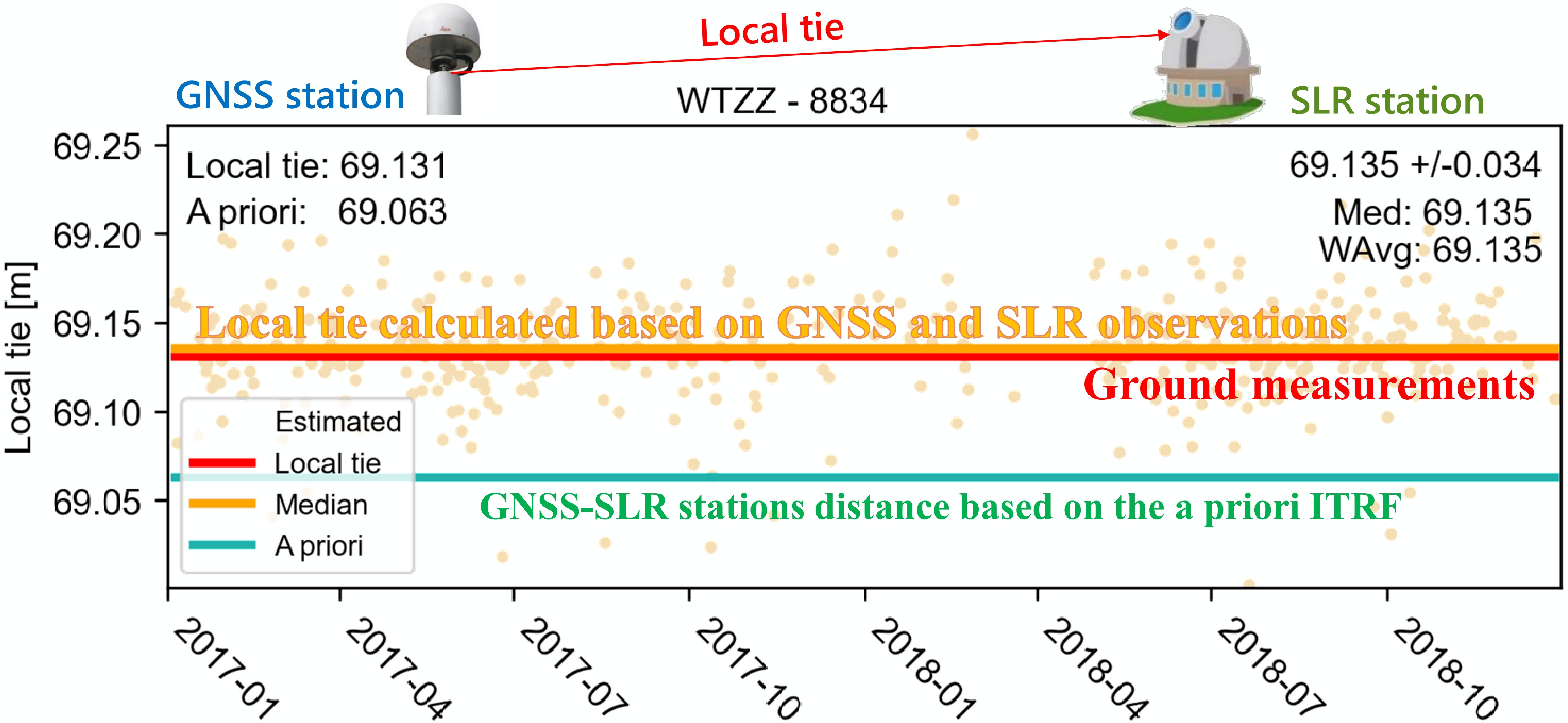
Integration of SLR and GNSS onboard Galileo (GNSS)





APC – GNSS antenna phase center
APR – GNSS antenna reference point
TRP – SLR telescope reference point
LRA – laser retroreflector array
C-o-M – GNSS satellite center-of-mass

3D local tie reconstructed based on space tie onboard Galileo



Strength of the 1-day connection: 30-50 mm

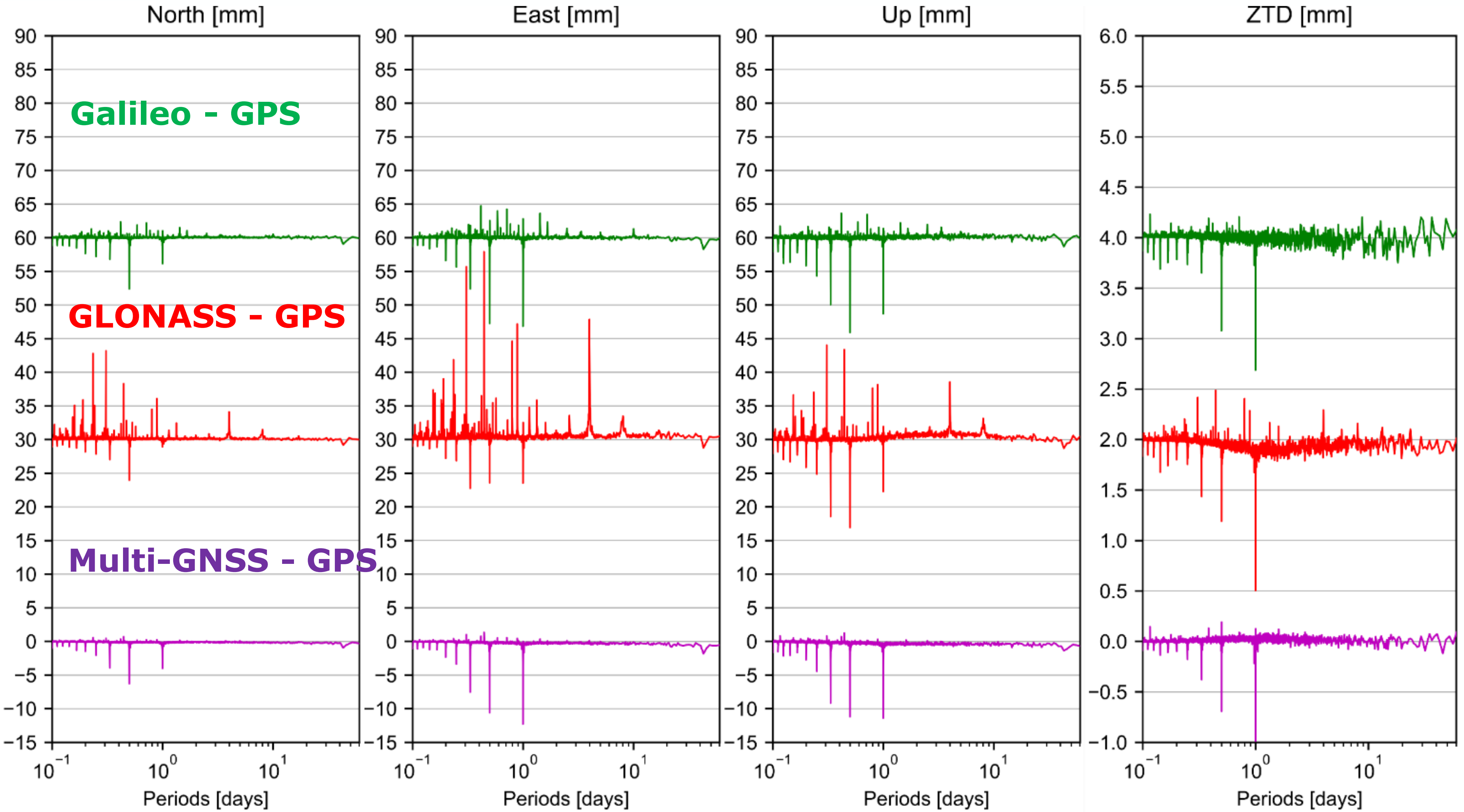
Long-term agreement: 3-4 mm

Bury G., Sośnica K., Zajdel R., Strugarek D., Hugentobler U. (2021) ***Geodetic datum realization using SLR-GNSS co-location onboard Galileo and GLONASS*** Journal of Geophysical Research, DOI: 10.1029/2021JB022211

Sub-daily Precise Point Positioning (PPP) solutions

- Stacked periodogram from 13 stations
- Series shifted along y-axis
  Signals above „0" – **Insertion of system-specific artifacts**
  Signals below „0" – **Reduction of GPS artifacts**

Stacked periodogram of FFT differences w.r.t. GPS-only solution

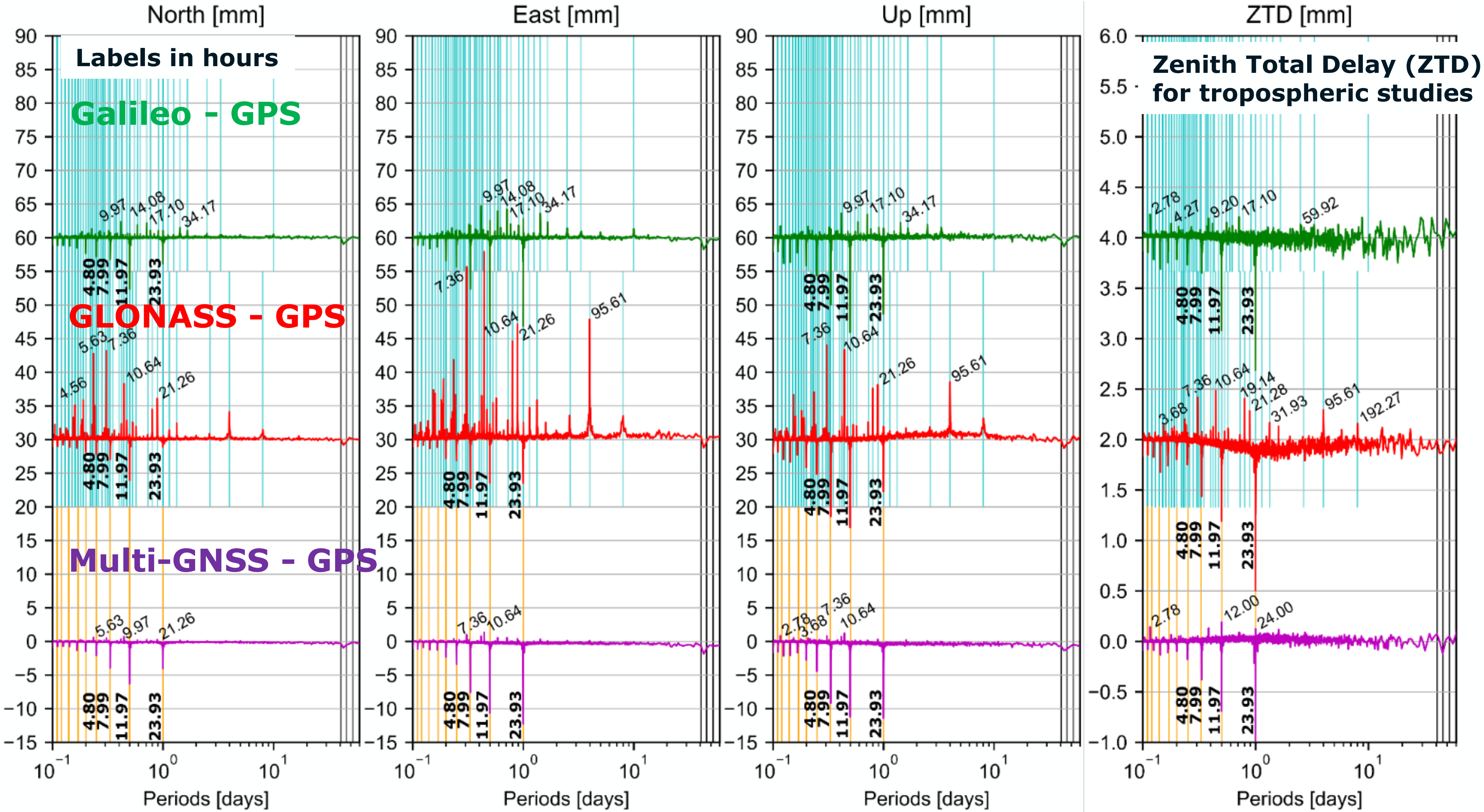


Sub-daily Precise Point Positioning (PPP) solutions

- Stacked periodogram from 13 stations
- Series shifted along y-axis
  Signals above „0" – **Insertion of system-specific artifacts**
  Signals below „0" – **Reduction of GPS artifacts**
- **Signals at the orbital periods specific for each system**
- **Using-multi GNSS reduces the spuriously large GPS signals at the harmonics of sidereal day**

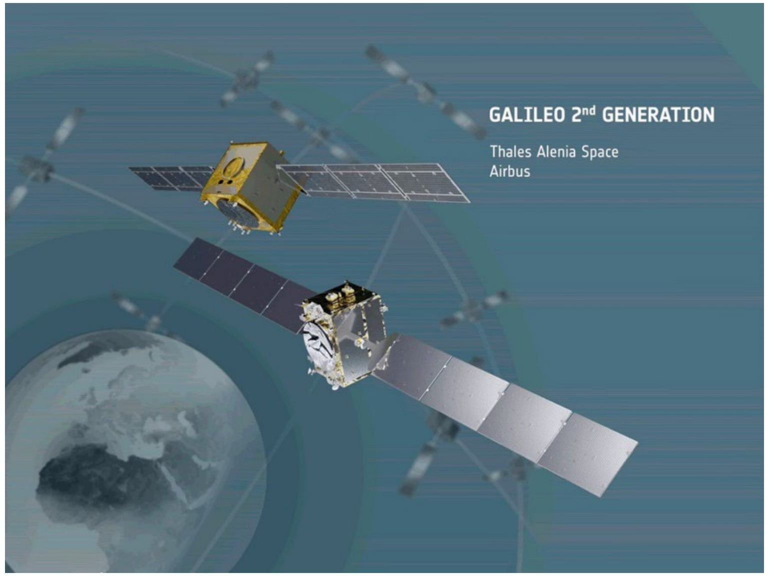
Zajdel R., Kaźmierski K., Sośnica K. (2022) ***Orbital artifacts in multi-GNSS Precise Point Positioning time series.*** Journal of Geophysical Research: Solid Earth,

Stacked periodogram of FFT differences w.r.t. GPS-only solution



Galileo – I & II generation

- Galileo I generation – launch of 10 satellites between January 2025 and the end of 2026
- High Accuracy Service (HAS) launched in early 2023
- 16 satellites transmit I/NAV (all by mid-2023)
- 4 billion users
- Galileo II generation – launch from 2026 (Airbus) and 2025 (TAS) with clocks: 2 x PHM, 2 x RAF, 2 x upgraded, 1 x experimental



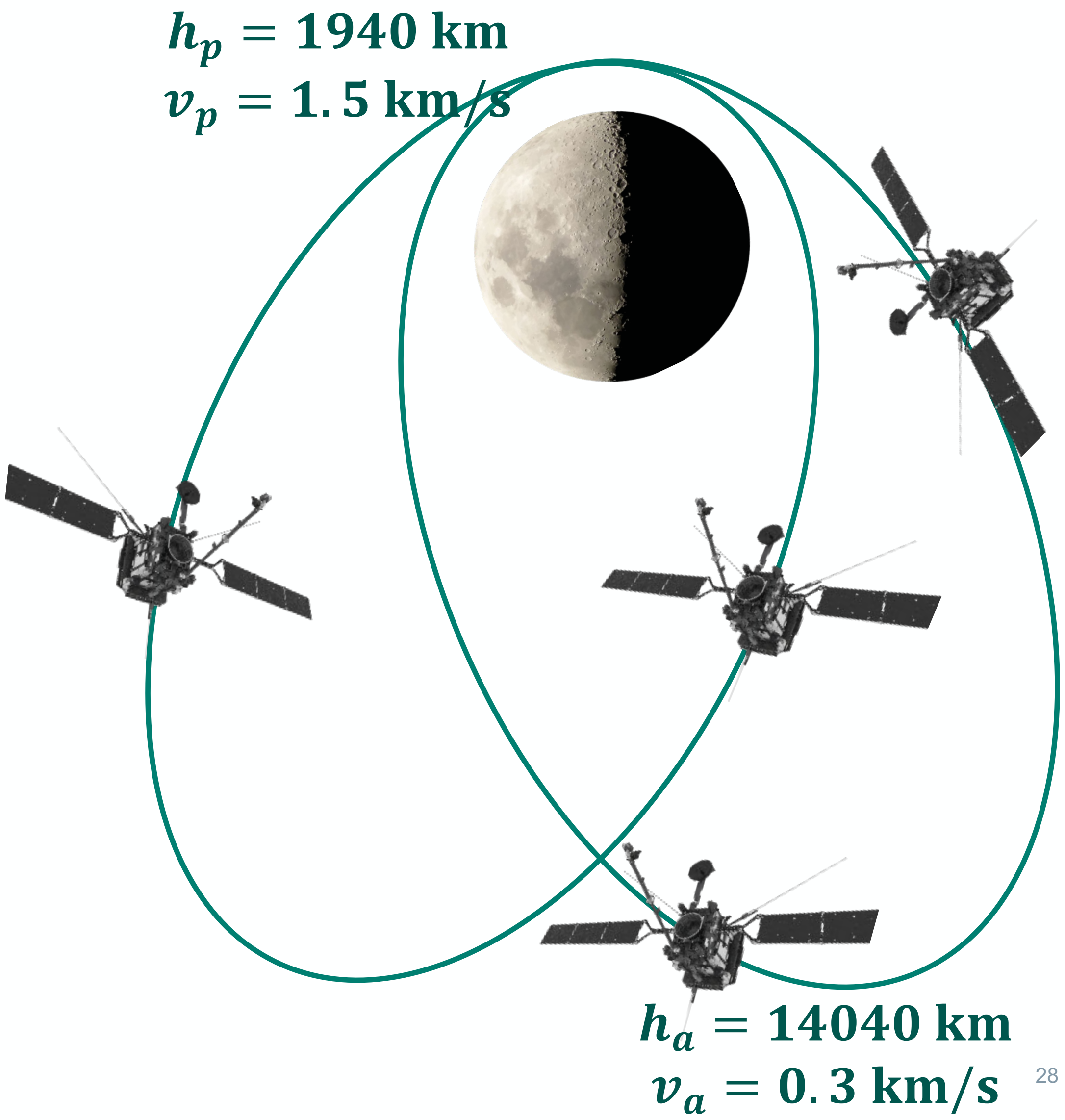
LEO PNT (Positioning-Navigation-Timing)

- Constellation in LEO orbit supporting GNSS
- Cheap clocks, small satellites
- A large number of satellites,
- first tests soon
- Probable altitude: 550-600 km

Moonlight

Moonlight

- Navigation and communication system for the Moon
- 400 planned missions to the Moon by 2030 (in 2022 there were 250)
- Recent Japanese&Russian mission landing failures
- China will invest $3 trillions in lunar missions by 2030
- Mission design completed for Moonlight: 3-4 lunar orbiters

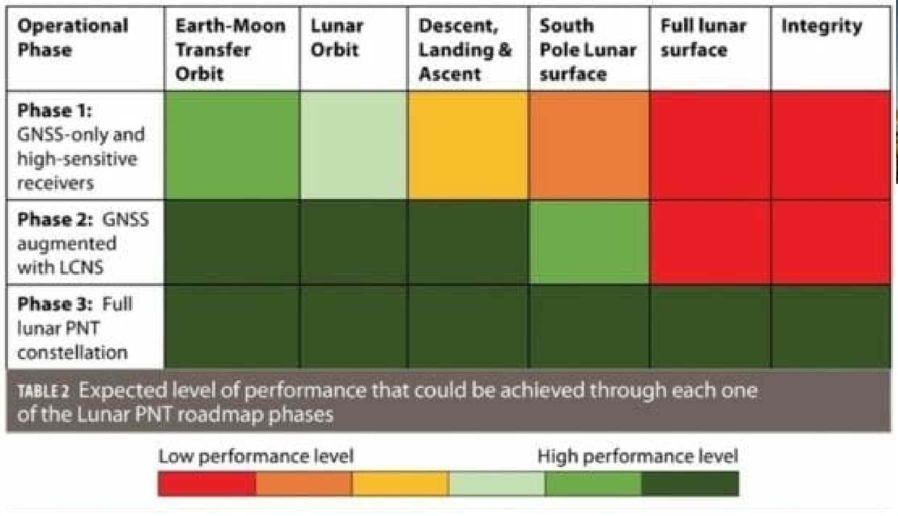


Sośnica, K., Zajdel, R., Bury, G., Di Benedetto, M., Durante, D., Sesta, A., ... & Iess, L. (2023). *Precise orbits for the lunar navigation system: challenges in the modeling of perturbing forces and broadcast orbit representation* (No. EGU23-5575). Copernicus Meetings. https://doi.org/10.5194/egusphere-egu23-5575

ESA Roadmap


STEP 1: LUNAR PATHFINDER
Low-rate satellite communications service + Moon GNSS Receiver
Development
Pathfinder Service
2025
STEP 2: MOONLIGHT PROGRAMME
High-data rate satellite communications and navigation service
Design
Development
Initial Services
2020
2021
2022
2023
2024
2025
2026
2027
2028

Satellite navigation system for the Moon



Operational Phase	Earth-Moon Transfer Orbit	Lunar Orbit	Descent, Landing & Ascent	South Pole Lunar surface	Full lunar surface	Integrity
Phase 1: GNSS-only and high-sensitive receivers						
Phase 2: GNSS augmented with LCNS						
Phase 3: Full lunar PNT constellation						

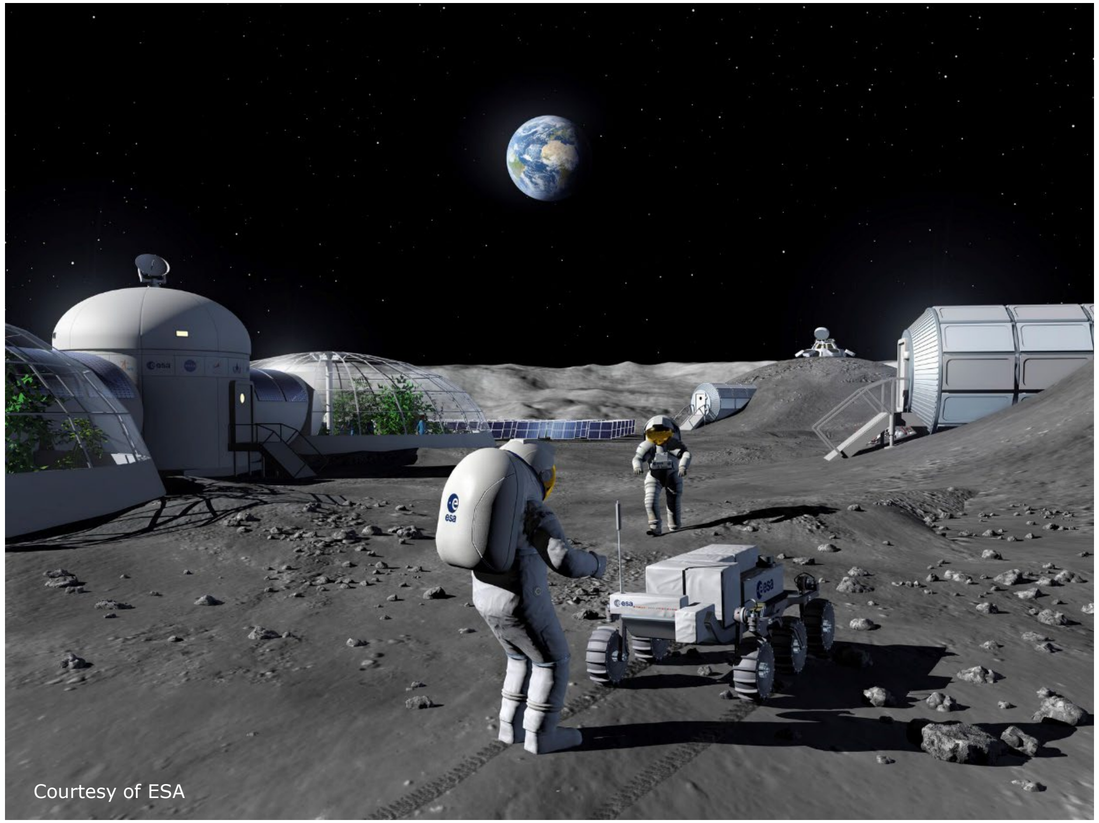
TABLE 2 Expected level of performance that could be achieved through each one of the Lunar PNT roadmap phases

ESA Project AO/1-10712/21/NL/CRS

Fundamental techniques, models and algorithms for a Lunar Radio Navigation system

Consortium:

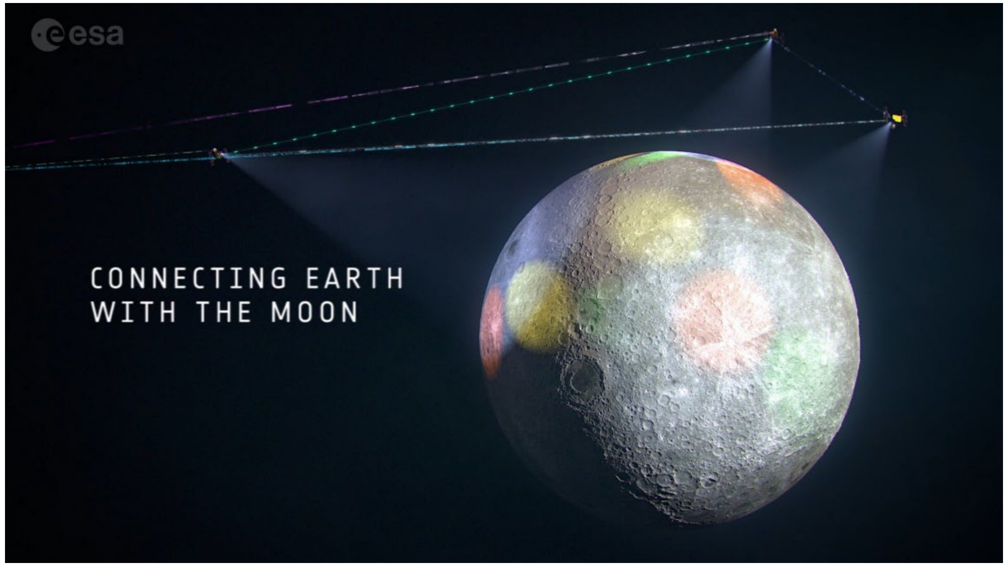
- **Sapienza Aerospace Research Centre – CRAS**
  Sapienza Università di Roma, Italy
- Centre National de Recherche Scientifique CNRS delegation Côte d’Azur Campus, Nice, France
- **Wrocław University of Environmental and Life Sciences, Wrocław, Poland**
- Argotec S.r.l., Turin, Italy
- Leonardo S.p.A., Italy



Courtesy of ESA

Reference frames on the Moon

- The Moon has a "natural" meridian zero (unlike the Earth)
- No troposphere or ionosphere
- No non-tidal mass transport (hydrology, oceans, atmosphere)
- The only tides are those of the solid crust
- The gravitational field is better known than on Earth (GRAIL orbited at an altitude of up to 17 km)
- Transformations between celestial and lunar frames with centimeter accuracy thanks to, e.g., INPOP ephemerides and Lunar Laser Ranging data

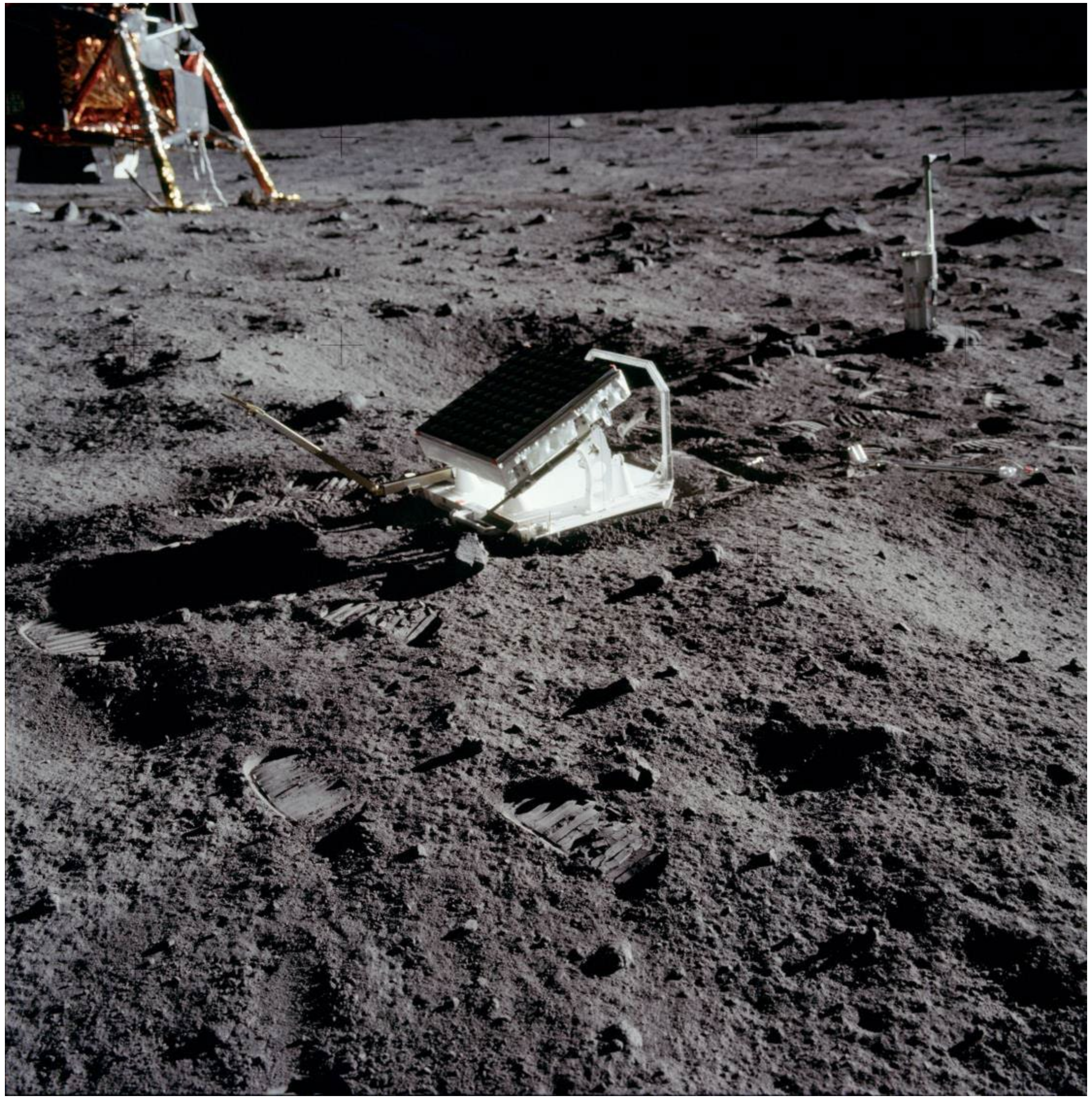


Lunar retroreflectors

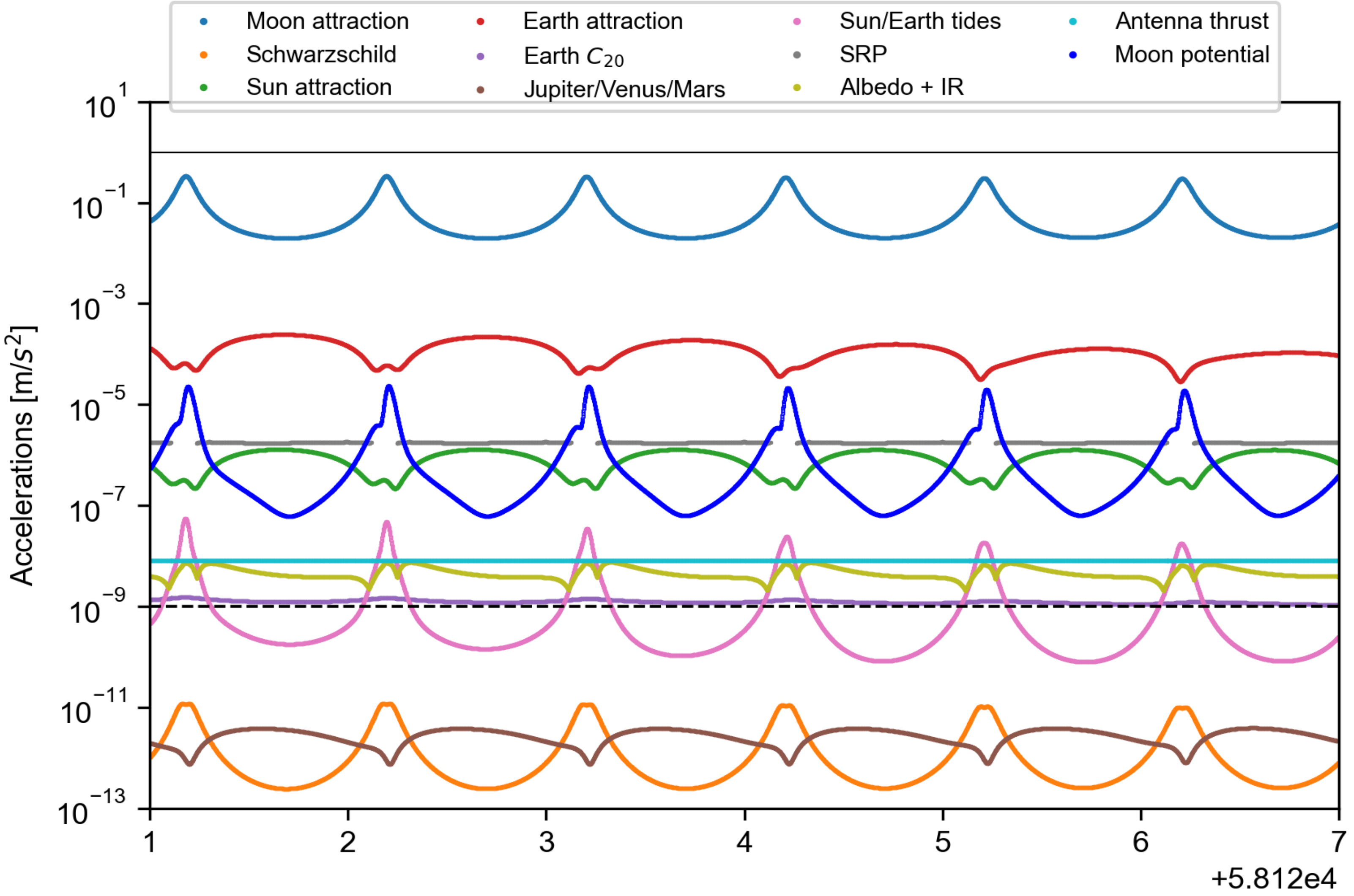
So far there are 5 retroreflectors for LLR:
Apollo 11, 14, 15, Luna 17 and 21.

The Moon moves away from the Earth by 3.8 cm every year.

Future retros to install in 2024.



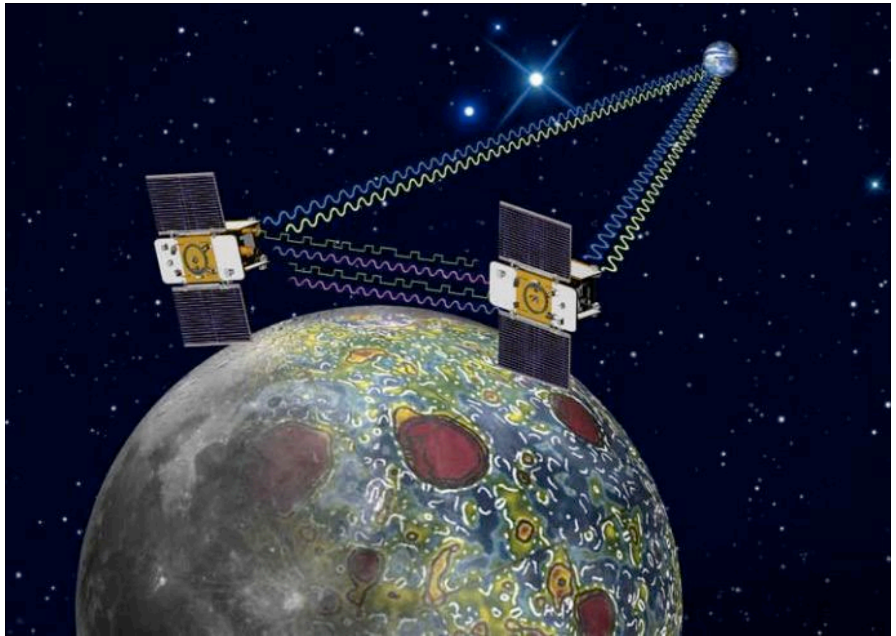
Orbit perturbations: design of the broadcast message

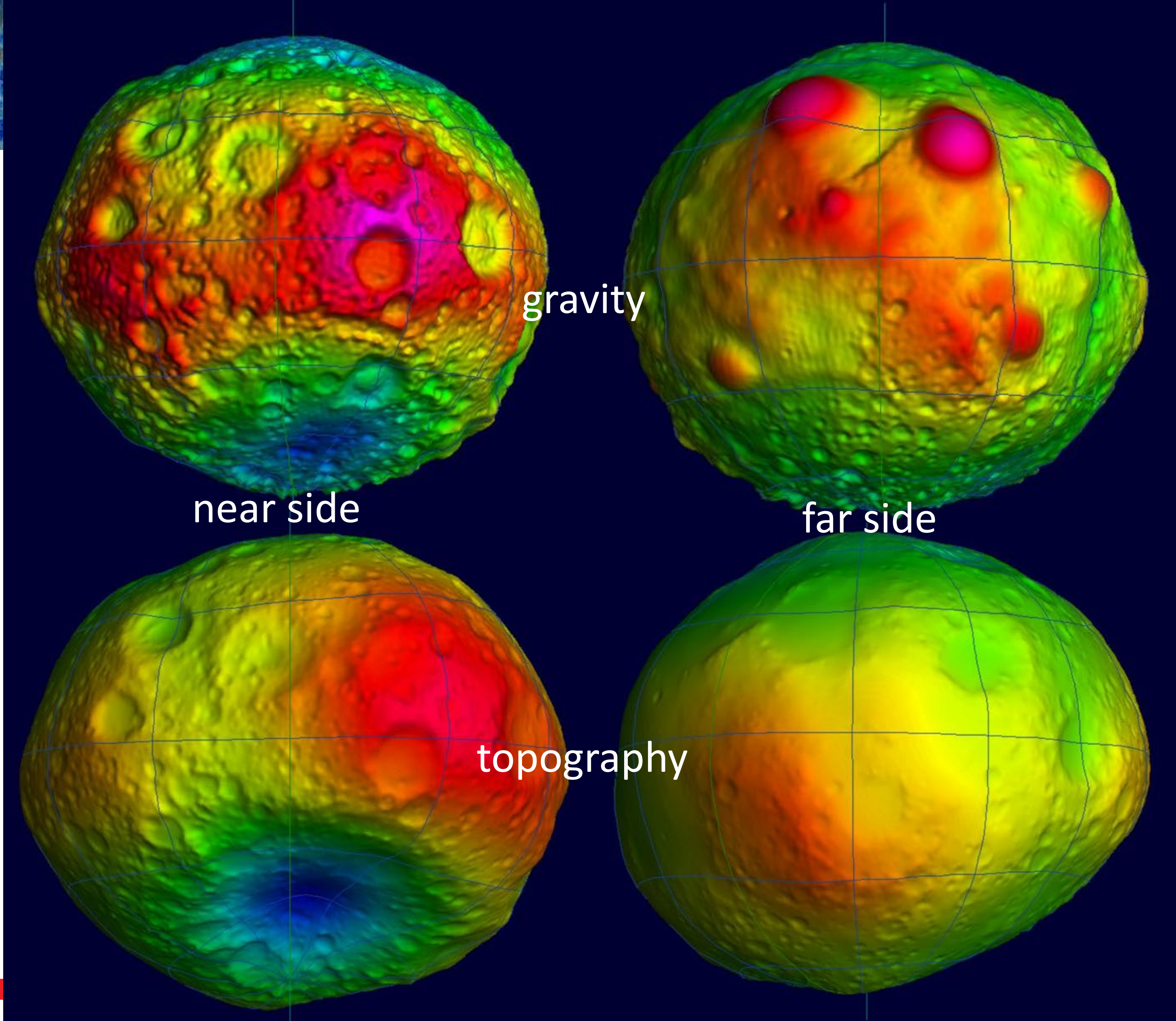


Force	Median (m/s²)
Gravitational	
Moon attraction GM_M	$6.5 \cdot 10^{-2}$
Earth attraction GM_E	$1.2 \cdot 10^{-4}$
Moon potential	$1.7 \cdot 10^{-6}$
Sun attraction GM_S	$8.3 \cdot 10^{-7}$
Earth C_{20}	$1.3 \cdot 10^{-9}$
Sun/Earth tides	$2.5 \cdot 10^{-9}$
Schwarzschild	$2.2 \cdot 10^{-12}$
Jupiter/Venus/Mars	$9.3 \cdot 10^{-13}$
Non-gravitational	
Direct solar radiation pressure	$1.5 \cdot 10^{-6}$
Antenna thrust (100W)	$8.3 \cdot 10^{-9}$
Albedo/IR	$4.8 \cdot 10^{-9}$

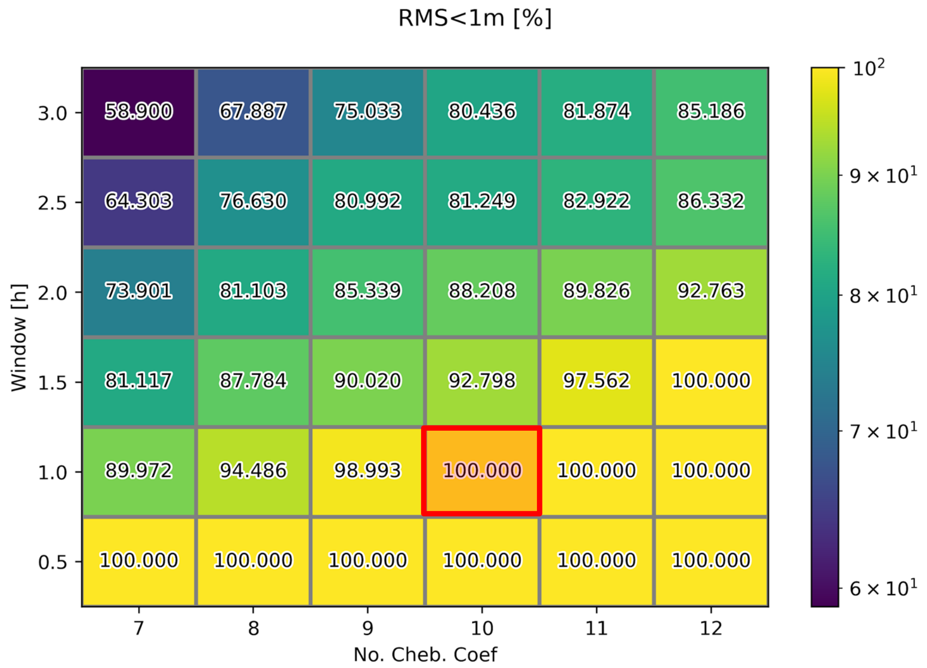
Lunar Gravity

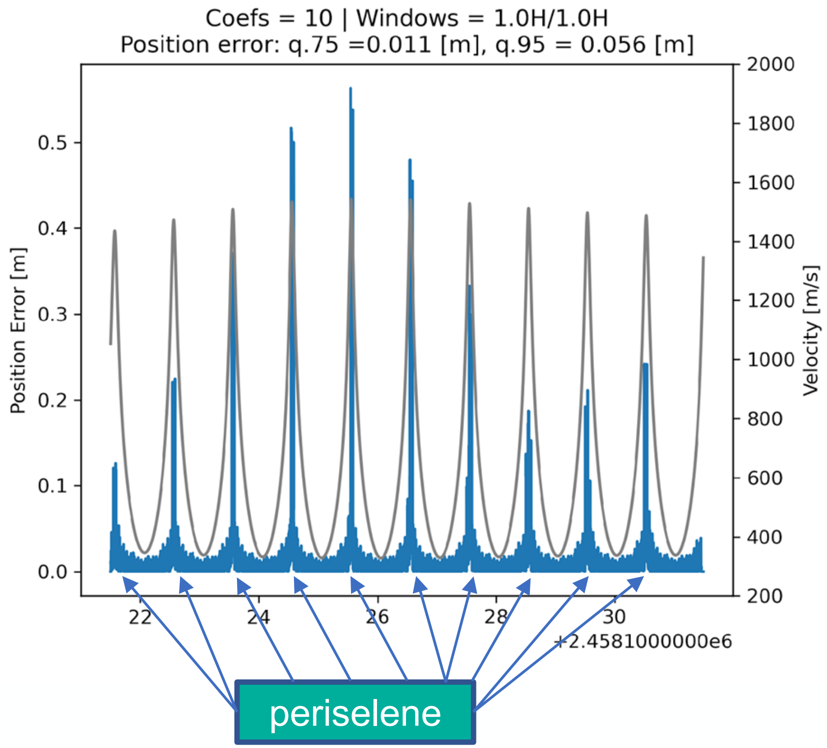
Variable densities of the lunar lithosphere results in substantial differences between the topography and gravity field.

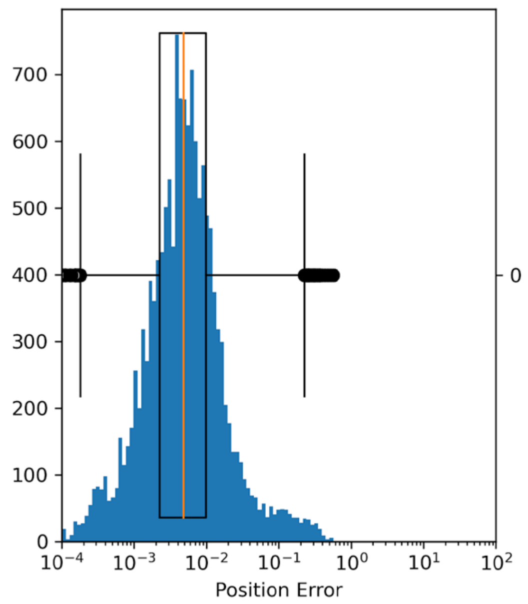




Design of the broadcast message







10 Chebyshev coefficients are fine to get orbit quality better than 1 m with 1h windows. Maximum residuals do not exceed 60 cm.

$$T_n(x) = 2xT_{n-1}(x) - T_{n-2}(x), \text{ with } T_0 = 1, T_1 = x$$

Thank you for your attention!

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Design of the broadcast message – updates every 1h in periselene

- Increasing the frequency of the updates of the navigation message in periselene leads to better accuracy of the broadcast message
- Periselene assumption: (v_{max}>1000 m/s)
- With 11 coefficients:
  q.75 = 0.016 m
  q.95 = **0.032 m**