

# WG2 GNSS

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11:00 Introduction

11:05 Status of IGS ACs regarding Genesis

- 10' Report GRGS
- 5' Report JPL
- 5' Report GFZ
- 10' Report ESOC
- 10' Report CODE

11:45 GNSS Instrument and Payload

11:55 Discussion

- Receiver
- Calibration
- Orbit modeling

12:25 Summary

# WG2 GNSS

- Activities:
  - IAG WG meeting in Nov. 2025 (Frankfurt)
  - WG2 meeting in Feb. 2026 with focus on the GNSS receiver
  - Contribution to the calibration splinter meeting
- Upcoming:
  - Presentation at IGS Workshop 2026 and discussion with ACs

# Status of IGS ACs regarding Genesis

- JGX:
  - working on incorporating space based GNSS observations into our software and preparing to simultaneously estimate GNSS and LEO satellite orbit parameters
- WHU:
  - preparing the LEO-borne GNSS data processing capabilities
  - As L1/L2 or L1/L5 is under debate, we have generated all-frequency phase biases to enable undifferenced ambiguity resolution

# GRG ACTIVITIES

## WG2 GNSS

Alvaro Santamaría (CNES/GET)

Sylvain Loyer, Adrien Mezerette, Eléonore Saquet, Georgia Katsigianni, Adrian Baños-García (CLS)

GENESIS SCIENCE WORKSHOP 2026  
**12-13 MARCH 2026, BRUSSELS**

# CNES/CLS (GRG) ANALYSIS OVERVIEW

The CNES/CLS group operates IGS, IDS and ILRS Analysis Centers which are based on the CNES's GINS software.

We routinely process several constellations/missions independently as a contribution to the different IAG services:

- GNSS MEO (GPS, Galileo, GLONASS, BeiDou)
- DORIS LEO (Cryosat-2, Saral, Jason-3, Sentinel-3A, Sentinel-3B, Sentinel-6A, HY-2C, HY-2D, SWOT)
- SLR LEO (LAGEOS-1, LAGEOS-2, ETALON-1, ETALON-2, LARES-2)

In preparation for the ESA GENESIS mission, we are:

- 1) simulating GNSS/SLR/DORIS/VLBI observations with GINS.
- 2) combining GNSS/SLR/DORIS observations at the normal equation level using the pole coordinates and the Sentinel-6A orbit as space ties. Both Sentinel-3A/B have also been recently added.

The objective is to:

- Be prepared for the processing of the GENESIS observations.
- Assess the contribution of existing multi-technique missions to a TRF realization.
- Assess the benefits of including LEO satellites in the IGS solution (and inversely for POD).



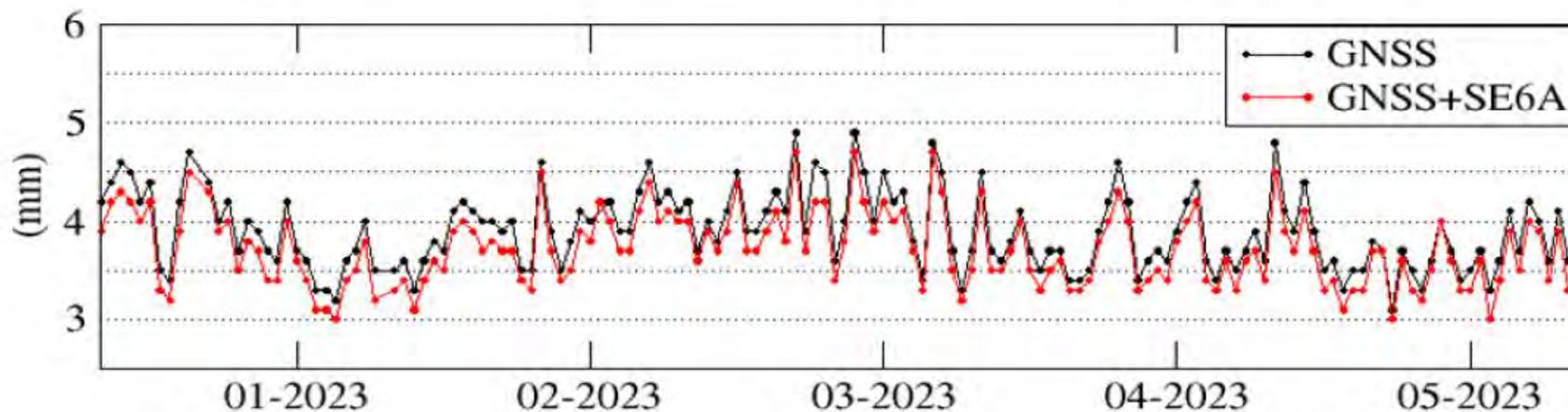
# IMPACT OF SENTINEL-6A IN THE GRG SOLUTION: NETWORK GEOMETRY

Reprocessing of 1.5 years of our GRG final GNSS products including Sentinel-6A observations.

Sentinel-6A maneuvers skipped.

Daily 3D WRMS of the station position residuals with respect to the IGS20 frame.

The inclusion of the Sentinel-6A GPS and Galileo observations slightly improve the geometry of the GNSS frame solution.

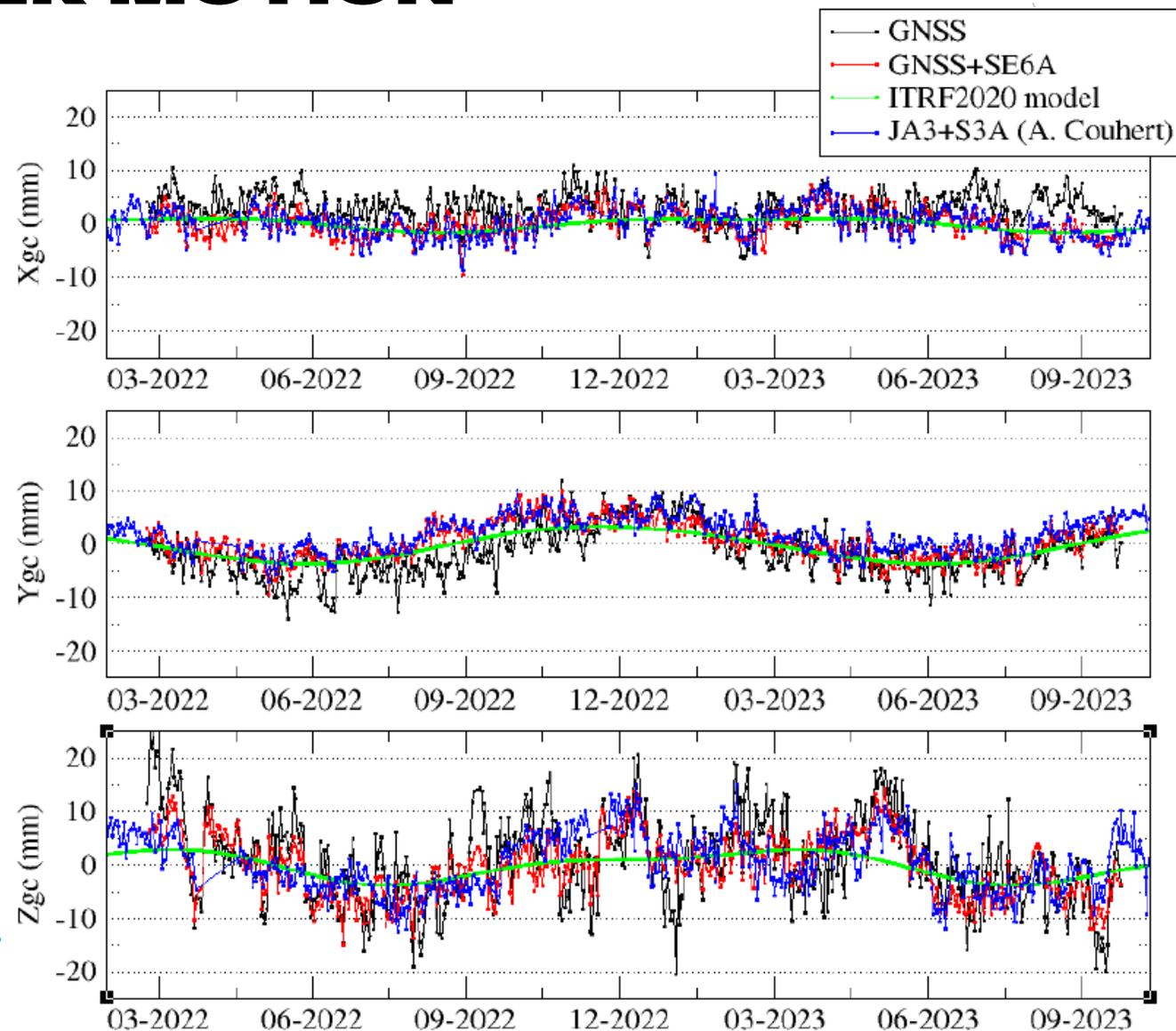


# IMPACT OF SENTINEL-6A IN THE GRG SOLUTION: GEOCENTER MOTION

Geocenter motion series obtained from the GNSS (black) and the GNSS + Sentinel-6A (red) solutions with respect to the IGS20 frame.

Geocenter motion is better constrained with the addition of Sentinel-6A.

Better agreement to the smooth seasonal ITRF2020 geocenter motion model (green), and especially, to the geocenter motion series obtained from the Jason-3 and Sentinel-3A missions (blue).

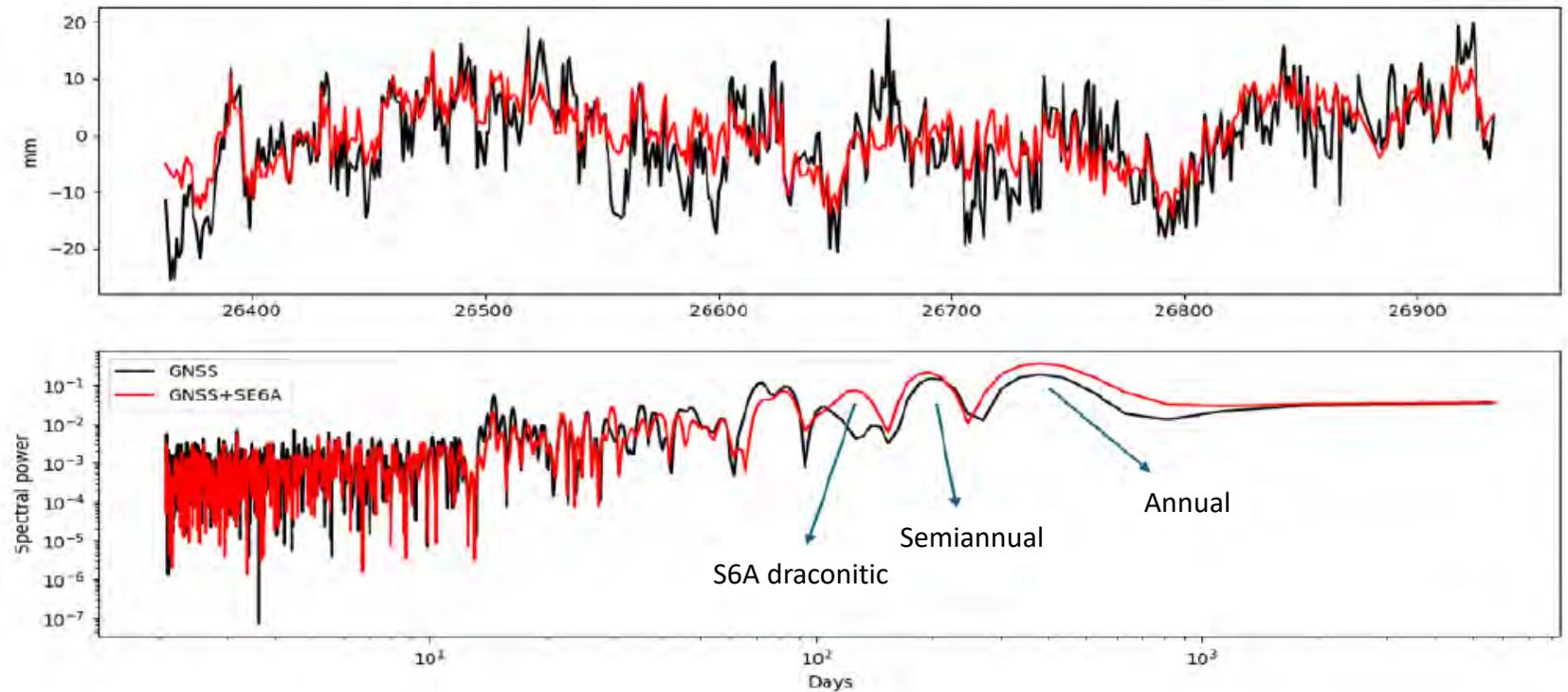


# IMPACT OF SENTINEL-6A IN THE GRG SOLUTION: DRACONITIC OSCILLATION

Geocenter motion series in the Z axis and its power spectral density obtained from the GNSS (black) and the GNSS + Sentinel-6A (red) solutions with respect to the IGS20 frame.

The reduction of the geocenter series noise is clearly visible.

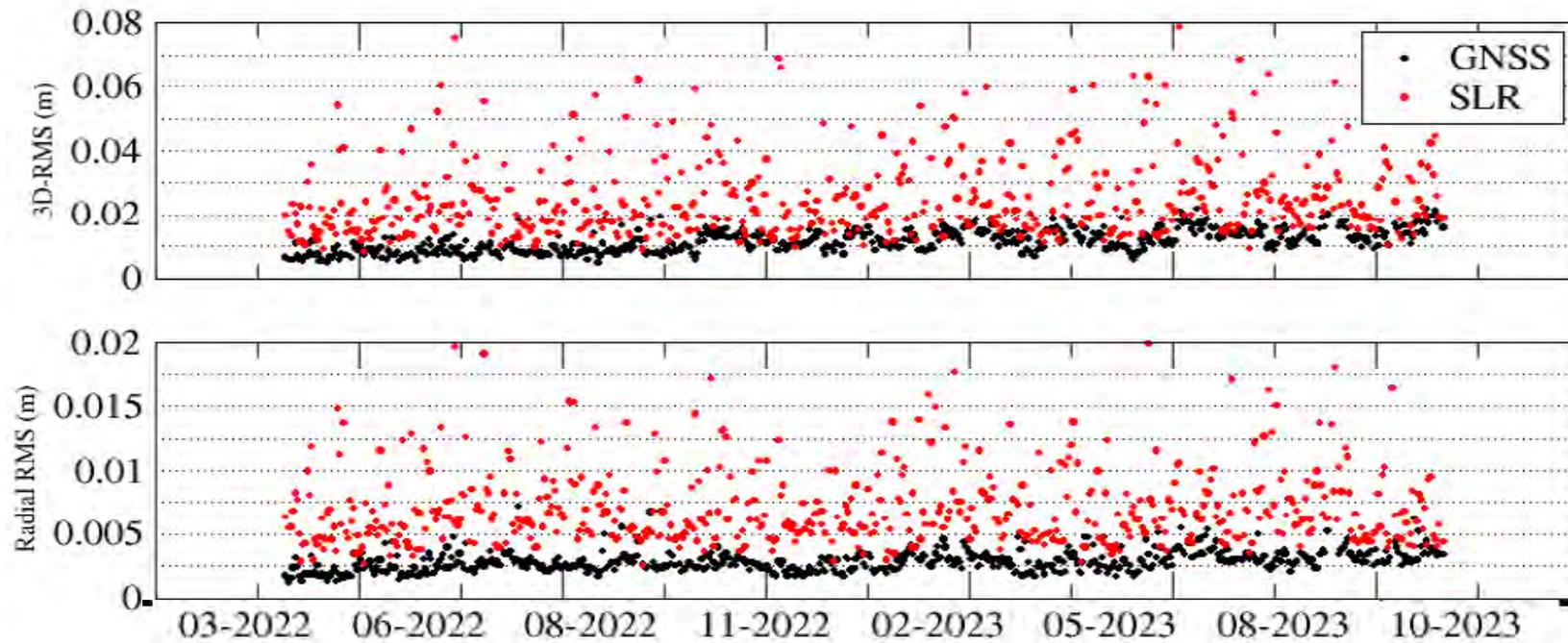
The Sentinel-6A draconitic oscillation (118 days) contaminates the geocenter motion series despite the inclined orbit and accurate attitude and SRP modeling.



# SENTINEL-6A ORBIT FROM THE GRG SOLUTION: LEO POD

Comparison of the Sentinel-6A orbit obtained from the GNSS (black) and SLR (red) GRG solutions with respect to the CNES POE orbit (GNSS + DORIS).

Sentinel-6A orbit from GRG GNSS solution at ~1 cm RMS 3D and 5 mm RMS in the radial direction.



# FUTURE STEPS

- Processing simulated GNSS observations with both the zenith and nadir antennas.
- Assessing additional parametric ties between GNSS/DORIS : clock/doppler biases and wet tropospheric delays.
- Assessing multi-technique PCO estimation on the Sentinel-6A/3A/3B.
- Expanding the list of OSB to GPS L5 and Galileo E5b/E6.
- Development of GINS to export the estimated orbital parameters in a normal equation solution to allow for LEO orbit combination.



## Preparing for GENESIS at the JPL IGS Analysis Center

**Paul Ries**, Bruce Haines, Willy Bertiger, Shailen Desai, Michael Heflin, Da Kuang, Charles Naudet, Athina Peidou

Jet Propulsion Laboratory, California Institute of Technology



**Jet Propulsion Laboratory**  
California Institute of Technology

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# Introduction

- WG1 poster highlights recent progress in TRF (go visit!)
- This talk highlights GNSS processing related to GENESIS at JPL IGS analysis center

**Combining Geodetic Techniques at the Observation Level: Challenges and New Perspective for the Terrestrial Reference Frame**

Paul Ries,<sup>1,2</sup> Bruce Haines,<sup>1</sup> Willy Bertiger,<sup>1</sup> Shailen Desai,<sup>1</sup> Michael Hefflin,<sup>1</sup> Da Kuang,<sup>1</sup> Charles Naudet,<sup>1</sup> Athina Peldou<sup>1</sup>

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, <sup>2</sup>ESA, ESA-ESRIN, Frascati, Italy

**Observation Level Frames**

Each of the four space geodetic techniques (GNSS, DORIS, VLBI, SLR) contributes with various strengths to a global terrestrial reference frame (TRF). The current International Terrestrial Reference Frame (ITRF) and frames preceding it have combined station positions and Earth orientation from each of the four techniques processed separately. Some such information is typically stored in a SINEX file, we refer to this form of reference frame as a combination of SINEX level files, where the four techniques are processed independently, then their outputs are later combined.

Recently, JPL has begun exploring reference frames which process measurements of the observation level from all four techniques concurrently (Haines 2020), resulting naturally in the combination of the four techniques. We refer to this as a Combination of observation level frames.

**Space Ties**

In typical TRF solutions, techniques were tied together using surveyed site ties between different ground sites (e.g. between an SLR station and a nearby GNSS receiver). Measuring such ties is challenging. In our research, we use spacecraft which provide ties of opportunity with precisely measured realizations of realizations from multiple geodetic techniques.

By using Jason-2 and the GRACE mission we are able to tie together GNSS and SLR without using ground ties. Our most recent development is using Jason-2 to add DORIS to the solution with space ties.

Reference	GNSS	SLR	VLBI	DORIS	Years
Jason-2	X	X	X	X	2010-2010
Jason-3	X	X	X	X	2016-
GRACE-A/B	X	X			2002-2017
GRACE-FO	X	X			2016-
Satellite-A	X	X	X		2001-
Satellite-B	X	X	X		2005-
GOCE	X	X	X		2009-
GRACE	X	X	X		2006-
GENESIS	X	X	X	X	2020-

**3-technique reference frame at measurement level**

Time Span: 2010.0 – 2022.0  
Arc length: 3.25 d  
Number of GPS stations per solution: 45  
Subset of total: 250 stations.

- GNSS (385)
- SLR (4)
- VLBI

Linear and areal models for:  
- 215 GNSS sites  
- 27 SLR observations  
- 17 VLBI stations

Derived GPS-SLR ties:  
- Site vs surveyed values  
- Mean E, N, V accuracy: 3, 8, 5 mm

**4-technique results**

Consistent geocenter results with unified 3-technique time series  
DORIS Jason 1600000000 reproduced at ~4 cm in horizontal

**Challenges with existing opportunistic ties**

- Adding ability to process multiple clocks for existing DORIS platforms
- Adding all necessary calibrations (e.g. SLR biases, VLBI antenna offset correction)
- No current space ties for VLBI (requires ground ties)
- Preprocessing of diverse array of file formats
- Acquiring all necessary data for LEOs (GNSS, SRP tracking, attitude modelizable quaternion)

**Future work**

- Add additional LEOs with DORIS
- Add additional SLR-only platforms (LARES 1 + 2)
- Extend 4-technique from 2010 to present (vs. 3-month bias)
- Convert output to SINEX files
- Process GENESIS

**Acknowledgements and References**

Paul Ries is supported by the Jet Propulsion Laboratory, California Institute of Technology, under a grant from NASA.

Haines, B., Bertiger, W., Desai, S., Hefflin, M., Kuang, D., Lemoine, F., Naudet, C., Peldou, A., Ries, P., Sideris, A., & Desai, S. (2020). Combining Geodetic Techniques at the Observation Level: Challenges and New Perspective for the Terrestrial Reference Frame. *Journal of Geodesy*, 94(1), 1-12.

Haines, B. (2020). Exploring reference frames which process measurements of the observation level from all four techniques concurrently. *International Geodesy and Earth Observation*, 10(1), 1-12.

Hefflin, M., Bertiger, W., & Ries, P. (2019). Combining Geodetic Techniques at the Observation Level: Challenges and New Perspective for the Terrestrial Reference Frame. *Journal of Geodesy*, 93(1), 1-12.



# Readiness to process GENESIS

- Can we process GNSS receiver with multiple antennas?
  - **Yes**, but some work desirable
  - Sentinel-6A has main POD receiver (PODRIX) and JPL-supplied RO (TRiG)
  - Produce good orbit using simultaneous data from both receivers
- Can we perform precise OD with GNSS receivers in MEO and beyond?
  - **Yes**
  - Already done with NTS-3 (GEO, nadir antenna)
  - Extensive simulations for SunRISE mission (highly eccentric orbit)
- Can we perform simultaneous OD of both GNSS transmitters and orbiting GNSS receivers and a ground network?
  - **Yes**
  - Already done over a period of years as part of combination-at-observation-level frames
- Can we exchange info on non-GNSS satellites with other ACs/ACC?
  - **No!**
  - Need to define format of exchange



# Experience testing flight receivers

JPL has built and tested many GNSS Receivers

- Jason-1,2,3, GRACE, GRACE-FO, NISAR, SWOT, S6
- Experience evaluating receivers pre-launch

## Good

- Testing receiver with flight-like scenario in GNSS simulator

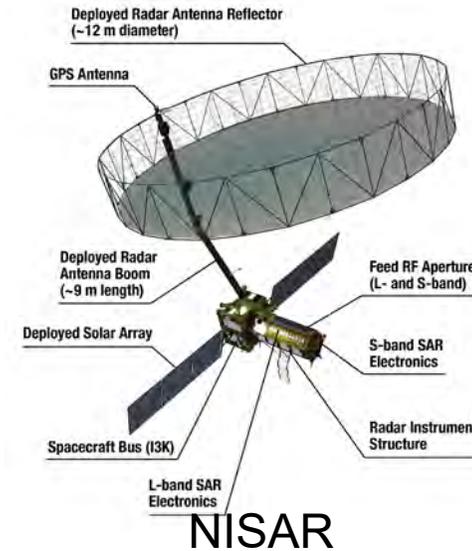
## Better

- Testing receiver with live-sky data from rooftop antenna

## Best

- Testing receiver with live-sky data from rooftop antenna along with known geodetic reference receiver (e.g. Septentrio POLARX5, Leica GR50, Trimble Alloy), to test double differences

**Live-sky data enable evaluation of ambiguity resolution; simulator data does not**



Sentinel-6



SWOT



# Experience testing flight antennas

JPL has built and tested some flight antennas

- TOPEX, GRACE

## Good

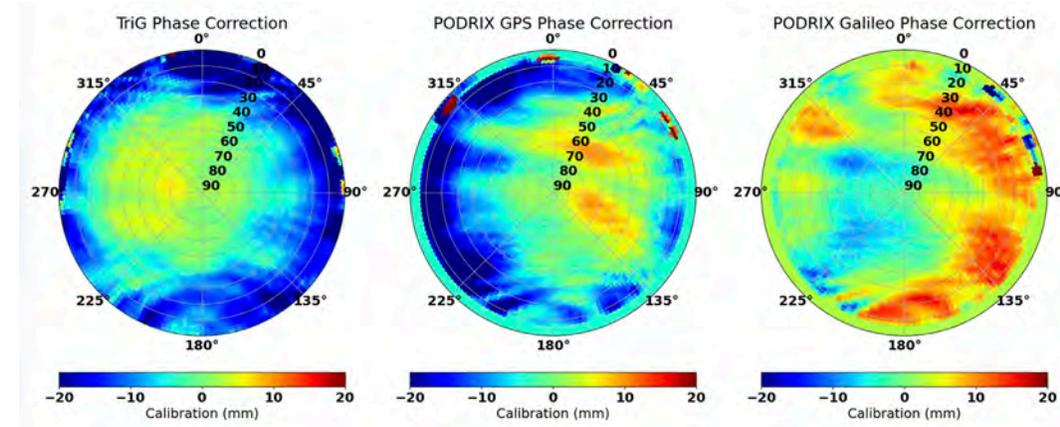
- Testing antenna in anechoic chamber
- Testing antenna in a test range

## Better

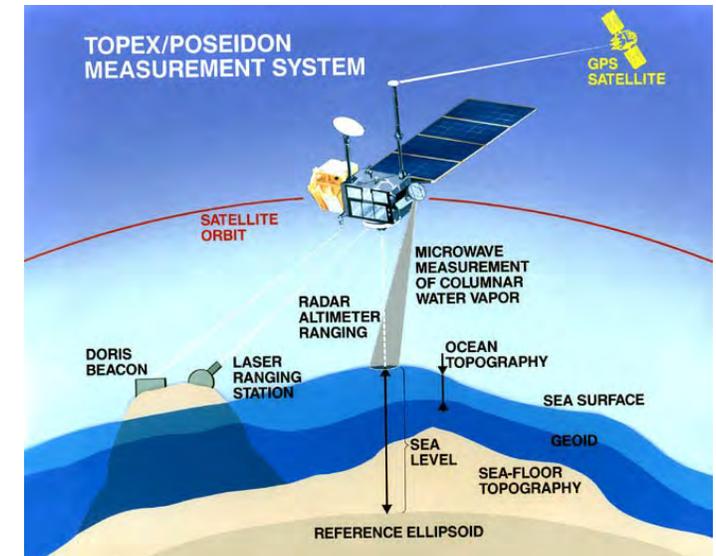
- Testing antennas on spacecraft mock-up in anechoic chamber
- Solving for antenna patterns on-orbit (e.g. Conrad et al. 2024 for Sentinel-6A)

## Best

- Testing antenna on full spacecraft bus in anechoic chamber



Sentinel-6A



# GFZ investigations on space-based GNSS processing

B. Männel, L. Tang

GFZ Helmholtz Centre for Geosciences

Potsdam, March 13 2026

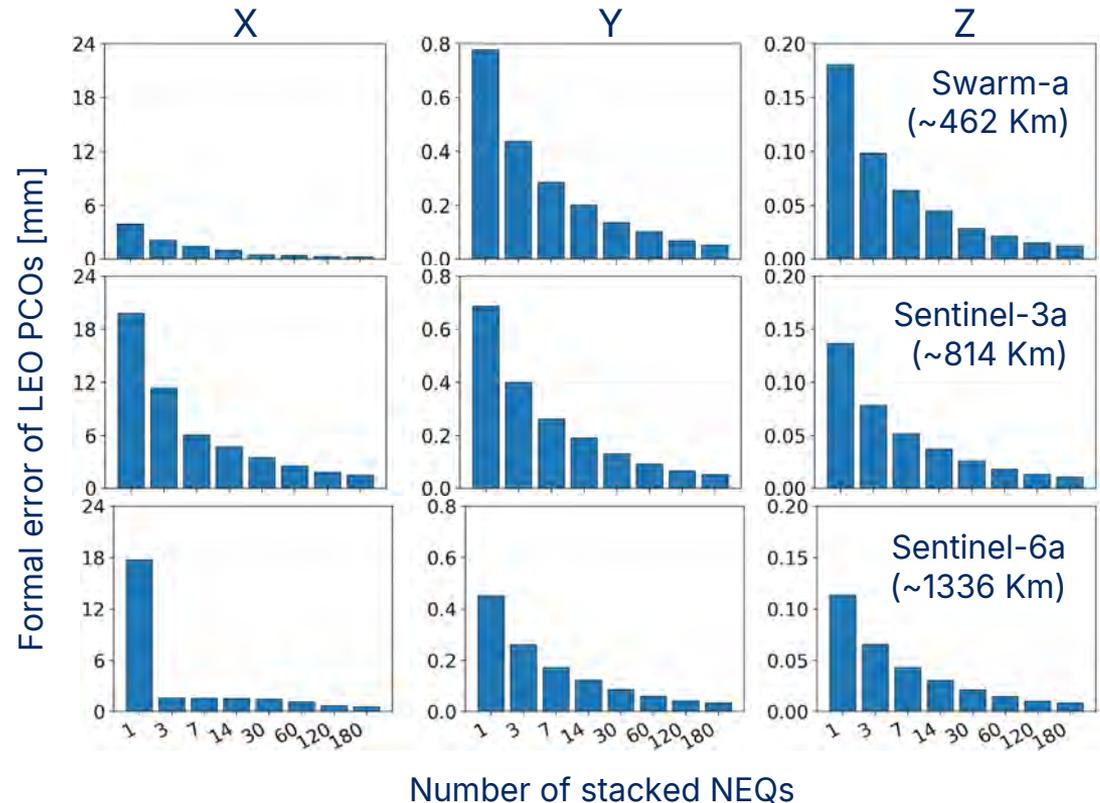


**GFZ** Helmholtz Centre  
for Geosciences

**HELMHOLTZ**

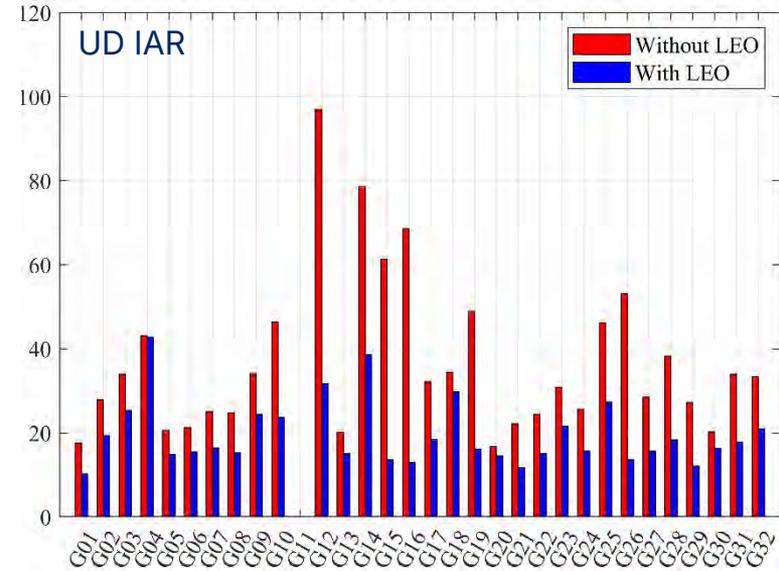
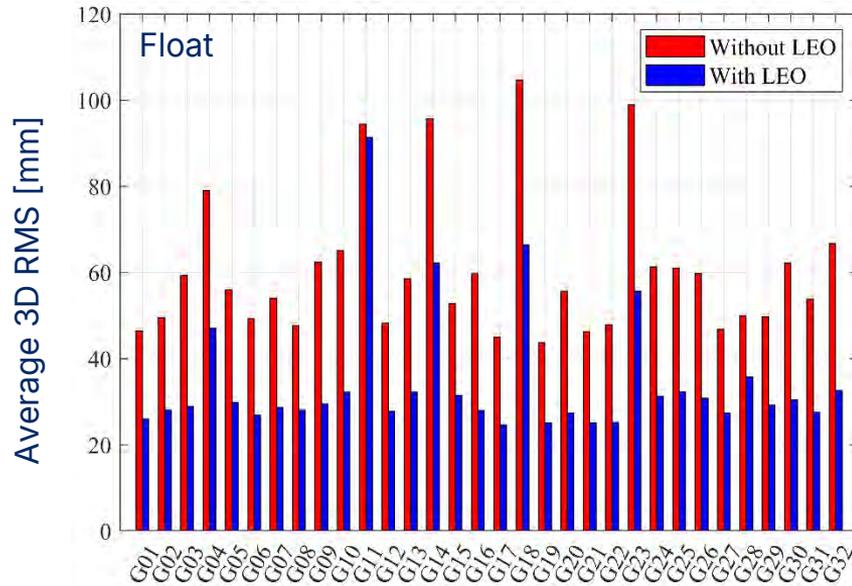
# LEO antenna in-flight calibration

- LEO PCOs and PVs are calibrated simultaneously via multi-day GNSS/LEO solution (= in-flight calibration)
- Multi-day parameter stacking reduces the formal error significantly
- Z component shows smaller formal errors than X and Y (expected)



# Contribution to GNSS orbits

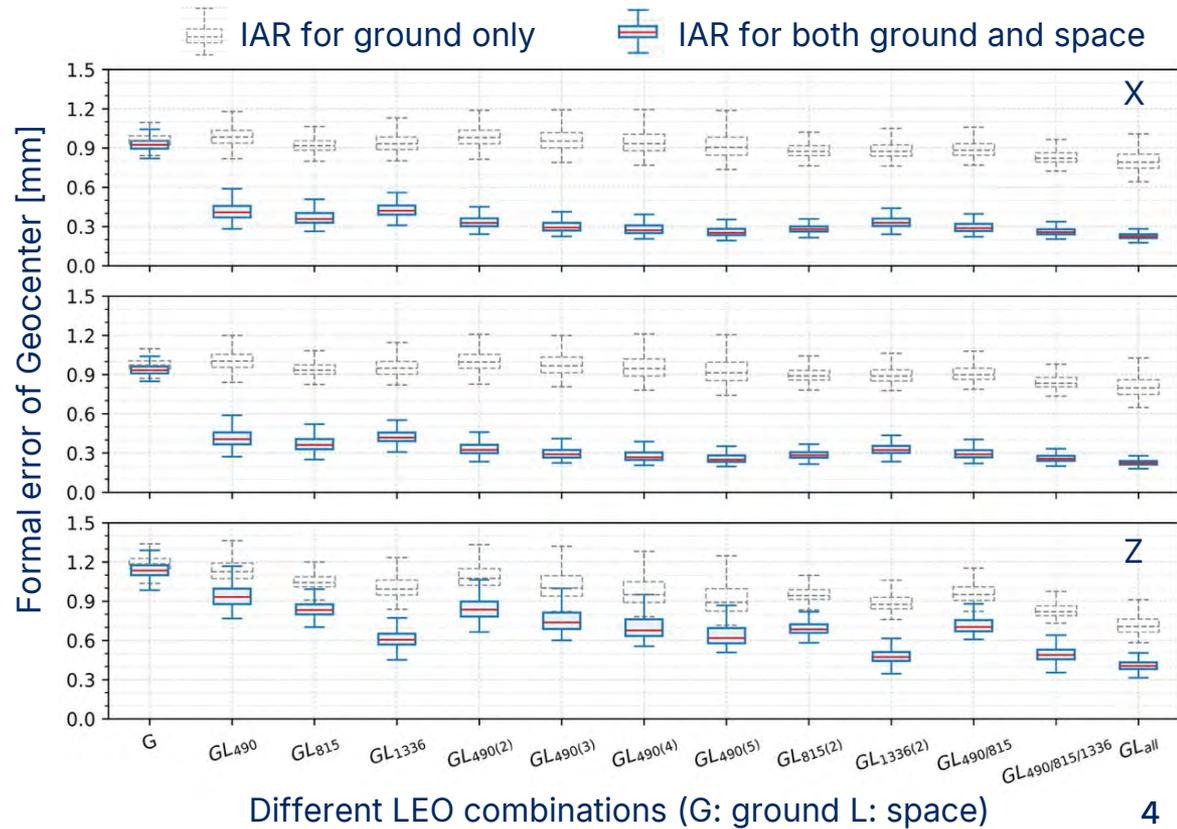
## ➤ Comparison against IGS final orbits



- Without LEO: 3D RMS is reduced from 60.4 to 41.0
- With LEO : 3D RMS is reduced from 34.5 to 20.9

# Contribution to Geocenter

- ✓ Integer ambiguity resolution (IAR) for LEO observations reduces formal errors especially in the X/Y directions
- ✓ High-altitude LEOs significantly improves the estimation of Z component
- ✓ Increasing the number of LEOs enhances the solution stability



# ESA AC – Overview of Genesis-related activities

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Genesis Workshop - GNSS WG2

ESA Navigation Support Office at ESOC

Bruxelles 12-13/03/2026

1. Preparation for Genesis: COOL processing
2. Genesis internal activities
3. Support to industry
4. Collaboration with scientific community

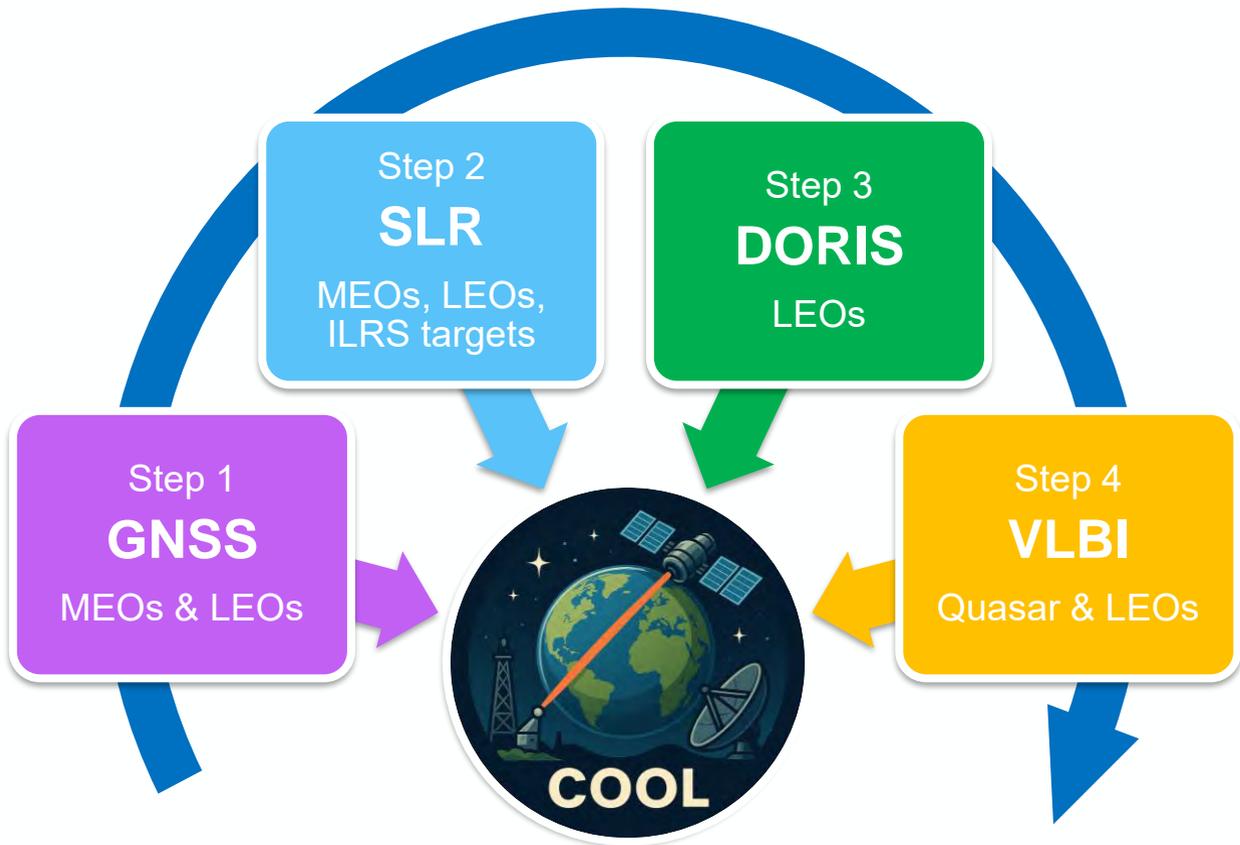


The combined multi-satellite, multi-technique processing takes advantage of the currently independent geodetic products:

- **GNSS** products:
  - **ESA IGS** Final Multi-GNSS contribution (MEO and GEO satellites)
  - **ESA Sentinel POD Copernicus** contribution (LEO satellites)
- **SLR** products:
  - **ESA ILRS** Final contribution (SLR targets)
- **DORIS** products
  - **ESA IDS** contribution (LEO satellites)
- **VLBI** products:
  - **ESA IVS** contribution [Unofficial] (Quasars and soon also satellites!)



... and builds on top to make the most of the satellite space-ties!



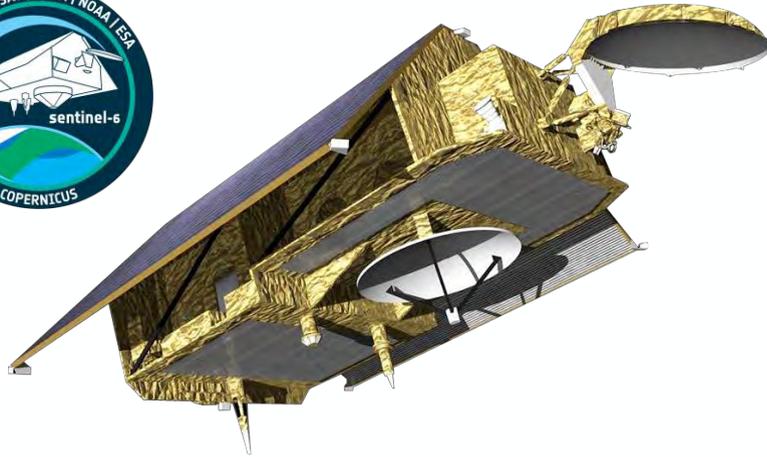
## Main objectives:

- Combine **all 4 geodetic techniques** together in one single processing run
- Benefit from the **strengths of each technique**
- Detect and **reduce technique-specific systematics**
- Exploit additional **Normal Equation Stacking**
- Get the **ESA Precise Navigation System** software and knowledge **ready for routine Genesis processing**, contributing to the achievement of the mission objectives

# Sentinel satellites as Genesis proxies

In preparation for Genesis, the team focuses on using current LEOs observations which already accommodate multiple geodetic techniques: GNSS, SLR and DORIS (VLBI to come)

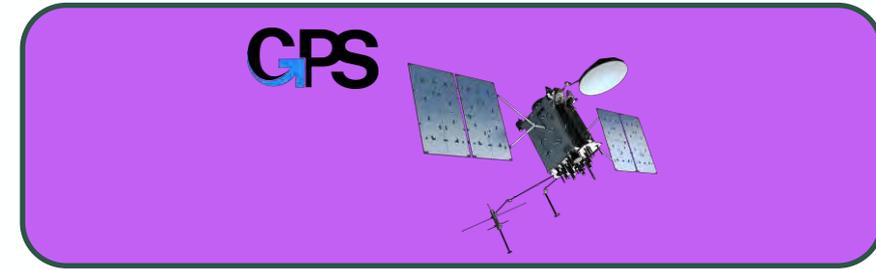
## Sentinel-6 Michael Freilich



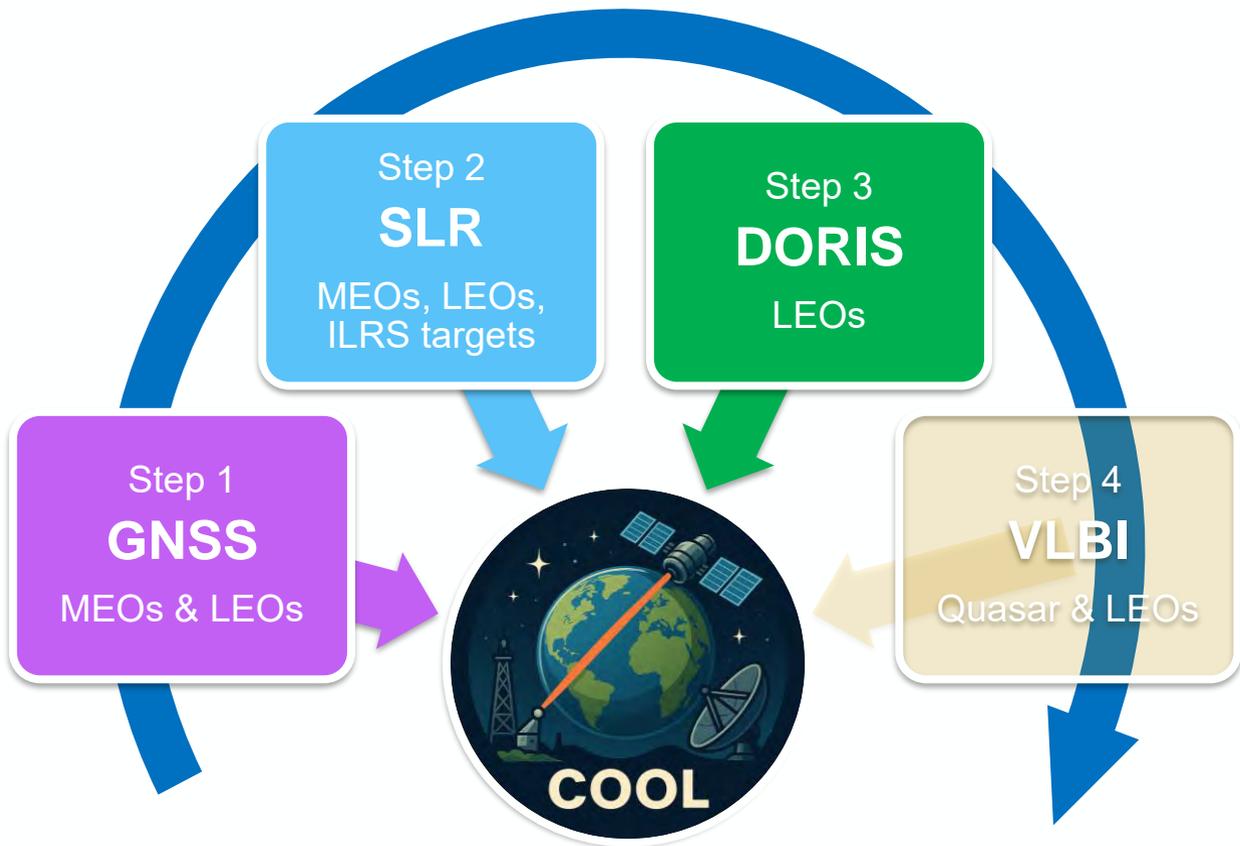
## Sentinel-3 A&B



GNSS (GAL+GPS), SLR, DORIS



GNSS (GPS), SLR, DORIS



**Step 1**  
**GNSS + Sentinel satellites**

- Sentinel satellites added to Galileo and GPS processing
- Sentinel satellites added to the Multi-GNSS processing

**Step 2**  
**SLR to Galileo, Sentinel and ILRS targets**

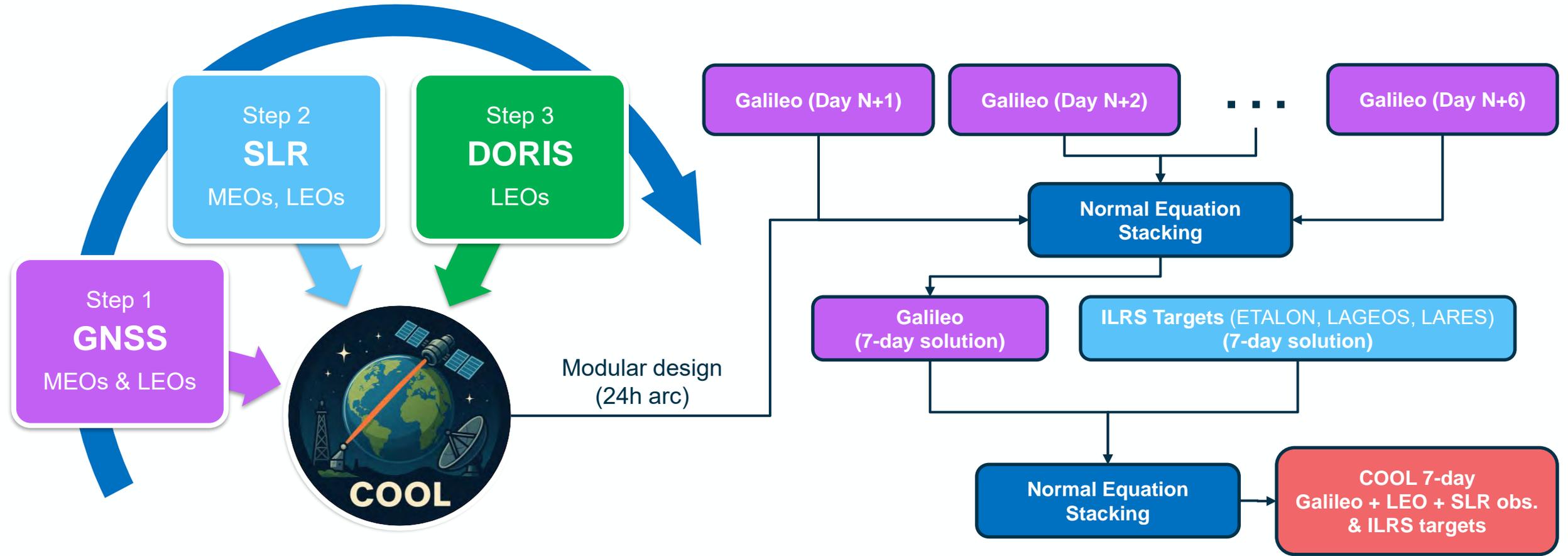
- SLR observations to Galileo and Sentinel added to the GNSS processing at the observation level
- SLR observations to ILRS targets (ETALON, LARES & LAGEOS) added to the GNSS processing at the normal equation level

**Step 3**  
**DORIS (Work in Progress)**

- DORIS observation to Sentinel added to the GNSS+SLR processing at the observation level
- DORIS observations to IDS targets added to the GNSS+SLR processing at the normal equation level



# COOL processing + NEQ stacking (w. ILRS)



**Galileo (Day N) stands for:**  
**GNSS:** MEO (Galileo) + LEO (Sentinel-6A)  
**SLR:** MEO (Galileo) + LEO (Sentinel-6A)  
**DORIS:** LEO (Sentinel-6A)

### Ongoing iterative process to fine tune:

- ensuring consistency (same EOP parameterization, UTS→GPS conversion)
- identifying optimal inter-technique relative weighting (and bias handling)

- **Improved orbit repeatability for Galileo and Sentinel satellites**
  - Reducing more than 10% the 3D RMS of the orbit overlaps from the stand-alone Galileo solution
  - Reducing around 15% the 3D RMS of the orbit overlaps for Sentinel-6A compared to the Sentinel POD Copernicus contribution
- **Improved Geocentre consistency:**
  - COOL solutions more aligned to ITRF2020-u2023 origin than the stand-alone Galileo, benefiting from LEO and SLR contributions
- COOL solutions show **consistent Earth Orientation Parameter standard deviation**, maintaining the GNSS-only level accuracy with respect to IERS 20 C04
- Many aspects are still “**work in progress**” but ...

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- COOL solutions show **consistent Earth Orientation Parameter standard deviation**, maintaining the GNSS-only level accuracy with respect to IERS 20 C04
- Many aspects are still “**work in progress**” but ...

... the **COOL** Genesis effect has already begun

## ESOC Internal Activities (Ongoing and Upcoming)

- Conducting **Genesis software simulations** (IFEN NCS Nova) at ESOC, utilizing the Genesis PDR orbit (sim. for 2025)
- Performing **link budget and visibility analysis** for GPS L1-L2-L5 and Galileo E1-E5a
- Evaluating the accuracy of **Solar Radiation Pressure modeling** by comparing ray-tracing methods\* with traditional approaches
- (Planned) Activities for the **generation of GPS L5 products\***

## Support to industry

- Carrying out a preliminary **performance evaluation of the Genesis SpacePNT NavIMEO receiver** through hardware-in-the-loop simulations by SpacePNT. The receiver is being fine-tuned by SpacePNT based on ESA's feedback to achieve desired performance levels.

## Collaboration with the Scientific Community

- Active participation in all **Genesis Working Groups**
- **Collecting recommendations to facilitate their effective integration** into project and industry activities
- **Produce and Release of the Reference Orbit(s)** to enable coordination of scientific analysis

# Thank You!

## ESA AC – Overview of Genesis-related activities

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We welcome and encourage questions, comments  
and recommendations:

[Navigation-Office@esa.int](mailto:Navigation-Office@esa.int)

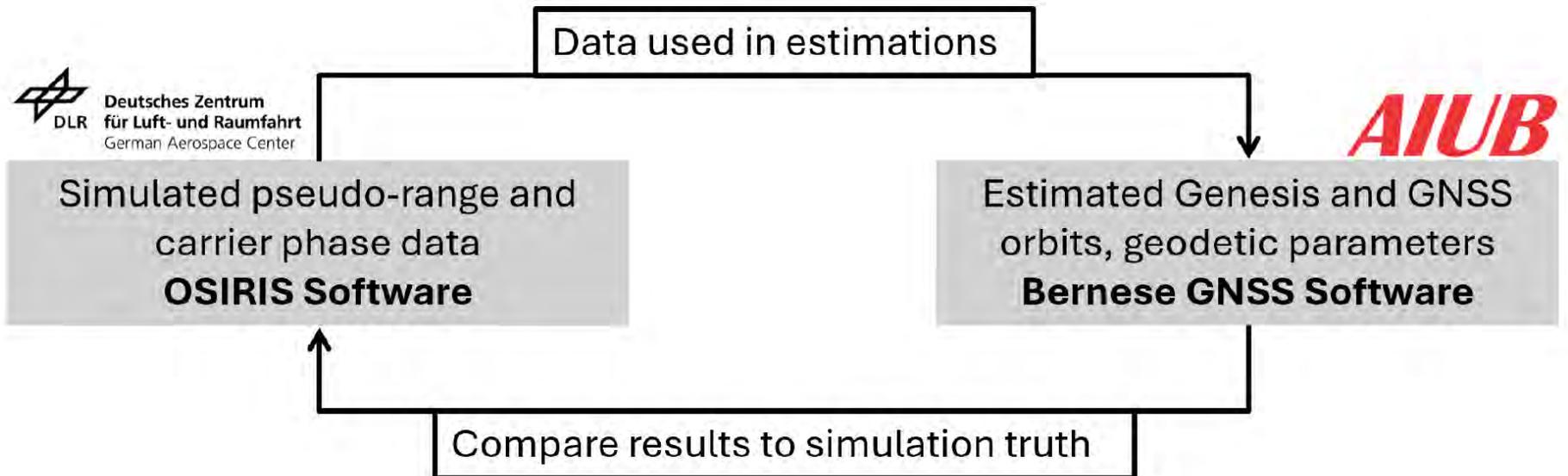
# Towards Genesis: Status report from CODE

CODE AC Team

*Astronomisches Institut*

# Genesis Simulation Set-Up

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



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

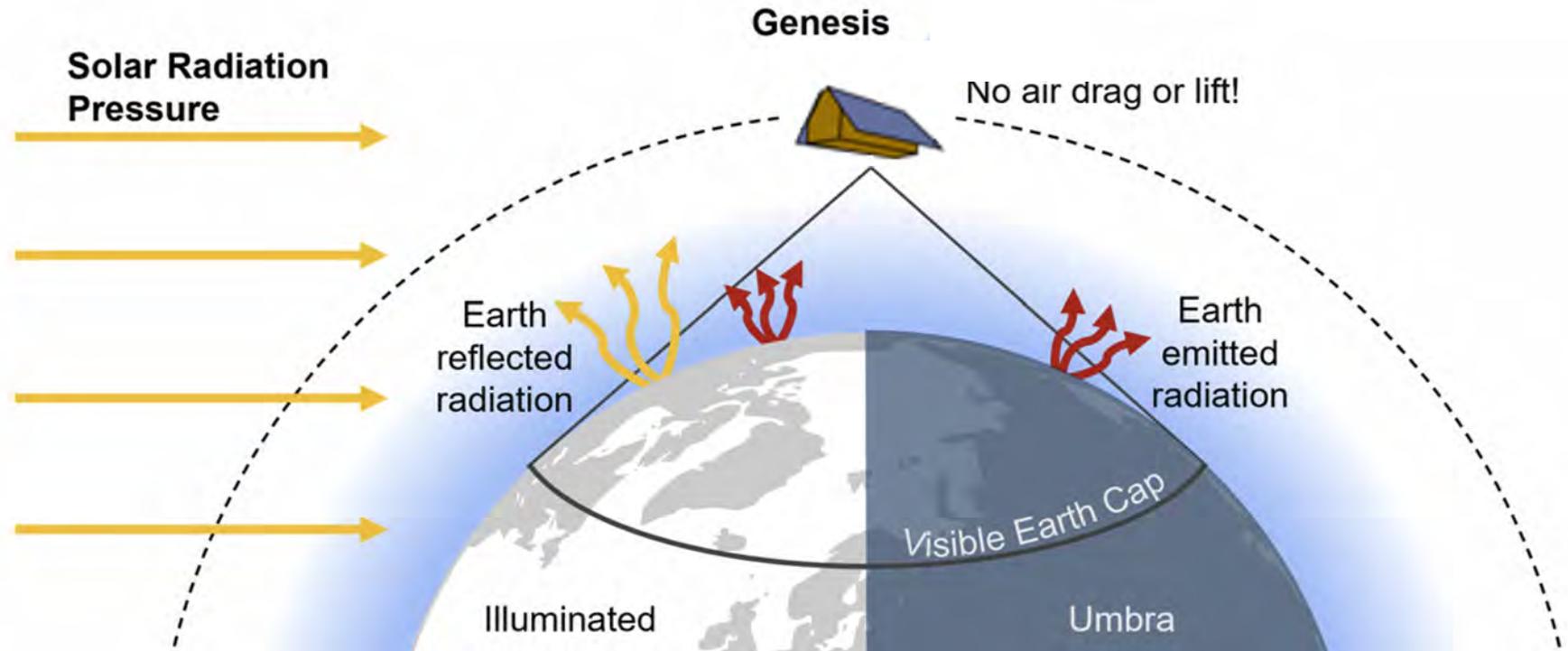
To absorb possible mismodeling, Piecewise Constant Accelerations (PCAs) are estimated for the Genesis orbit over 6 min intervals. Their magnitude is constrained using different a priori standard deviations.

**Relaxed:** orbit is more data-driven,

**Strict:** orbit is more model-driven

# Genesis Simulation Set-Up

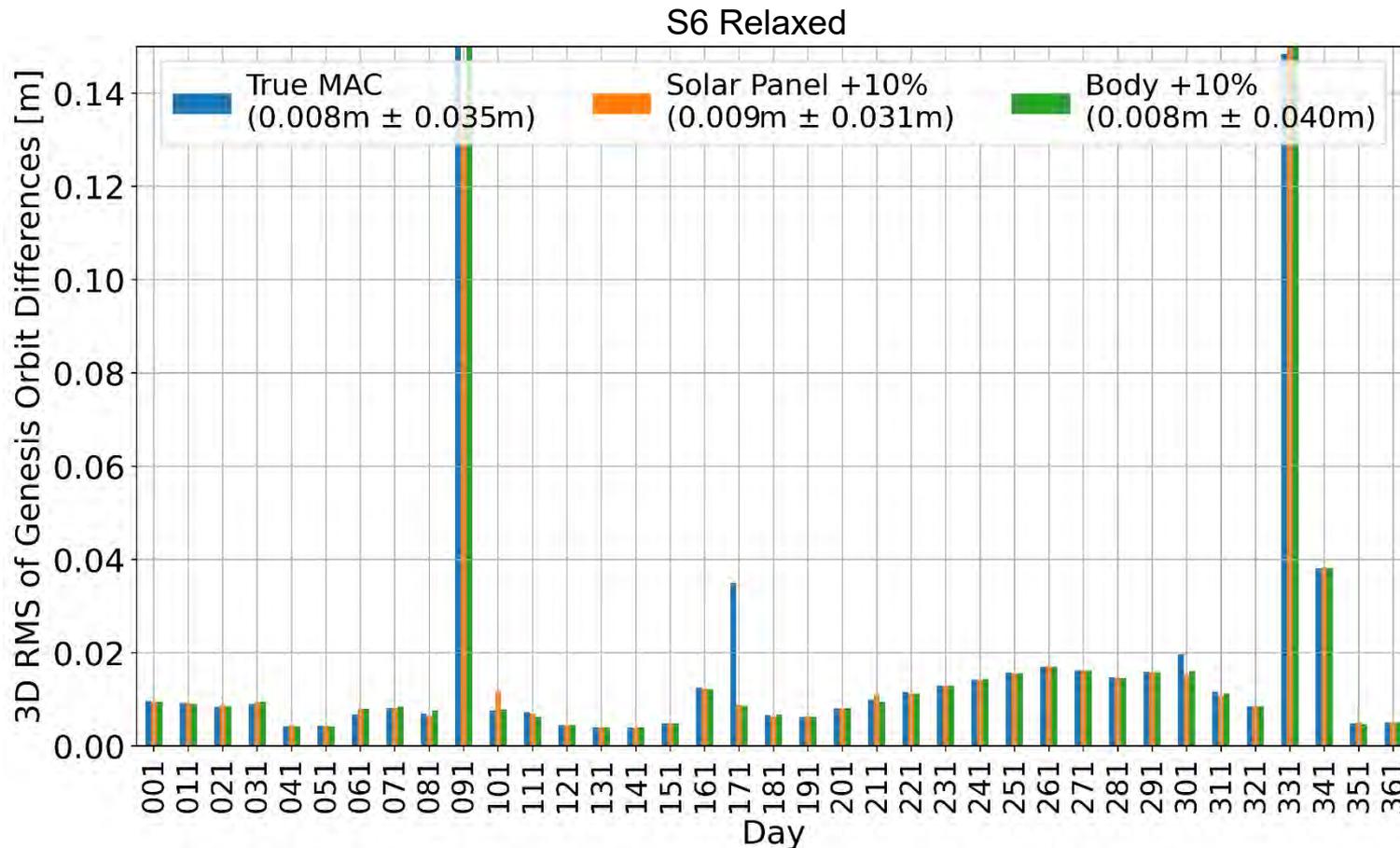
Master Thesis of Alexandra Miller:



Different Genesis designs → different spacecraft geometry and optical properties, described by the macro model (MAC).

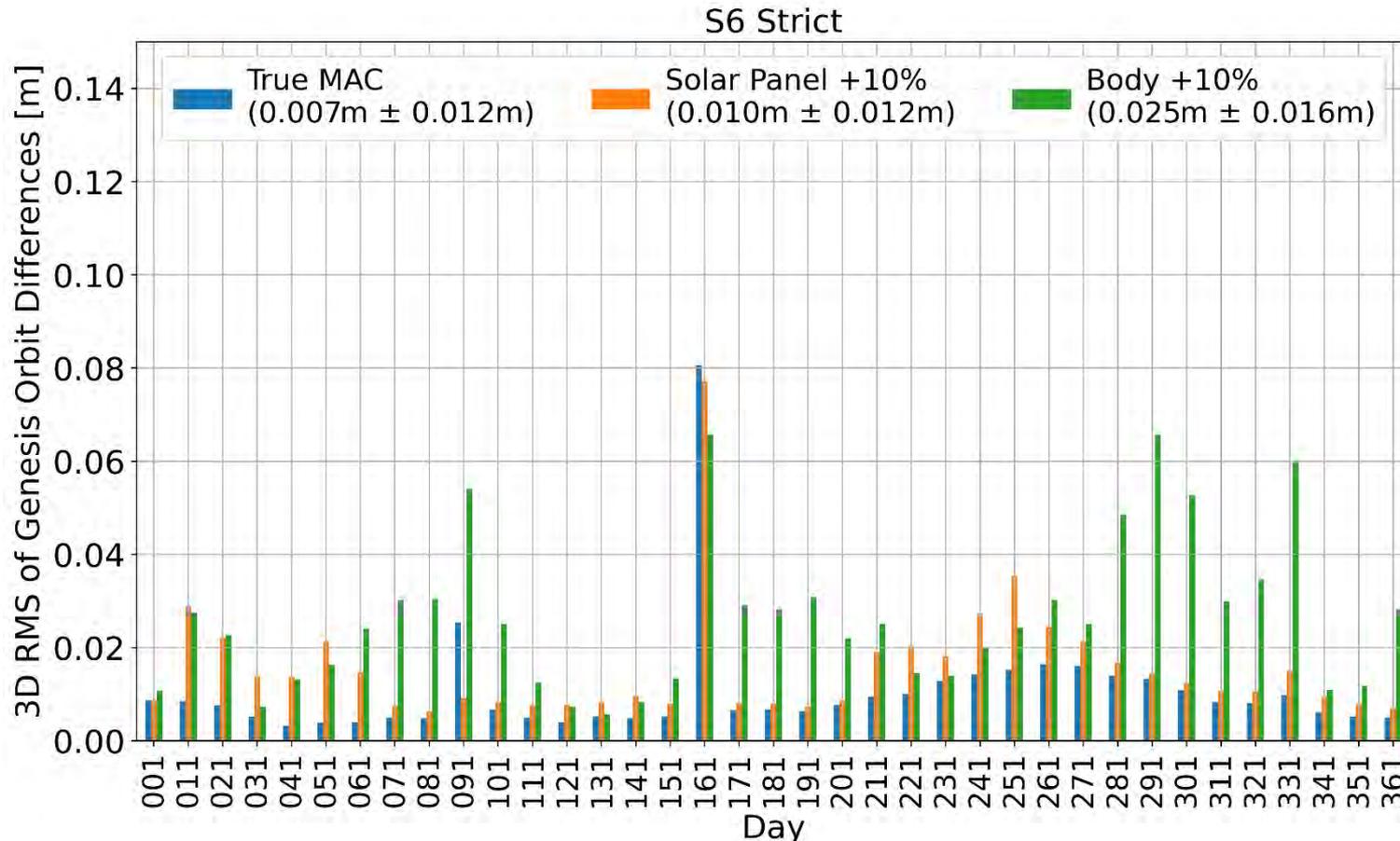
In this presentation we will focus on the Sentinel-6-like (S6) model. Uncertainties of 10% will be introduced on the optical properties.

# Genesis-Only Orbit Determination



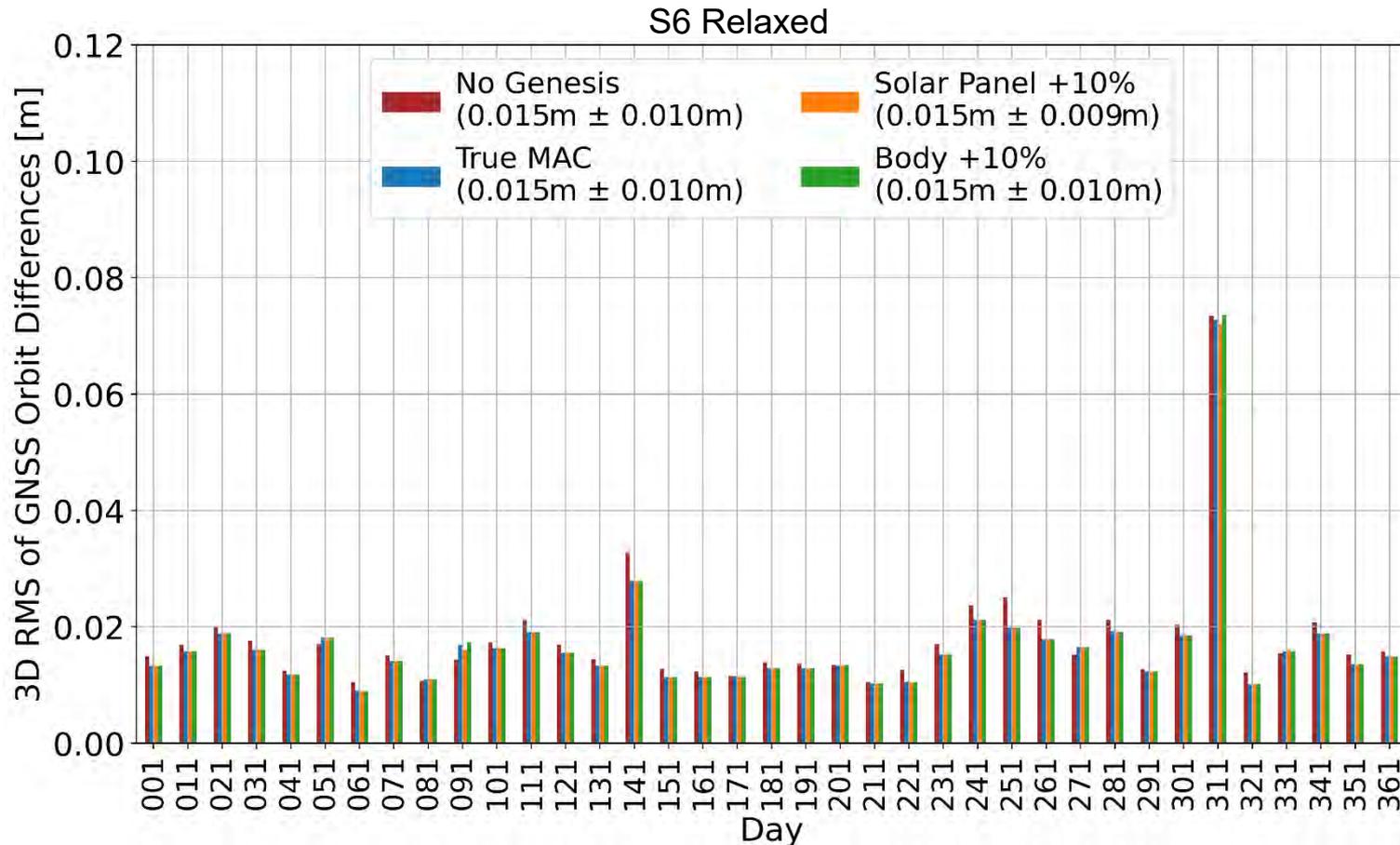
Genesis orbits estimated during the Genesis-only processing are compared to the simulation truth. The true geodetic parameters and GNSS orbits and clocks are used. Modeling errors are absorbed by **relaxed** constraining.

# Genesis-Only Orbit Determination



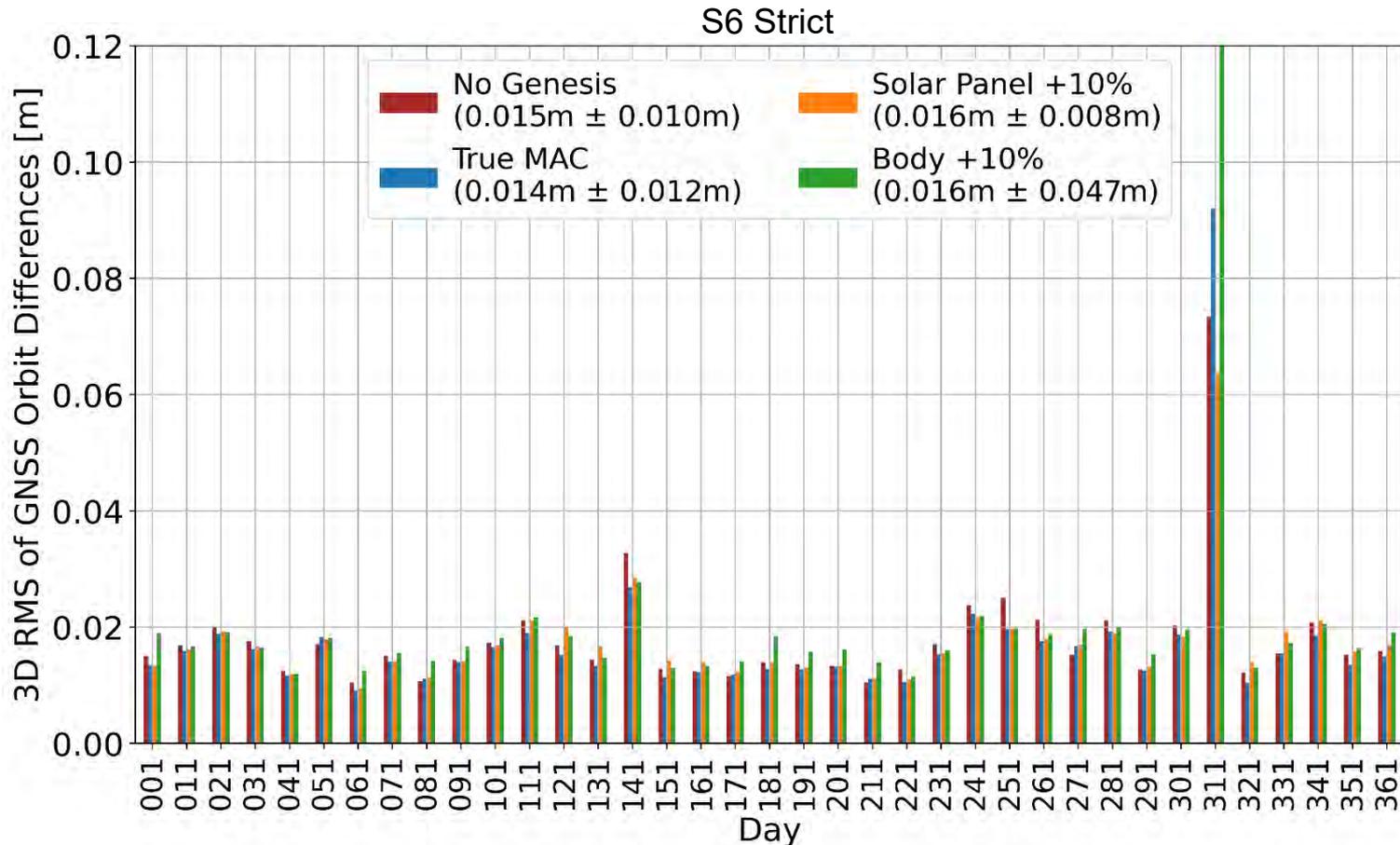
Genesis orbits estimated during the Genesis-only processing are compared to the simulation truth. The true geodetic parameters and GNSS orbits and clocks are used. Modeling errors are visible for **strict** constraining.

# GNSS Orbit Estimations



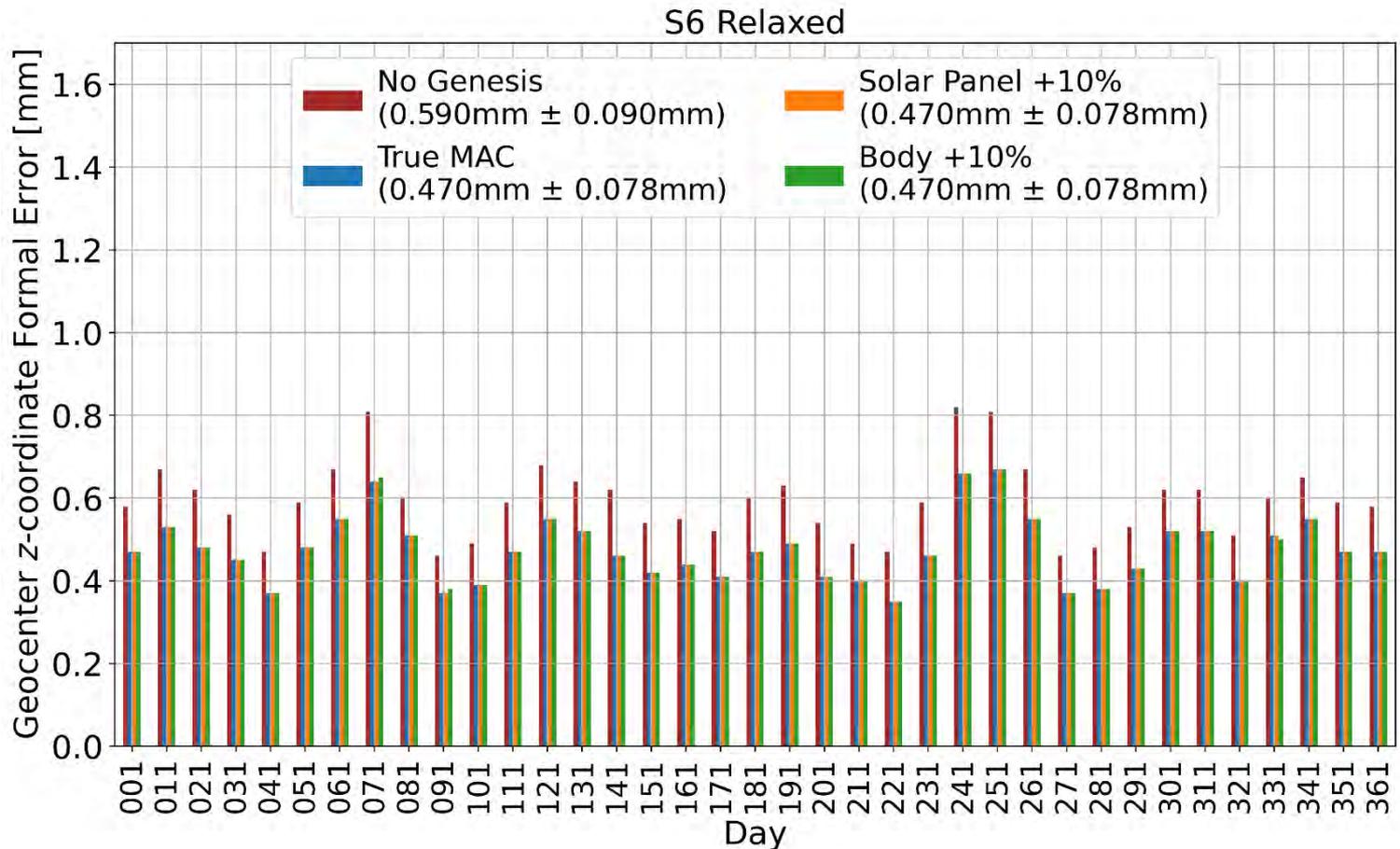
The addition of Genesis GNSS data is able to improve the GNSS orbit estimation in a global solution. The impact of Genesis orbit mismodelings on the GNSS orbits can be mitigated by the **relaxed** constraining.

# GNSS Orbit Estimations



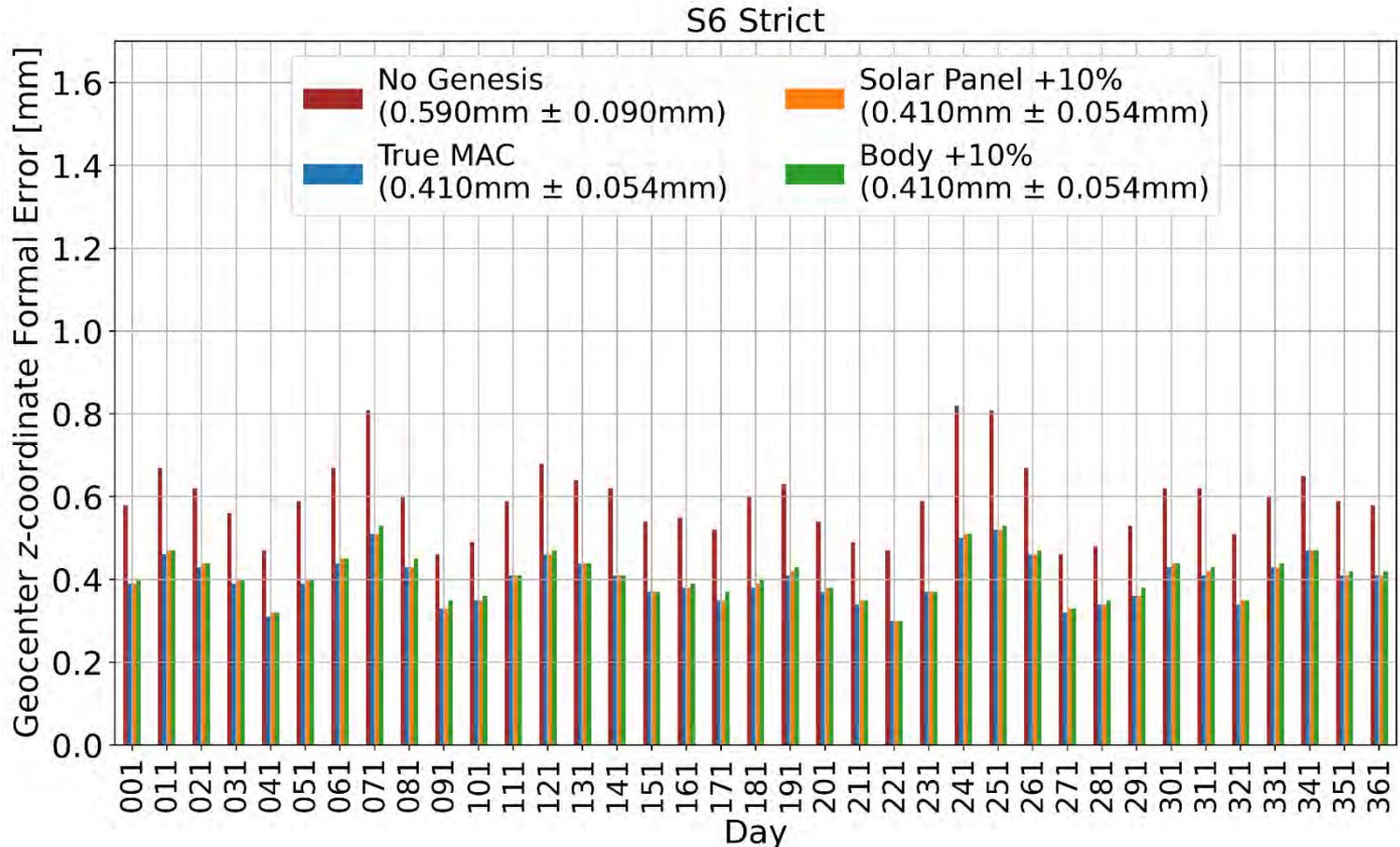
The addition of Genesis GNSS data is able to improve the GNSS orbit estimation in a global solution. Genesis orbit mismodelings can deteriorate the GNSS orbits when the **strict** constraining is applied.

# Geodetic Parameters



The addition of Genesis GNSS data improves GCC Z-estimates. The impact of Genesis orbit mismodelings can be mitigated for **relaxed** constraining. But the full potential of the Genesis GNSS will then **not be exploited**.

# Geodetic Parameters



**Stricter constraining** clearly further improves the GCC Z-estimates, but again enhances the impact of Genesis orbit mismodelings.

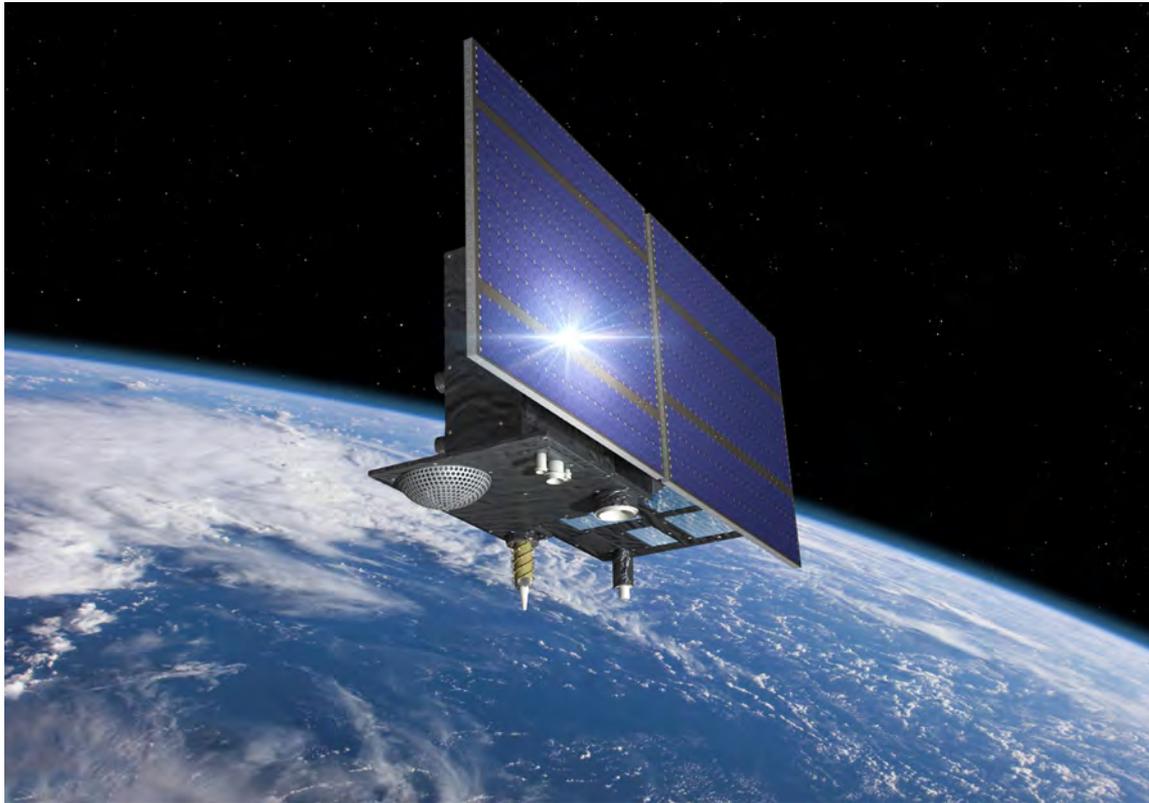
# Conclusions

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- The addition of Genesis GNSS data generally improves both the GNSS orbit as well as the geodetic parameter estimations.
- Genesis orbit mismodelings deteriorate both GNSS orbits and geodetic parameters.
- Genesis orbit mismodelings may be reduced by empirical orbit parameters (PCAs).
- Constraining of PCAs need to be carefully chosen, since
  - strict constraining increases the impact of Genesis orbit mismodelings,
  - relaxed constraining reduces the sensitivity to geodetic parameters.
- Optical properties of the spacecraft need to be accurately known to allow for a strict constraining of empirical parameters in order to exploit the full potential of the Genesis data.

# Conclusions

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- The new Genesis satellite design seems to be particularly challenging for non-gravitational force modeling (large solar panel, self-shadowing, ...).
- Accurate knowledge of meta data will thus be of crucial importance to exploit the full potential of the Genesis data.

# Genesis GNSS Instrument and Processing Aspects – A Short Recapitulation

Compiled by Rolf Dach

*Astronomical Institute, University of Bern, Switzerland*

Genesis Science Workshop 2026  
12.-13. March 2026; Brussels, Belgium

July 23, 2024

## Genesis GNSS Instrument and Processing Aspects

### Genesis WG 2: GNSS

With contributions from P. Axelrad, L. Grunwaldt, U. Hugentobler, T. Junique, F. Lemoine, S. Loyer, B. Männel, F.-X. Marmet, F. Mercier, G. Möller, O. Montenbruck, F. Perosanz, H. Peter, C. Siemes, P. Steigenberger

### Version:

- preliminary version submitted to ESA on July 17, 2024
- updated version distributed to WG2 on July 18, 2024
- consolidated version distributed to WG2 on July 23, 2024
- final version submitted to ESA ...

### Disclaimer:

This document summarizes a set of suggestions for the GENESIS GNSS instrumentation and other mission aspects and reflects our view of the respective mission needs. The document was drafted without access to the GENESIS system requirements or current design studies.

Furthermore, the document does not reflect constraints due to project organization, design requirements, or budgetary limitations. Various points and quantitative specifications in this

# The Document

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- GNSS System Concept
- Antenna System
- Supported Signals
- GNSS Tracking
- Measurement Sampling and Timing
- Clock reference
- Ambiguities
- Sensitivity, Noise
- GNSS Data
- Interference
- Test Requirements

# GNSS Tracking

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- As a critical element our “wish list” did specify:  
The receiver shall enable concurrent tracking of all supported signals for at least 8 satellites of each constellation with a zenith antenna and 11 satellites with a nadir antenna (at least 114 channels for GPS+GAL+BDS-3 tracking).

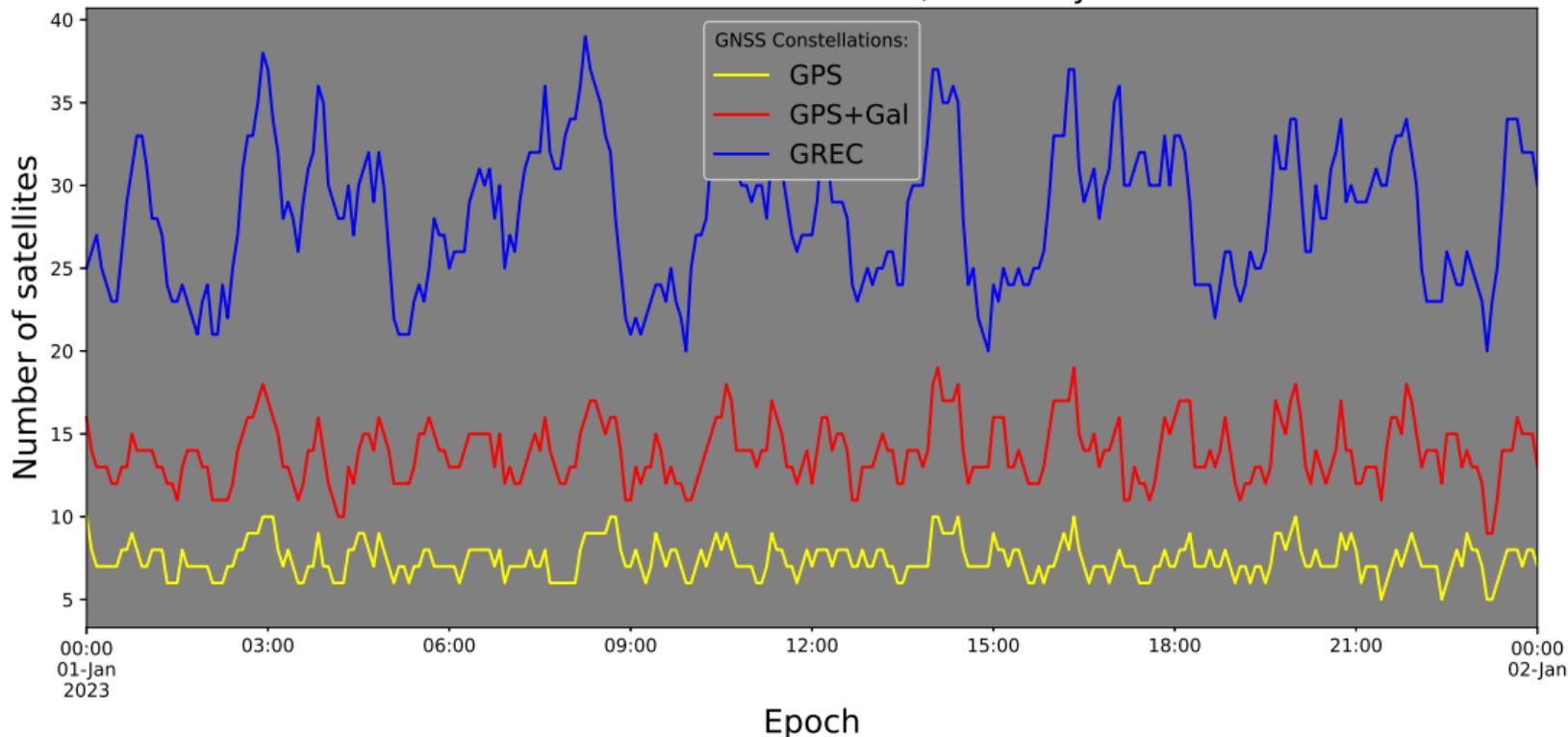
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- Considering no BDS-tracking, we end up roughly with about up at about 30. . . 40 satellites that are theoretically visible and at least 60 to 80 channels.

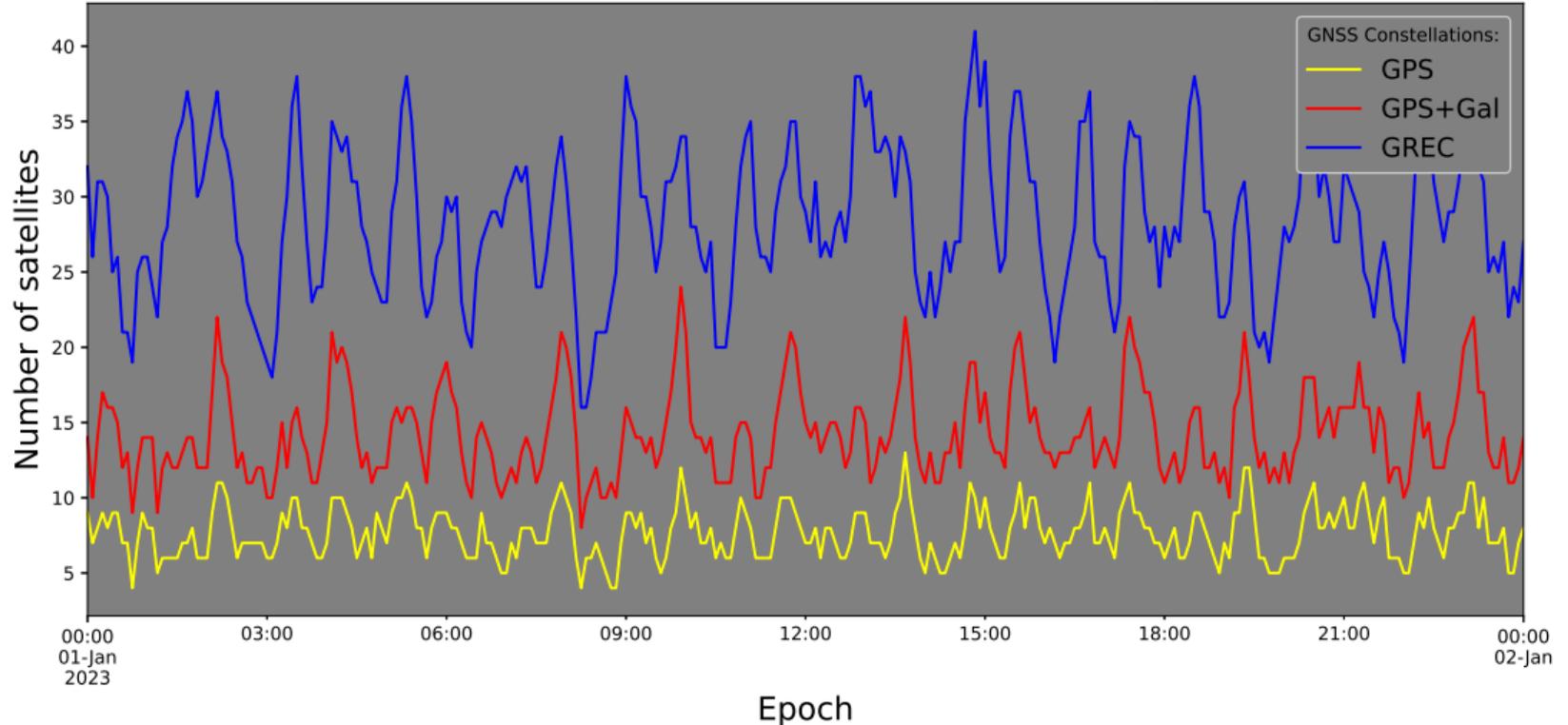
# Zenith Antenna from Genesis

Number of satellites Genesis; 2023 day 001



# Nadir Antenna from Genesis

Number of satellites Genesis (nadir ant); 2023 day 001



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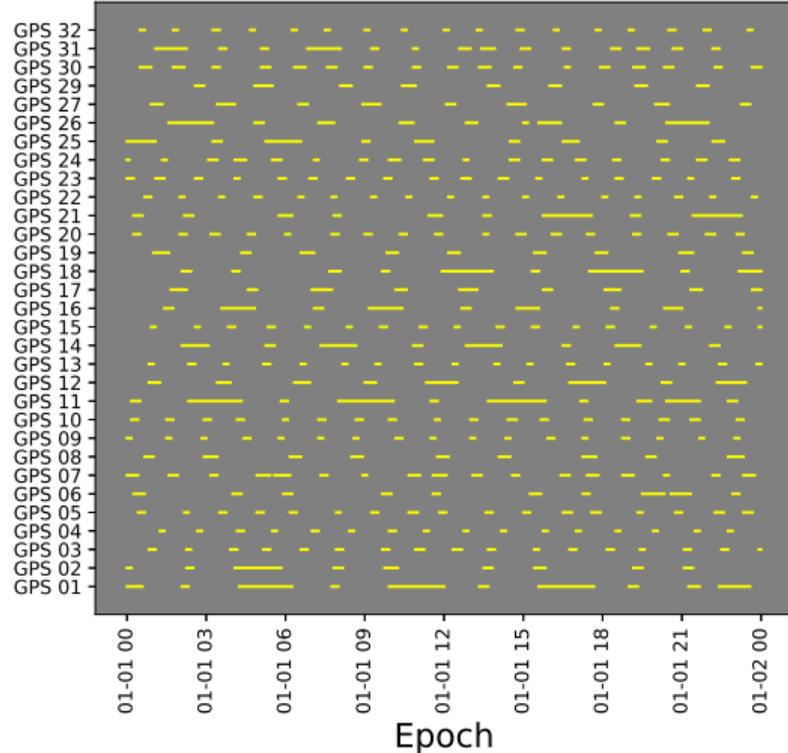
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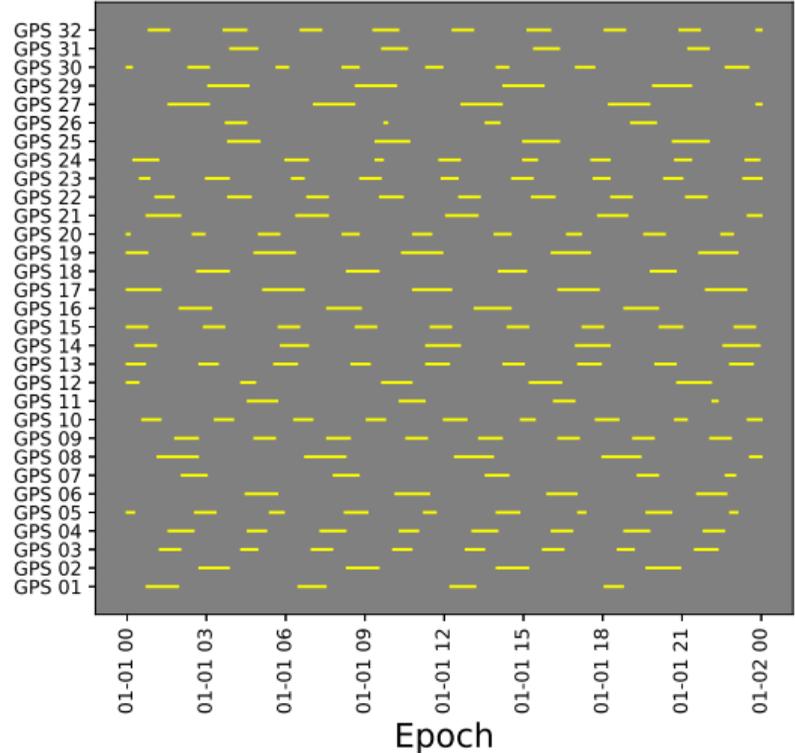
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- SpacePNT stated that the tracking can even be limited to 2 signals per satellite allowing to track up to 31 satellites at the same time,

# GNSS Satellite Visibility from Genesis

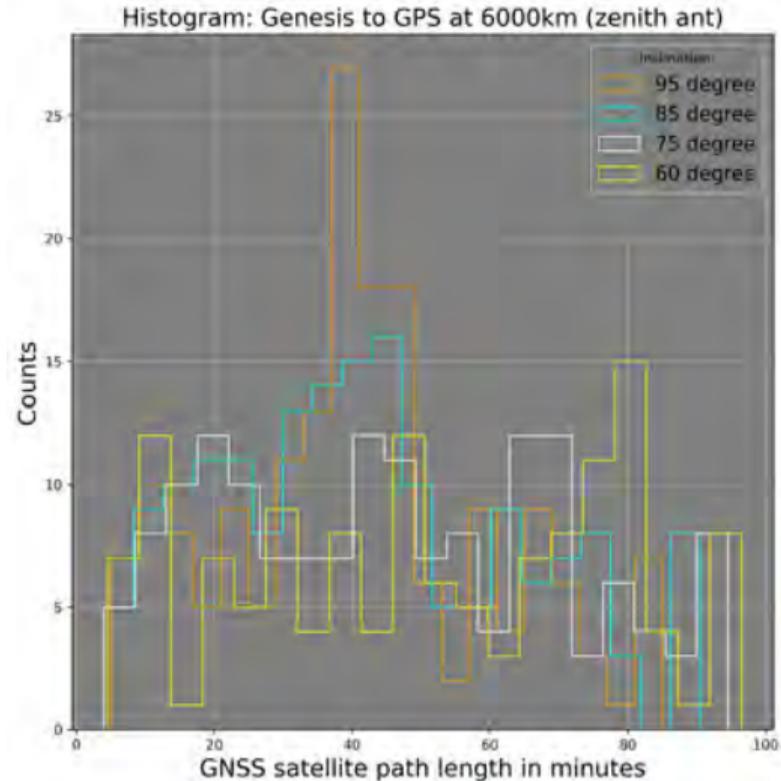
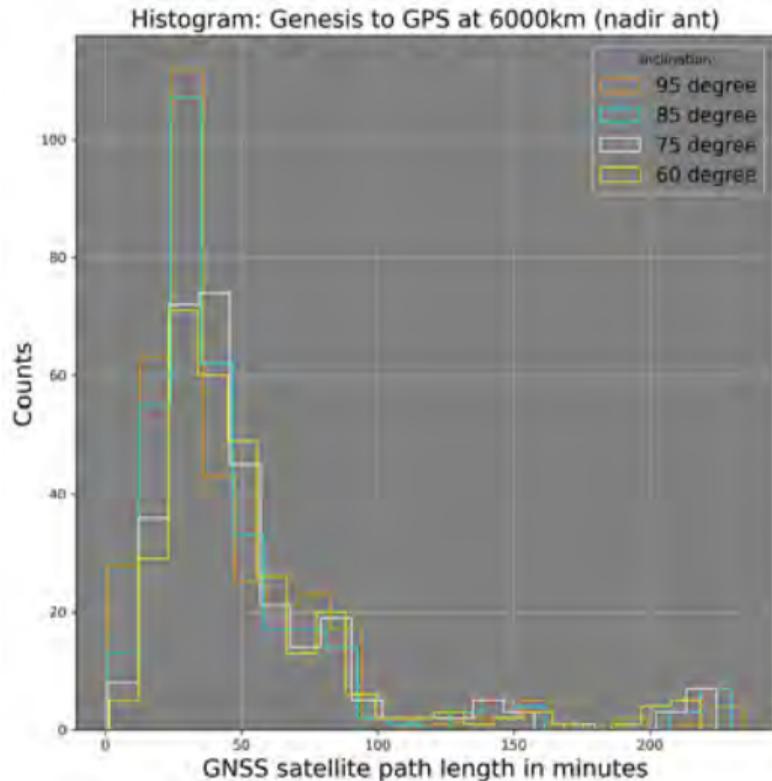
Satellite visibility for Genesis (nadir-ant); 2023 da



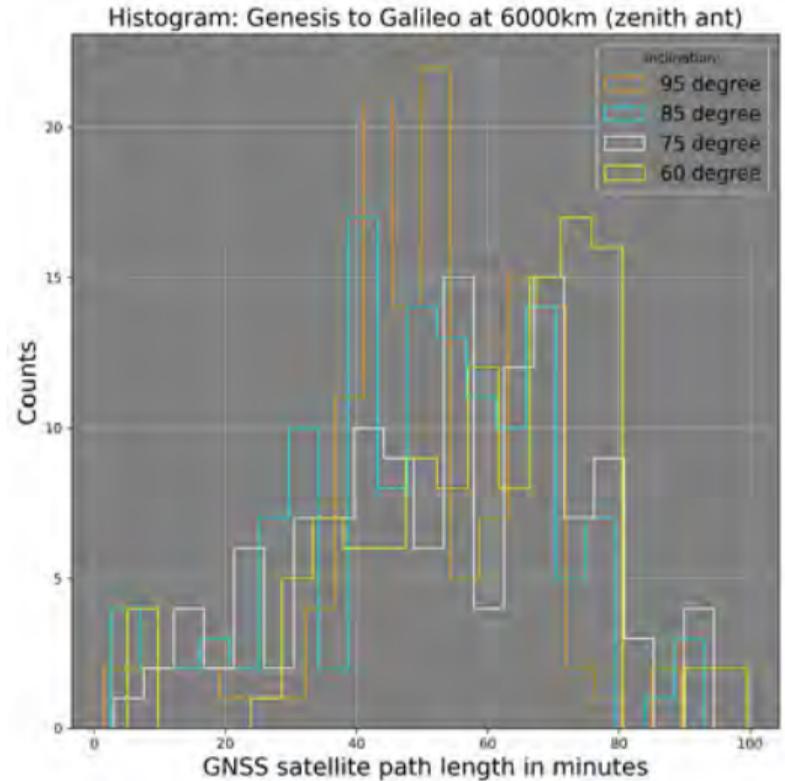
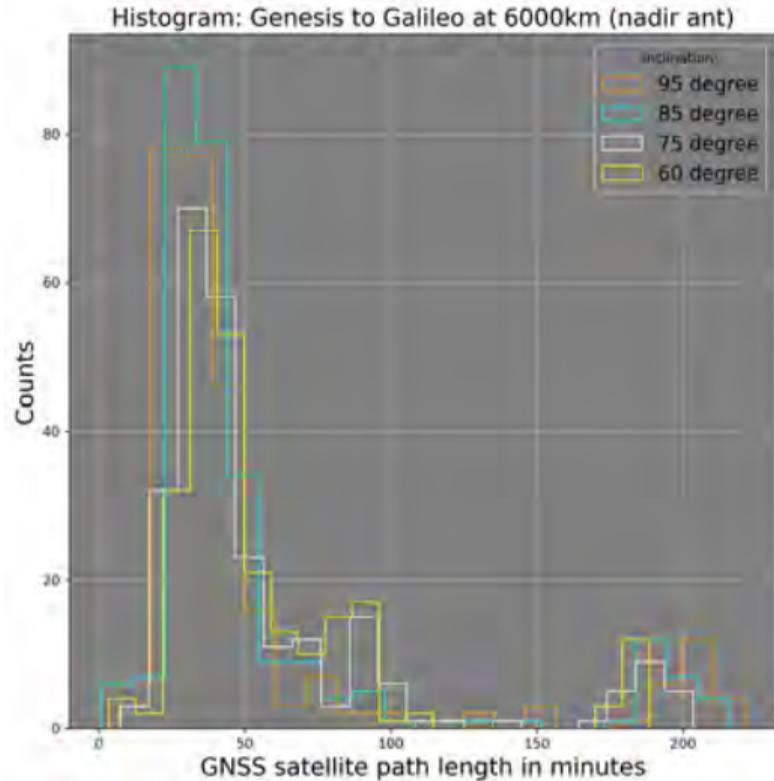
Satellite visibility Genesis; 2023 day 001



# Length of GNSS Satellite Paths (GPS)



# Length of GNSS Satellite Paths (Galileo)



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  - to Genesis: what do we loose when having only 21 satellites (selecting those with long satellite paths)
  - asking for simulations under as realistic conditions as possible

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The following information is needed to make the related simulation:

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- link budget analysis for realistic simulation scenarios
- acquisition and channel allocation strategy

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  - VLBI- and SLR-measurements at different epochs can only be connected with a DORIS-based orbit in that case – assuming that DORIS and VLBI is available at the same time without disturbing interferences.
  - DORIS observations have reduced geometric strength compared to GNSS and require a more detailed modeling of non-gravitational forces, which is a big challenge with the currently proposed spacecraft design.

# WG2 GNSS

11:00 Introduction

11:05 Status of IGS ACs regarding Genesis

- 10' Report GRGS
- 5' Report JPL
- 5' Report GFZ
- 10' Report ESOC
- 10' Report CODE

11:45 GNSS Instrument and Payload

11:55 Discussion

- Receiver
- Calibration
- Orbit modeling

12:25 Summary