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Benefits for geodesy from SLR tracking of future GENESIS mission

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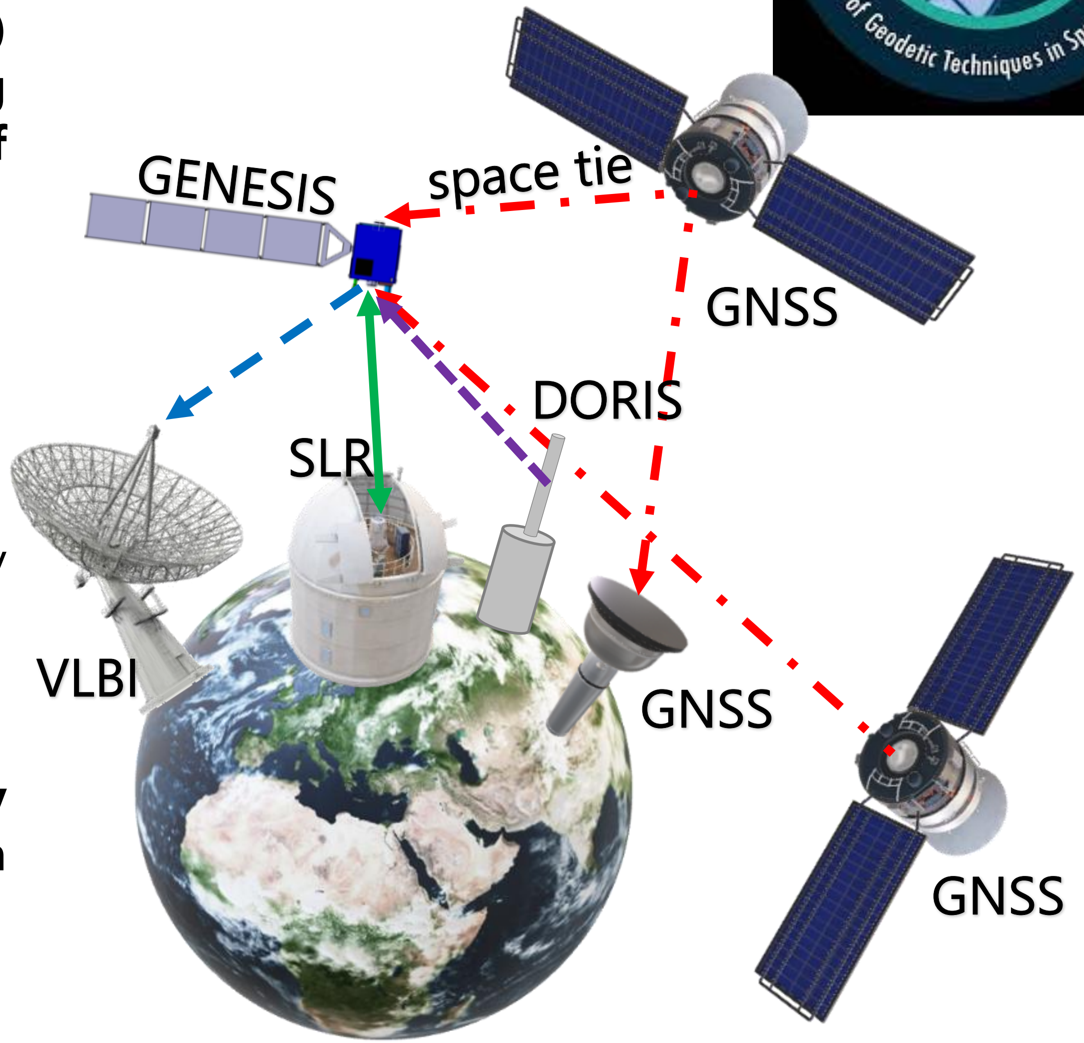
GENESIS

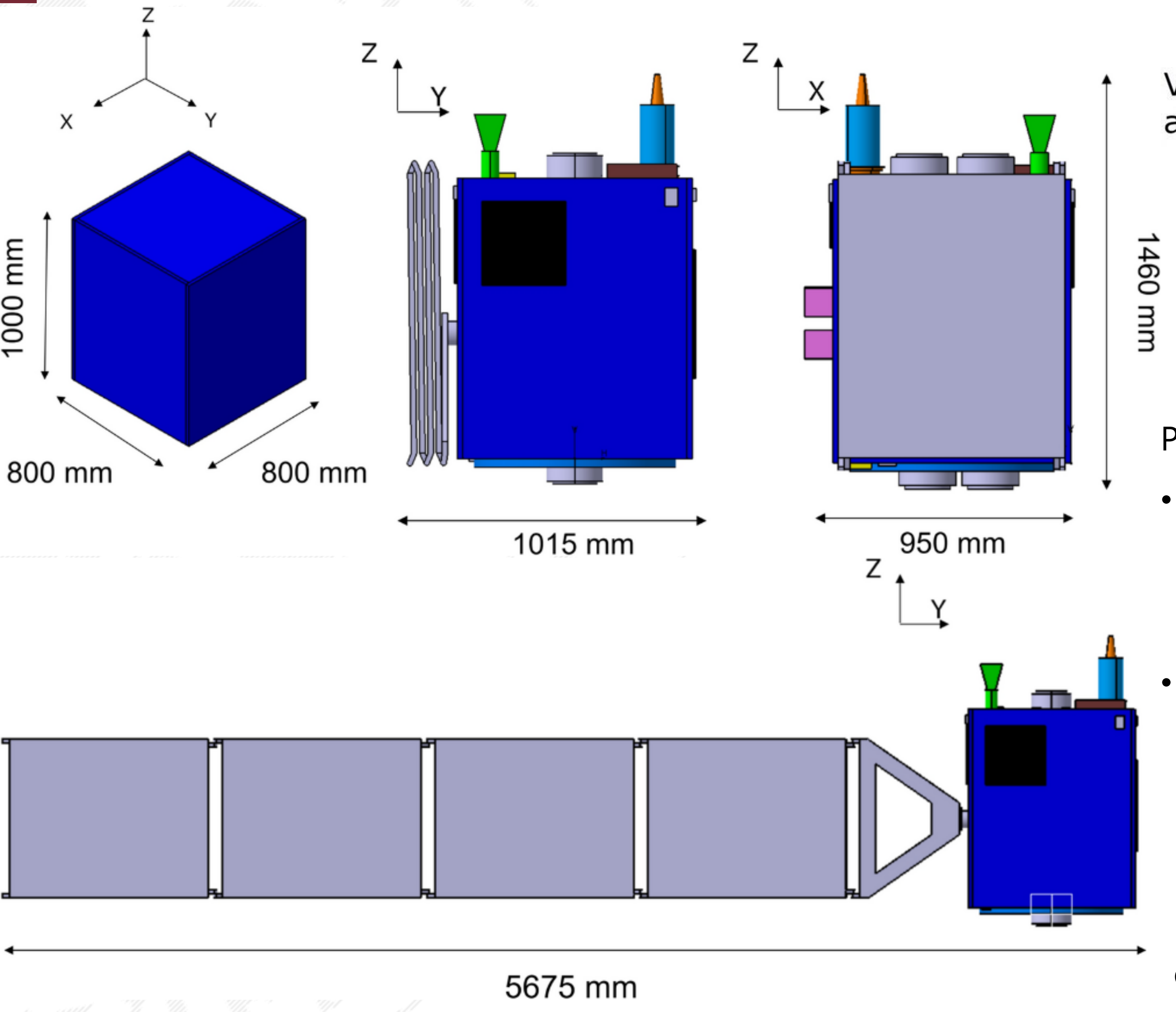
The realization of **future Terrestrial Reference System (TRS)** shall follow the objectives of the Global Geodetic Observing System (GGOS), i.e., **1 mm accuracy and long-term stability of 0.1 mm/year**.

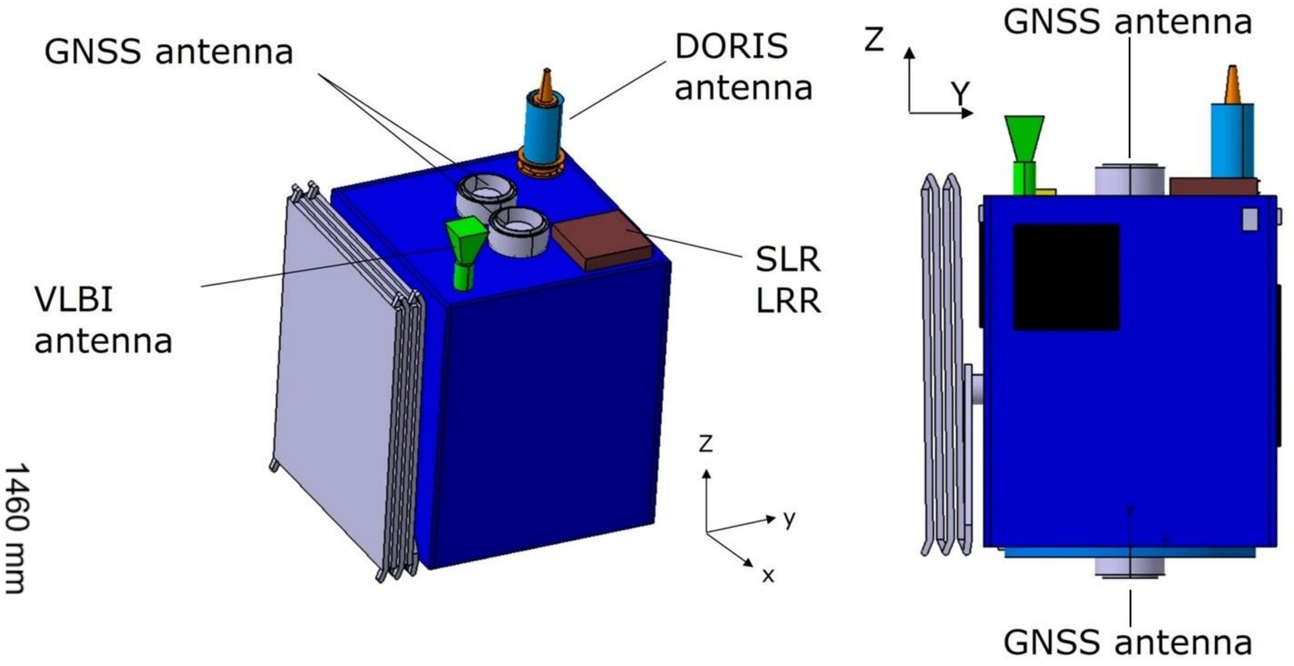
- Global Navigation Satellite System (**GNSS**),
- Very Long Baseline Interferometry (**VLBI**),
- Satellite Laser Ranging (**SLR**),
- Doppler Orbitography and Radiopositioning Integrated by Satellite (**DORIS**).

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



GENESIS - instruments





Proposed hardware extensions:

- Active laser retro-reflector (A-LRR) for a high precision synchronization of the onboard USO with ground clocks through time transfer by laser links from ground stations.
- On-board accelerometer - would provide insight in non-conservative forces and their effect on the GENESIS orbit - a well tested macro-model of the satellite's geometry and reflectance would be essential in such a case.

Delva, P., Altamimi, Z., Blazquez, A., Blossfeld, M., Böhm, J., Bonnefond, P., et al. (2023). GENESIS: co-location of geodetic techniques in space. *Earth, Planets and Space*, *75*(1). https://doi.org/10.1186/s40623-022-01752-w

GENESIS – selected mission requirements

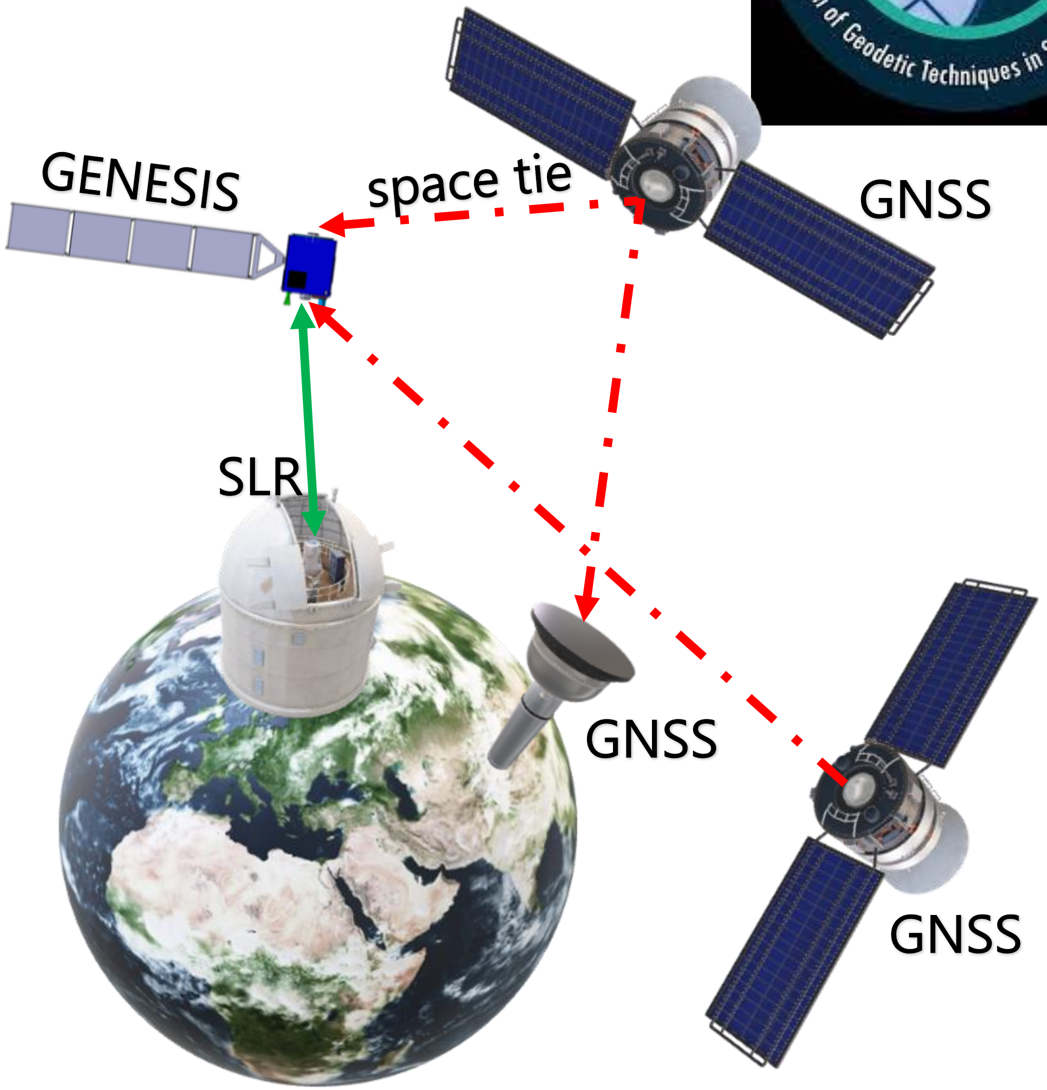
Delva, P., Altamimi, Z., Blazquez, A., Blossfeld, M., Böhm, J., Bonnefond, P., et al. (2023). GENESIS: co-location of geodetic techniques in space. *Earth, Planets and Space*, *75*(1). https://doi.org/10.1186/s40623-022-01752-w

Requirement ID	Statement
001	The GENESIS mission shall be designed to achieve the main mission objective Obj-1, through **the co-location in space of the following 4 geodetic techniques: GNSS, VLBI, SLR, DORIS**
006	**The mission operational lifetime shall be at least 3 years, as a minimum, excluding LEOP, commissioning and disposal**
007	**The GENESIS mission should be designed for a development time of 3 to 4 years**
008	The GENESIS mission should target a **launch date in 2027**
015	**The offset between each payload and the satellite CoM shall be known with accuracy of 1 mm. Offset stability shall remain within 1 mm level during the whole duration of the mission**
016	The CoM position should be known with 1 mm accuracy in the satellite reference frame
017	The satellite shall have a Nadir-pointing face for the whole mission duration, with a pointing accuracy less than 1 degree and a pointing stability of 0.1 degree along the whole orbit
018	**The satellite platform shall be able to operate at the least 2 geodetic techniques in parallel at all times**
019	Attitude determination shall be maintained at all times with accuracy below 0.1 degree
020	**The POD will have to be able to determine the orbit with an accuracy better than 1 cm.** POD is also affected by optical and thermal material properties (absorption, reflection and such) of the satellite outer surfaces to make an accurate radiation pressure model of the satellite. This has to be taken into account in CDF in particular with respect to impact on costs
022	**To provide the link with current ITRF realizations, the selected orbit shall be accessible by the established global tracking networks of the different techniques**
025	A common time reference for all onboard instruments

Motivation

Investigation of the **benefits for geodesy** from **SLR tracking** of future GENESIS mission, i.e., impact of adding observations of the proposed satellites on the determination of geodetic parameters from SLR measurements:

- ✓ low-degree spherical harmonics of the **Earth's gravity field** up to d/o 4;
- ✓ **geocenter coordinates** (GCC);
- ✓ **Earth rotation parameters** (ERPs);
- ✓ advantage of **GENESIS precise orbit determination from GNSS observations** included in the SLR-based solutions.



Simulation overview

- ✓ Simulations are done with **Bernese GNSS Software Version 5.3** with modifications
- ✓ **20** of the best-performing **SLR stations**
- ✓ Satellites: **LAGEOS 1**, **LAGEOS 2**, **LARES 1**, **LARES 2**, **GENESIS** simulated in **five** combinations
- ✓ **7-day** solutions for 2013
- ✓ The number of simulated observations corresponds with the number of real observations
- ✓ Observation noises assigned to each satellite:
  - ❖ LAGEOS 1/2 - 6 mm
  - ❖ LARES 1 - 9 mm
  - ❖ LARES 2 - 6 mm
  - ❖ GENESIS – 6 mm
- ✓ Relative weighting on individual satellites in the combined solutions:
  - ❖ LAGEOS 1/2 – 1.00
  - ❖ LARES 1 – 0.44
  - ❖ LARES 2 - 1.00
  - ❖ GENESIS – 1.00

Simulation overview - estimated parameters per simulation scenario

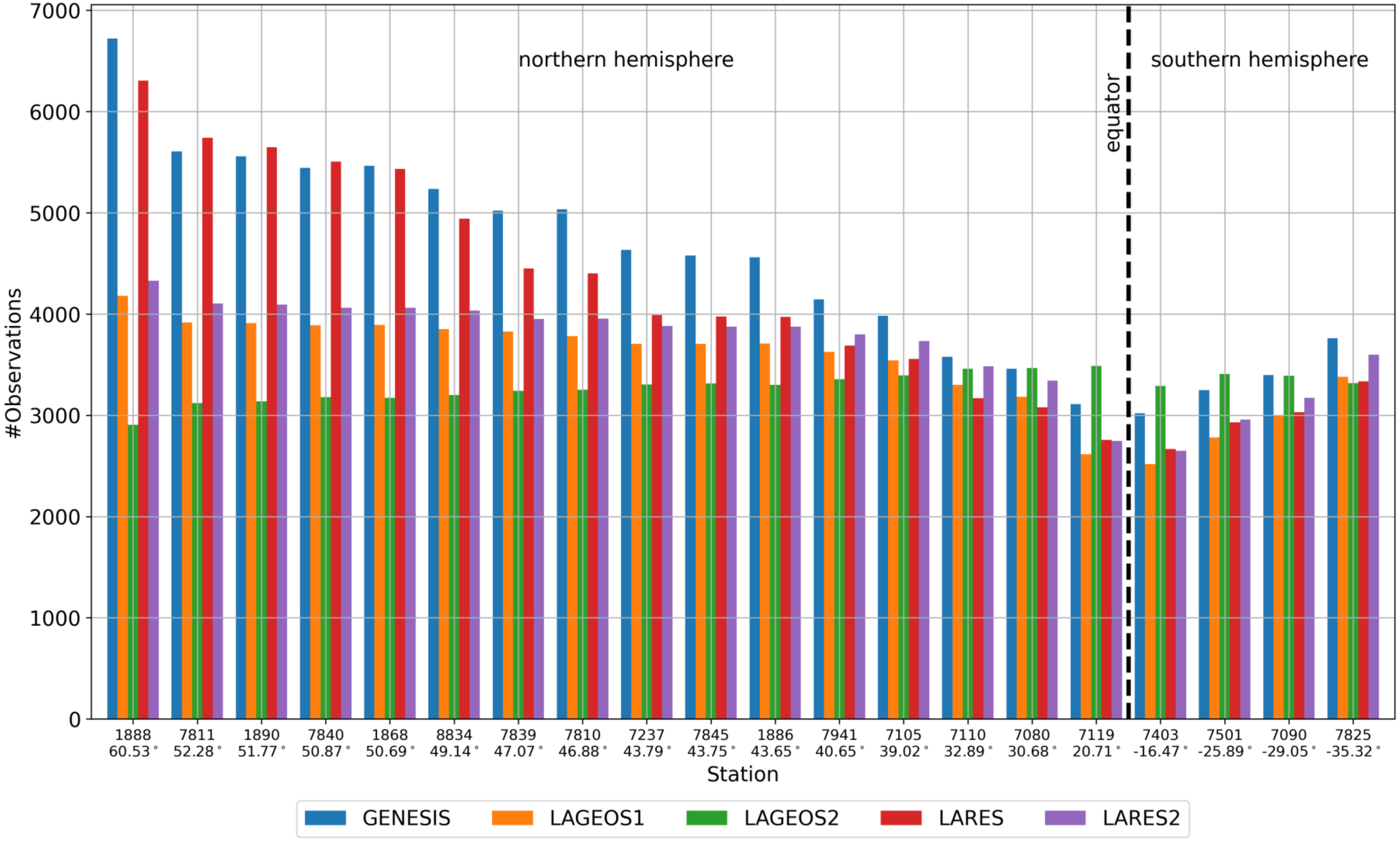
Parameter group	Number of parameters	Parameter names
Station coordinates	60 parameters	{X,Y,Z} for 20 stations
Orbital elements	Up to 12 parameters	Semi-major axis Eccentricity Inclination Ascending node Perigee Argument of latitude Radiation pressure terms
Earth rotation parameters	24 parameters	{x pole, y pole, UT1-UTC} x 8 day boundaries
Earth potential parameters	21 parameters	up to d/o 4
Geocenter coordinates	3 parameters	X, Y, Z

Simulation scenarios

	Diameter (m)	Mass (kg)	Area-to-mass (m^2/kg)	Radiation coeff. C_R	Semi-major axis a (km)	Altitude (km)	Eccentricity	Inclination (°)	Drift of node (days)	Drift of perigee (days)	Draconitic year (days)	Orbital period (hh:mm)	Launch
LAGEOS 1	0.60	407.0	$6.95 \cdot 10^{-4}$	1.13	12274	5860	0.00474	109.89	1046.1	1689.7	561	3:46	1976
LAGEOS 2	0.60	405.4	$6.97 \cdot 10^{-4}$	1.11	12158	5620	0.01328	52.63	567.0	817.5	222	3:42	1992
LARES 1	0.36	386.8	$2.63 \cdot 10^{-4}$	1.07	7820	1450	0.00125	69.50	209.8	379.9	133	1:55	2012
LARES 2	0.40	350.0	$3.59 \cdot 10^{-4}$	~1.1	12270	5860	0.00125	70.17	1048.0	1674.5	270	3:45	2022
GENESIS	**0.8x0.8x1.0**	**375.0 (wet) 310.0 (dry)**	**ca. $2.0 \cdot 10^{-3}$ - $2.6 \cdot 10^{-3}$**	**NA**	**12378**	**6000**	**≤0.02**	**95.5**	**3789.5**	**771.2**	**404**	**3:49**	**2027**

Simulation scenarios	
LAGEOS 1 + LAGEOS 2	LAG 1/2
LAGEOS 1 + LAGEOS 2 + GENESIS	LAG 1/2 + GEN
LAGEOS 1 + LAGEOS 2 + LARES 1 + LARES 2	LAG 1/2 + LAR 1/2
LAGEOS 1 + LAGEOS 2 + LARES 1 + LARES 2 + GENESIS	LAG 1/2 + LAR 1/2 + GEN
LAGEOS 1 + LAGEOS 2 + LARES 1 + LARES 2 + GENESIS with fixed GNSS based orbit	LAG 1/2 + LAR 1/2 + GEN_{fix}

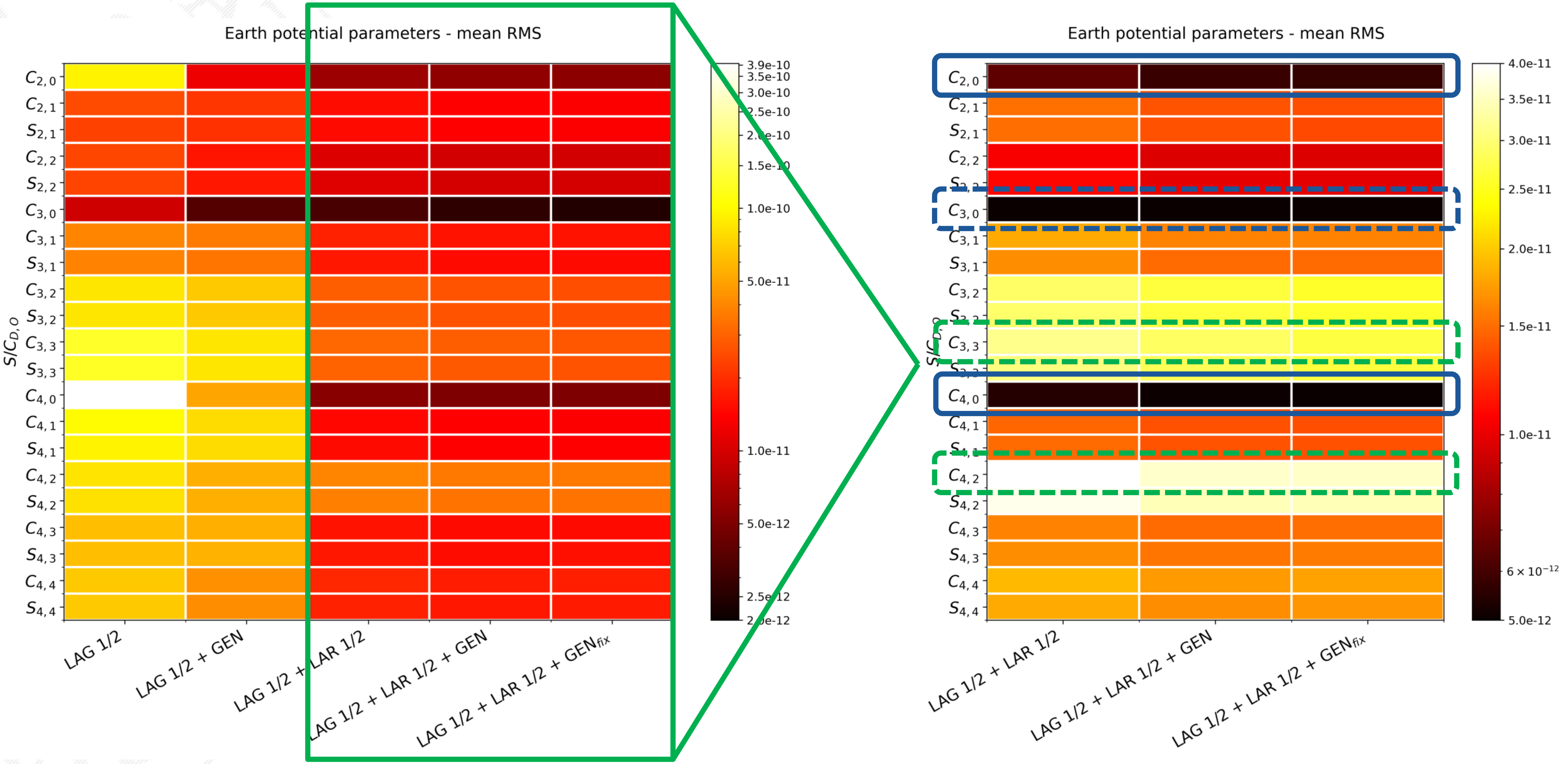
SLR observations to satellites



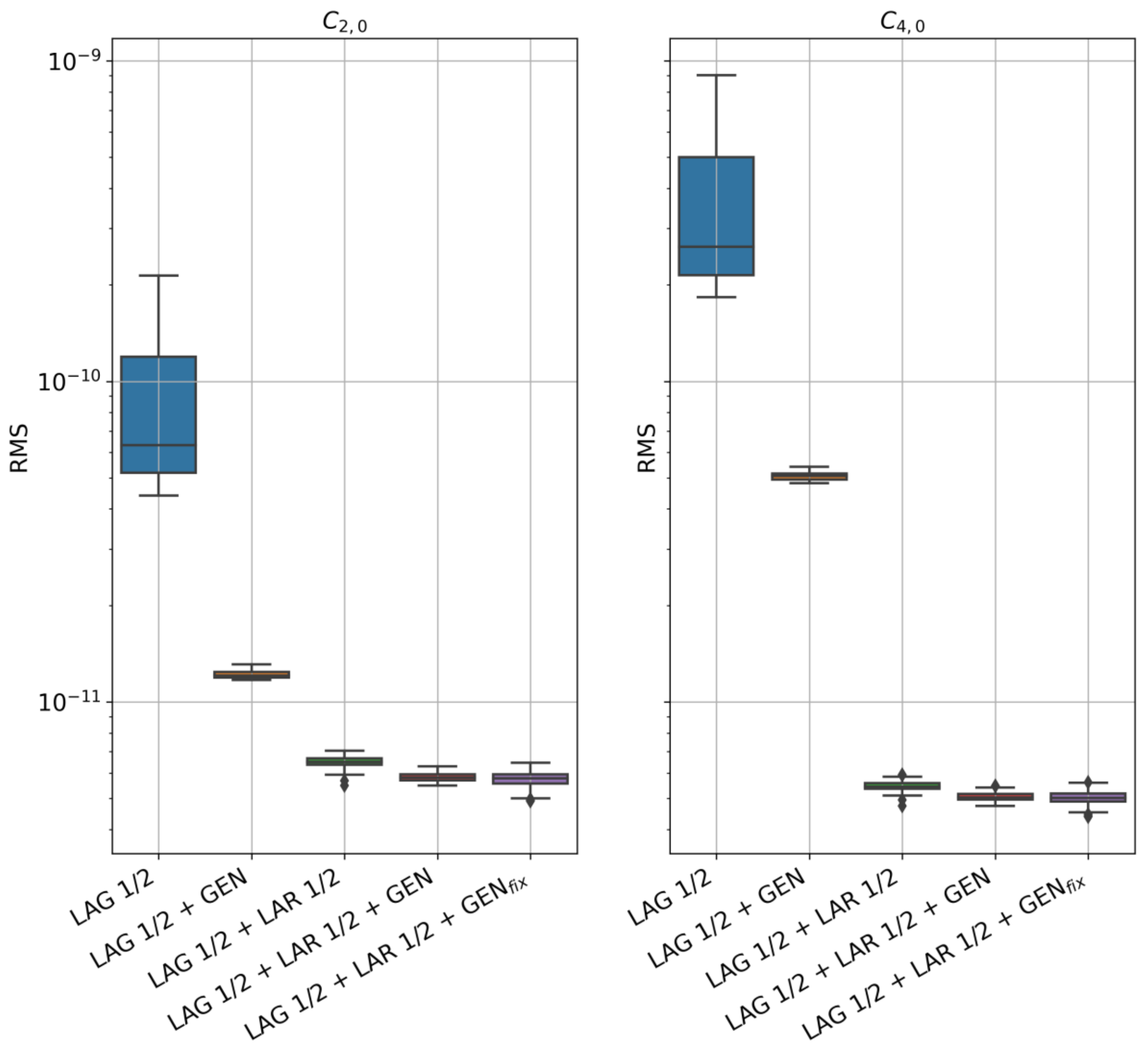
- The higher latitude the higher number of observation to GENESIS
- The number of SLR measurements to GENESIS is comparable to LARES for almost all stations.

Satellite	Total	Weekly
GENESIS	89 550	1741
LARES 1	82 556	1605
LARES 2	73 691	1433
LAGEOS 1	70 295	1367
LAGEOS 2	65 691	1277

Earth potential parameters (up to d/o 4)



Earth potential parameters ($C_{2,0}$, $C_{3,0}$, $C_{4,0}$)

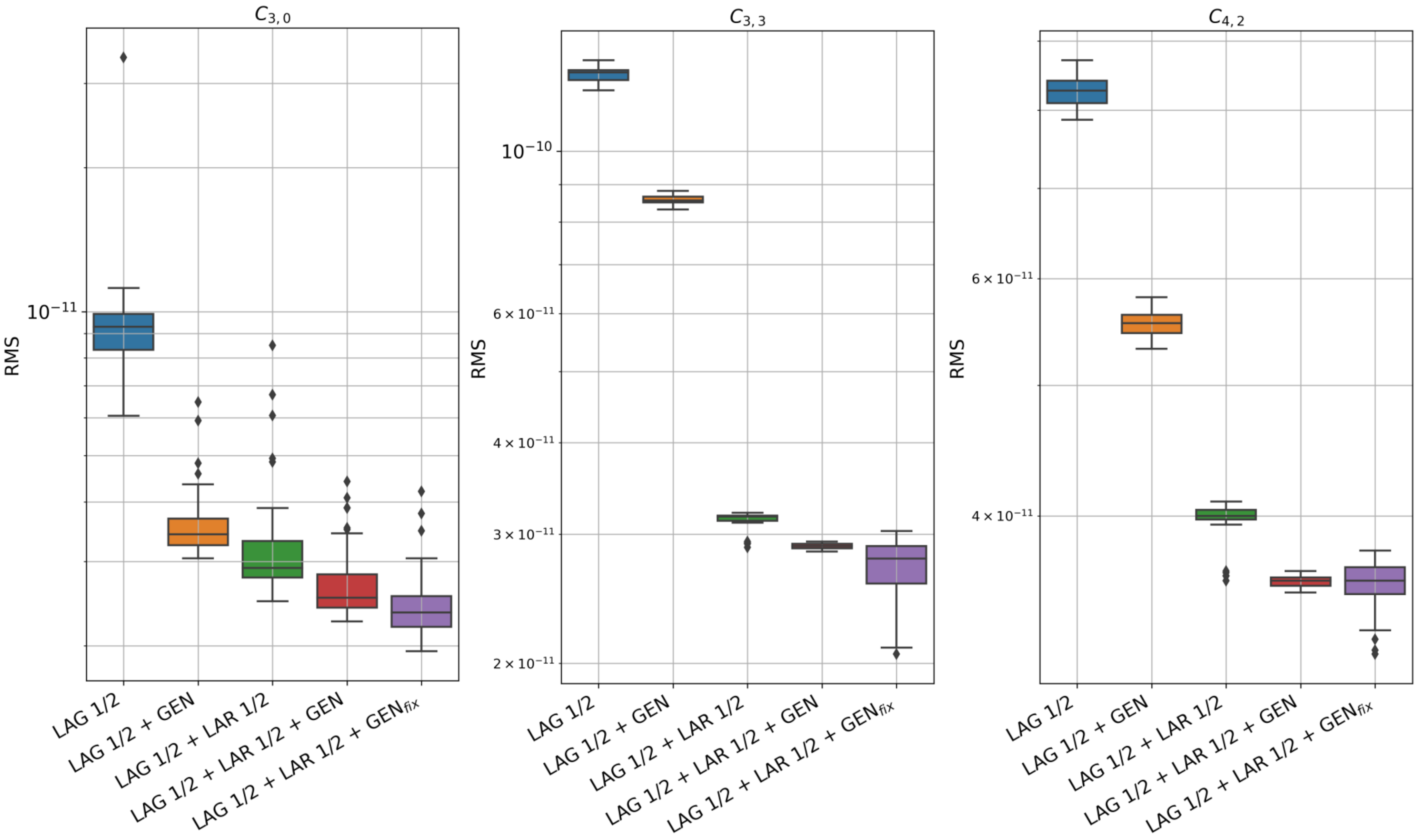


- No substantial improvement in $C_{2,0}$ and $C_{4,0}$ in LAG 1/2 + LAR 1/2 + GEN vs LAG 1/2 + LAR 1/2.
- LAG 1/2 + GEN is comparable to LAG 1/2 + LAR 1/2 in $C_{3,0}$ while in $C_{2,0}$ and $C_{4,0}$ the difference is larger than one order of magnitude.

mean	$C_{2,0}$	$C_{3,0}$	$C_{4,0}$
LAG 1/2	9.5e-11	9.5e-12	4.0e-10
LAG 1/2 + GEN	1.2e-11	3.6e-12	5.1e-11
LAG 1/2 + LAR 1/2	6.5e-12	3.3e-12	5.5e-12
LAG 1/2 + LAR 1/2 + GEN	5.8e-12	2.7e-12	5.1e-12
LAG 1/2 + LAR 1/2 + GEN$_{fix}$	5.7e-12	2.4e-12	5.0e-12

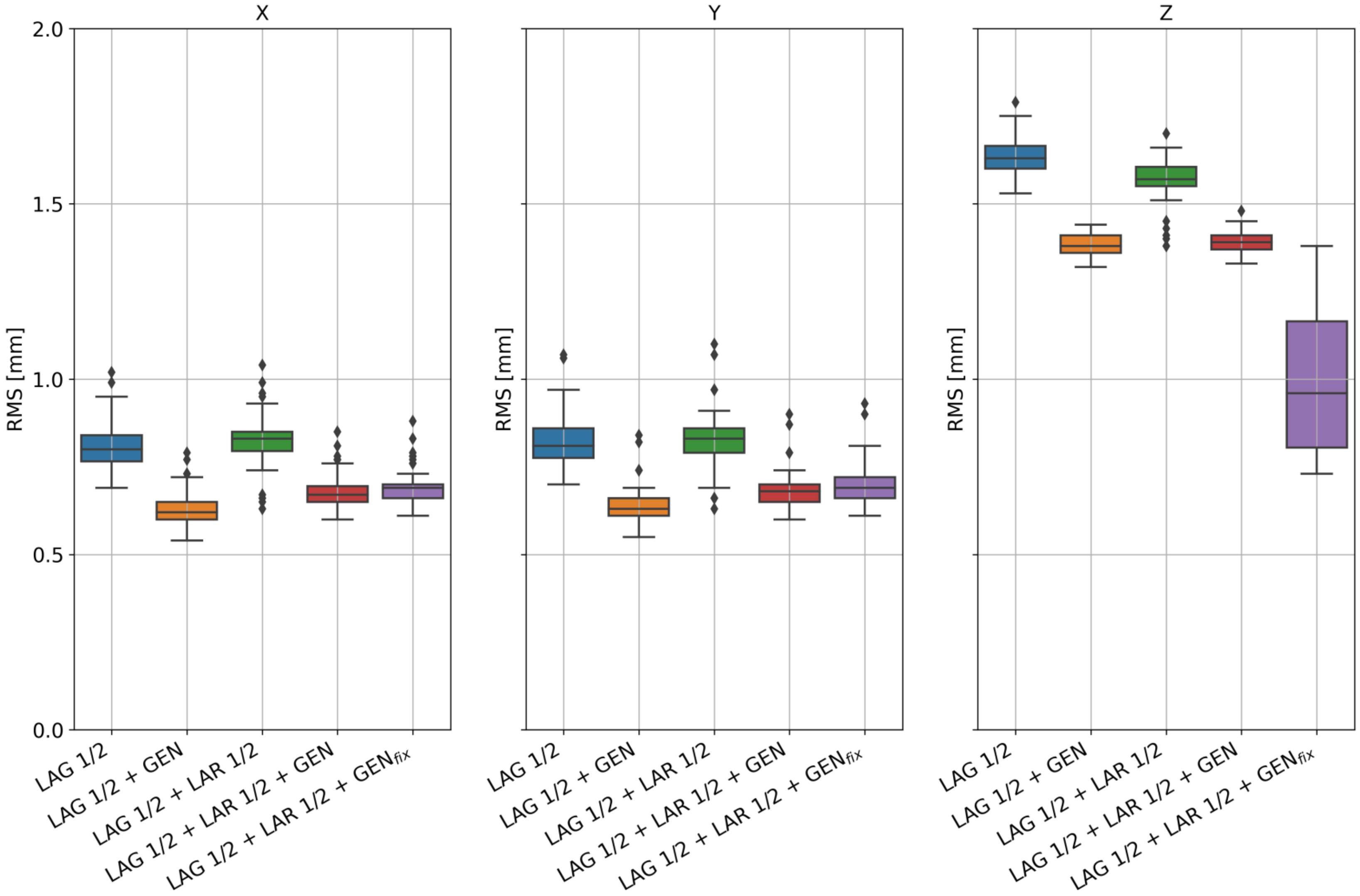
Percentage change w.r.t. to LAG 1/2 + LAR 1/2	$C_{2,0}$	$C_{3,0}$	$C_{4,0}$
LAG 1/2	1357.7%	187.8%	7150.1%
LAG 1/2 + GEN	87.2%	8.8%	827.6%
LAG 1/2 + LAR 1/2	X	X	X
LAG 1/2 + LAR 1/2 + GEN	-10.1%	-18.2%	-7.3%
LAG 1/2 + LAR 1/2 + GEN$_{fix}$	-11.9%	-26.6%	-8.3%

Earth potential parameters ($C_{3,0}$, $C_{3,3}$, $C_{4,2}$)



- GENESIS improves the estimation of $C_{3,0}$ as well as $C_{3,3}$ and $C_{4,2}$ even for the LAG 1/2 + LAR 1/2 combinations.
- Fixed GENESIS orbit increases the formal errors of estimated parameters due to the same number of observations with lower number of estimated parameters.

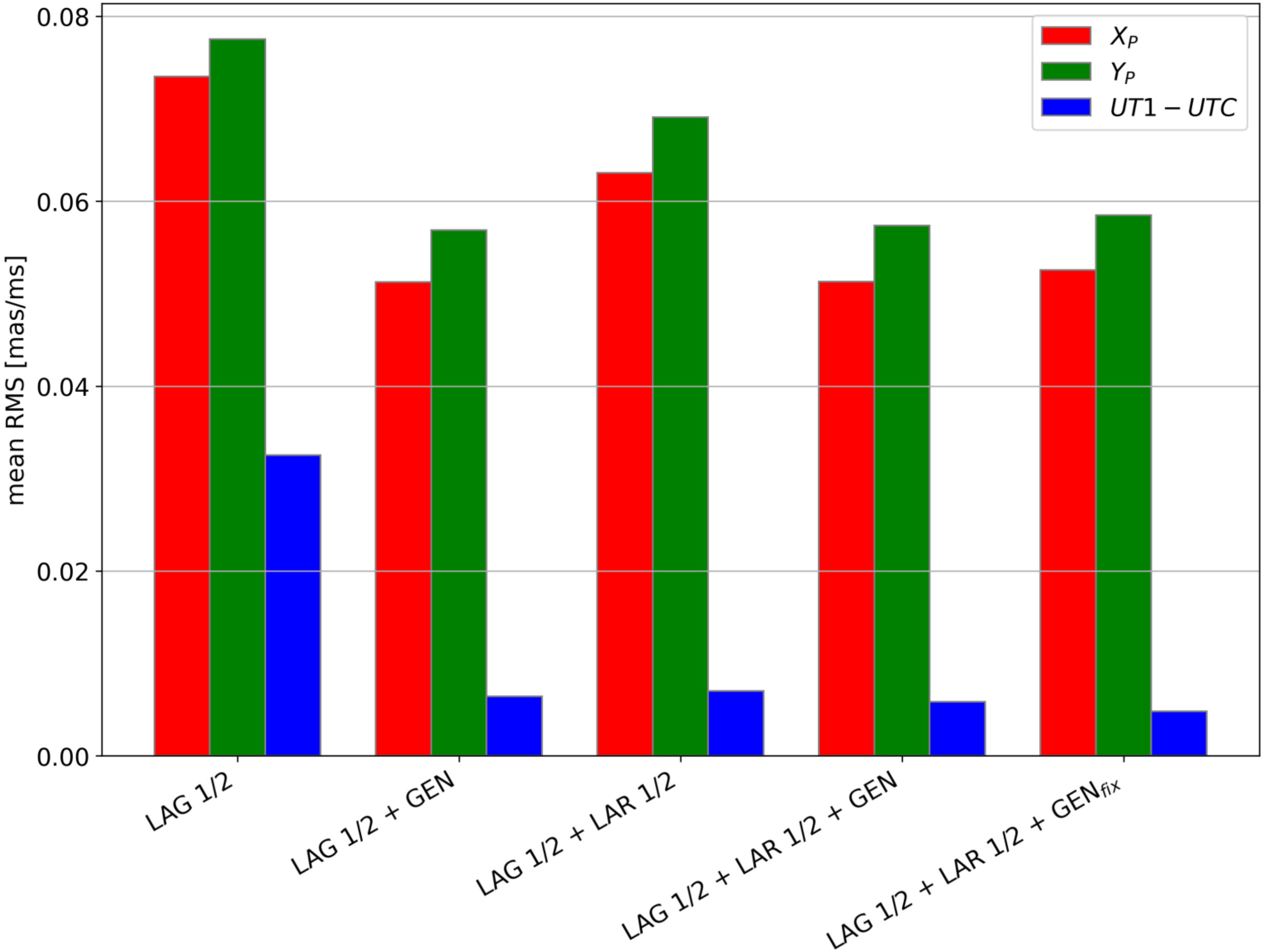
Geocenter coordinates



- GENESIS with fixed orbit impacts on Z coordinate the most.
- GENESIS solutions based on GNSS onboard receiver result in all geocenter components better than **1 mm - the GGOS goal can be reached!** All other solutions (without GENESIS) exceed the 1 mm value for the Z geocenter component.

mean [mm]	X	Y	Z
LAG 1/2	**0.80**	**0.81**	**1.63**
LAG 1/2 + GEN	**0.62**	**0.63**	**1.38**
LAG 1/2 + LAR 1/2	**0.83**	**0.83**	**1.39**
LAG 1/2 + LAR 1/2 + GEN	**0.67**	**0.68**	**1.39**
LAG 1/2 + LAR 1/2 + GEN_{fix}	**0.69**	**0.69**	**0.96**

Earth rotation parameters



- Adding GENESIS satellite improves pole coordinates by about 20-30%.
- Scenario LAG 1/2 + GEN is comparable to LAG 1/2 + LAR 1/2 + GEN and results are only slightly better than in the LAG 1/2 + LAR 1/2 case.
- UT1-UTC estimates are more dependent on observation geometry than on including GENESIS in the solution.

	X_P [mas]	Y_P [mas]	UT1-UTC [ms]
LAG 1/2	0.073	0.077	0.032
Change in reference to LAG 1/2	X_P [%]	Y_P [%]	UT1-UTC [%]
LAG 1/2 + GEN	**-30.2**	**-26.6**	**-80.2**
LAG 1/2 + LAR 1/2	-14.2	-10.9	-78.5
LAG 1/2 + LAR 1/2 + GEN	**-30.2**	**-26.0**	**-82.0**
LAG 1/2 + LAR 1/2 + GEN_{fix}	**-28.5**	**-24.5**	**-85.1**

Summary

1. **Number of SLR observations** to GENESIS is substantially **higher** for stations on the **higher latitudes**.
2. GENESIS will have **small effect on $C_{2,0}$ and $C_{4,0}$** when added to the **LAGEOS 1/2 + LARES 1/2.** About **50% improvement** is noticed in **LAGEOS 1/2** scenario. **$C_{3,0}$** can remarkably be improved by GENESIS when even compared to LAGEOS 1/2 + LARES 1/2 solutions.
3. **Earth rotation parameters** are the **least sensitive** to the selected combination of satellites used for processing (excluding LAGEOS 1/2 solution) among the presented results.
4. **Fixed GENESIS orbit** (e.g., computed from GNSS observations) **usually has a small impact** on the Earth potential parameters, earth rotation parameters or geocenter coordinates – the mean value is not considerably improved but range of the weekly solutions is higher, however…
5. … Z component of geocenter coordinates or $C_{3,3}$ **have the lowest error** with **fixed GENESIS orbit**. GNSS-based orbits of GENESIS may result in improvements of the **Z geocenter component** with error **below 1 mm**.

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Benefits for geodesy from SLR tracking of future GENESIS mission

Thank you for your attention

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