Genesis Science Workshop

3rd -4th April 2025

Matera, Italy

GNSS Session

Working Group 2

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→ THE EUROPEAN SPACE AGENCY

Towards Genesis: Status report from CODE

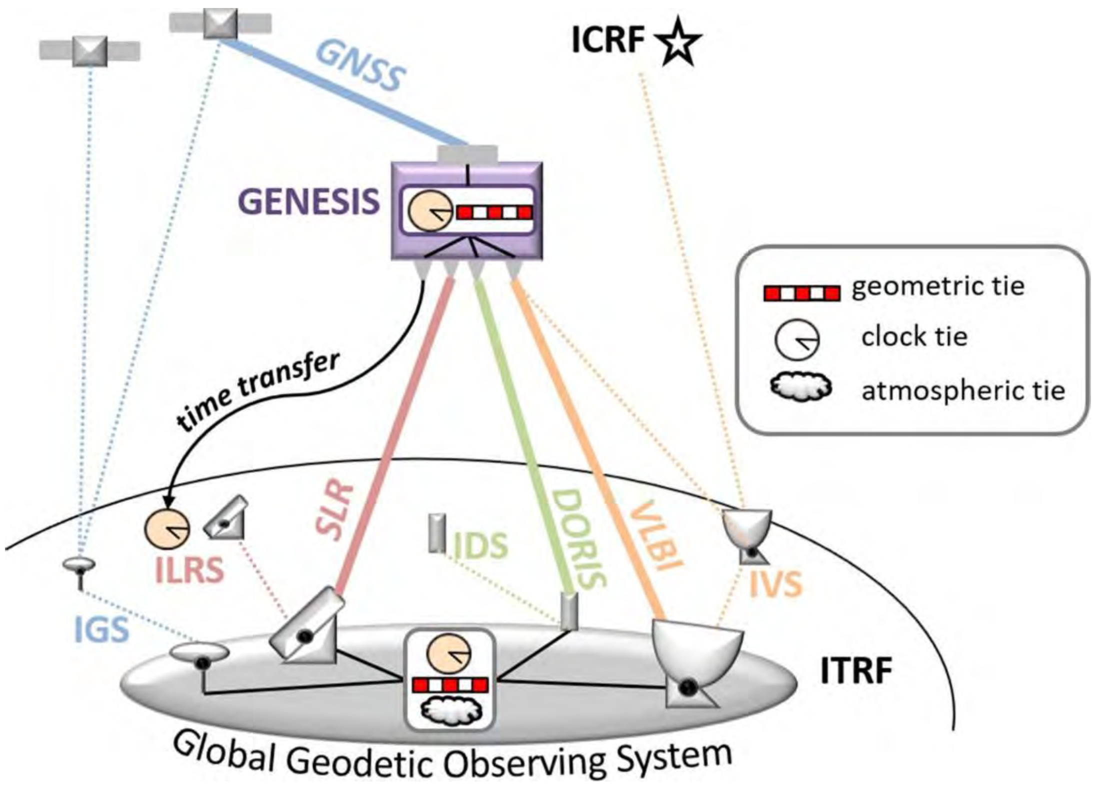
CODE AC Team

Astronomical Institute, University of Bern, Switzerland

Genesis Workshop 2025, WG 2
Matera, Italy
3 April 2025

European Research Council
Established by the European Commission

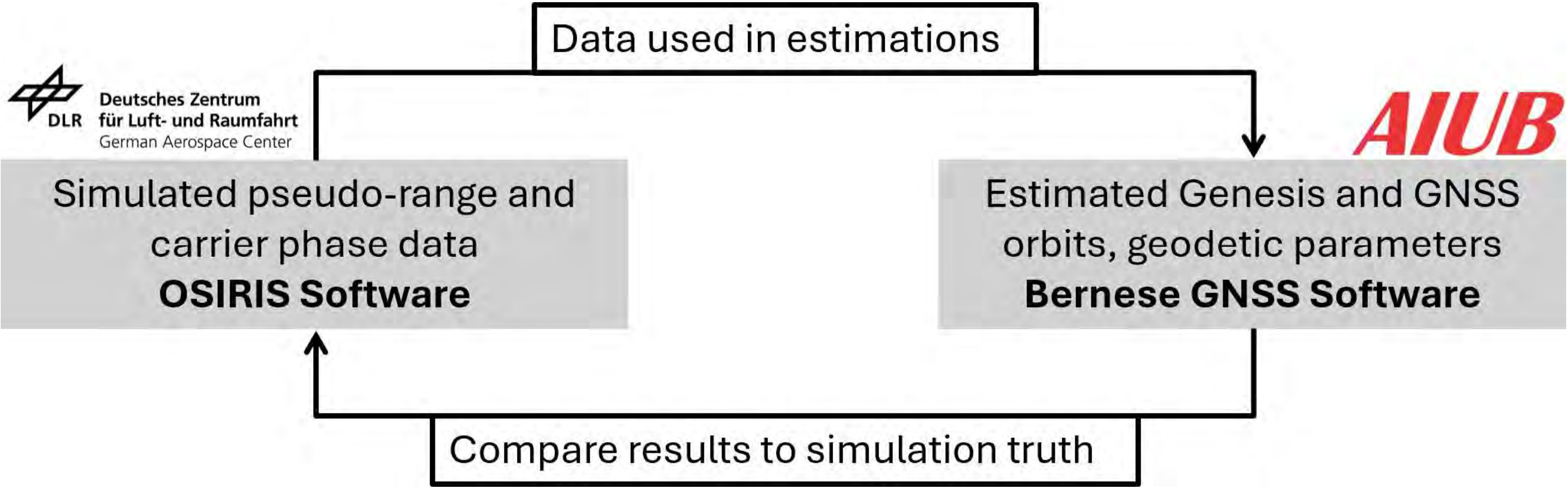
Space-geodetic techniques in the BSW



- The Center for Orbit Determination in Europe (CODE) employs the Bernese GNSS Software (BSW) for its IGS-related analyses
- GNSS: Mature/state of the art
- SLR: Mature/state of the art (associated ILRS AC)
- VLBI: Under development
- DORIS: Planned (BSW version used within IDS exists)
- Combinations: On observation level

Genesis simulation study

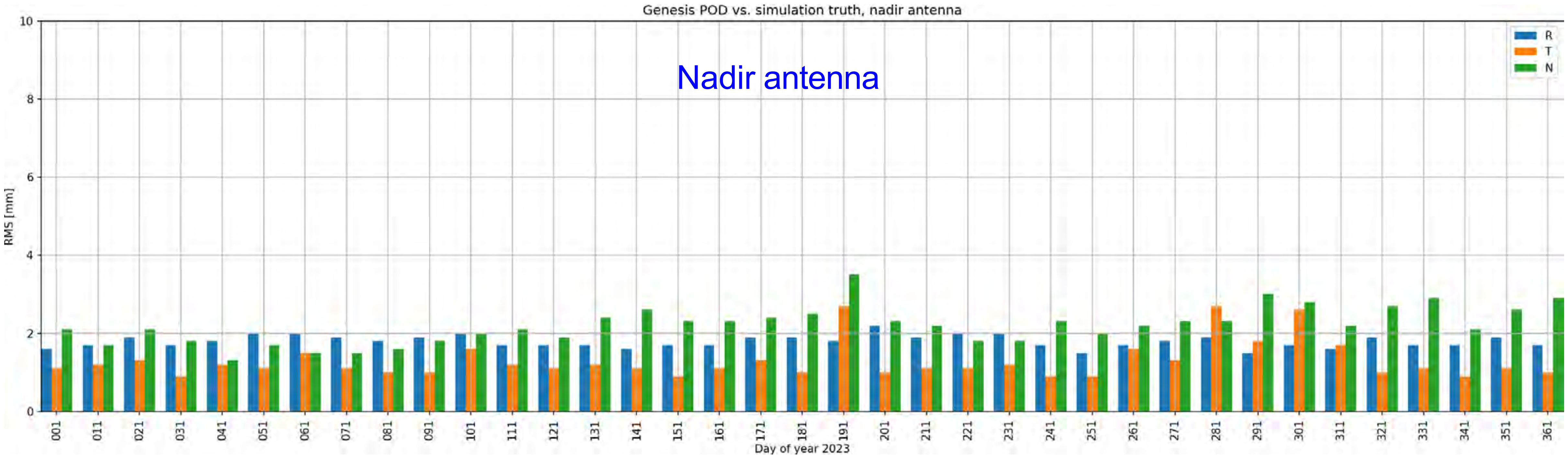
Closed-loop simulation study with GNSS data (100 ground stations and Genesis):



Slightly different models between simulation and reconstruction lead to “natural” uncertainties.

Genesis orbit reconstruction

Genesis POD using CODE final GNSS products. Differences to “true” Genesis orbit (used for simulation):



Genesis orbit reconstruction

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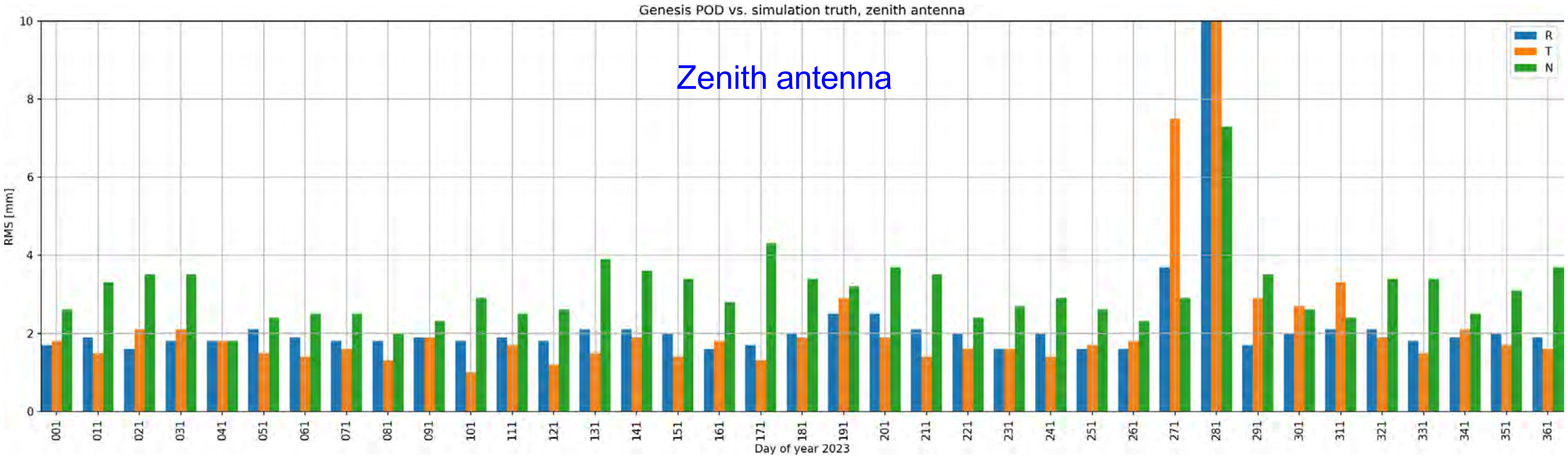
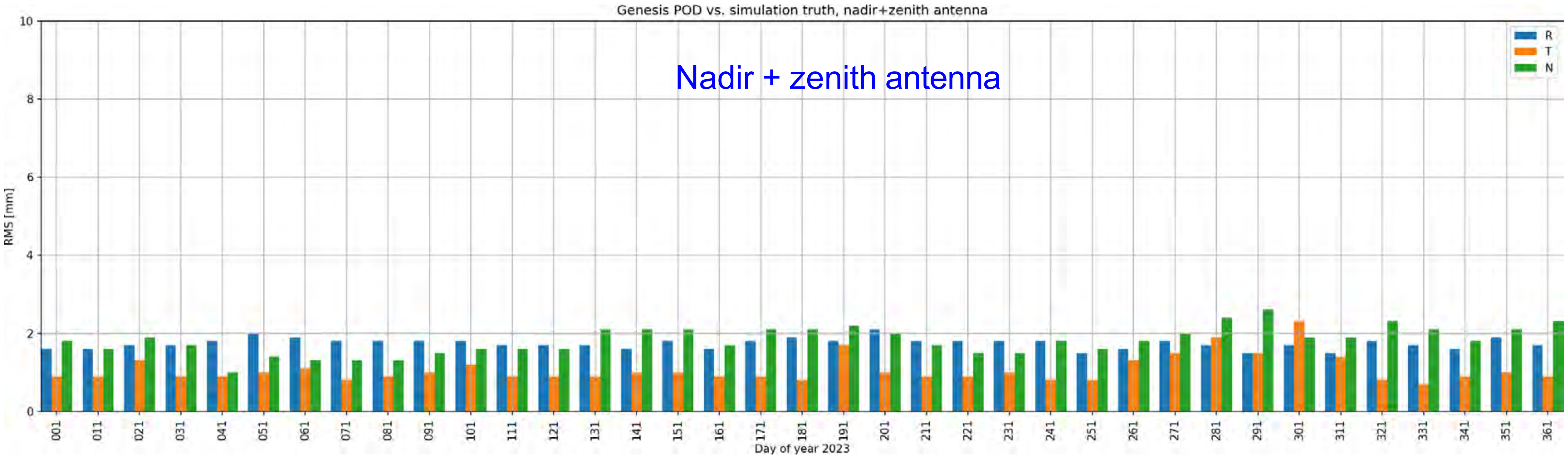


Zenith-antenna based POD more challenging

Genesis orbit reconstruction

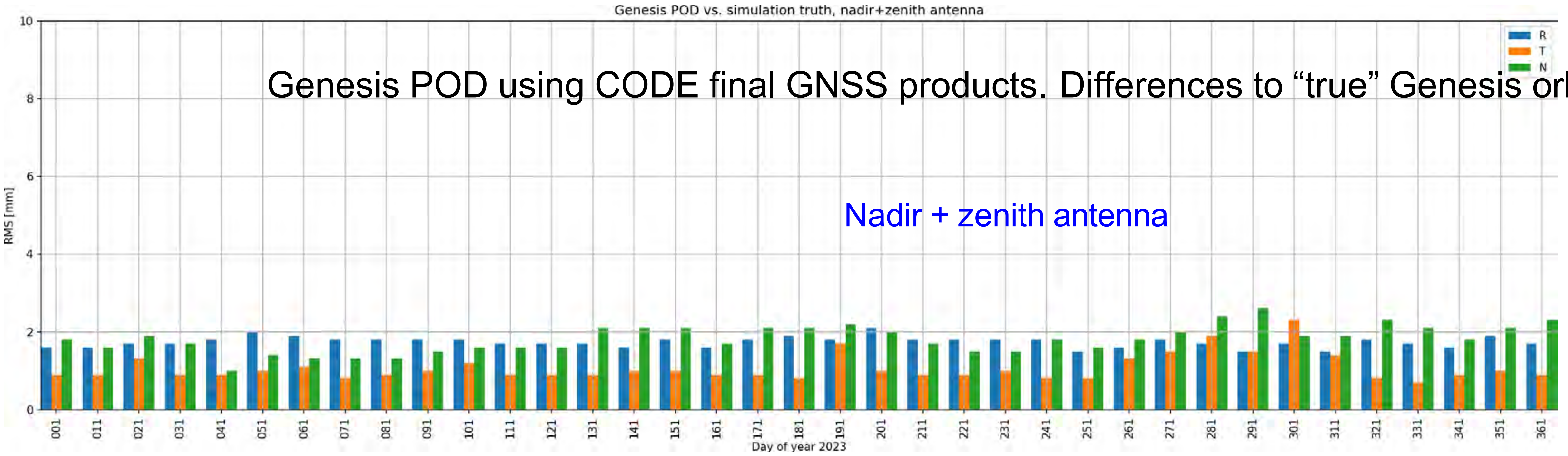
Genesis POD using CODE final GNSS products. Differences to “true” Genesis orbit (used for simulation):



Genesis orbit reconstruction

Genesis POD using CODE final GNSS products. Differences to “true” Genesis orbi

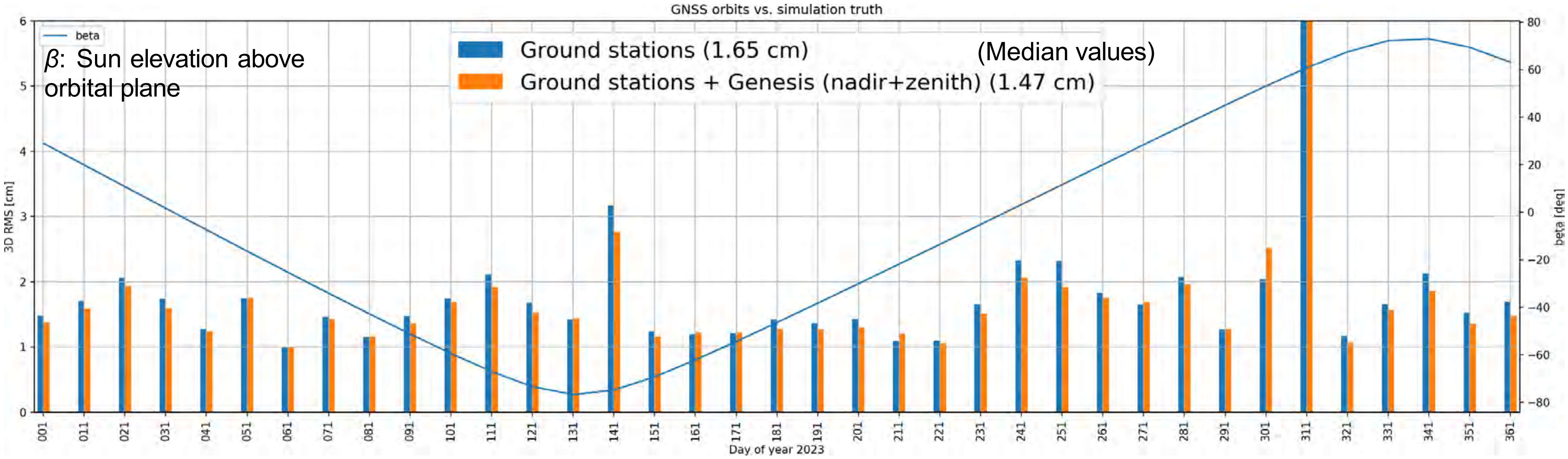
Nadir + zenith antenna



GNSS processing NOT straightforward: challenging geometry, limited number of observations, ambiguity resolution, ...

GNSS orbit reconstruction

Estimating orbit and geodetic parameters using ground stations and Genesis data.
Differences of estimated GNSS orbits compared to “true” orbits:

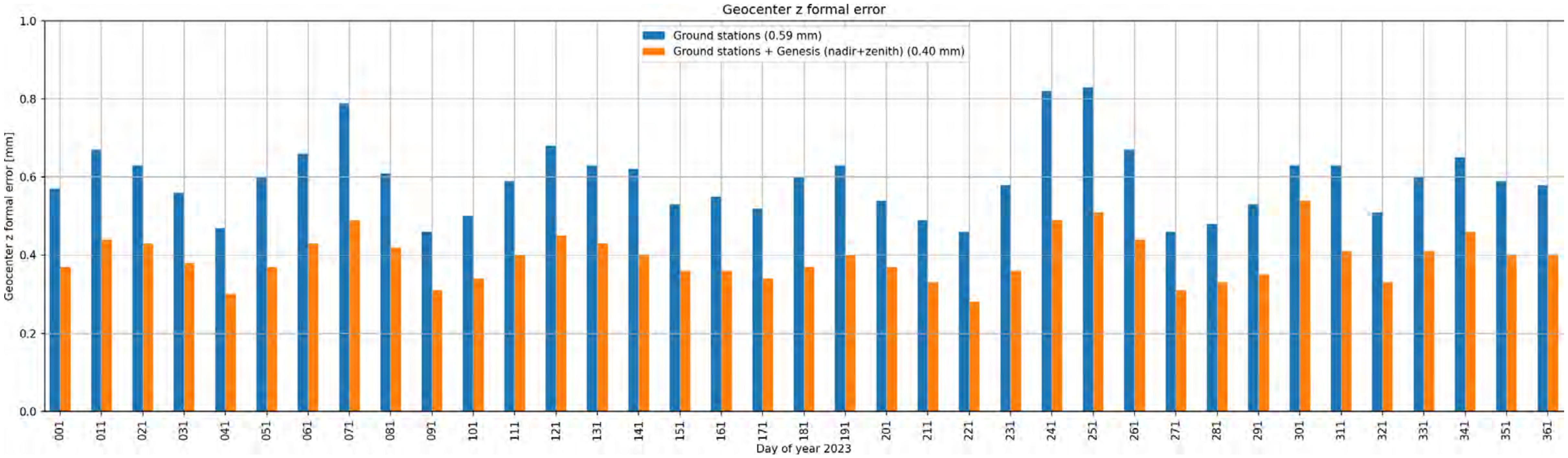


GNSS-wise median values:

	GPS	Galileo
Ground stations	1.56 cm	1.81 cm
Ground stations + Genesis	1.48 cm	1.30 cm

Geocenter

Formal errors of geocenter z coordinates:

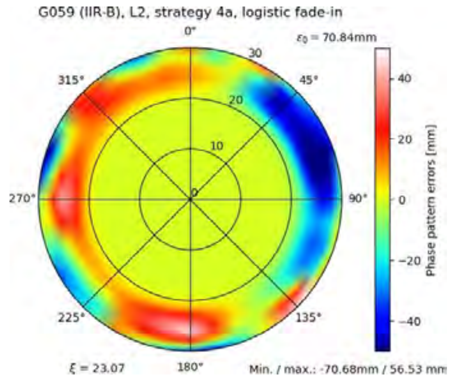


Analysis of systematic errors

Impact of systematic errors in Genesis GNSS processing:

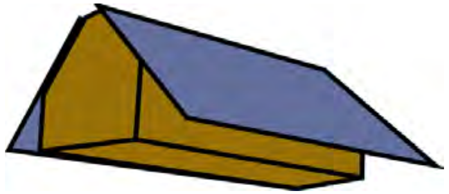
- **Phase pattern uncertainties of GNSS transmit antennas** at large nadir angles, presented at IGS Symposium and Workshop 2024 and 9th International Colloquium on Scientific and Fundamental Aspects of GNSS

  → can clearly counteract the potential benefit of Genesis on GNSS orbits and geodetic parameters



- **Satellite macro model uncertainties** for non-gravitational force modeling, presented at 45th COSPAR Scientific Assembly and AGU24

  → have the potential to degrade GNSS-derived global solutions including Genesis, but can be well absorbed by (constrained) empirical Genesis orbit parameters (might change in combination of different space-geodetic techniques).



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ESA: IGS AC and PROAD

Erik SCHOENEMANN[1], Iván SERMANOUKIAN[2], Francesco GINI[1],
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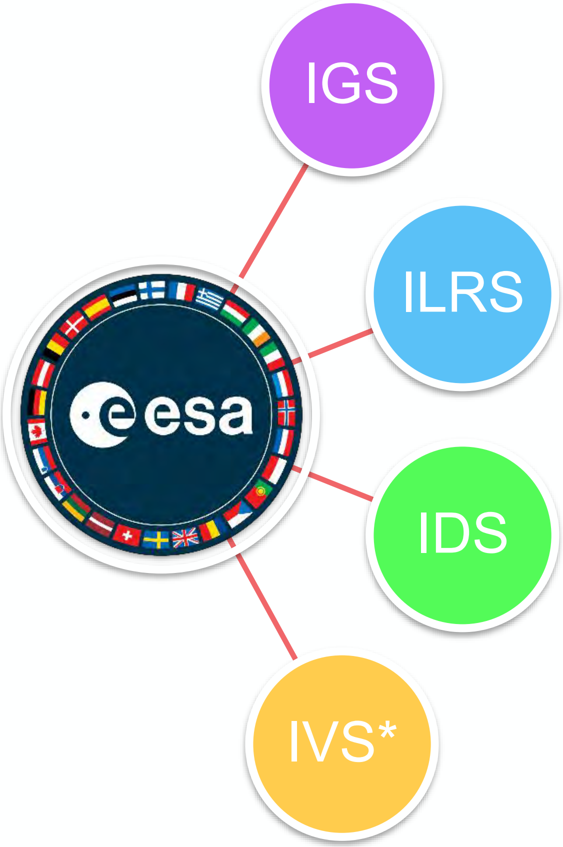
The Navigation Support Office
1: ESA/ESOC, 2: VisionSpace Technologies Gmbh, 3:PosiTim UG

ESA ESOC

Genesis Workshop, Matera Italy, 03-04/04/2025

ESA's current capabilities

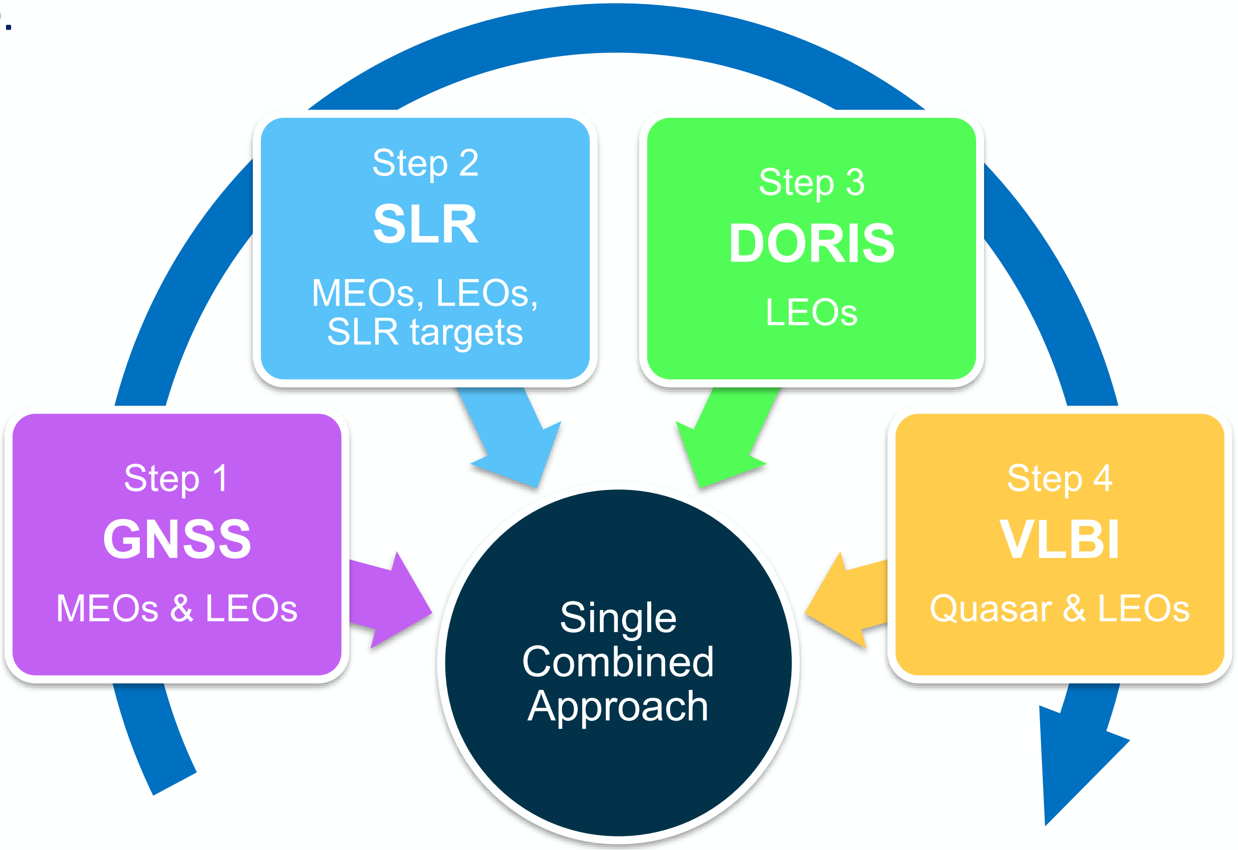
- **GNSS** products, contributing to **IGS**
  - **CHAMP** - *Consolidated High Accuracy Multi-GNSS Processing*
  - Constellation-wise processing with Normal Equation stacking
- **SLR** products:
  - SLR targets: contributing to **ILRS**
  - SLR to MEOs & LEOs, for validation purposes
- **DORIS** products
  - DORIS-equipped LEOs: contributing to **IDS**
- **VLBI** products:
  - VLBI to Quasars and *soon* to contribute to **IVS**



ESA regularly processes all 4 techniques, and satellites in different orbital regimes: MEOs, LEOs, GEOs and HEO.

ESA's plan for Genesis

ESA's (IGS AC + PROAD) objectives: to process *all space geodetic observations* in a single combined approach, incrementally adding one technique at a time.



- **Genesis** will be the common element to all four techniques, linking them together
- As IGS AC, ESA plans to include LEOs and Genesis into its current IGS GNSS processing

Our plan towards Genesis

Planned ESA IGS AC

GNSS
MEO & LEO

- GPS + LEOs
- GAL + LEOs
- others

MS1 →

GNSS & SLR
MEO & LEO

- GPS + LEOs
- GAL + LEOs (GNSS&SLR)
- others (GNSS&SLR)

MS2 →

GNSS & SLR
MEO & LEO & SLR targets

- GPS + LEOs
- GAL + LEOs + SLR targets (GNSS&SLR)
- others (GNSS & SLR)

MS3 →

GNSS & SLR & DORIS
MEO & LEO & SLR targets & DORIS sat

- GPS + LEOs
- GAL + LEOs + SLR & DORIS targets (GNSS&SLR&DORIS)
- others (GNSS & SLR)

MS4 →

GNSS & SLR & DORIS & VLBI
Quasar & LEO

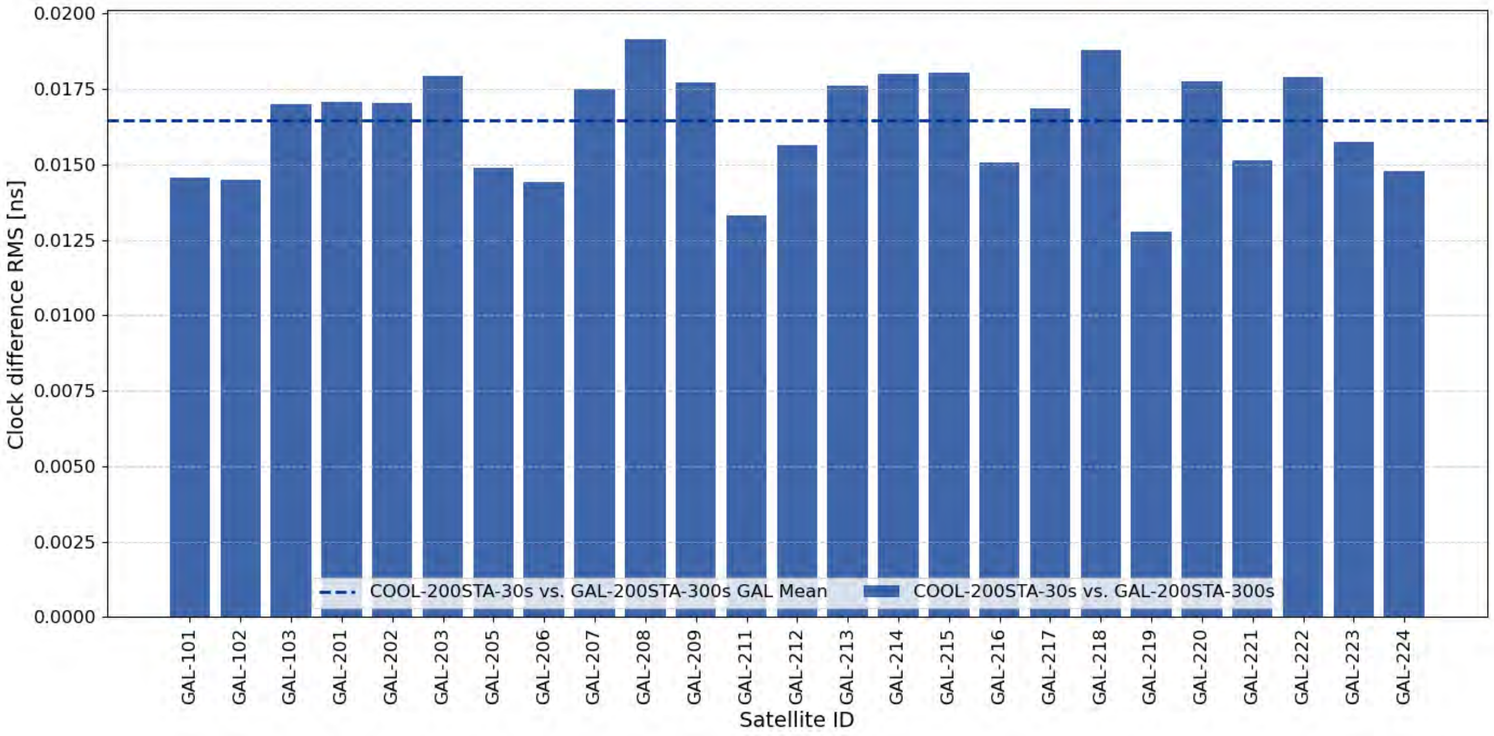
- GNSS
- SLR
- DORIS
- VLBI to Quasar
- VLBI to satellite
- To all targets

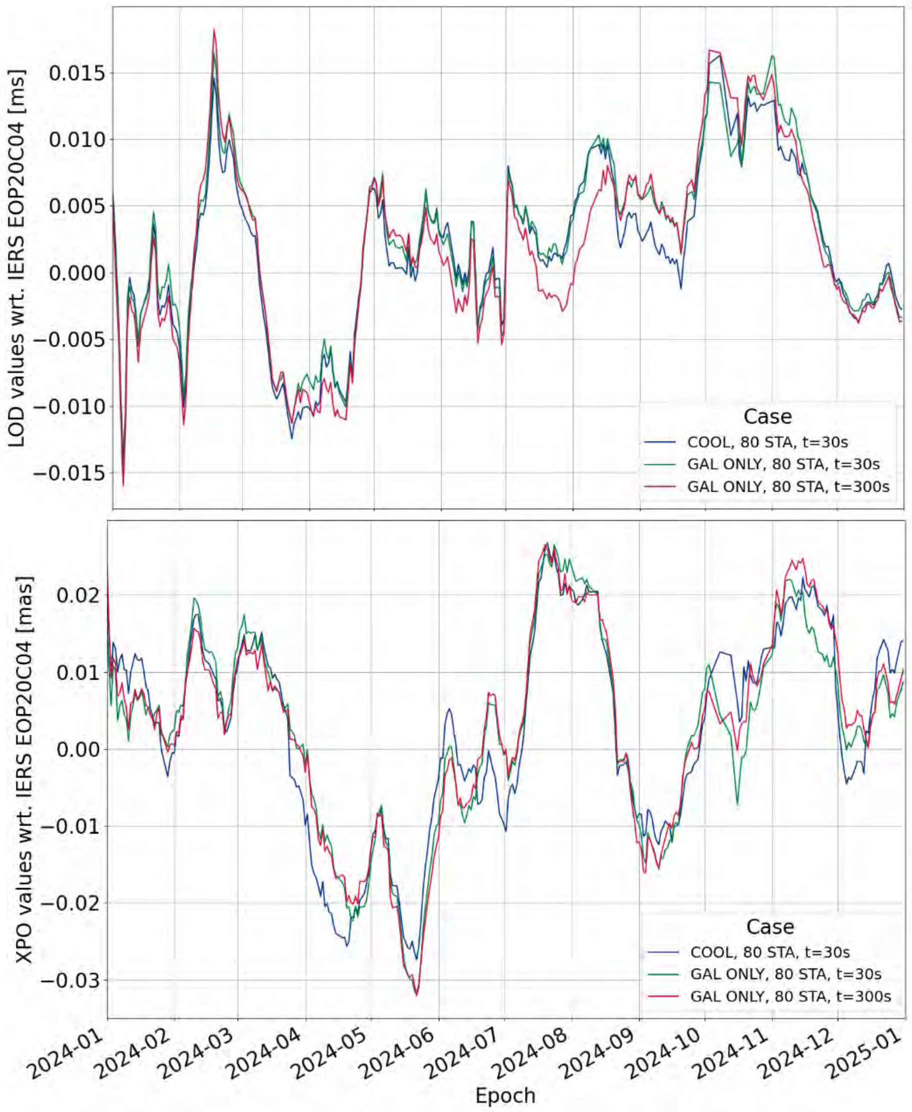
- Our plan to **combine all geodetic technique** in one single processing
- Processing based on **Normal Equation Stacking** approach developed for *CHAMP*
- Planning to include all LEOs and geodetic targets (e.g., LAGEOS, LARES)
- Currently **adding Sentinel-6A to Galileo** (which enables the combination of multi-GNSS, SLR and DORIS)

Step 1: Combined GNSS MEO-LEO processing: initial results

Impact on the estimated parameters of the COOL approach wrt. the current Galileo-only solution

- Mean of clock difference RMS is around 0.016 ns (4.8 mm)
- Mean of satellite orbit difference 3D RMS is around 6 mm
- Small differences in Length of Day and Pole Values wrt. IERS EOP20C04





Thank you for your attention!

Follow the next steps of the Navigation Support Office in the EGU, ENC and IAG 2025 conferences

Erik Schoenemann, Iván Sermanoukian, Francesco Gini,

Tim Springer, Michiel Otten, Sara Bruni, Mark Van Kints, Jean-Cristophe Berton, Werner Enderle

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navigation-office.esa.int/Products.html

GNSS ground- and space-based processing at GFZ

Benjamin Männel, Longjiang Tang

Matera, April 3, 2025

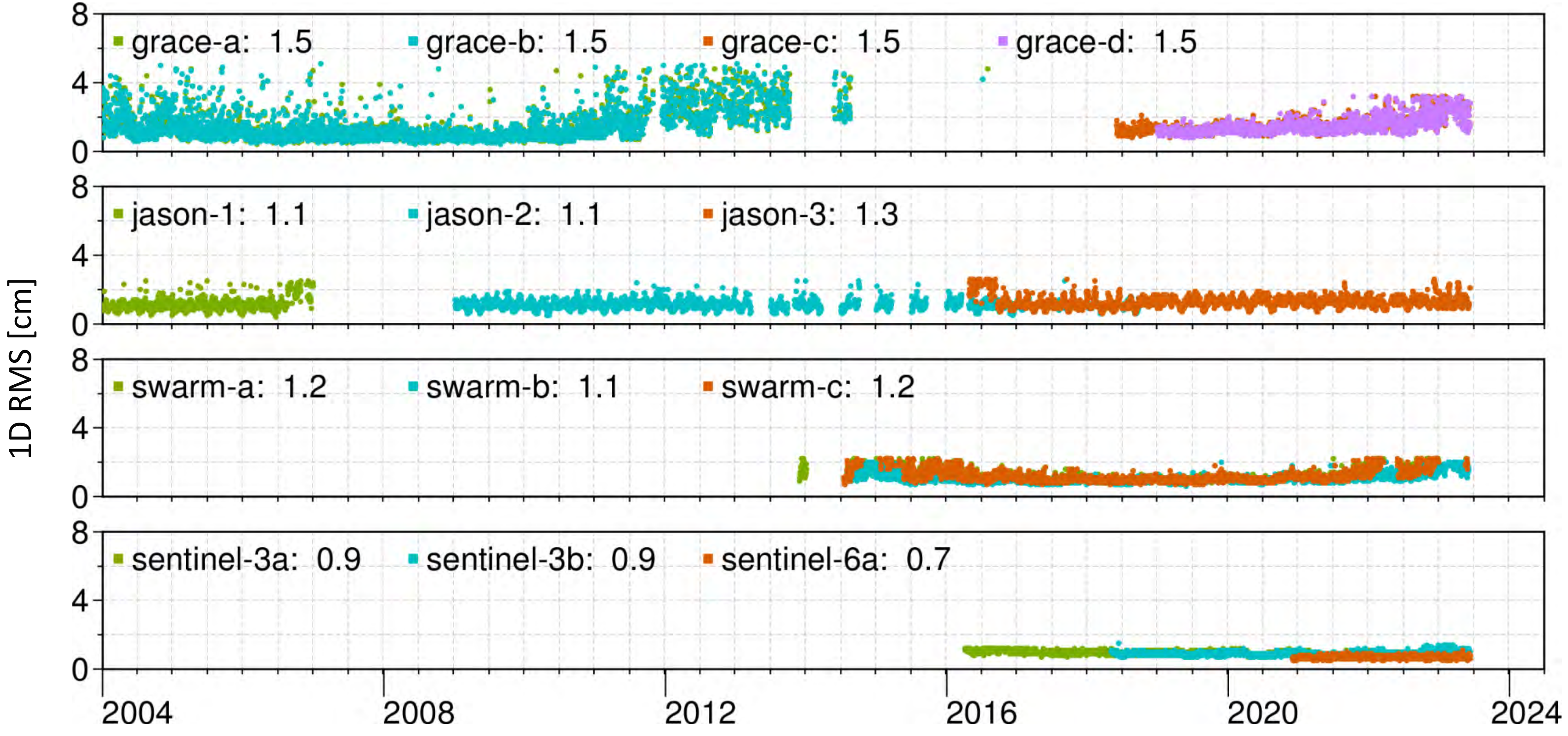
GFZ Helmholtz Centre for Geosciences

Current software status

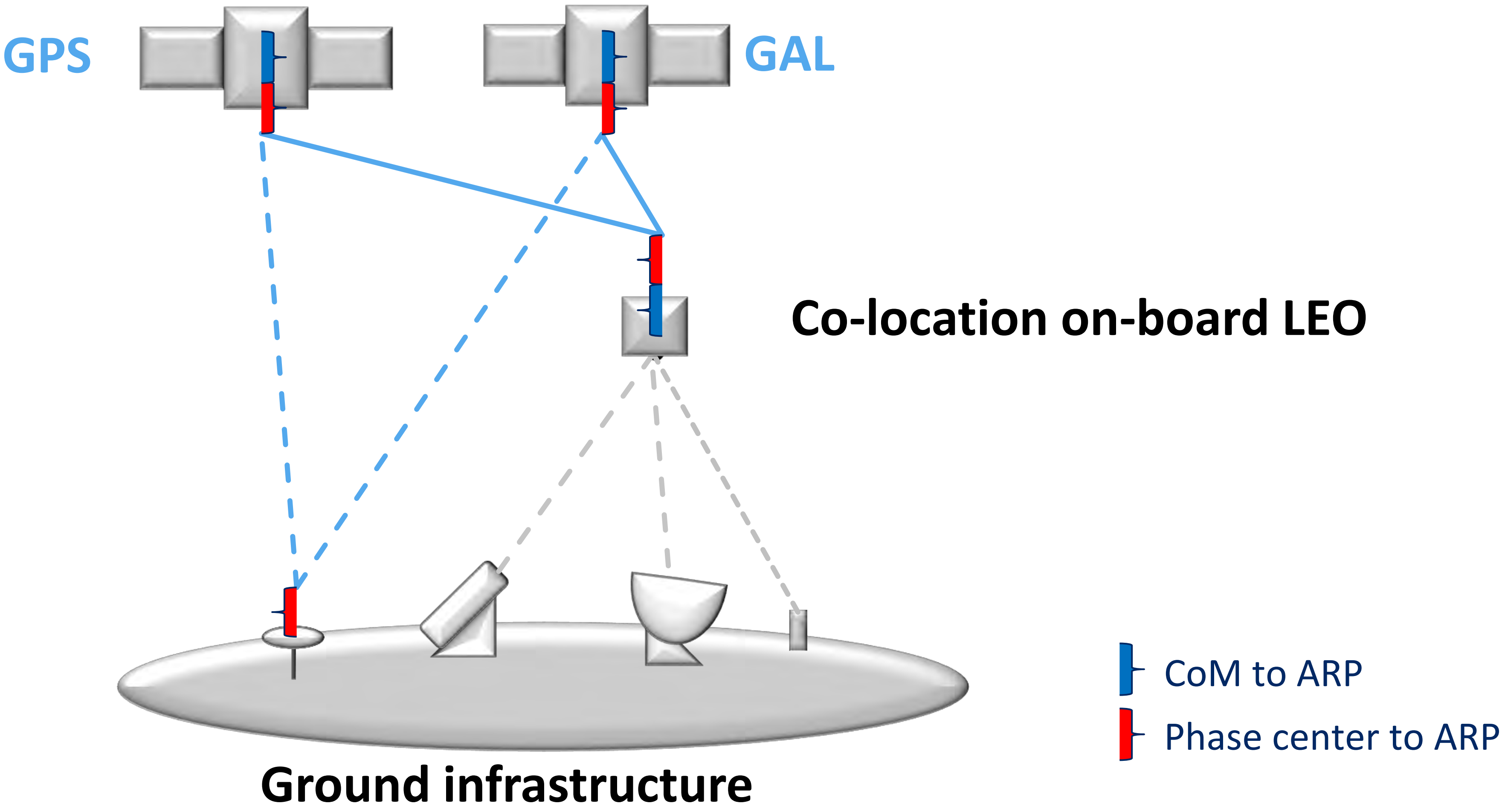
- IGS processing with in-house software EPOS.P8
- Ongoing development of EPOS.X (transition scheduled for 2025Q3)
- Ongoing implementation of LEO and extended SLR capabilities in EPOS.X
- Newly developed metadata system (Stationeer & Orbiteer)

- Integrated processing of ground and space-based GNSS performed during previous projects

LEO POD results

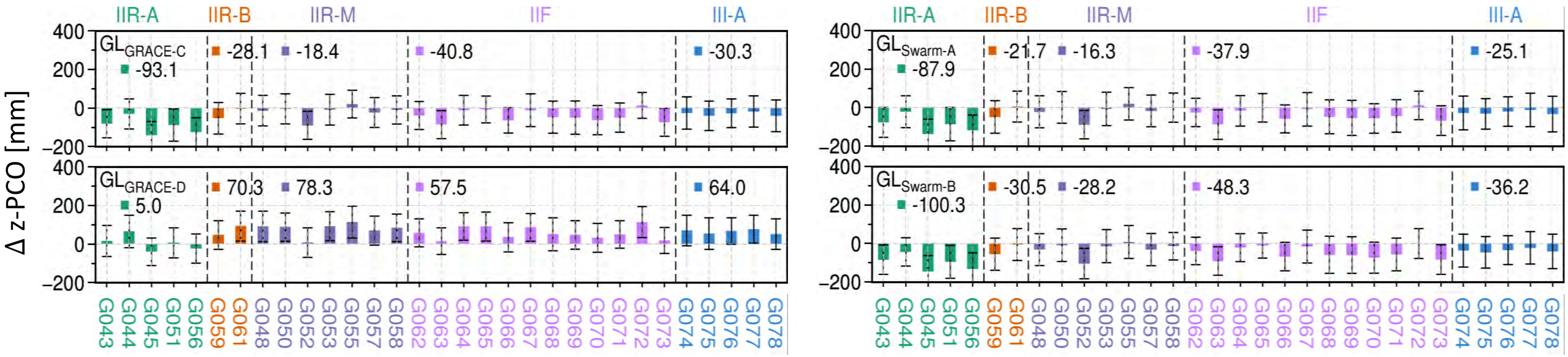


Integrated processing ground + space

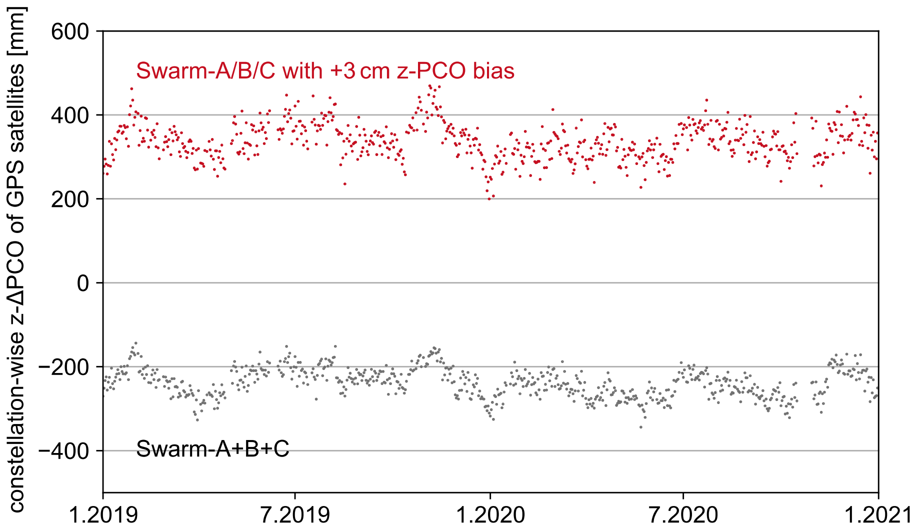


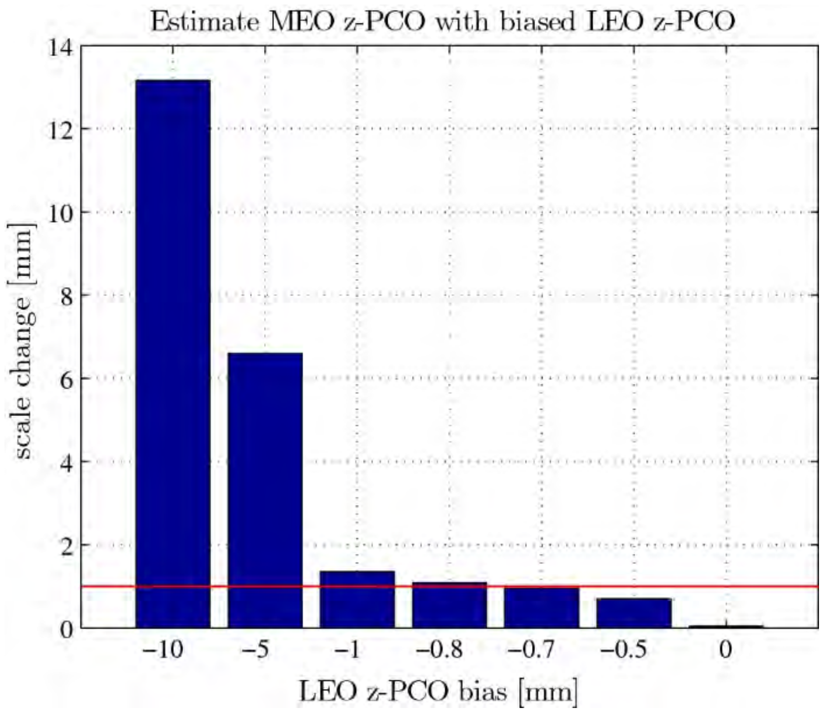
GPS z-PCO determination

- Estimation of transmitter PCOs with pre-flight LEO PCOs
- Estimates w.r.t. IGSR3 antex
- Difference between GFO-C and GFO-D
  (GPS_{PCO} = 100 mm → radial component at LEO = 5 mm)



GPS z-PCO determination





Real data: +3 cm z-PCO for Swarm → GPS PCO (-574 mm) and terrestrial scale (+27mm)

Simulated data: +1 mm z-PCO for simulated LEO → terrestrial scale (+1.4mm)

Huang et al., 2021 (https://doi.org/10.1007/s10291-020-01035-5)
Glaser et al., 2021 (https://doi.org/10.1007/s00190-020-01441-0)

GFZ Helmholtz Centre for Geosciences

GRGS GENESIS report

Alvaro Santamaría [1,2]

with inputs from
Hanane Ait-Lakbir [2], Jean-Charles Marty [1,2], Pacôme Delva [3],
Miltiadis Chatzinikos [3], Arnaud Pollet [4,5], Sylvain Loyer [6], Hugues Capdeville[6], Adrián Baños[6]

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CNES – CLS (GRGS) AC

1) Operational activities:

Contribution to IGS (GNSS) + IDS (DORIS) + ILRS (SLR)

Contribution to POD of altimeters + Copernicus POD WG.

2) Activities in preparation to include GENESIS in the GINS/DYNAMO software and to assess the benefits for TRF realization:

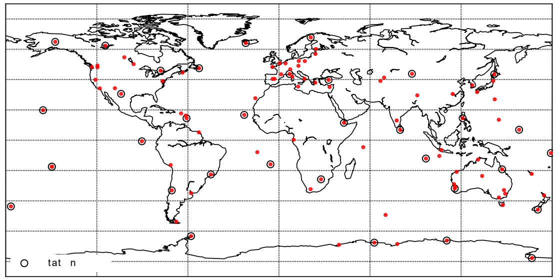
- Multi-technique solution including the **Sentinel-6A** mission (GNSS, DORIS, SLR)
  S. Loyer et al. (IGS WS2024): Geocenter motion formal error reduced + Sentinel-6A orbit draconitic (~3 cpy) introduced in the Z component of the geocenter motion.
  The draconitic problem reduces with the new macro-model (Conrad et al., 2022).

- Single-technique and multi-technique **simulations** (GNSS, DORIS, SLR, VLBI): optimal GENESIS orbit, observation geometry, measurement errors, modelling errors, common multi-technique parameters

Simulation settings

Overview

	Sma/altitude [km]	Ecc.	Inclination [deg]
GENESIS (Delva et al, 2023)	12371 (5992)	0.001	**95.5**
GEN - inc	12371 (5992)	0.001	**61.0**



Software

GINS (CNES), common for simulation and data procession, for all techniques

Stations

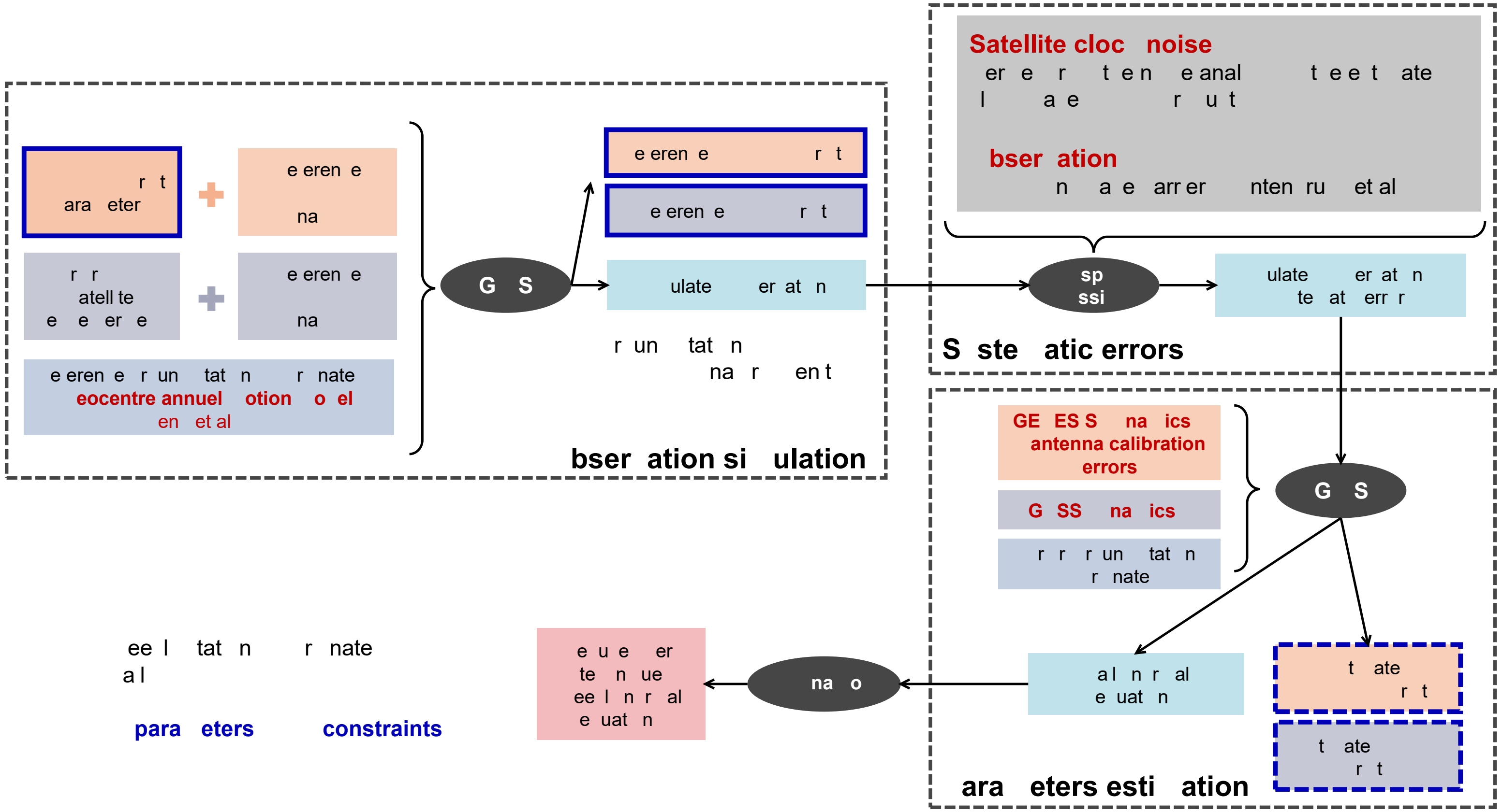
- Globally distributed stations from IGS network
- A priori reference frame : ITRF2020 (Altimimi et al, 2023) + geocenter motion annual motion (Cheng et al, 2013)

Satellites

- GPS and Galileo orbits simulated with reference dynamics
- GENESIS-like : test of two orbital configurations

Systematic errors

- RF : geocenter annual motion
- Satellite clock noise
- Observation noise
- GEN antenna calibration
- GNSS/GEN dynamical modeling (SRP)

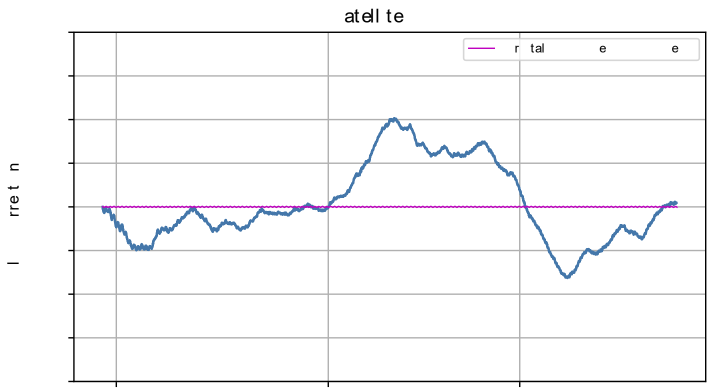


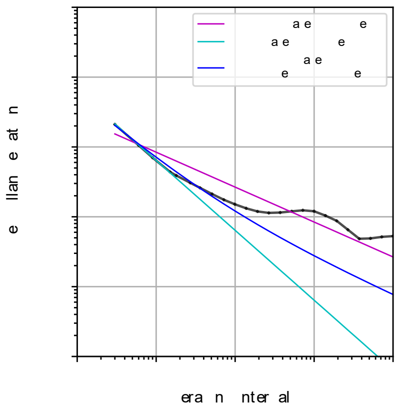
Simulation settings
Systematic errors - GNSS

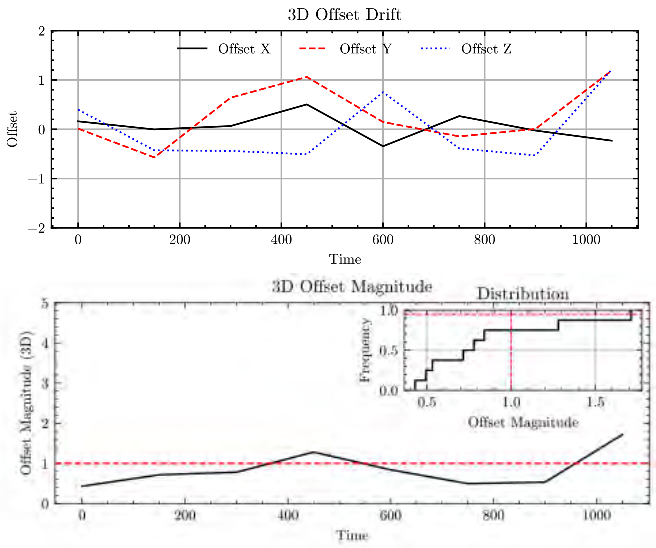
- Satellite clock noise (extension of noise analysis for Galileo in Senior et al, 2014 ; Maciuk et al., 2021)
  - GRG final clock products
  - Satellite-specific noise model with RW, FN using SARI

- Observation noise level (from link budget analysis in Montenbruck et al, 2023)
  - max 10 mm WN on carrier phase for GENESIS (nadir antenna)

- Antenna calibration:
  - GNSS : uncertainties of currently available PCV
  - GENESIS : specs of 1-2 mm PCO + off-boresight PCV







GNSS rec. ant. PCO errors

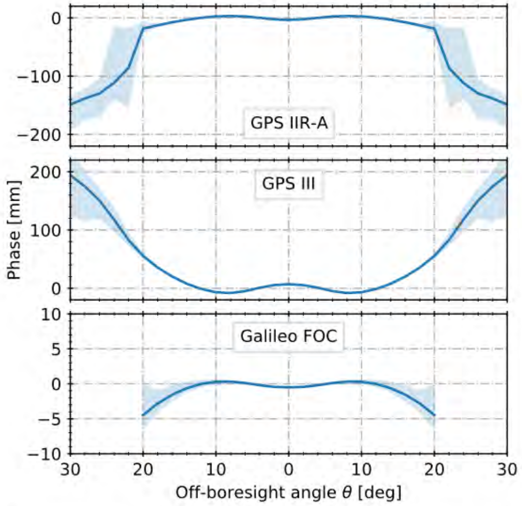


Fig. 7 Azimuth-averaged L1/E1 phase variations of representative GPS IIR-A, GPS III, and Galileo FOC satellites (solid lines) as obtained in manufacturer calibrations. Shaded areas describe the range of phase variations at a given off-boresight angle for different azimuth angles. Note the different scales. All phase variations refer to phase centers minimizing the variation over the Earth coverage zone

(from Montenbruck et al, 2023)

GNSS positioning: preliminary results (2 years)

Internal accuracy of TRF parameters with GNSS+GEN

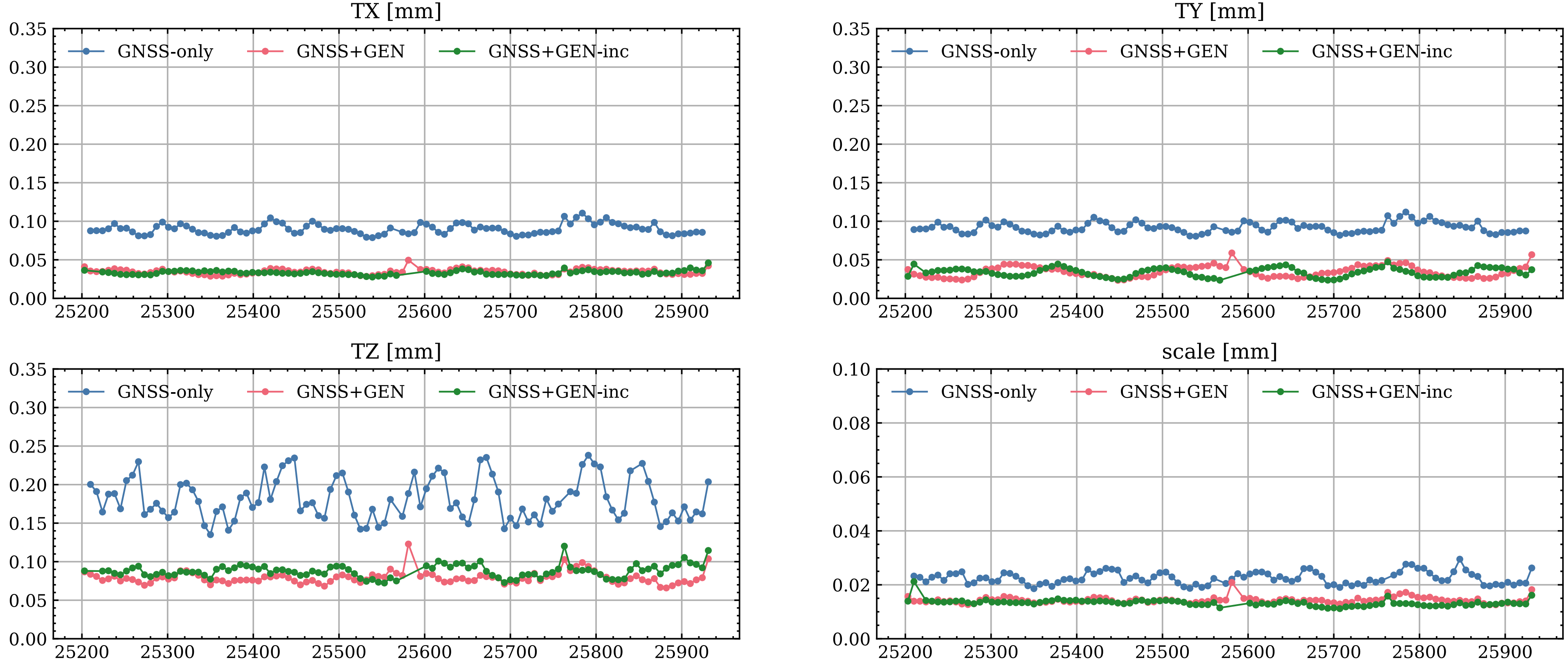
Propagation of the station coordinates covariance matrix into the TRF parameters space

- Formal errors: improvement x2 with GENESIS (confirms results with Sentinel-6A)
- Error dispersion: depends mostly on the GENESIS draconitic period

$$C_{\vartheta} = (EE^T)^{-1} E C_x E^T (EE^T)^{-1}$$

C_{ϑ}: Covariance matrix of TRF parameters

E: Inner constraint matrix



JGX status for the Genesis project

Yuki Igarashi
Satellite Navigation Unit, JAXA

13th IGS Analysis Center, organized by the Geospatial Information Authority of Japan (GSI) and the Japan Aerospace Exploration Agency (JAXA)

POD software (MADOCA)
GNSS orbit analysis
QZSS payload development

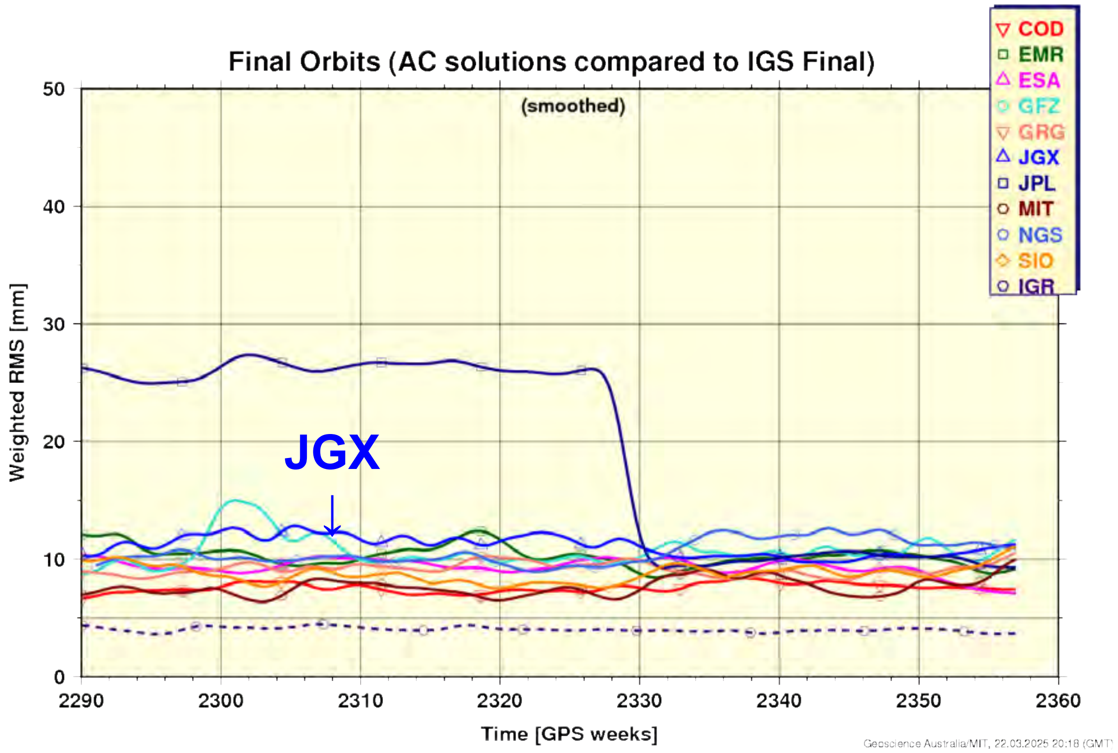
Software Improvement

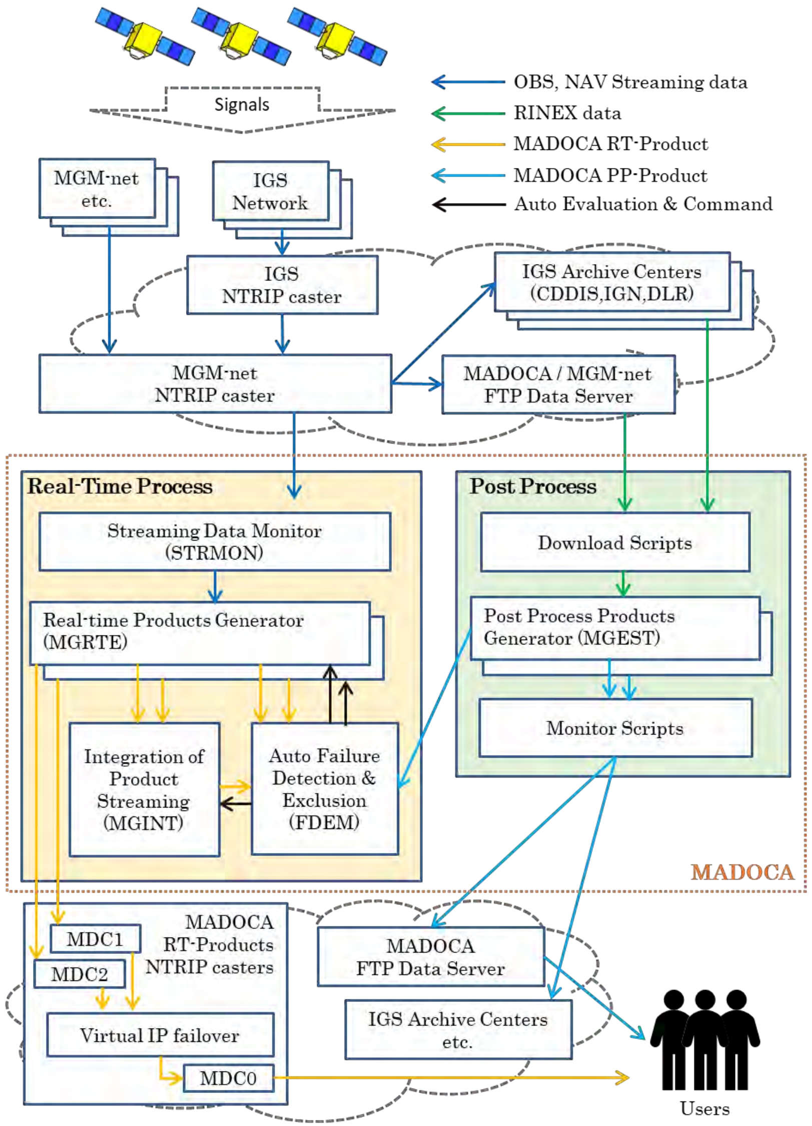
CORS operation (GEONET)
GNSS data analysis
Reference frame realization

Operation of AC

Status of POD software, MADOCA

- MADOCA （Kawate 2023）
  - Models consistent with IGS recommendations
  - Capability of batch and real-time process
  - Support Multi-GNSS (GRECJ), but **NOT LEO**

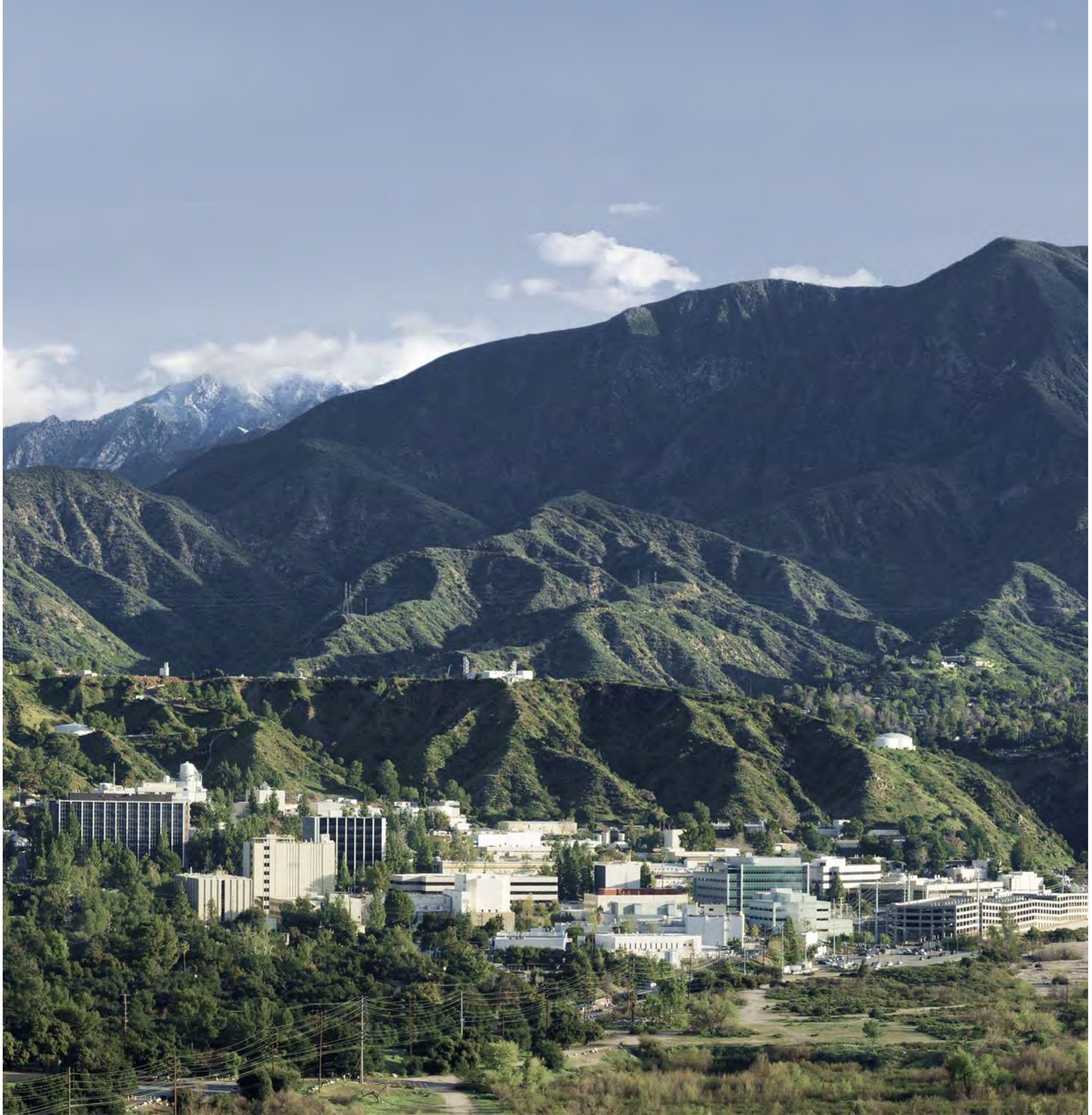




Capabilities and Plans

- T KU — a branch version of MADOCA, has a POD function for GNSS + LEO satellites
- Capabilities
  - Dual GNSS antennas processing, Integer Ambiguity Resolution etc.
  - Since TAKUMI branched off more than 10 years ago, its GNSS-related models are not state-of-the-art.
- Plans
  - We are working on the integration of these TAKUMI and MADOCA for future LEO related projects including Genesis project.
  - For a more specific plan, it would be helpful if requirements and recommendations are presented.

- Discussions
  - VLBI and DORIS observables have never been utilized in TAKUMI or MADOCA. Is it essential to apply these observables?
  - Any other requirements or preferrable functions for Genesis?
- Others
  - T ear e ’re et t la un a L atell te t a t l l e r r PPP(-AR) on orbit using MADOCA-PPP corrections from QZSS satellites in the user-end software MALILB-LEO, with some models are compatible with MADOCA.
  - Also, QZS-5 and 7 are going to be launched in this fiscal year.

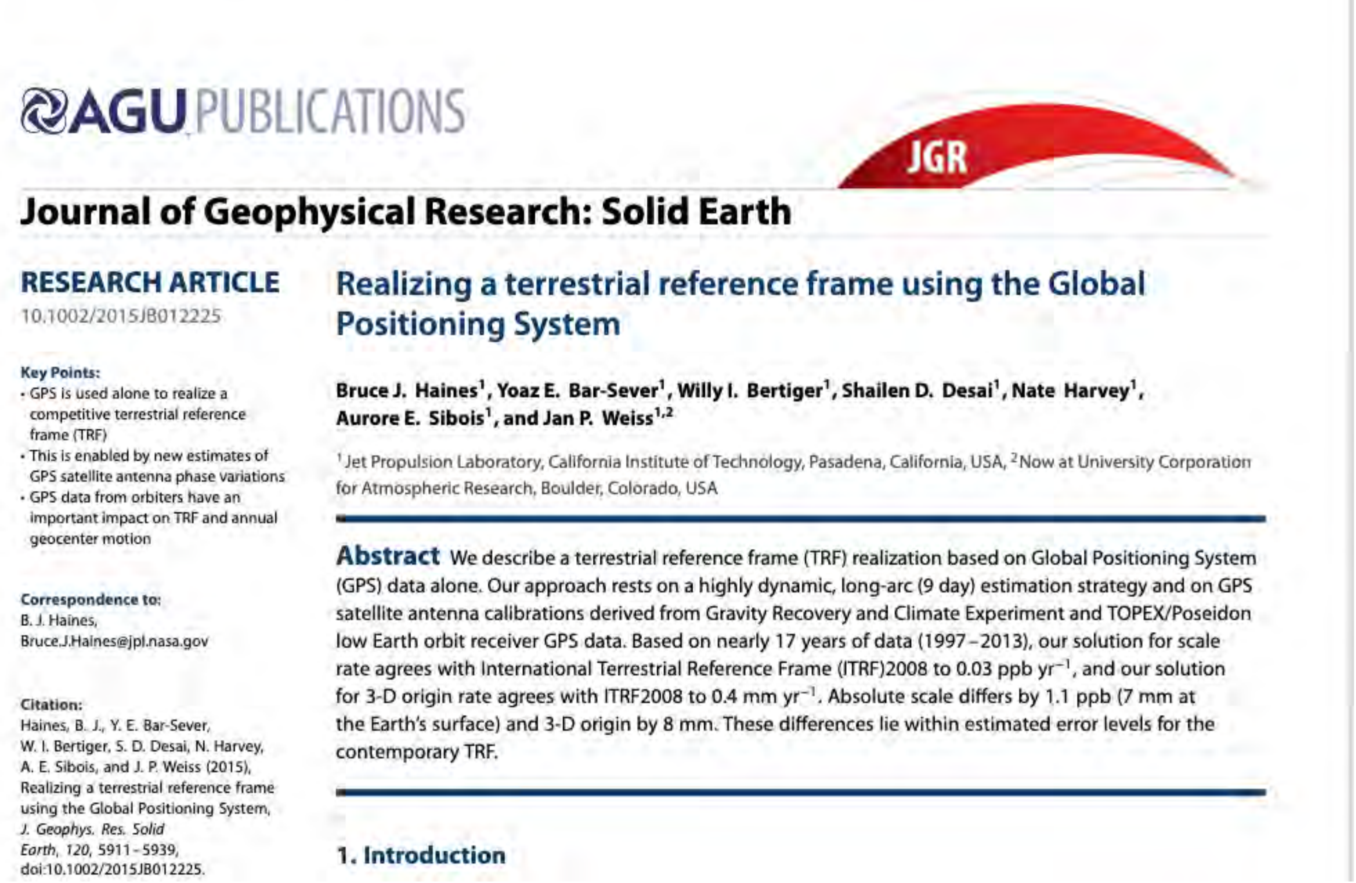


Preparing for GENESIS at the JPL IGS Analysis Center: GNSS network solutions with LEOs

Paul Ries, Bruce Haines, Michael Heflin, Athina Peidou
Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

- WG1 presentation on combination at observation level
- This presentation shows how adding orbiting GNSS receiver platforms (e.g. GENESIS, GRACEs, JASON, Sentinel) to GNSS-only solutions show benefits even without combining other techniques


AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE
10.1002/2015JB012225

Key Points:
- GPS is used alone to realize a competitive terrestrial reference frame (TRF)
- This is enabled by new estimates of GPS satellite antenna phase variations
- GPS data from orbiters have an important impact on TRF and annual geocenter motion

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Citation:
Haines, B. J., Y. E. Bar-Sever, W. I. Bertiger, S. D. Desai, N. Harvey, A. E. Sibois, and J. P. Weiss (2015), Realizing a terrestrial reference frame using the Global Positioning System, *J. Geophys. Res. Solid Earth*, 120, 5911–5939, doi:10.1002/2015JB012225.

Realizing a terrestrial reference frame using the Global Positioning System

Bruce J. Haines[1], Yoaz E. Bar-Sever[1], Willy I. Bertiger[1], Shailen D. Desai[1], Nate Harvey[1], Aurore E. Sibois[1], and Jan P. Weiss[1,2]

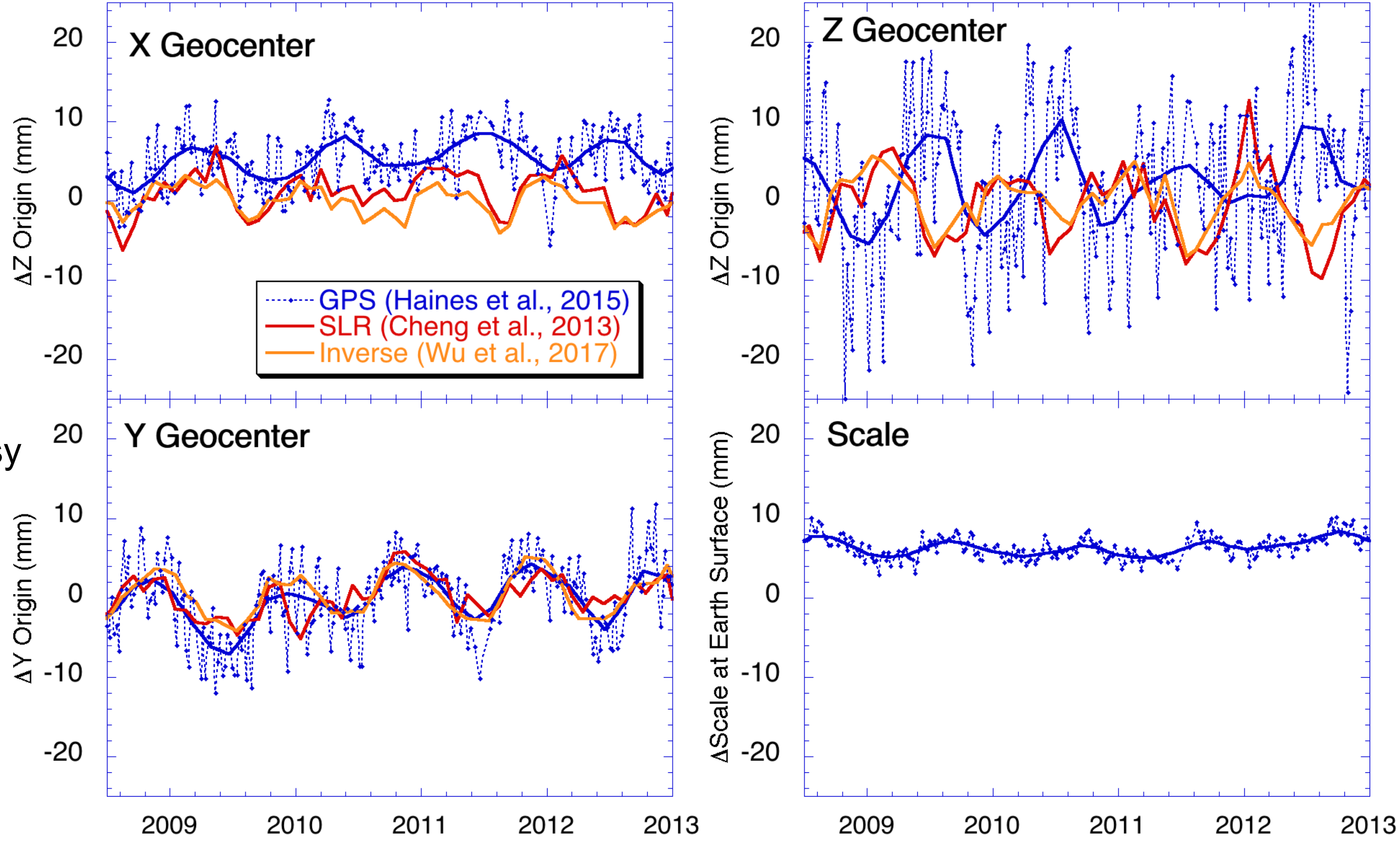
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [2]Now at University Corporation for Atmospheric Research, Boulder, Colorado, USA

Abstract We describe a terrestrial reference frame (TRF) realization based on Global Positioning System (GPS) data alone. Our approach rests on a highly dynamic, long-arc (9 day) estimation strategy and on GPS satellite antenna calibrations derived from Gravity Recovery and Climate Experiment and TOPEX/Poseidon low Earth orbit receiver GPS data. Based on nearly 17 years of data (1997–2013), our solution for scale rate agrees with International Terrestrial Reference Frame (ITRF)2008 to 0.03 ppb yr^{-1}, and our solution for 3-D origin rate agrees with ITRF2008 to 0.4 mm yr^{-1}. Absolute scale differs by 1.1 ppb (7 mm at the Earth's surface) and 3-D origin by 8 mm. These differences lie within estimated error levels for the contemporary TRF.

1. Introduction

Geocenter seen by GPS satellites

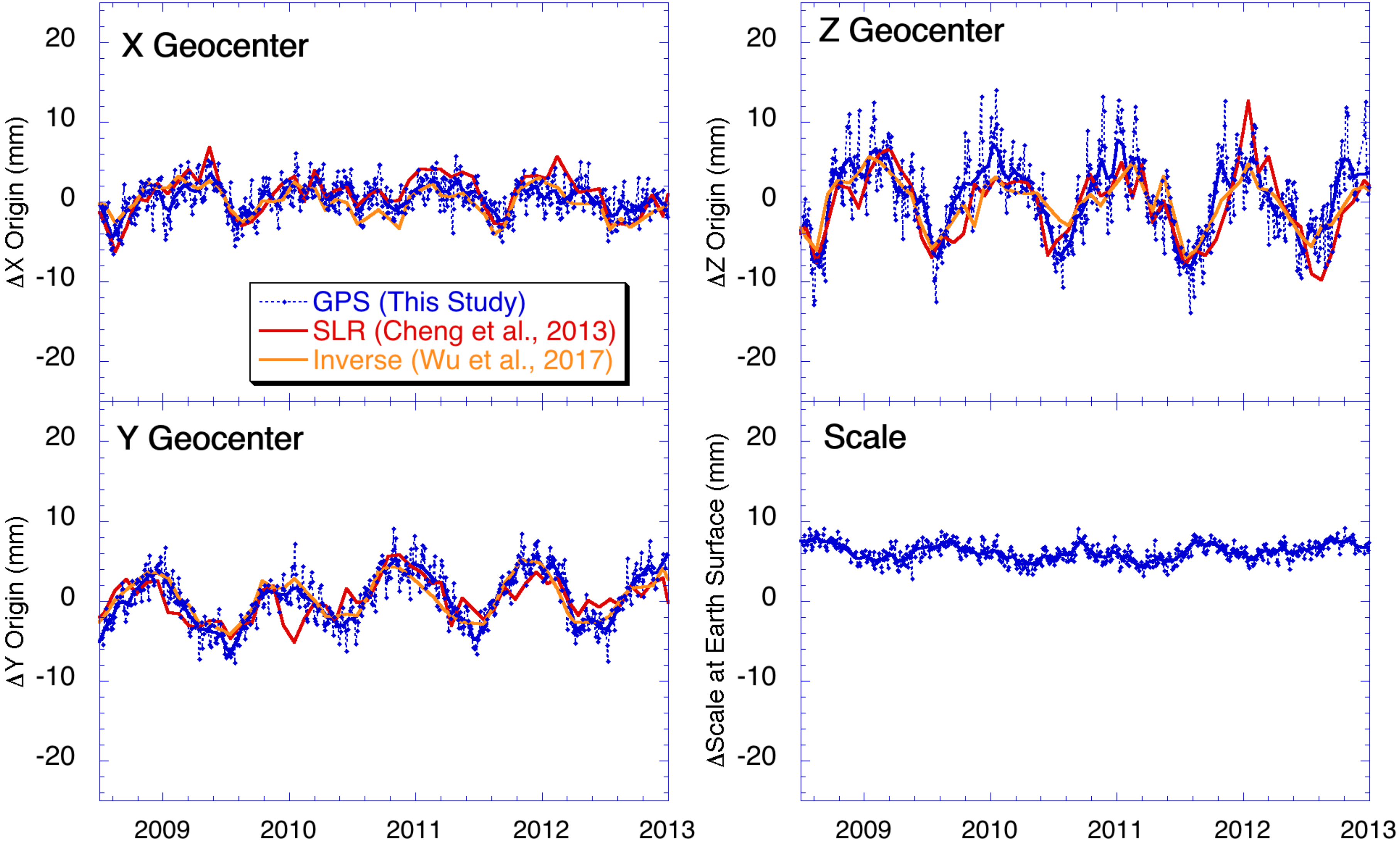
- GNSS transmitters alone are insensitive to geocenter
- Geocenter has bias and is noisy relative to other solutions



Haines et al., Realizing a terrestrial reference frame using the Global Positioning System, J. Geophys. Res., 10.1002/2015JB012225, 2015

Geocenter seen by GPS + 3x LEO

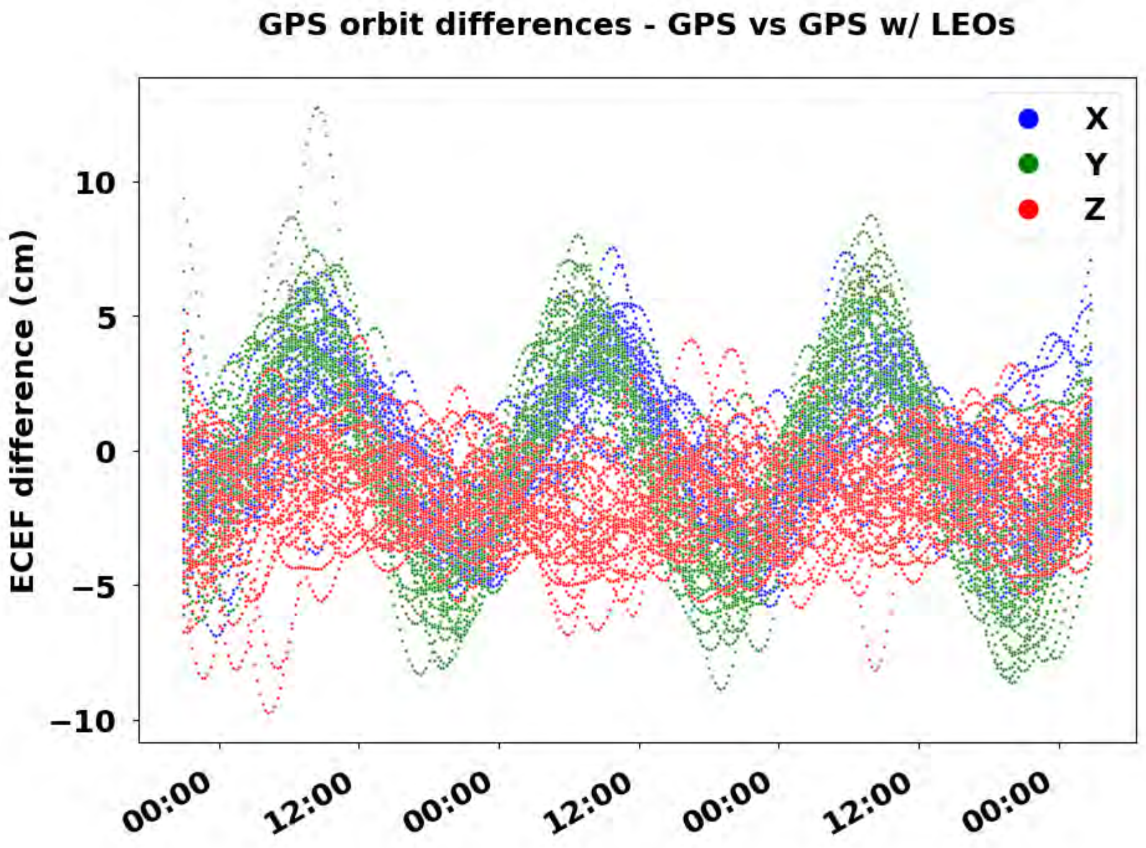
- Adding GRACEA/B and Jason-2 to solution
- Adding LEOs reduces both scatter and bias in geocenter motion

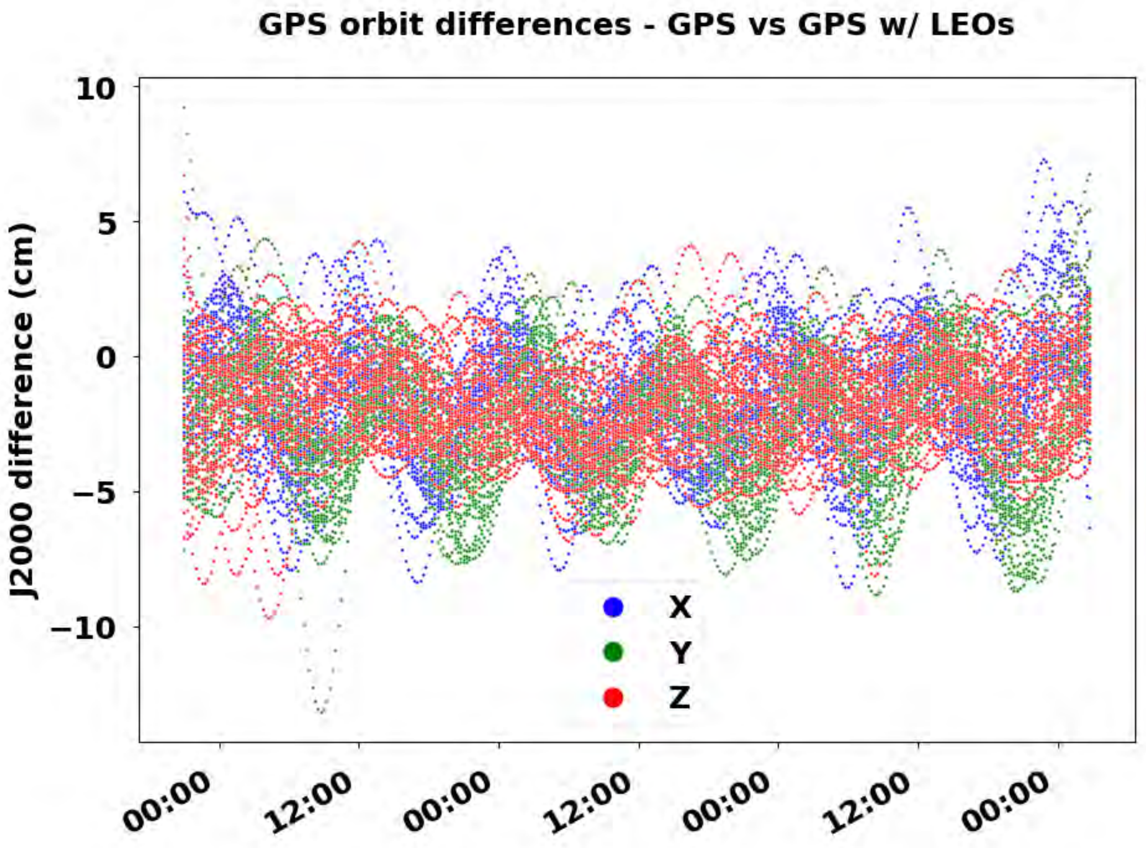


Haines et al., Realizing a terrestrial reference frame using the Global Positioning System, J. Geophys. Res., 10.1002/2015JB012225, 2015

LEOs change nature of GPS orbits

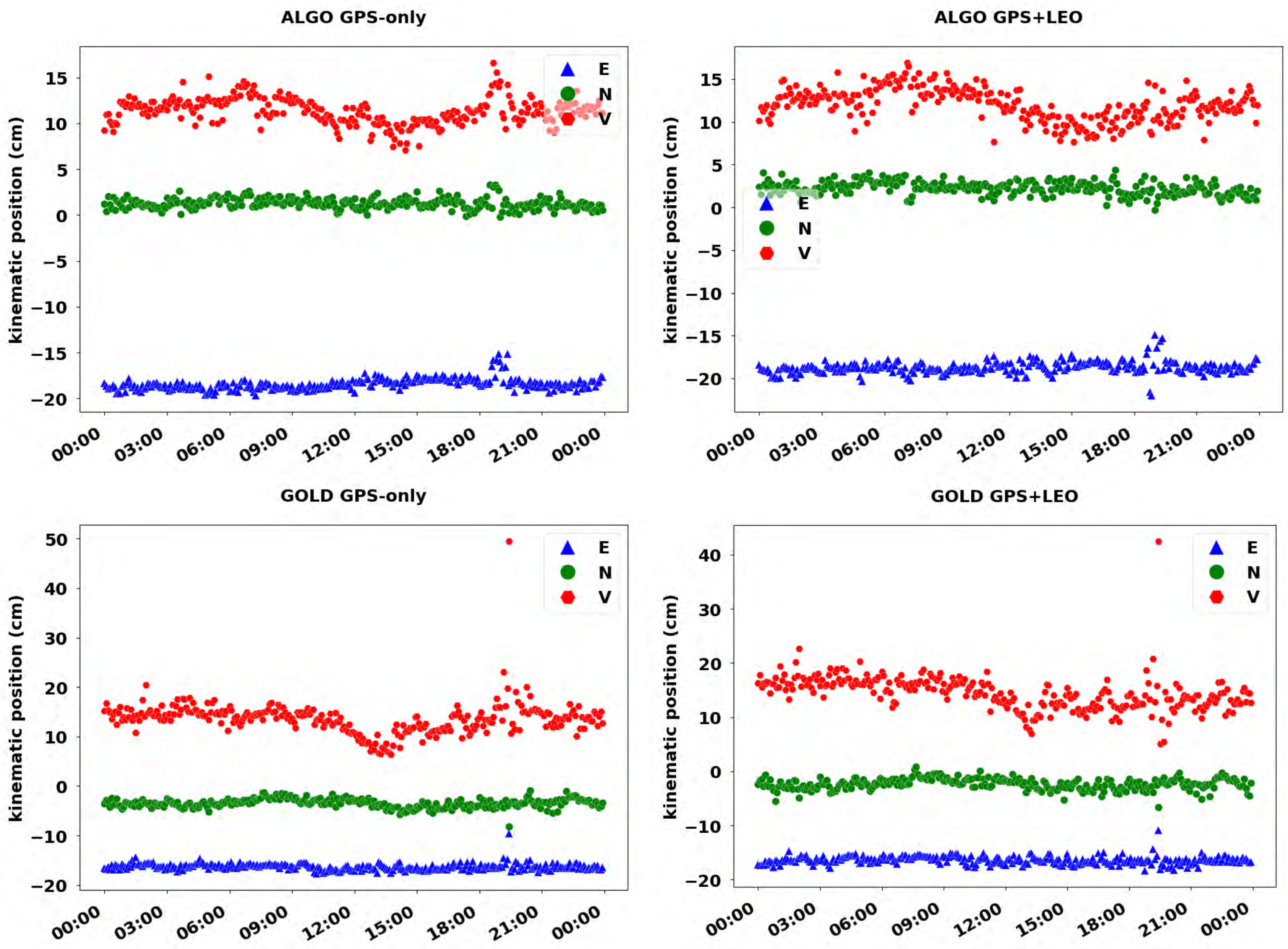
- LEOS may help reduce pervasive draconitics – substantial change in resulting GPS orbits





Effects on GNSS end users?

- Test PPP with GPS orbit and clocks with and without LEOs in solution
- Even though orbits differ by cm, PPP differences much smaller
- GPS orbit and clock artifact at ~1900 disappears when LEOs are added – intriguing!



Conclusions

- Adding LEO GNSS receivers to ground network and GNSS transmitter solutions can improve recovery of geocenter
- Adding LEO GNSS receivers changes substantially the recovered GNSS orbits (removal of draconitics?)
- Implications for PPP with orbit and clocks from solutions incorporating LEO GNSS receivers unclear. Area of further study.
- Implications for GENESIS
  - GENESIS altitude much higher than LEOs, lower than GNSS transmitters, similar to LAGEOS
  - May not recover geocenter due to altitude, but may help with draconitic removal
  - May also enable recovery of low-order gravity terms like LAGEOS
  - Have not looked at dual antenna setup, but GipsyX has previously been used to do POD with multiple GNSS receivers (e.g. Sentinel-6)

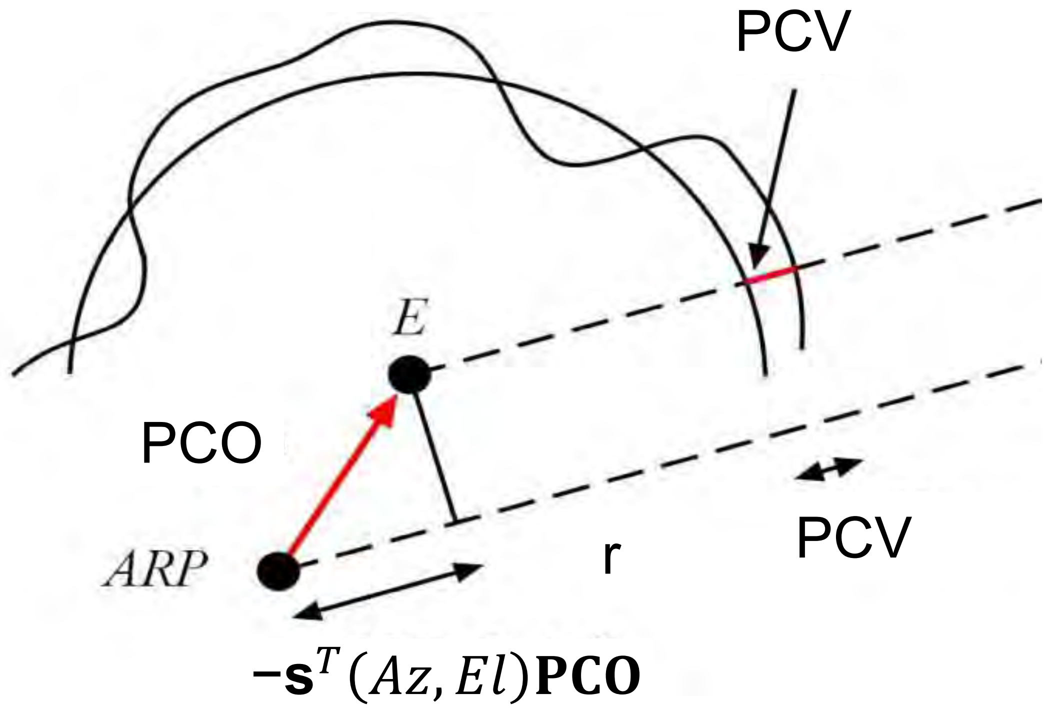
Institut für Erdmessung

Leibniz Universität Hannover

Ground antenna calibration

Steffen Schön

GNSS Phase center variations



$$PCC = -\mathbf{s}^T \mathbf{PCO1} + PCV1 + r1$$
$$= -\mathbf{s}^T \mathbf{PCO2} + PCV2 + r2$$

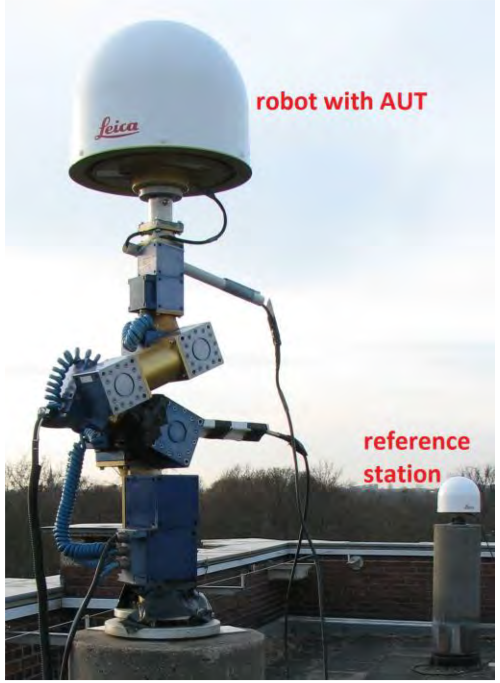
with

$$PCV2 = -\mathbf{s}^T (\mathbf{PCO1} - \mathbf{POC2}) + PCV1 + r2 - r1$$

PCC: phase center corrections
PCO: phase center offset vector
PCV: phase center variations
s: line-of-sight unit vector
r: additional indeterminable constant

Arbitrary separation in PCO and PCV
Constant part undetermined

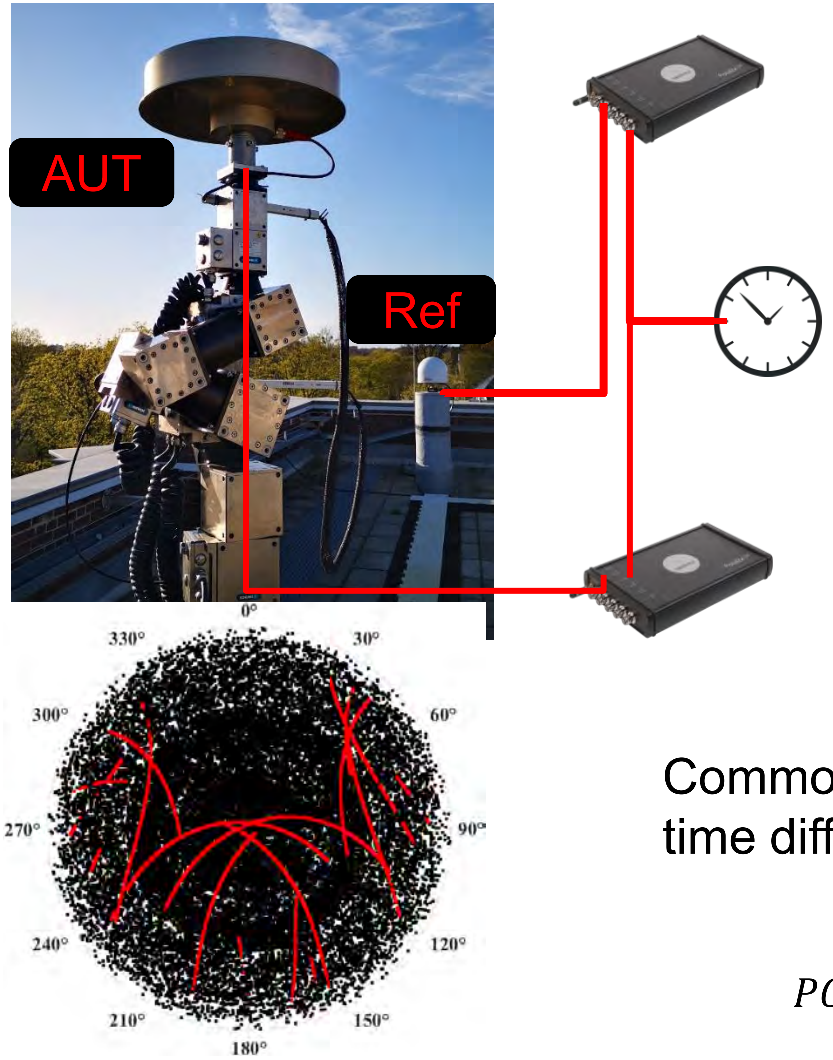
Infrastructures and Approaches

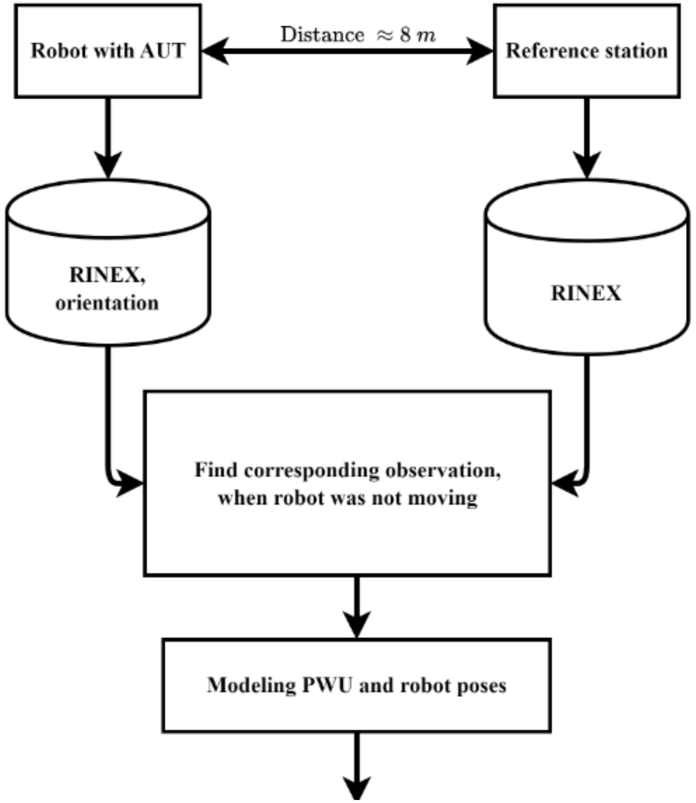


IfE facilities

Facilities participating in the IGS ring calibration test

PCC Determination at IfE



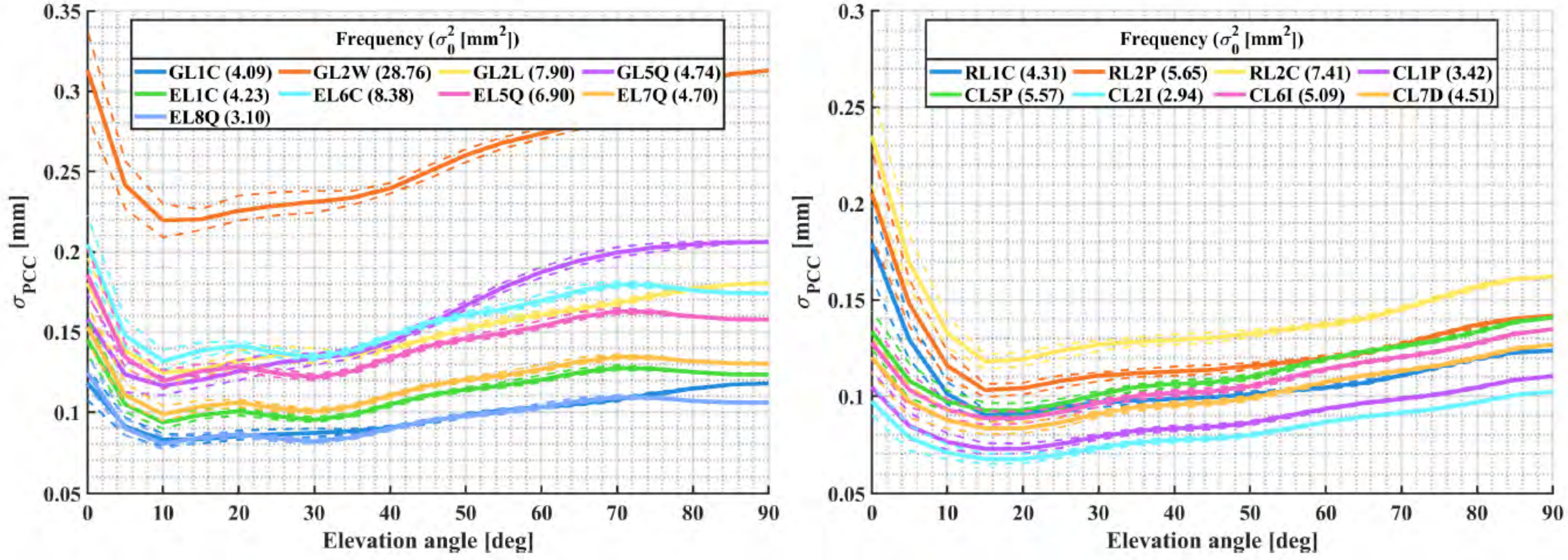


Common clock
time differenced SD

$$dSD = PCC_{AUT}(t_{i+1})\text{-}PCC_{AUT}(t_i) + \epsilon(t_i, t_{i+1})$$

$$PCC(\alpha^k, z^k) = \sum_{m=1}^{m_{max}} \sum_{n=0}^{m} \tilde{P}_{mn}(k_1 \cos(z^k) + k_2) \cdot (a_{mn} \cdot \cos(n\alpha^k) + b_{mn} \cdot \sin(n\alpha^k))$$

Formal Errors, Repeatability



(a) GPS and Galileo frequencies (b) GLONASS and BeiDou frequencies

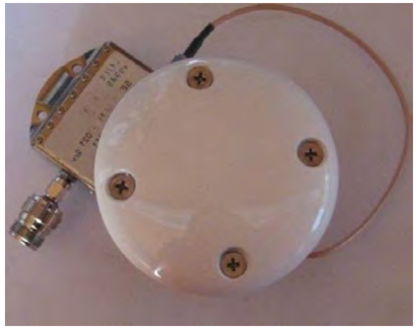
Figure 5.11: Averaged formal errors per 5° elevation angle for estimated NOV PCC. Note the different y-axes scales.

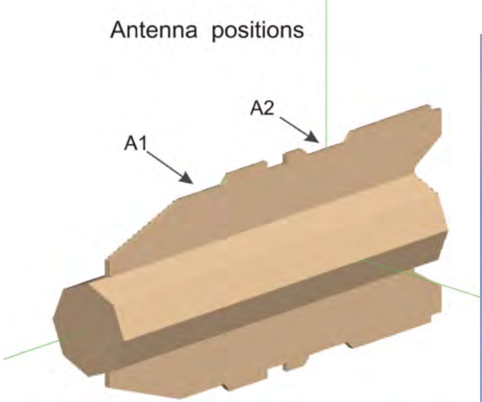
Kröger (2025)

Repeatability: typical max < 0.5 mm GPS L1

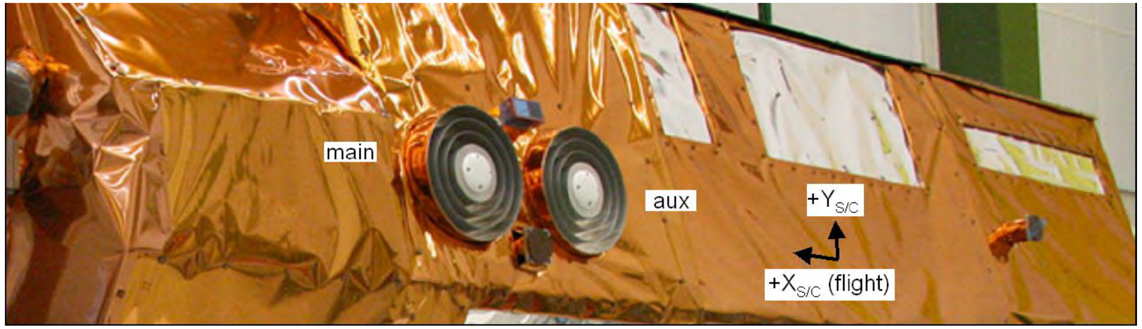
Examples TanDEM-X, GOCE calibrated at IfE

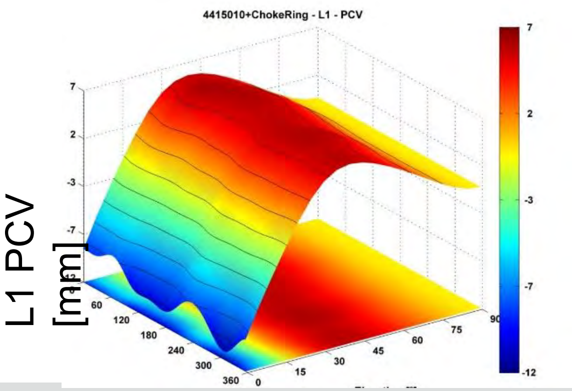
- Navigation antenne for LEO satellites (CHAMP, TERRA-SAR,...)
  Passive antenna element (Sensor-Systems) + Choke-Ring (GFZ/JPL)
- 4 samples
- Montenbruck et al.(2009)





Dilßner et al.(2006)



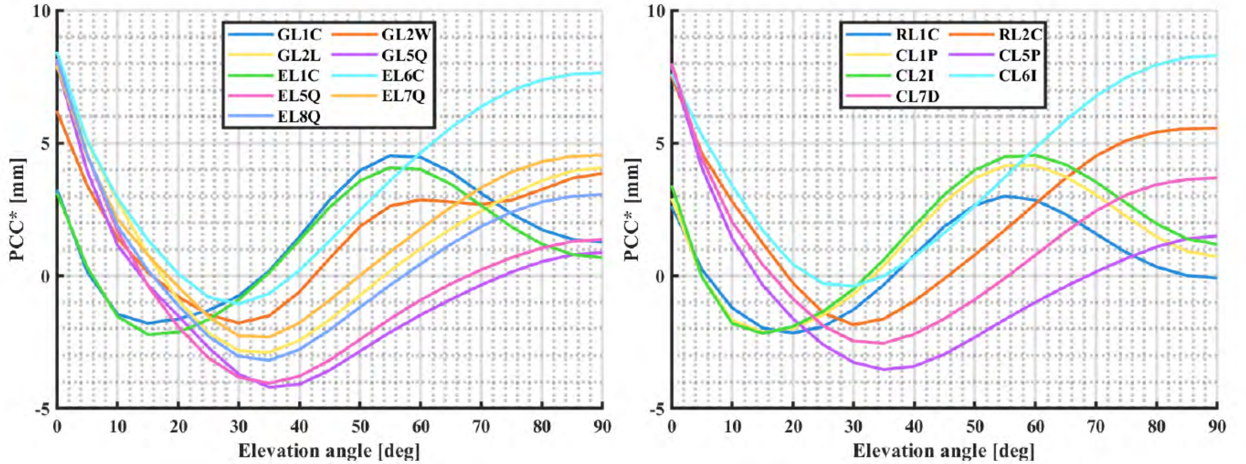


Open questions / suggestions

- Calibration antenna only (which holder ?)
  and as installed, i.e. on a mockup or satellite

- Frequency dependent or
  signal dependent calibration ?

- Phase only or also code?



(a) GPS and Galileo PCC*　　(b) GLONASS and BeiDou PCC*

Figure 5.13: Estimated LEI PCC* for various frequencies and systems, represented as mean values per elevation angle.

Kröger (2025)

References

- Kröger (2025). Estimation and Validation of multi-GNSS multi-Frequency Phase Center Corrections, PhD Dissertation Uni Hannover (defended, to be published)
- Kersten, T., Sutyagin, I., Bilich, A., and Schön, S. (2024). Uniting Global Efforts to Calibrate GNSS Antennas: Models, analyses and pilot results. IGS Symposium and Workshop 2024, Bern, Schweiz. doi: 10.15488/17846
- Kersten, T., Kröger, J., & Schön, S. (2022). Comparison concept and quality metrics for GNSS antenna calibrations: Cause and effect on regional GNSS networks. *Journal of Geodesy*, *96*(7), Artikel 48. https://doi.org/10.1007/s00190-022-01635-8
- Kröger, J., Kersten, T., Breva, Y., & Schön, S. (2022). On the Potential of Image Similarity Metrics for Comparing Phase Center Corrections. In J. T. Freymueller, & L. Sánchez (Eds), *International Association of Geodesy Symposia* (S. 345-357). (International Association of Geodesy Symposia; Band 154). Springer Nature. https://doi.org/10.1007/1345_2022_146
- Kröger, J., Kersten, T., Breva, Y., & Schön, S. (2021). Multi-frequency multi-GNSS receiver antenna calibration at IfE: concept - calibration results - validation. *Advances in Space Research*, *68*(12), 4932-4947. https://doi.org/10.1016/j.asr.2021.01.029
- Montenbruck, O., Garcia-Fernandez, M., Yoon, Y., Schön, S., & Jäggi, A. (2009). Antenna phase center calibration for precise positioning of LEO satellites. *GPS solutions*, *13*, 23-34. https://doi.org/10.1007/s10291-008-0094-z
- Dilßner, F., Seeber, G., Schmitz, M., Wübbena, G., Toso, G., & Maeusli, D. (2006). Characterization of GOCE SSTI antennas. *ZfV-Zeitschrift für Geodäsie, Geoinformation und Landmanagement*, (zfv 2/2006). https://geodaesie.info/images/zfv/131-jahrgang-2006/downloads/zfv_2006_2_Dilssner_et-al.pdf

GNSS Receiver Antenna Calibration for LEOs

Compiled by Rolf Dach

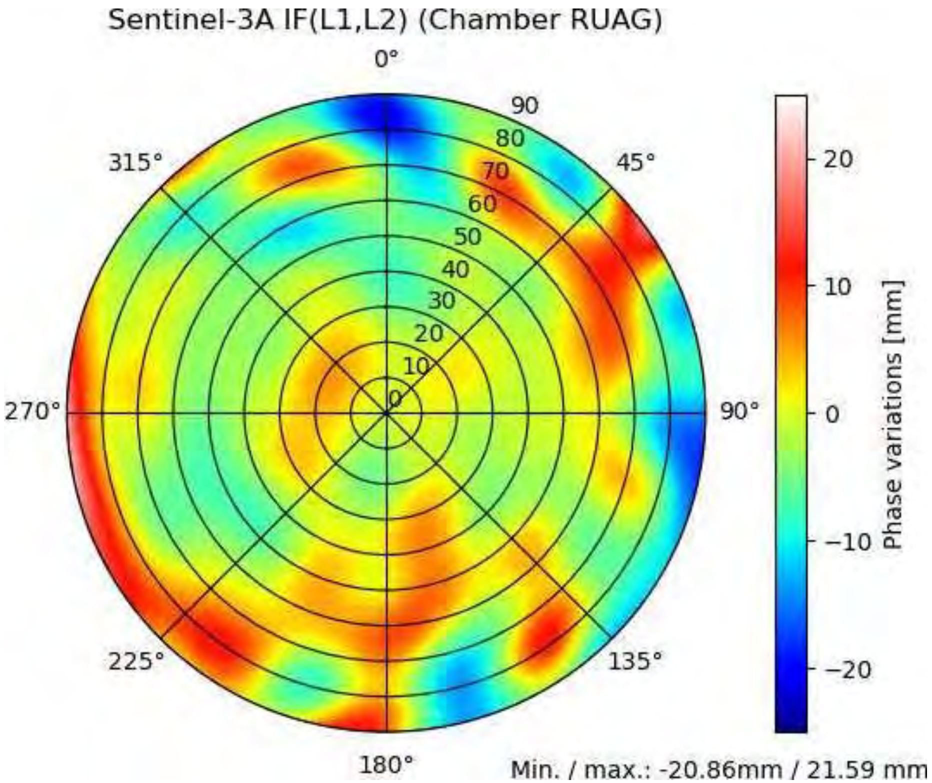
Astronomical Institute, University of Bern, Switzerland

Genesis Science Working
03–04. April 2025, Matera, Italy

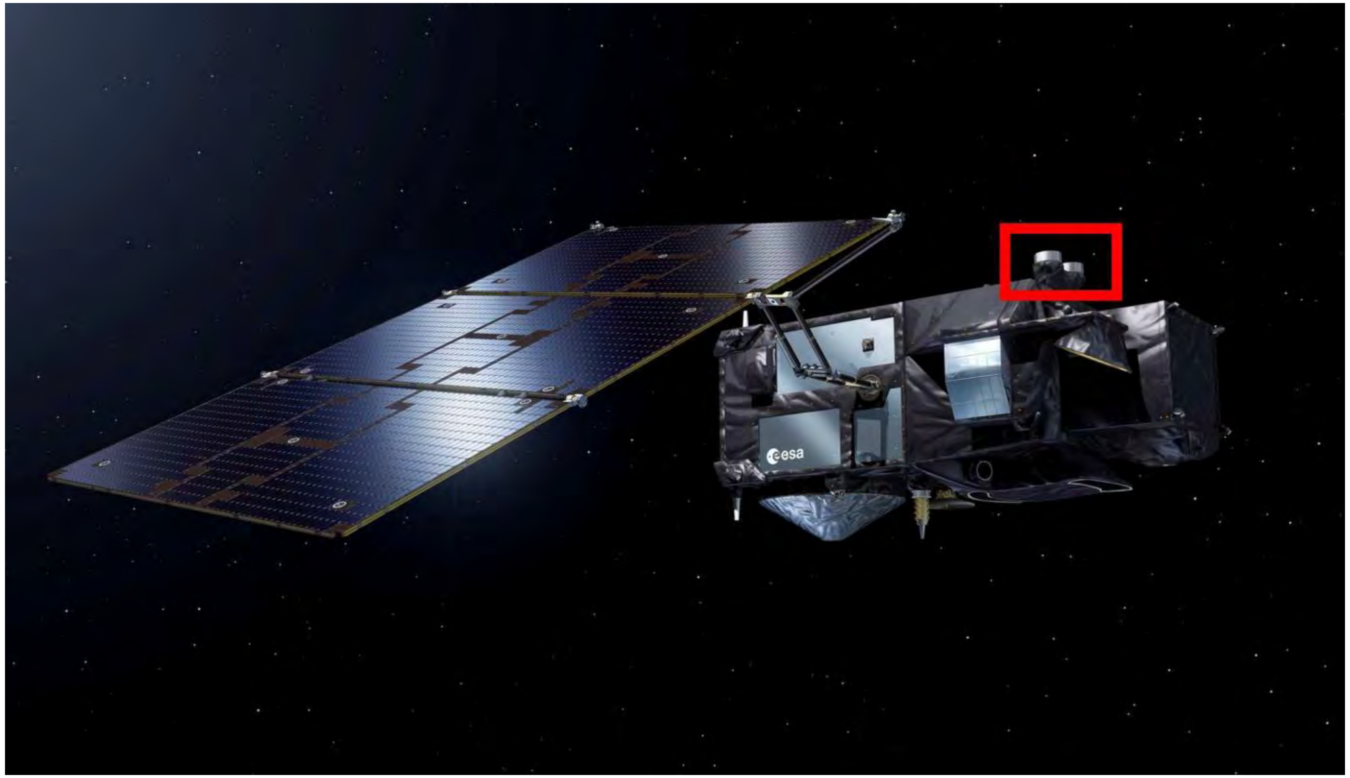
GNSS Antennas onboard from LEO satellites

Copernicus Sentinel-6 – ready for encapsulation (Courtesy: ESA)

Example Sentinel 3A



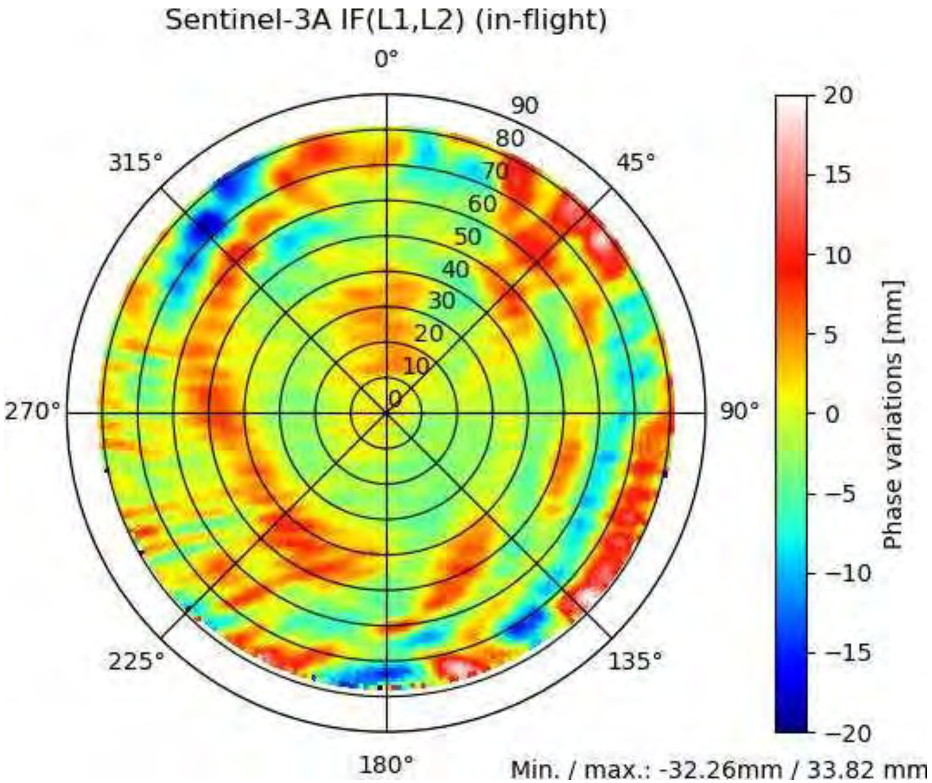
Pre-launch calibration by RUAG

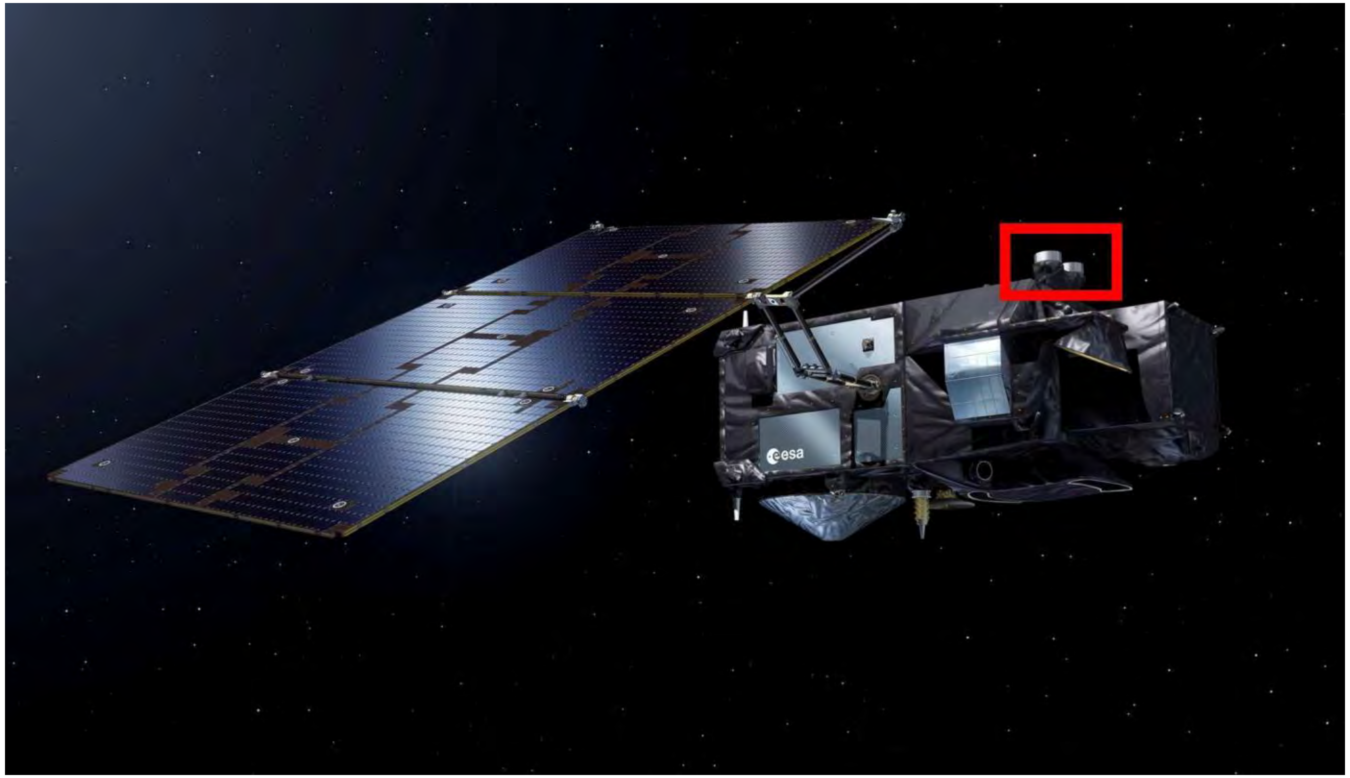


From https://sentiwiki.copernicus.eu/web/sentinel-3: An art t' impression of Sentinel-3. [Credits: https://www.esa.int/]

Provided by D. Arnold and H. Peter

Example Sentinel 3A





In-flight calibration by AIUB

From https://sentiwiki.copernicus.eu/web/sentinel-3: An art t' impression of Sentinel-3. [Credits: https://www.esa.int/]

Provided by D. Arnold and H. Peter

Genesis shall act as a flying tie

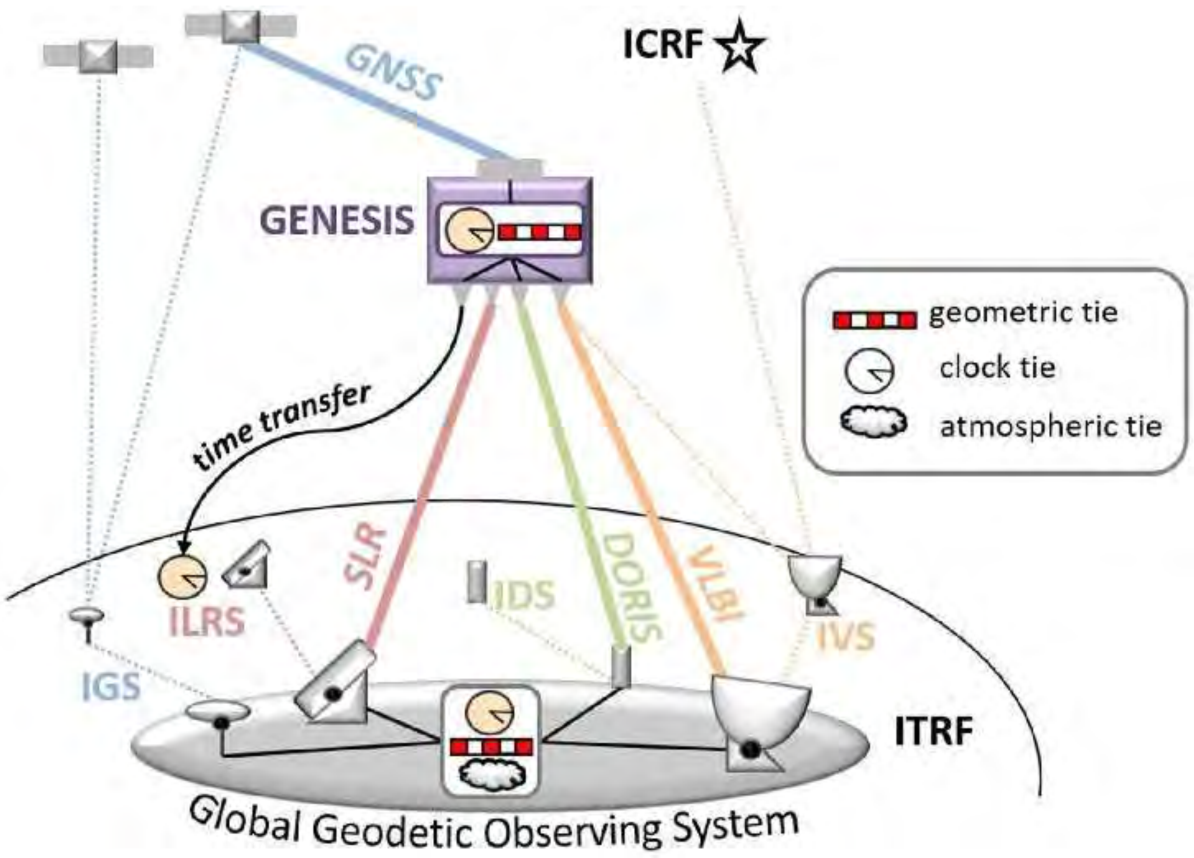
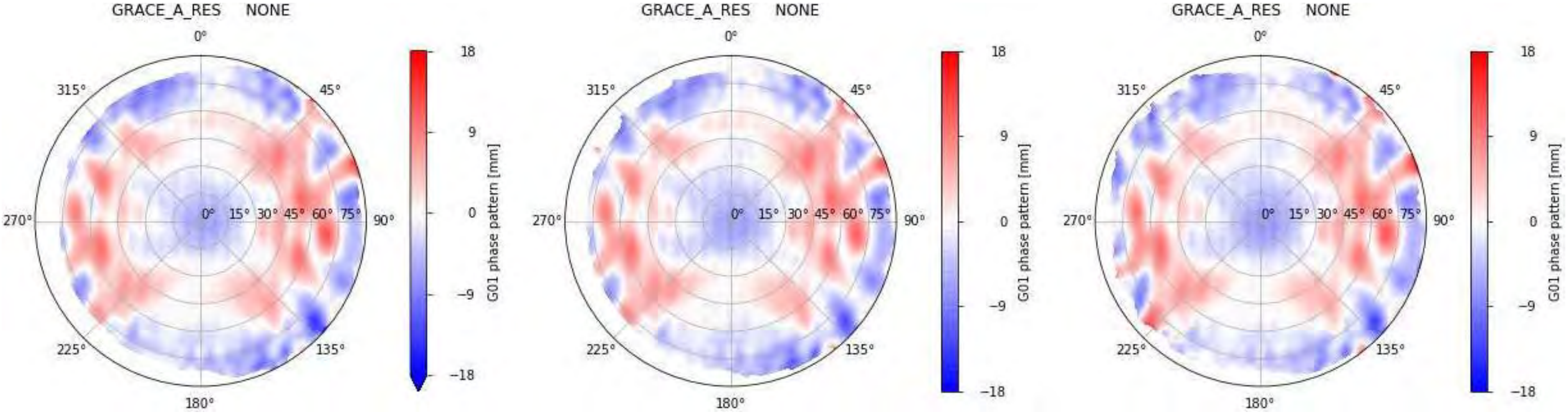


Figure 2 from Delva, P. et al., 2023

- We should avoid the need of in-flight calibrations to get an independent tie:
  calibrate the antenna on the fully assembled satellite!
- Even if is it obvious:
  The definition of the ARPs for GNSS and the other techniques (and the CoM) need to be clearly communicated to all components.

Crosstalk: example GRACE

GRACE-A as leader in three different time periods (occultation antenna off)

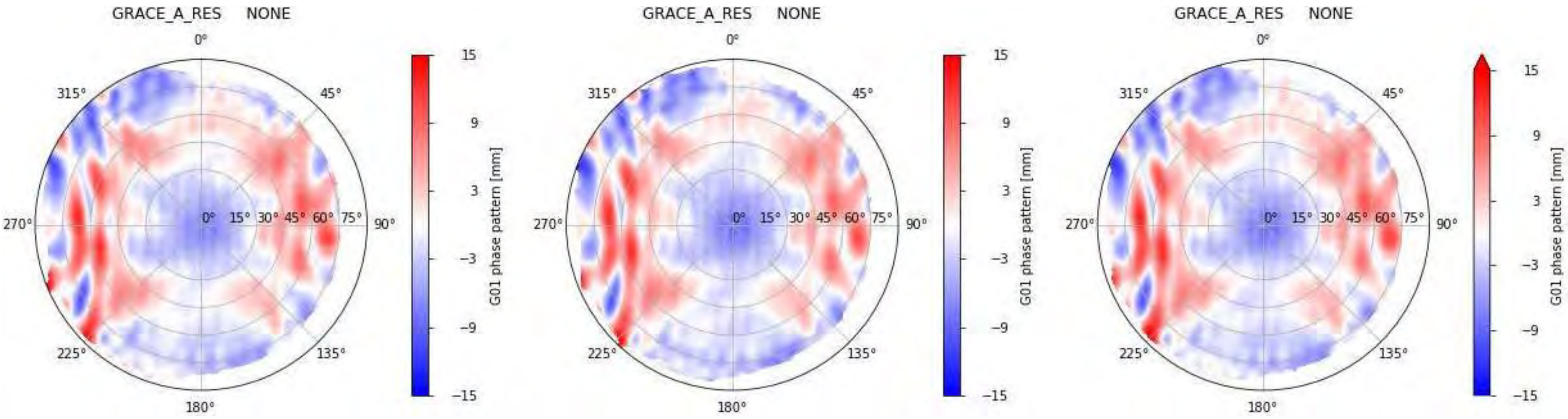


The in-flight PCV maps: ionosphere-free as obtained by the residual approach by DLR.

Provided by P. Steigenberger and O. Montenbruck

Crosstalk: example GRACE

GRACE-A as follower in three different time periods (occultation antenna on)

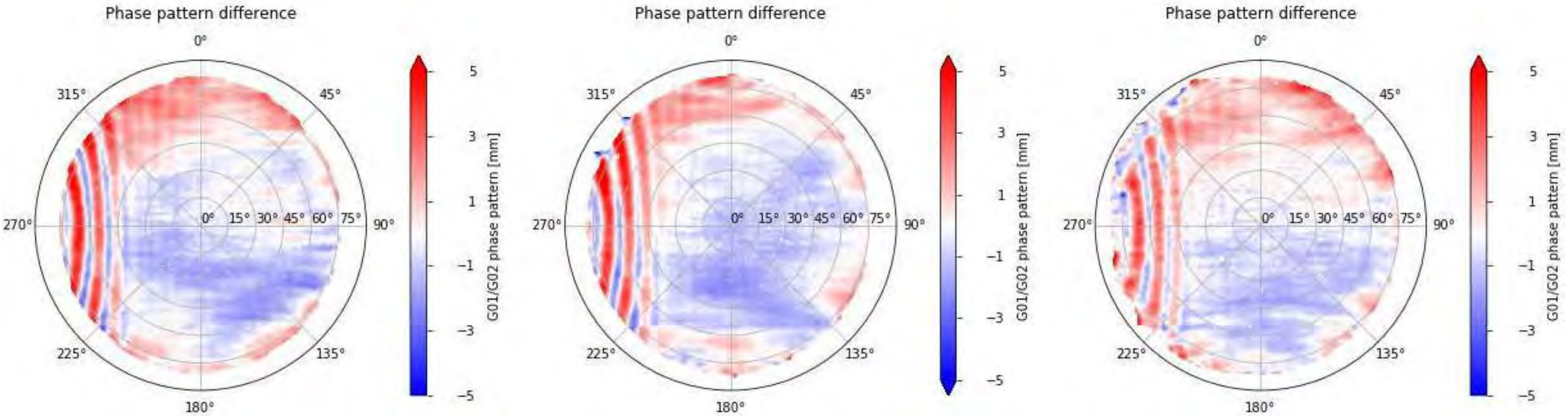


The in-flight PCV maps: ionosphere-free as obtained by the residual approach by DLR.

Provided by P. Steigenberger and O. Montenbruck

Crosstalk: example GRACE

Difference for GRACE-A between follower and leader configuration

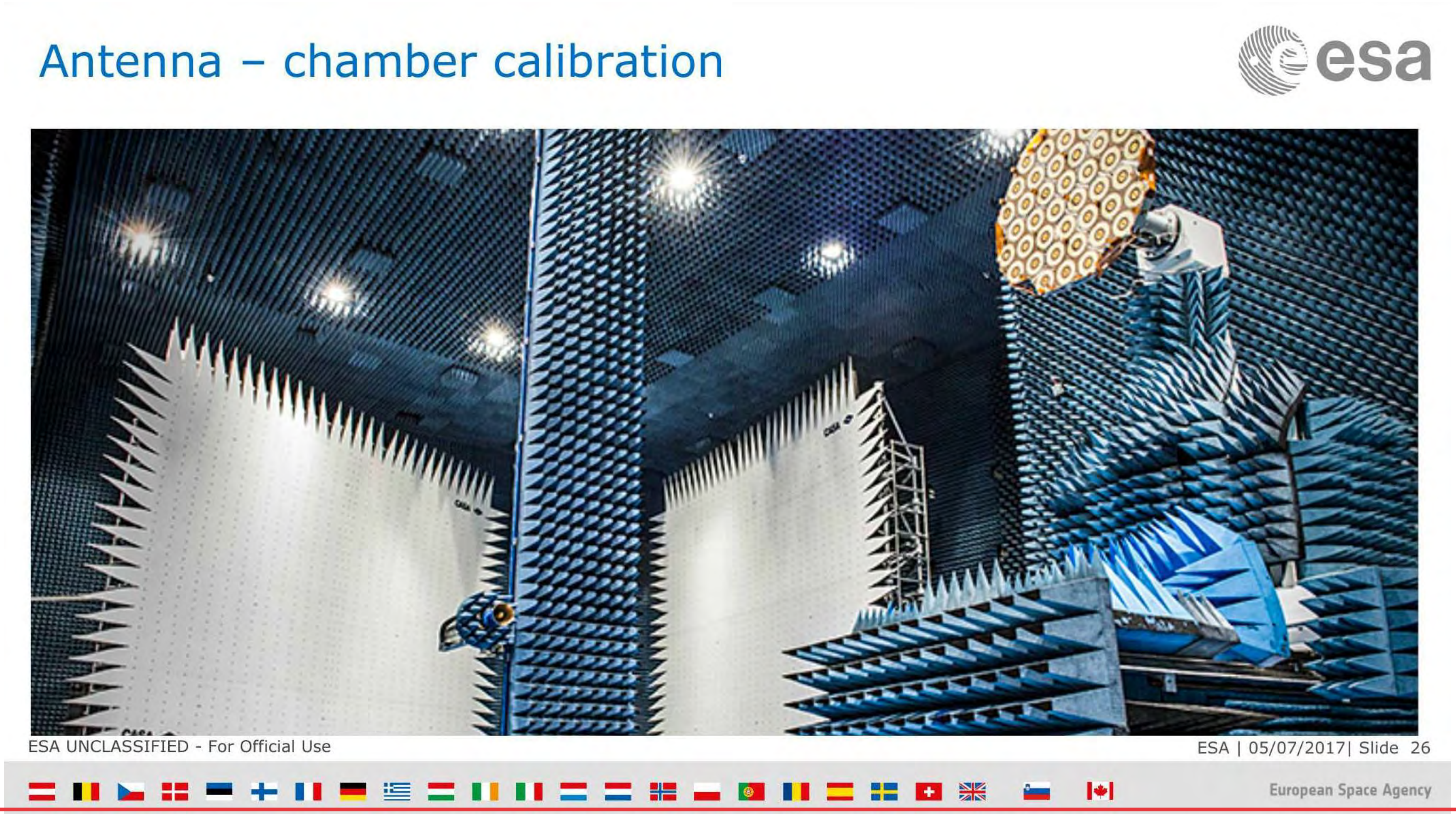


The in-flight PCV maps: ionosphere-free as obtained by the residual approach by DLR.

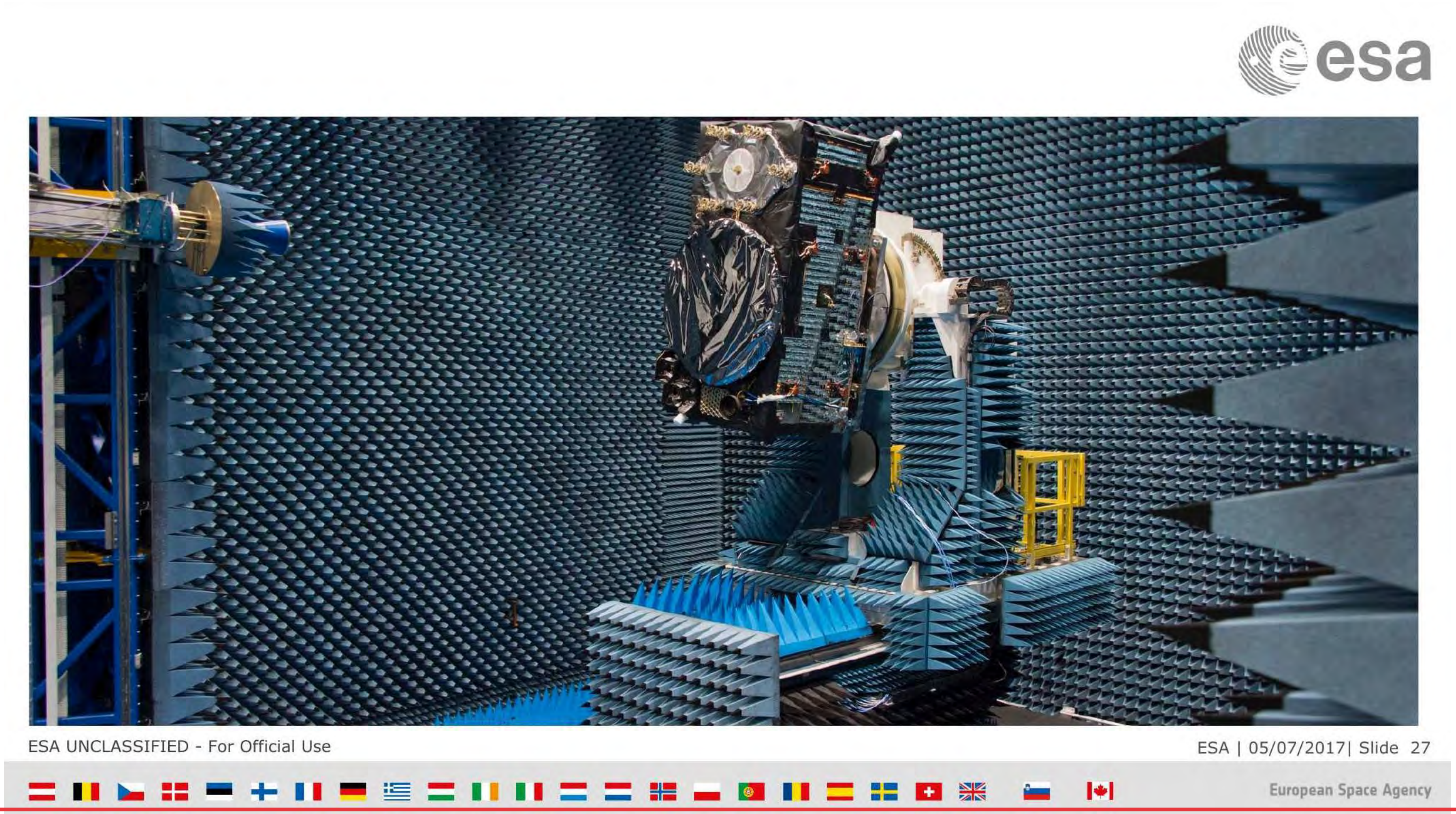
Provided by P. Steigenberger and O. Montenbruck

Calibration of Galileo satellite antennas

Calibration of Galileo satellite antennas



Calibration of Galileo satellite antennas



Summary

- We need to calibrate the antenna on the fully assembled satellite!
  The calibration should be done down to the horizon (0 degree elevation).

- The definition of the ARPs for GNSS and the other techniques (and the CoM) need to be clearly communicated to all components.

- Crosstalk: it can either be demonstrated that the instruments are sufficiently shielded, or it needs to be included in the calibration.

- Use the Galileo antenna facility to extend the antenna characterization up to 30 degree (preferable for Galileo 1st and 2nd generation).