GNSS-based scale realization by integrating LEOs

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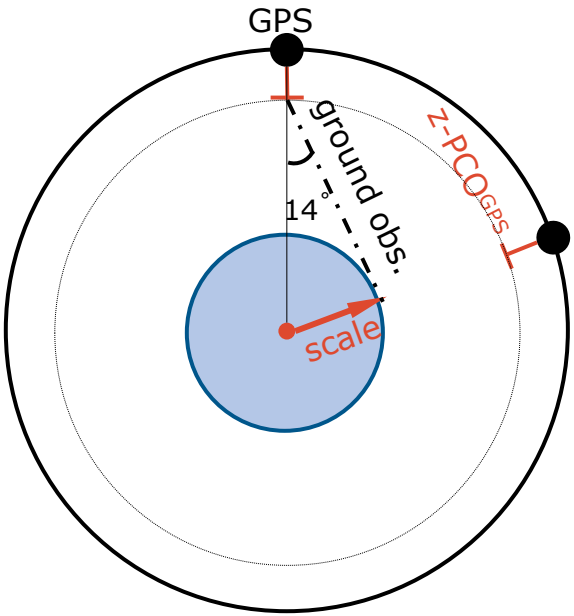
Can we derive a GNSS-based terrestrial scale?

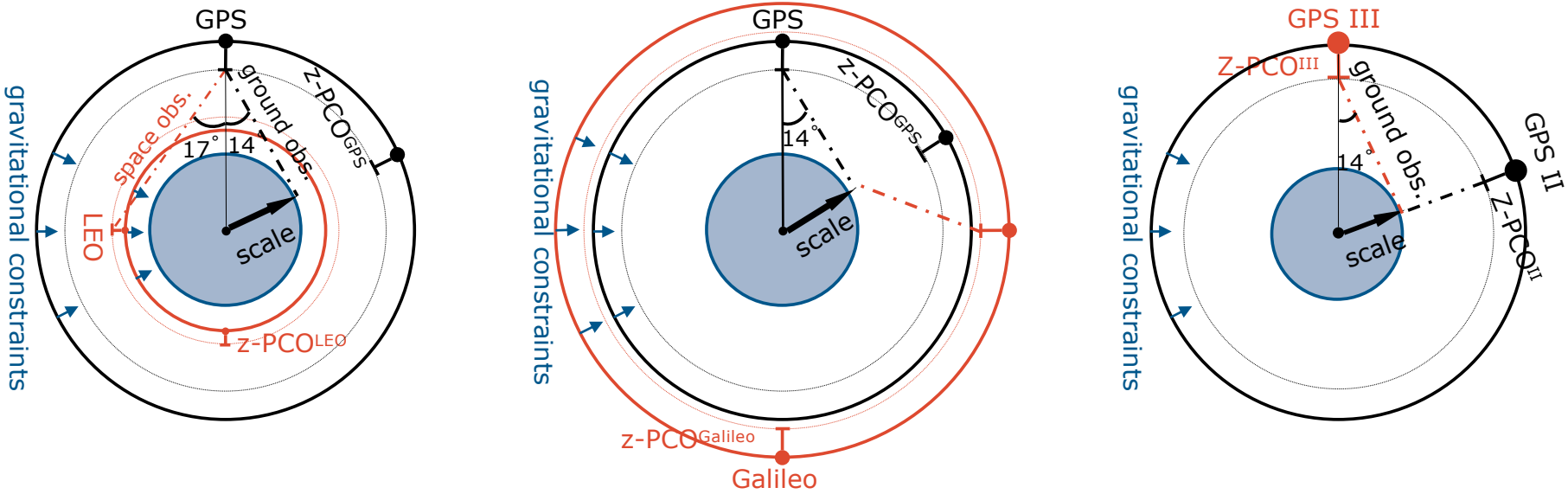


- Issues:
  - z-PCO^{GPS} are highly correlated with the scale:
    - 13 cm z-PCO^{GPS} → 1 ppb scale (Zhu et al. 2003)
    - 0.85 correlation coefficient (Huang et al. 2022)
  - z-PCO^{GPS} given by the manufacturers were not convincing (Ge et al. 2005)

- Solution of the IGS:
  - estimating GNSS z-PCOs by introducing scale determined by VLBI and SLR
  - ITRF scale is propagated to users and applications

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

Three methods of solving the issue

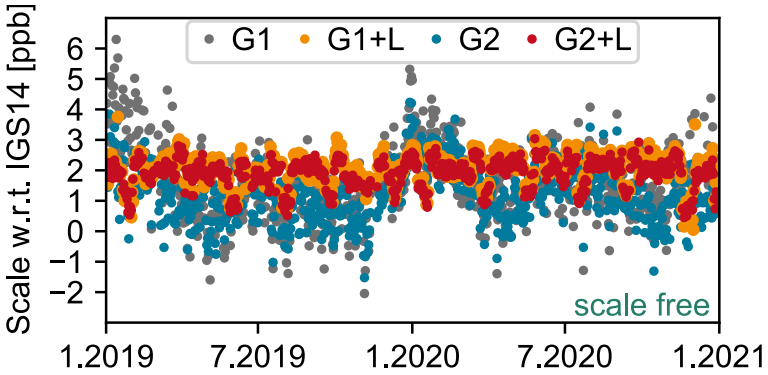


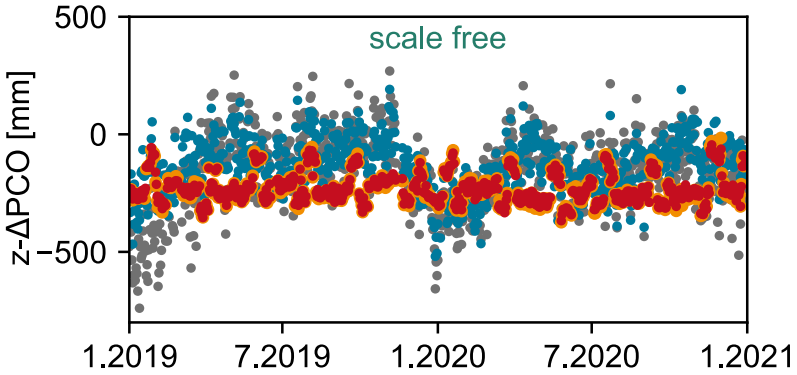
LEOs-based | Galileo-based | GPS III-based

- properly calibrated z-PCOs (Sat./Rev.)
- gravitational constrains (orb. dynamic)

• Without no-net-scale (NNS) condition

Solutions of LEOs-based method





- G1 and G2: networks with different numbers of stations
- L: six LEOs (GRACE-FO, Jason-3, Swarm)
- scale free: NNS not applied

stations only → large variation

LEO-based → consistent

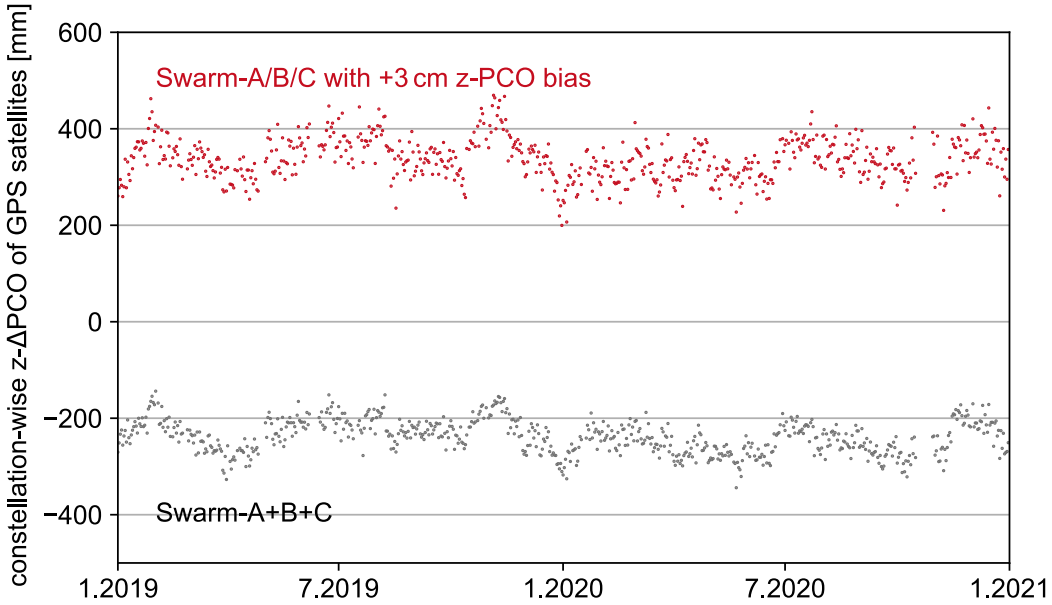
effective decorrelation

Solutions of subsets of the LEOs

subsets	LEOs	daily obs.	correlation	scale [ppb]	ΔPCO^{GPS} [mm]
GRACE-FO-1	1	1797	0.68	+1.60±0.80	−198±85
GRACE-FO-2	1	1876	0.67	+1.21±0.45	−138±52
Jason-3	1	2280	0.60	+1.85±1.56	−226±228
Swarm-A	1	2091	0.64	+1.85±0.40	−225±45
Swarm-B	1	2111	0.63	+1.87±0.42	−228±47
GRACE-FO-1/2	2	3705	0.58	+1.45±0.47	−177±47
Swarm-A/B/C	3	6282	0.46	+1.95±0.32	−238±35
Swarm + G-FO	5	9987	0.39	+1.83±0.30	−223±30
All LEOs	6	12275	0.32	+1.86±0.64	−228±82

- better decorrelation
  - more LEOs
  - more onboard observations
- Agreement
- GRACE-FO results?
  - Post-launched z-PCO

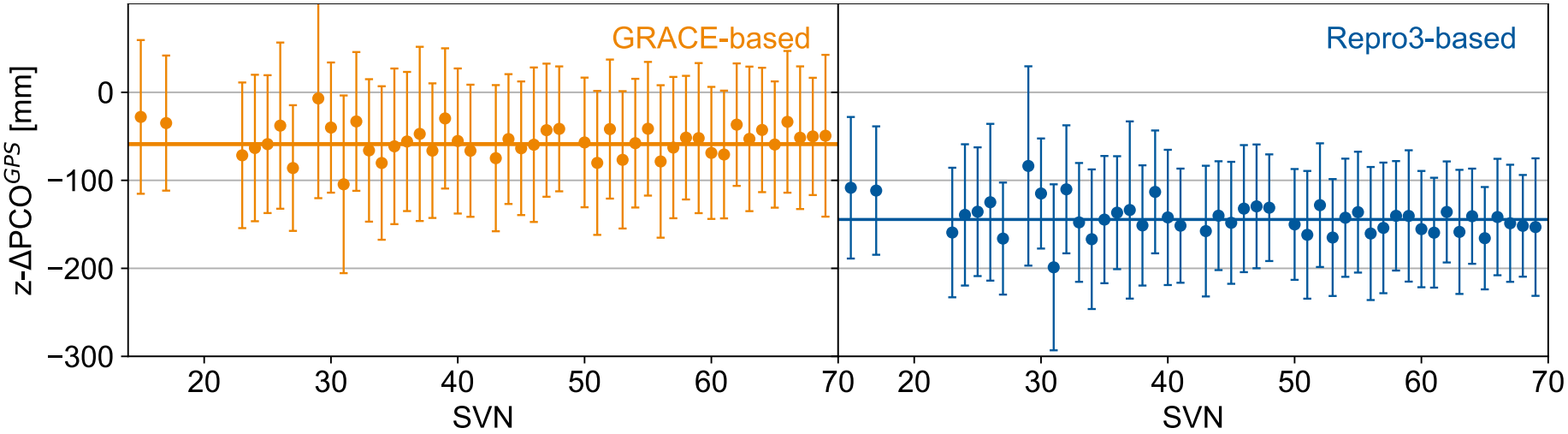
Requirement on the z-PCOs of LEOs



- +3 cm z-PCO of LEOs leads to:
  - -574 mm z-ΔPCO^{GPS}
  - +4.27 ppb scale (+27mm)
- 1 mm accuracy of z-PCO^{LEO} to achieve 1 mm scale
  - agrees with the simulation study by Glaser et al. (2020)

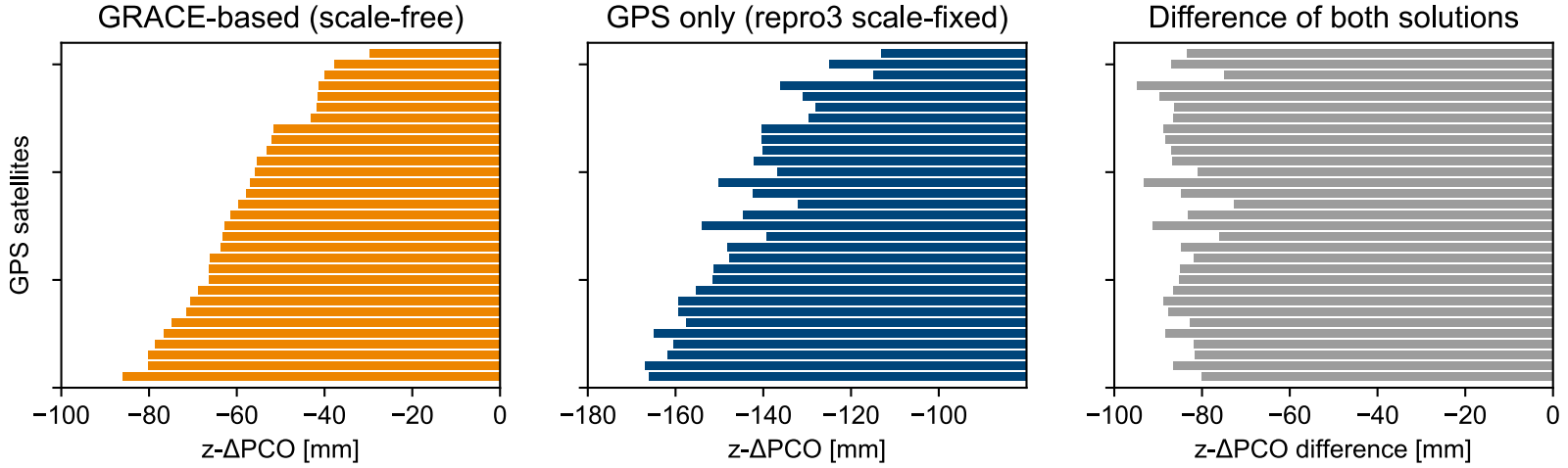
Huang et al. (2022) Estimation of GPS transmitter antenna phase center offsets by integrating space-based GPS observations
Glaser et al. (2020) Reference system origin and scale realization within the future GNSS constellation "Kepler"

Solutions of 12-year processing: z-ΔPCO^{GPS}



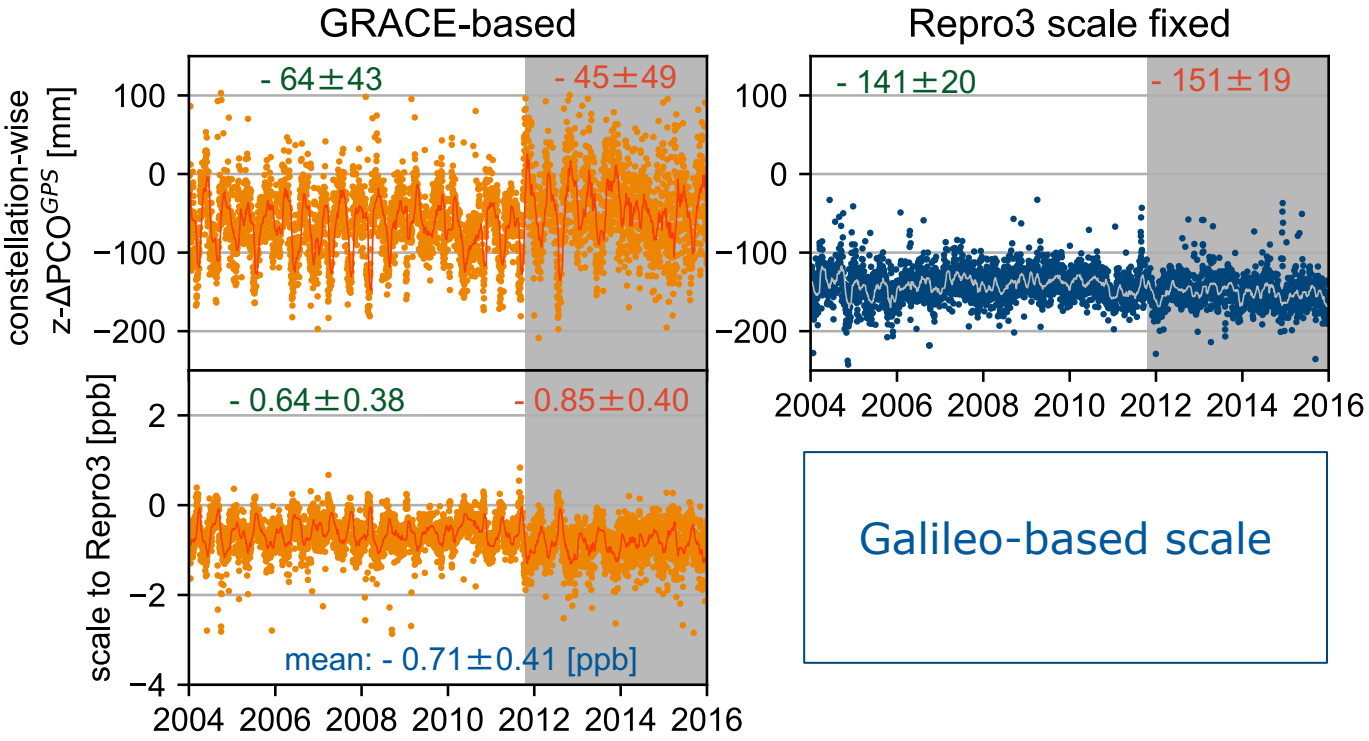
- 12-year processing
  - 2004-2015
  - GRACE-A/B (2 LEOs)
  - GPS (51 in total, 46 with 300+ days)
  - repro3 level 1&2 stations (100-130)
- compared to igs14.atx
- z-ΔPCO^{GPS}
  - 85 mm difference in average
  - post-launched z-PCO^{GRACE}
  - Repro3-based 144 instead of 160 mm

Solutions of 12-year processing: z-ΔPCO^{GPS}



- sorted by z-PCO^{GPS} corrections in GRACE-based solution
- agreement with an offset of 85±5 mm
  - precise and reliable
  - not accurate due to post-launched z-PCO^{GRACE}
- satellite-specific corrections
  - 5 cm difference between satellites in maximum

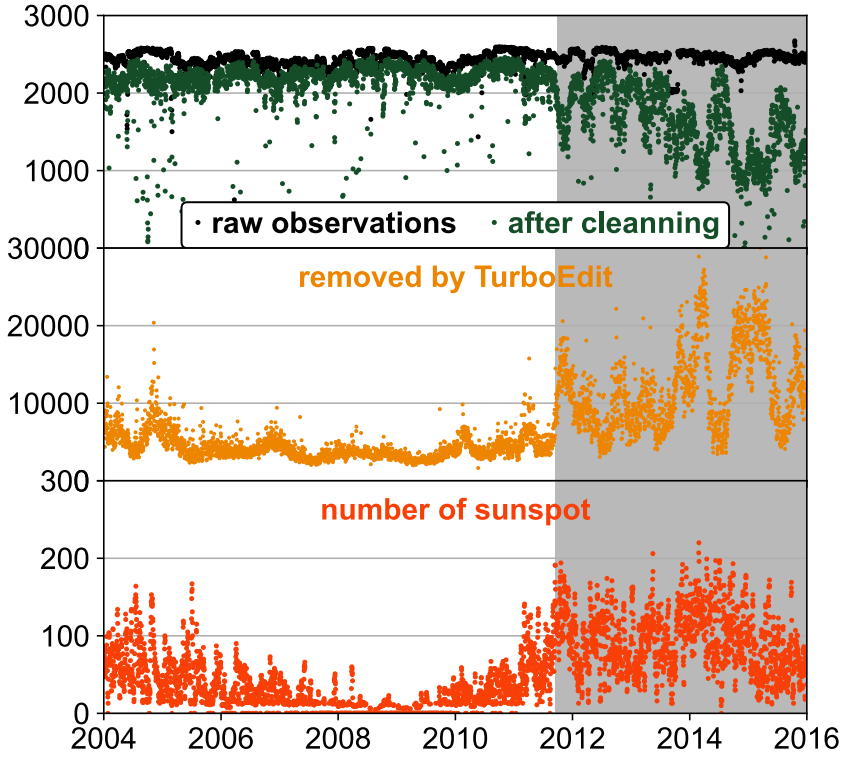
Solutions of 12-year processing: time series



Galileo-based scale

- consistent solution
  - annual signal
- steps start in 2011
  - in both solutions
  - different directions

Impact of solar activity



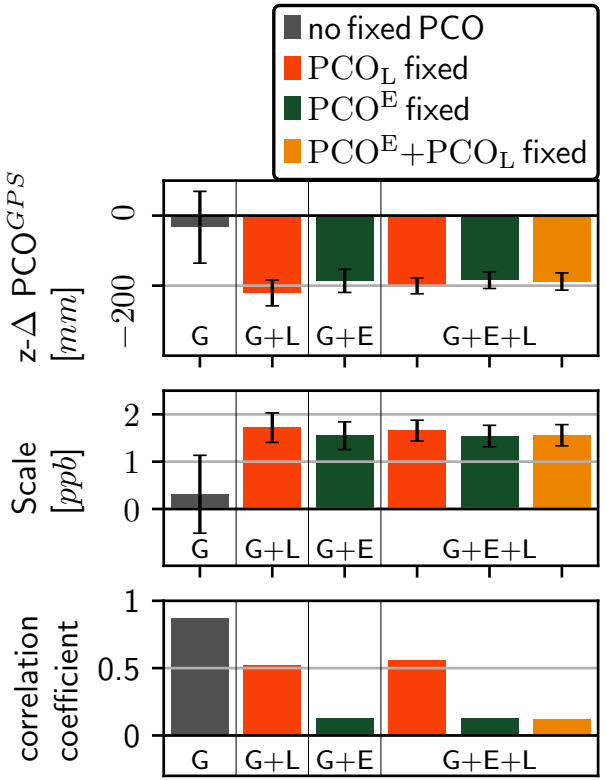
- reduced observation (after cleaning)
- newsletter of GRACE (2011.09&11)
  - degraded POD due to increased solar activity
  - re-optimized POD strategy
- more exclusion by TurboEdit
- highly related to solar activity
- further investigation needed
  - resolved by re-optimization?
  - step also in scale-fixed solution
    - first IOV of Galileo ? (2011.10)

Sunspot data from : https://www.sidc.be/silso/datafiles

Cross-check of LEO- and Galileo-based methods

- 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

- first validation of the two methods
- G: GPS (32); E: Galileo (24); L: Swarm (3)
- scale free: NNS not applied
- good agreement
- Galileo solution dominating due to the larger number of satellites (24 vs. 3)



Villiger et al. (2020) GNSS scale determination using calibrated receiver and Galileo satellite antenna patterns
Huang et al. (2021) Two methods to determine scale-independent GPS PCOs and GNSS-based terrestrial scale: comparison and cross-check

Conclusions

- The estimation z-PCO^{GPS} and the realization of a pure GNSS-based scale is achieved by integrating LEOs.
- More LEOs and more onboard observations lead to better decorrelation of the two parameters.
- A 1-mm accuracy of the LEO z-PCOs is required for the GGOS goal (1 mm scale).
- The LEO-based method has advantage in long-term study back in time. Satellite-specific z-PCO^{GPS} corrections are proposed based on a 12-year study.
- Solar activity has impact on the GRACE observations.
- Further study is need to explain all the phenomenon in the long-term results.
- LEOs- and Galileo-based methods agree well with each other with slight difference.

References

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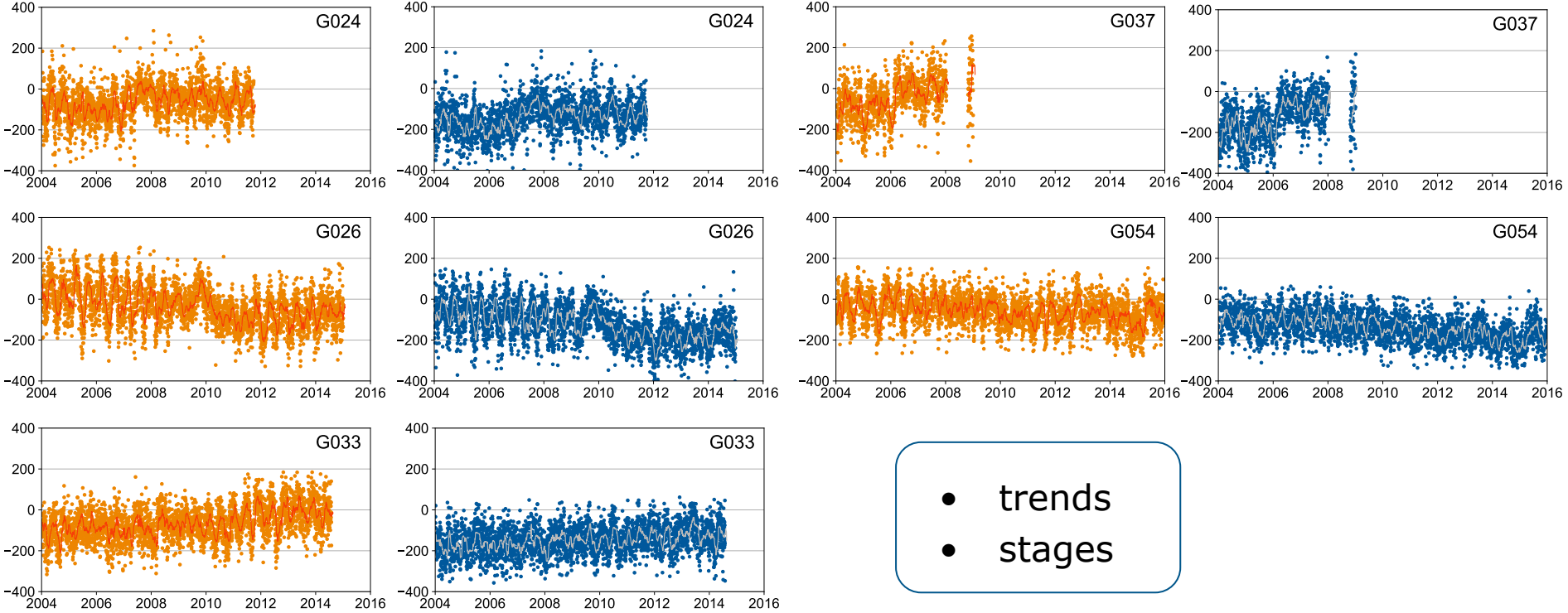
Thank you for your attention!

z-ΔPCO of Individual satellites



- trends
- stages