# Integrated processing of ground- and space-based GNSS

## the interest for GENESIS-1

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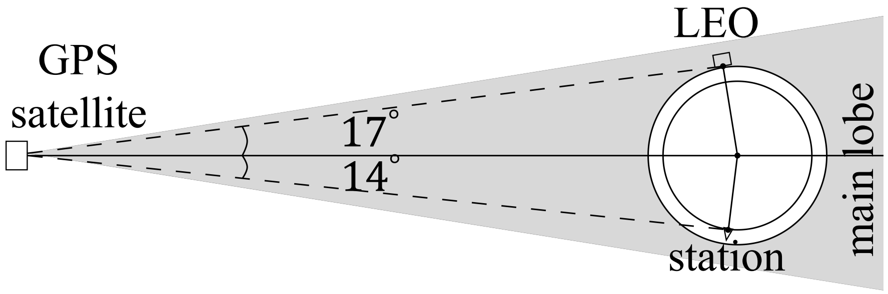
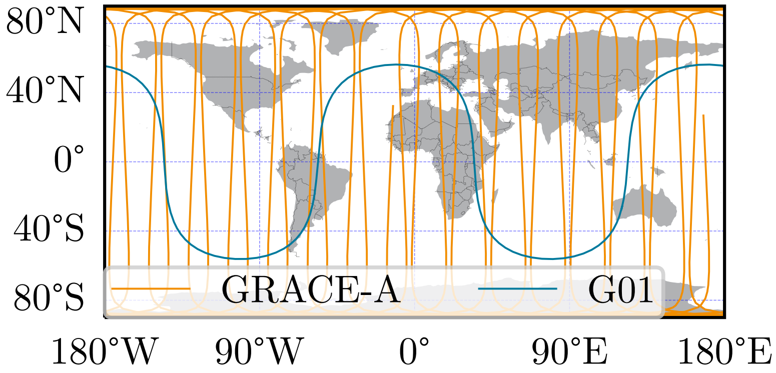
# Benefits of integrating LEOs

- larger bore-sight angle
- fast moving receiver
- troposphere-free observations
- gravitational constraint

Enhance →

- GNSS orbits
- geocenter
- GPS z-PCO and scale



# Integrated processing

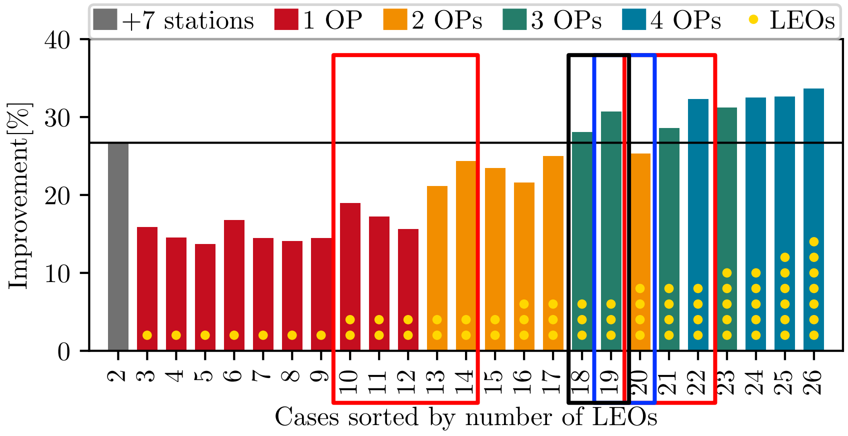
- ground-based observations
- space-based observations
- metadata
- other information

- ✓ data pre-processing
- ✓ initial orbits of GNSS and LEOs
- ✓ orbit integration
- ✓ least squares estimation
- ✓ data cleaning
- ✓ ambiguity fixing
- ✓ iterative processing

datum definition
- station constraints
- network constraints
  - NNT, NNS, NNR

- ✓ orbits
- ✓ clock offsets
- ✓ station coordinates
- ✓ PCOs
- ✓ geocenter
- ✓ tropospheric delay
- ✓ Earth orientation
- ✓ scale
- ✓ …

# Improvement in sparse-network-based POD




- integrating 26 stations with subsets of 7 LEOs (GRACE, OTSM/Jason2, Jason-3, Swarm)
- GPS orbits improvement: +3 LEOs better than +7 well-selected stations
- more improvement by LEOs in more orbital planes

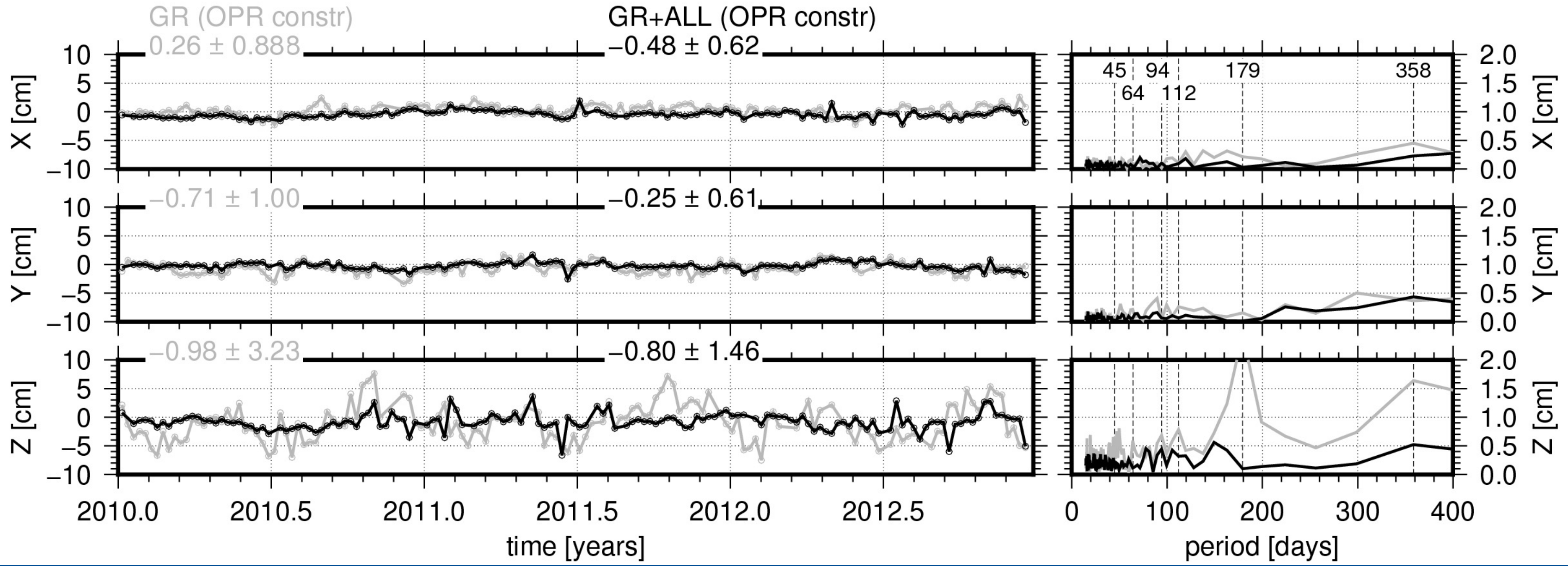
→ the orbital diversity is more critical than the number of the LEOs

→ GENESIS can contribute to this approach (for multi-GNSS)

Huang et al. (2020) Integrated processing of ground- and space-based GPS observations: improving GPS satellite orbits observed with sparse ground networks

# Improvement of geocenter estimation

- 53 stations integrated with four LEOs (GRACE, GOCE, OTSM/Jason-2)
- three year weekly solution of the geocenter
- more consistent solution by adding LEOs




Männel and Rothacher (2017) Geocenter variations derived from a combined processing of LEO- and ground-based GPS observations

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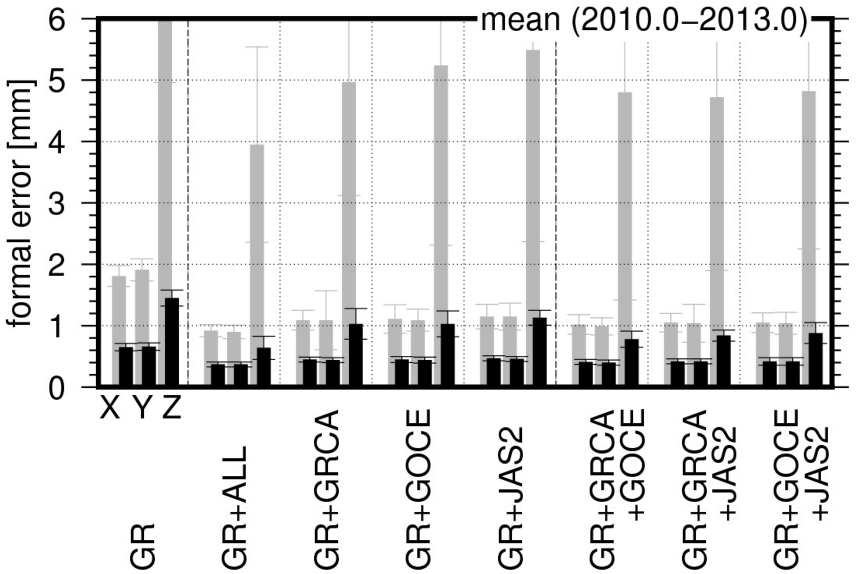
# Improvement of geocenter estimation

- mean of daily and weekly solutions
- adding LEOs leads to higher precision in all three components, especially z-component
- one LEO → 20% improvement



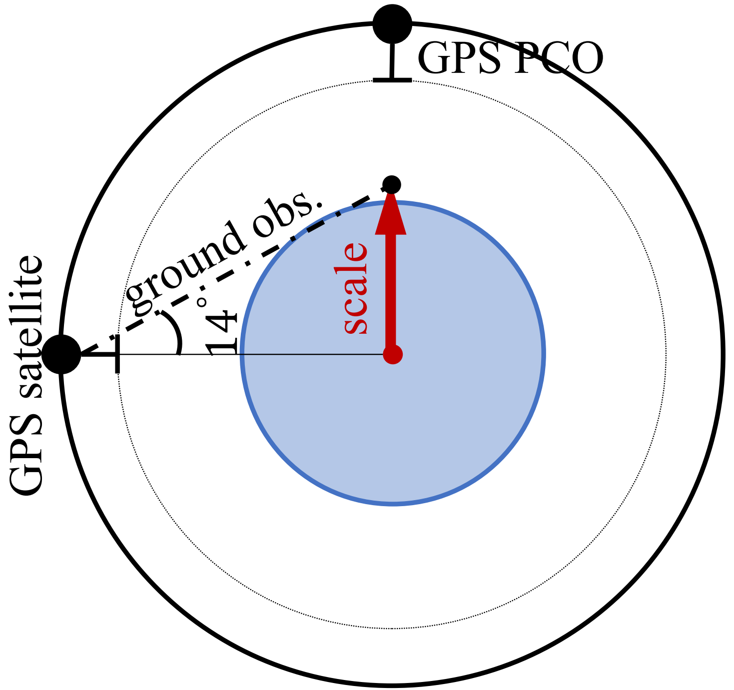

GENESIS can contribute to the geocenter estimation

Männel and Rothacher (2017) Geocenter variations derived from a combined processing of LEO- and ground-based GPS observations

# GPS z-PCOs and GNSS-based scale

- z-PCOs of transmitting antennas are highly correlated with the scale:
  - 13cm z-$PCO^{GPS}$ → 1 ppb scale (Zhu et al. 2003)
  - 0.85 correlation coefficient (Huang et al. 2022)

- z-PCOs of GPS (before Block III) given by the manufactories were not convincing (Ge et al. 2005)

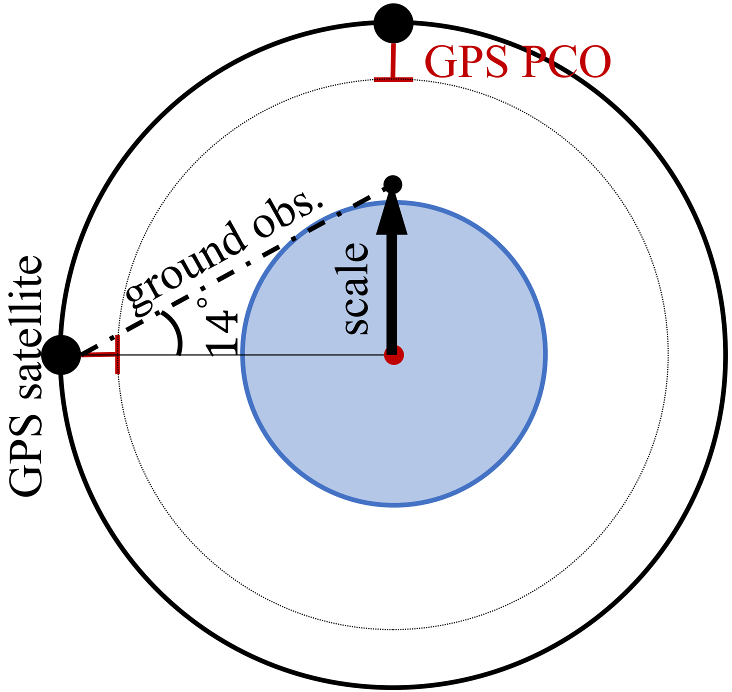




Zhu et al. (2003) Satellite antenna phase center offsets and scale errors in GPS solutions
Ge et al. (2005) Impact of GPS satellite antenna offsets on scale changes in global network solutions
Huang et al. (2022) Estimation of GPS transmitter antenna phase center offsets by integrating space-based GPS observations

# The approach of the IGS

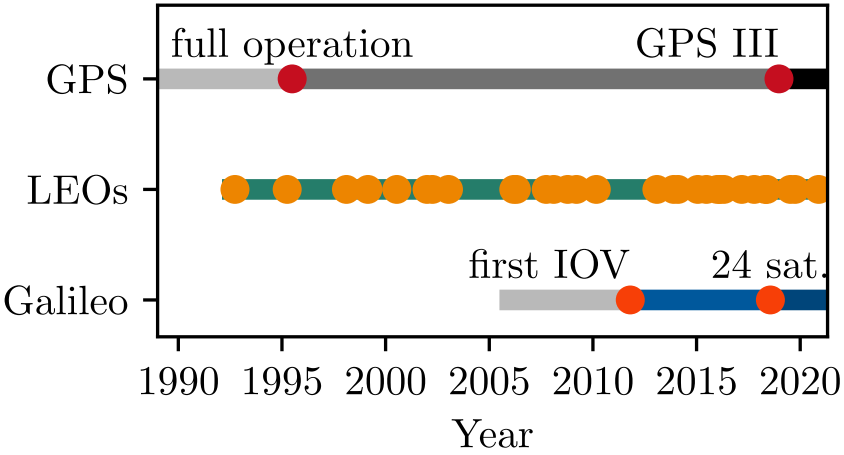
- estimated by introducing scale determined by VLBI and SLR
- agreement between z-PCO and ITRF.
- IGS antenna products were updated with ITRF, e.g., igb08.atx, igs14.atx, etc.
- scale is propagated to users and applications



# Updates in recent years

- LEOs with ground calibrated PCOs of receiving antenna from the past to now

- Galileo with ground calibrated PCOs of transmitting (chamber) and receiving(chamber and robot) antennas

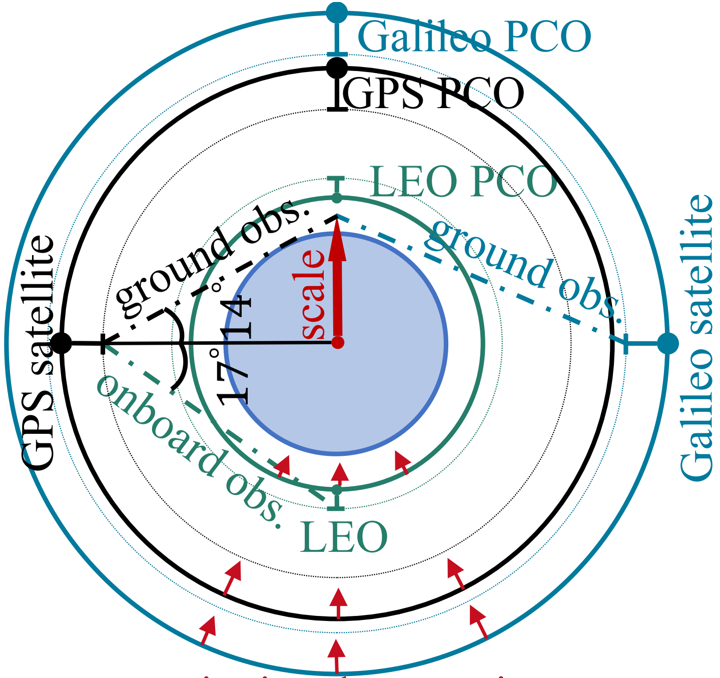



Goal: independent GNSS scale

# Two methods for z-PCO$^{GPS}$ and scale

- based on LEOs
  - calibrated PCOs and gravitational constraint
  - fast movement and larger bore-sight angle
  - historical data for long term study

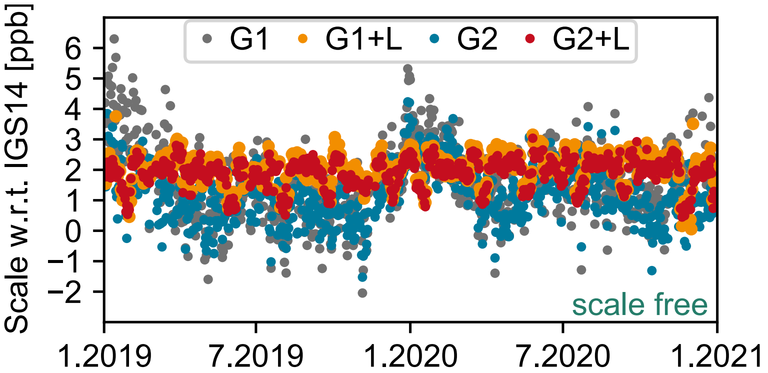
- based on Galileo
  - scale based on Galileo is propagated to GPS z-PCOs (Villiger et al. 2020)
    - GPS z-PCO: -160.0 mm
  - IGS repro3 derived a Galileo-based scale

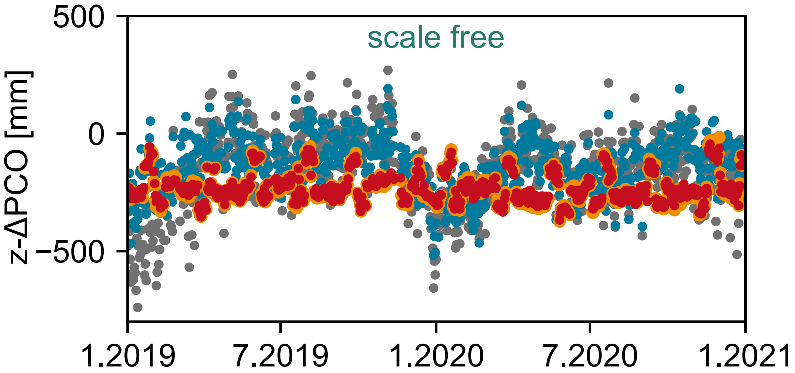



No-net-scale condition **NOT** applied

Villiger et al. (2020) GNSS scale determination using calibrated receiver and Galileo satellite antenna patterns

# LEO-based solution




- G1 and G2: networks with different numbers of stations
- L: six LEOs (GRACE-FO, Jason-3, Swarm)
- scale free: NO NNS

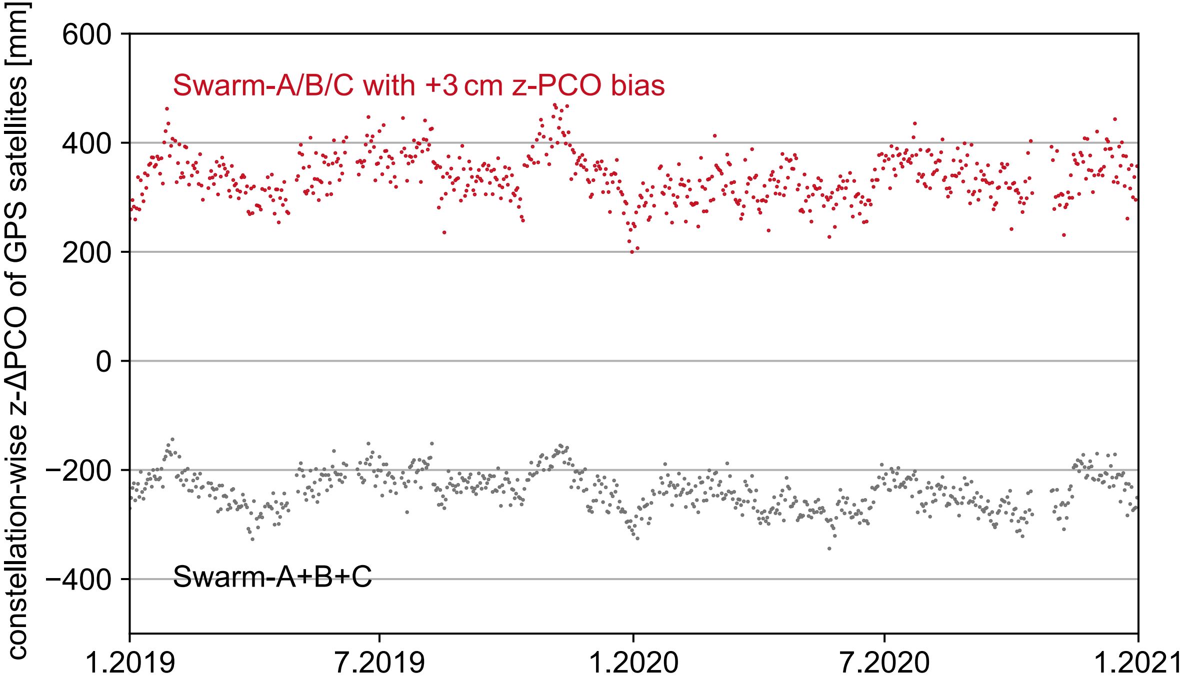
stations only => large variation

LEO-based => consistent

effective decorrelation

Huang et al. (2022) Estimation of GPS transmitter antenna phase center offsets by integrating space-based GPS observations

# Requirement on the z-PCOs of LEOs




+3 cm z-PCO of LEOs leads to

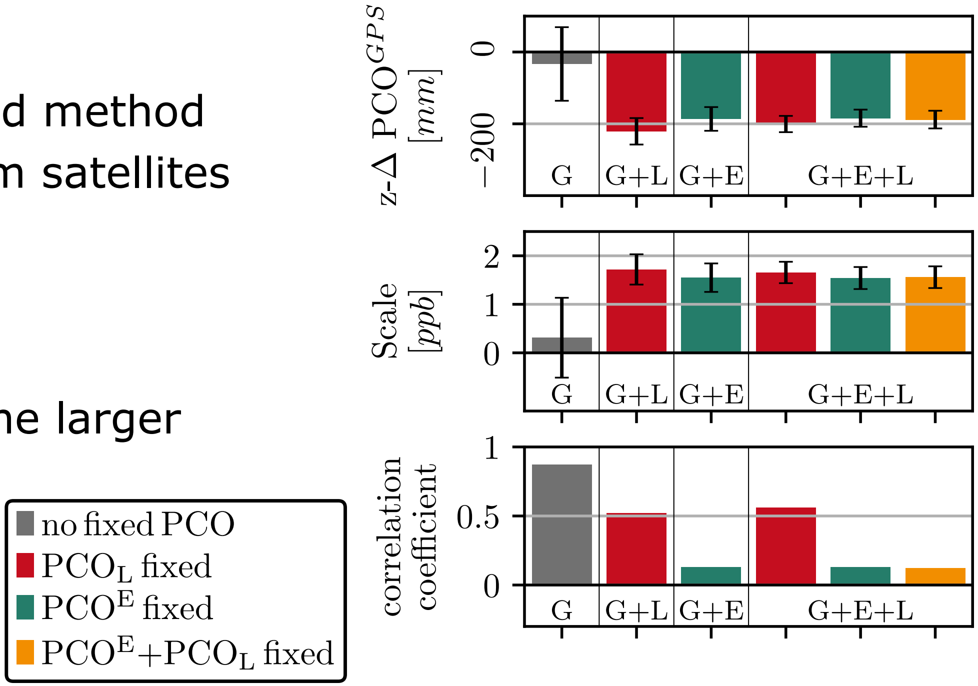
- -574 mm z-$\Delta PCO^{GPS}$
- +4.27 ppb scale (+27mm)

z-PCO of LEOs has to be 1 mm accurate to achieve 1 mm scale; agree well with the simulation study by Glaser et al. (2020)

Huang et al. (2022) Estimation of GPS transmitter antenna phase center offsets by integrating space-based GPS observations
Glaser et al. (2020) Reference system origin and scale realization within the future GNSS constellation “Kepler”

# Cross-check of both methods

- first-time validation of the LEO-based method
- 24 Galileo satellites and three Swarm satellites
- first half of 2019
- scale free
- good agreement
- Galileo solution dominating due to the larger number of satellites (24 vs. 3)




GENESIS can contribute to the z-PCO$^{GPS}$ and the scale

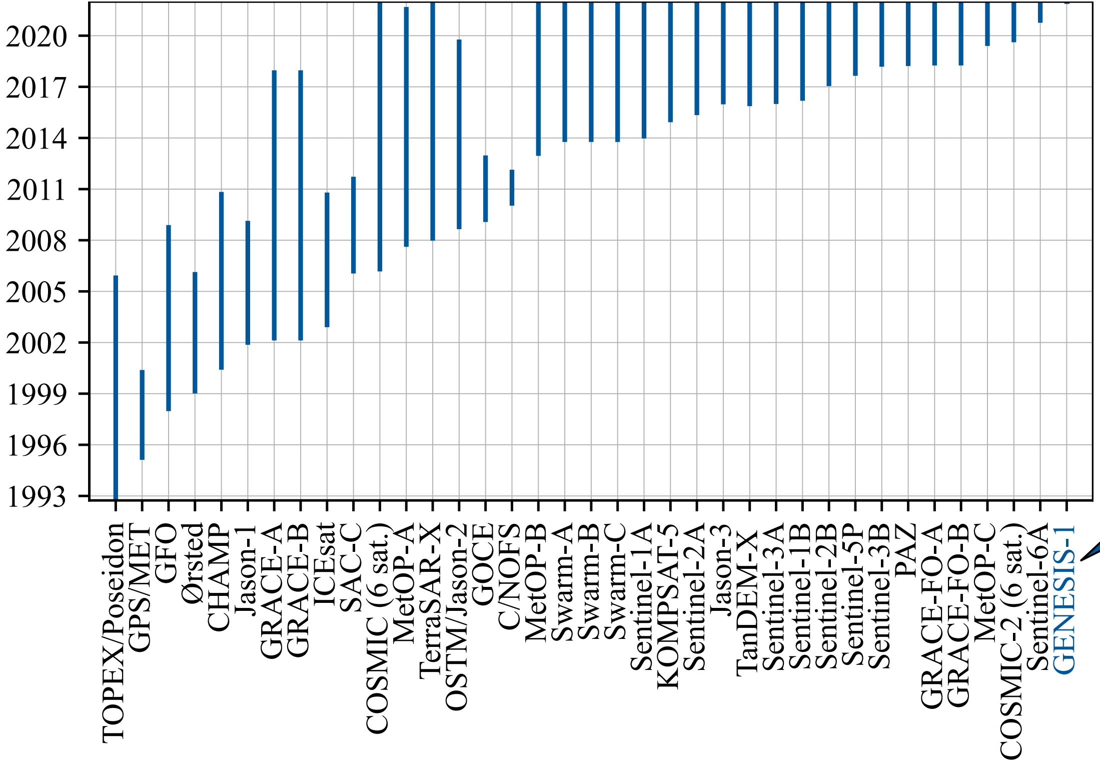
Huang et al. (2021) Two methods to determine scale-independent GPS PCOs and GNSS-based terrestrial scale: comparison and cross-check

# Summary

- The sparse-network-based POD of the GPS satellites is improved significantly by integrating LEOs. The orbital planes of the LEOs are more critical.
- By including LEOs, the geocenter is estimated more precisely.
- The LEOs-based solutions of the z-$PCO^{GPS}$ and scale agree well with the Galileo solution. It has advantage of a long-term data availability.
- A 1-mm accuracy of the LEO z-PCOs is required for the GGOS goal (1 mm scale).

# Importance of GENESIS

- GENESIS can increase the diversity of the orbital planes of the LEOs.
- More accurate dynamic orbits of GENESIS are expected due to its circular orbit with higher altitude.
- The additional geometry from GENESIS will increase the precision of the geocenter.
- As an additional LEO with higher altitude, GENESIS will contribute to the de-correlation of the z-PCO$^{GPS}$ and the scale.
- Accurate calibration of the PCOs of the GENESIS satellite is highly demanded.




looking forward to **GENESIS** !

# Thank you for your attention!

current project: Integrated GNSS Processing for Earth System Monitoring (**InGE**)

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DFG Deutsche Forschungsgemeinschaft German Research Foundation

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