Research Institute of Geodesy, Topography and Cartography
Geodetic observatory Pecný
Czechia

Three decades of geocenter motion from GNSS, SLR, LEO and Geophysical Fluid Models

Radosław Zajdel[1]

K Balidakis[2], A Nowak[3], T Kur[3], K Sośnica[3], J Douša[1]

05.02.2026

Terrestrial Reference Frame

Origin (Δx, Δy, Δz)

Orientation (R_x, R_y, R_z)

Scale (ΔL)

Total
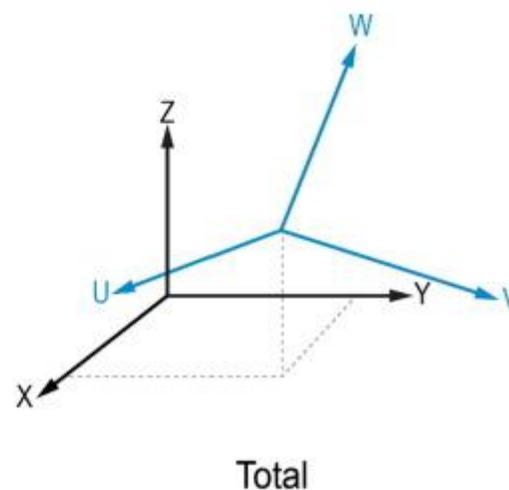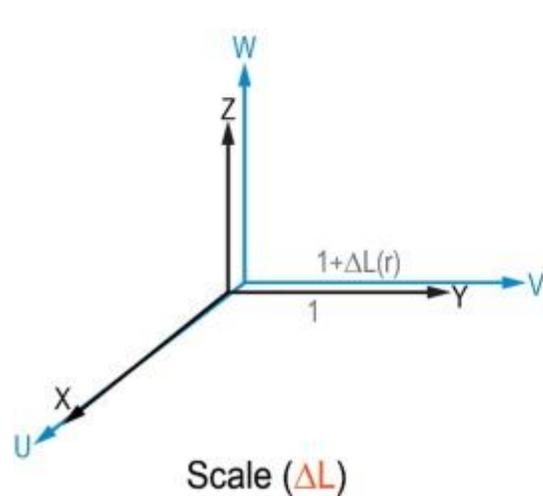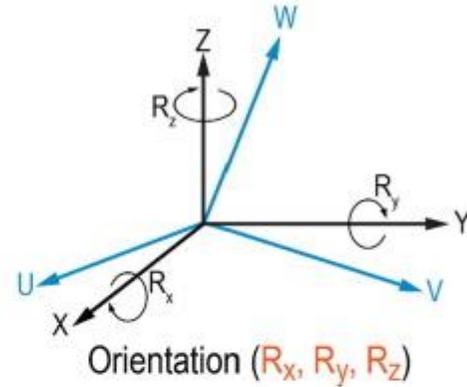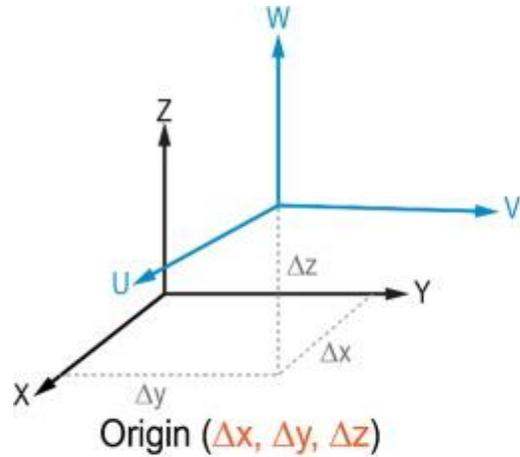
- In geodetic practice, we constantly work with the Terrestrial Reference Frames, which defines the framework for our regional and global analyses.

- A Terrestrial Reference Frame is defined as the realization of a Terrestrial Reference System, through the specification of its **origin, orientation axes and scale**, and their time evolution.

Origins of the terrestrial reference frame

- Centre of the solid Earth figure – **Center-of-Figure** (CoF)
- CoN (Center-of-Network) – the realisation of the International Terrestrial Reference Frame (ITRF) using a limited number of stations.
- CoM (Center-of-Mass of the total Earth system). It is used to describe Earth's motion in inertial space and serves as the orbital centre for all Earth satellites.
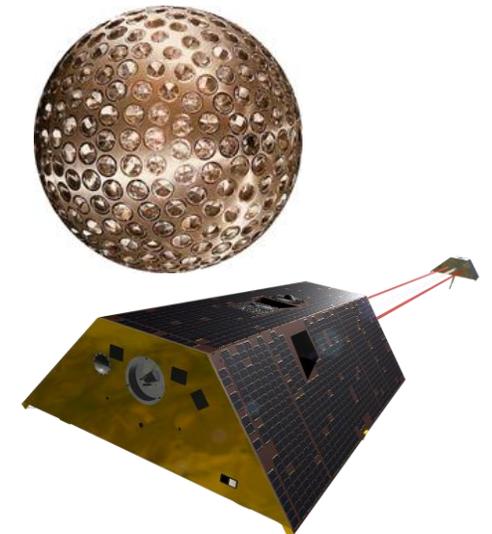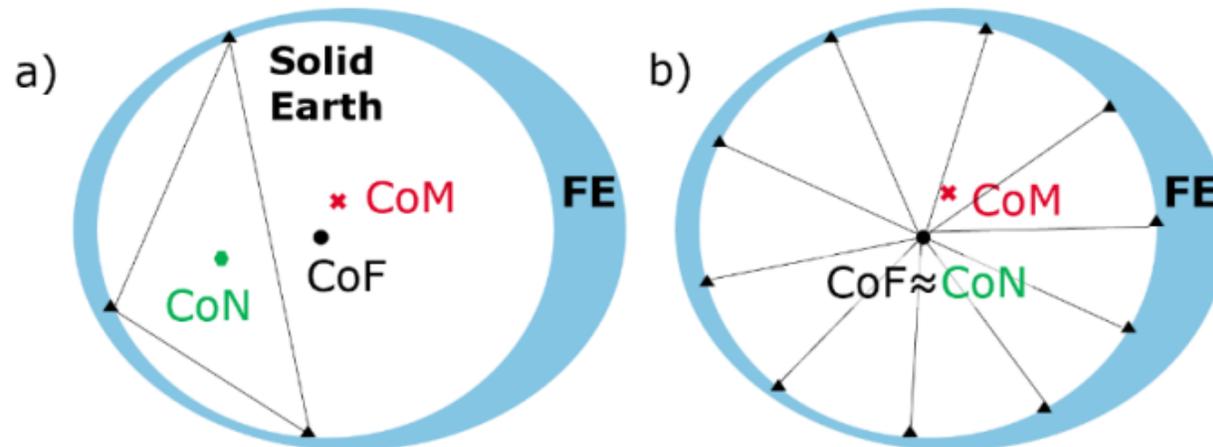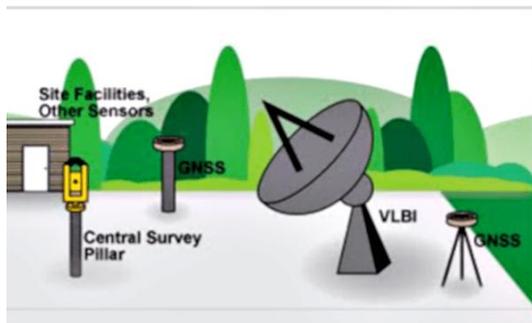
Geocenter motion

Geocenter motion represents the **time-varying translation (3D vector)** of the Earth's Center of Mass relative to the solid Earth figure's origin (CN/CF).

GEOCENTER
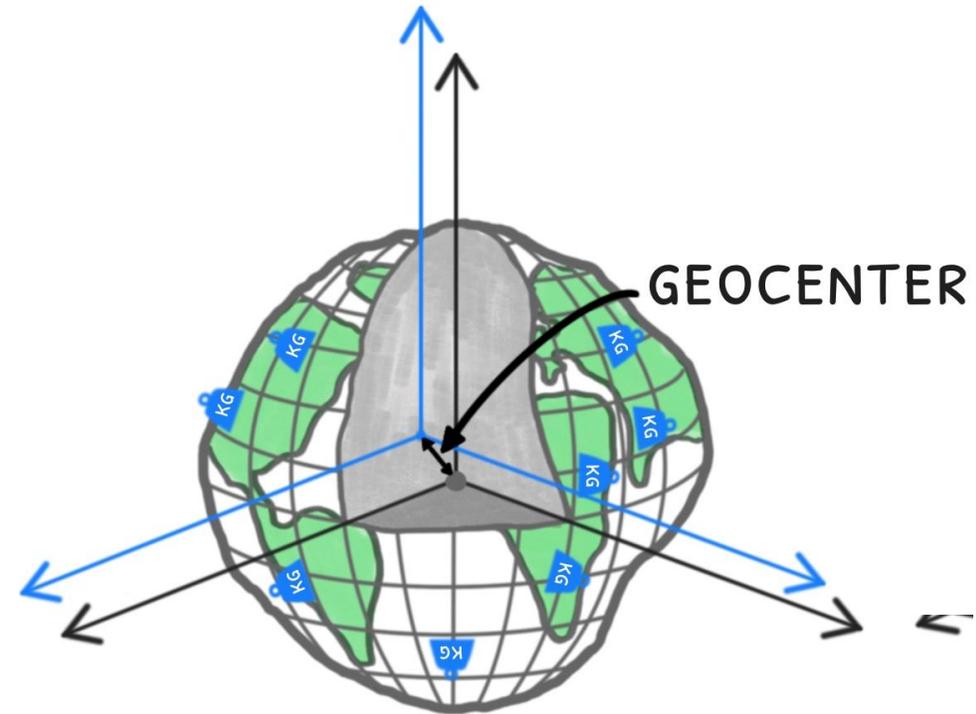
Geocenter motion

emerges from complex mass redistribution across Earth's fluid envelopes and solid interior.

the largest contributions stem from:
- atmospheric pressure variations,
- oceanic circulation patterns,
- continental water storage changes,
- snow accumulation and melting,
- bedrock thermal expansion,
- solid Earth deformation
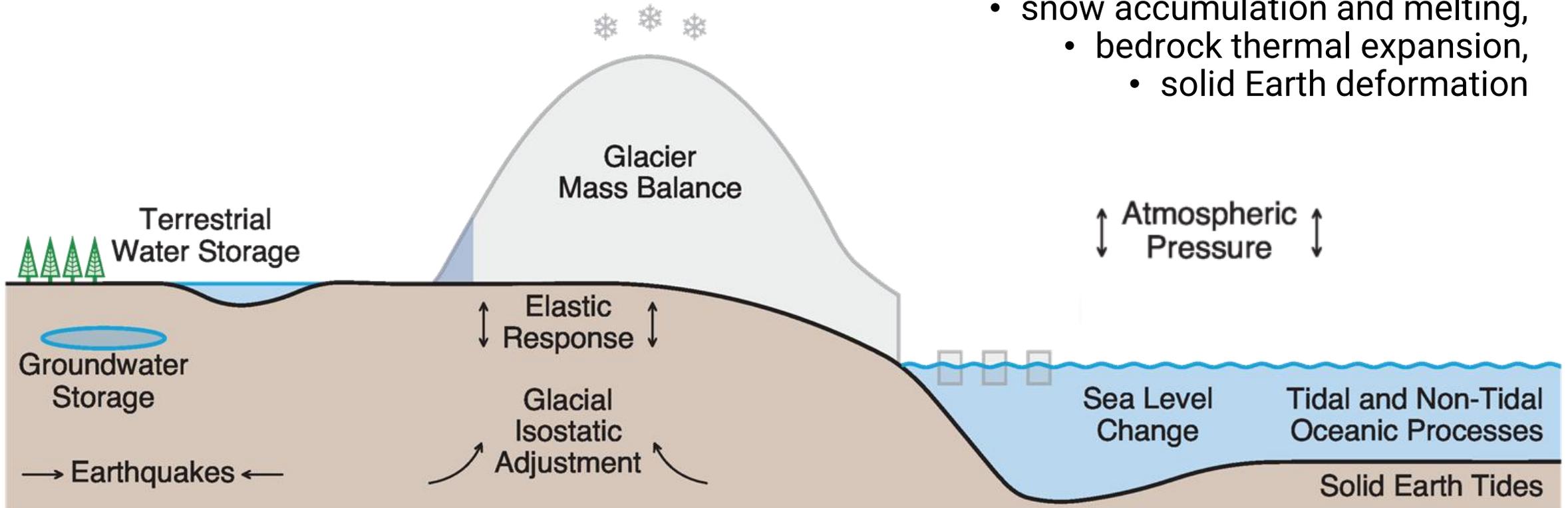
Geocenter motion

Seasonal variations dominate the signal, primarily driven by annual cycles in continental water storage, snow accumulation, and atmospheric mass redistribution,

longer-term processes such as glacial isostatic adjustment contribute to secular trends
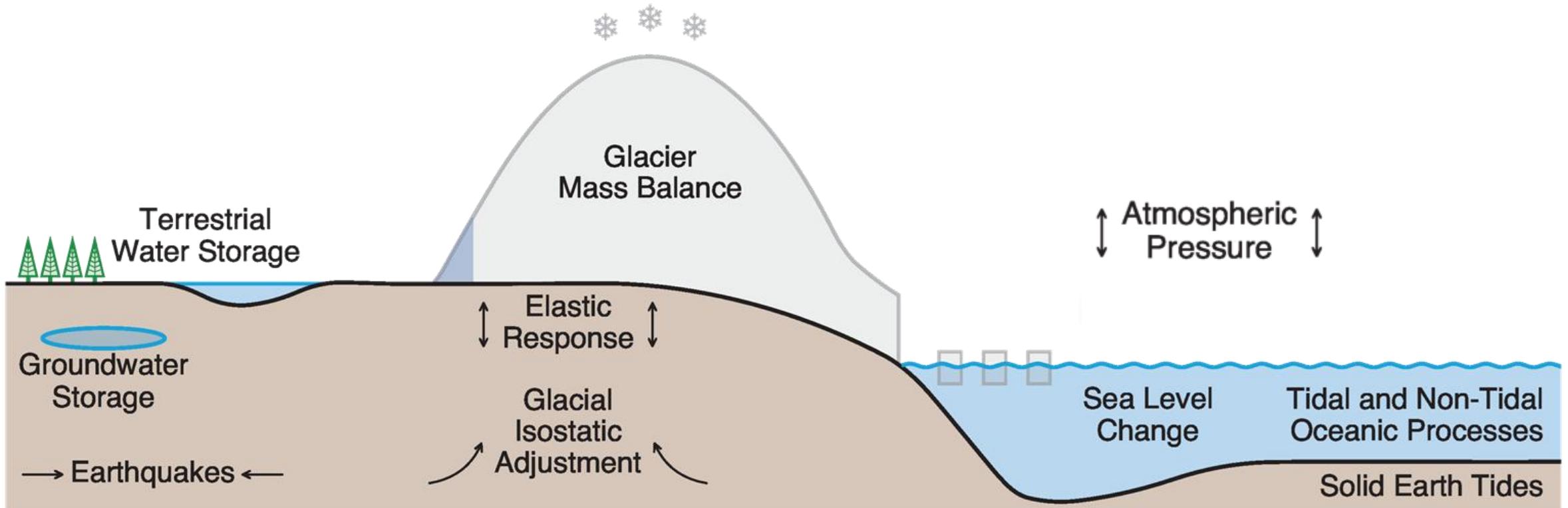
Geocenter motion – why do we care?
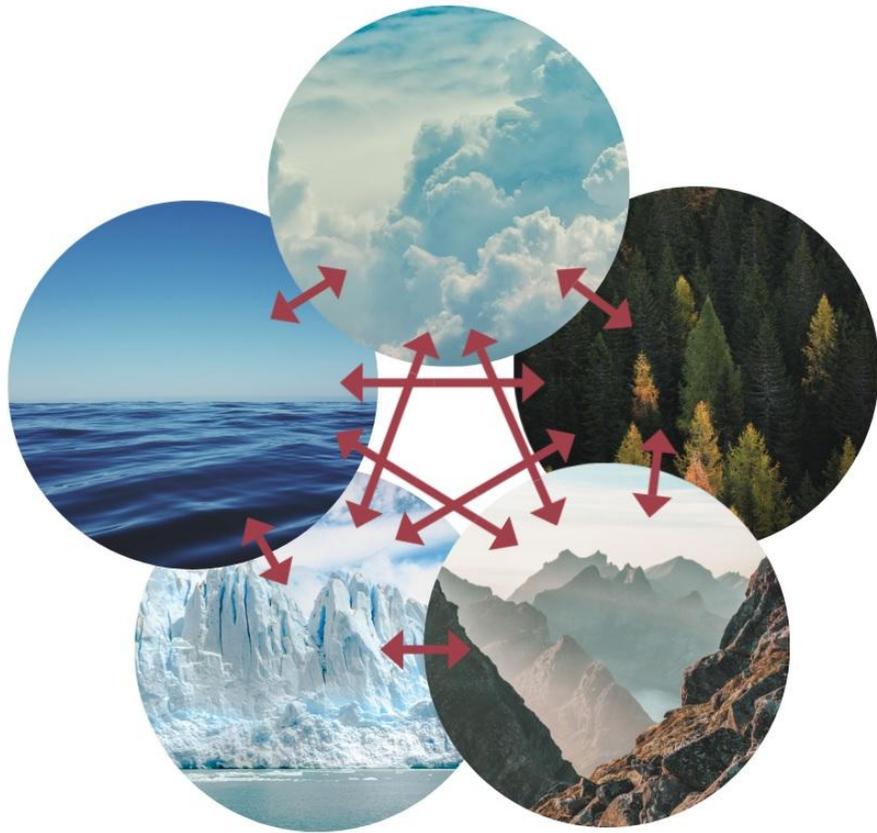
Earth System Understanding

Geocenter time series provide insights **into large-scale mass transport processes** and contribute to understanding global cycles (hydrological, atmospheric).

Geodetic excellence

Accurate geocenter estimates are essential for **maintaining inter-frame consistency** - millimeter-level reference frame accuracy required for satellite altimetry, LEO POD, and gravity field recovery.

Geocenter recovery

Technique	Key Pros	Key Cons
SLR	– Effective orbit modeling – High precision range measurements	– Sparse ground network; – Weather-dependent
DORIS	– All-weather, continuous tracking – Good network distribution	– Sensitive to satellite force model – LEO orbit quality worse than GNSS/SLR
GRACE	– Sensitive to large-scale hydrology/ice mass changes	– Cannot sense degree-1 (geocenter) directly (intersatellite ranging insensitive)
LEO POD	– High-frequency daily geocenter estimates (multi-mission) – High sensitivity to degree-1 mass variations	– Complex modeling
Geophysical Models (Surface Loading)	– Integrates major fluid mass changes (atmosphere, ocean, hydrology) – Global coverage, including regions with sparse stations (e.g. open oceans)	– Dependent on model accuracy/assumptions (not direct observation; uncertainties in outputs) – May omit unmodeled processes or biases (e.g. groundwater depletion, model errors)
GNSS (orbits)	– Direct product of GNSS POD solution	– Because of the high-attitude of GNSS satellites, these are less sensitive to geocenter motion – limited ability to separate the geocenter motion from the other parameters because of modeling deficiencies, particularly in the orbit determination.
GNSS (station disp.)	– Accounts for elastic Earth deformation at each site (degree-1 loading)	– Requires global coverage – Higher model complexity – Signals in GNSS displacements that are unrelated to surface mass redistribution

Geocenter recovery

Technique	Key Pros	Key Cons
SLR	– Effective orbit modeling – High precision range measurements	– Sparse ground network; – Weather-dependent
DORIS	– All-weather, continuous tracking – Good network distribution	– Sensitive to satellite force model – LEO orbit quality worse than GNSS/SLR
GRACE	– Sensitive to large-scale hydrology/ice mass changes	– Cannot sense degree-1 (geocenter) directly (intersatellite ranging insensitive)
LEO POD	– High-frequency daily geocenter estimates (multi-mission) – High sensitivity to degree-1 mass variations	– Complex modeling
Geophysical Models (Surface Loading)	– Integrates major fluid mass changes (atmosphere, ocean, hydrology) – Global coverage, including regions with sparse stations (e.g. open oceans)	– Dependent on model accuracy/assumptions (not direct observation; uncertainties in outputs) – May omit unmodeled processes or biases (e.g. groundwater depletion, model errors)
GNSS (orbits)	**– Direct product of GNSS POD solution**	**– Because of the high-altitude of GNSS satellites, these are less sensitive to geocenter motion** **– <u>limited ability to separate the geocenter motion from the other parameters because of modeling deficiencies, particularly in the orbit determination.</u>**
GNSS (station disp.)	– Accounts for elastic Earth deformation at each site (degree-1 loading)	– Requires global coverage – Higher model complexity – Signals in GNSS displacements that are unrelated to surface mass redistribution

IGS Repro3

- IGS Repro3 is the **third full reprocessing of all IGS GNSS products**, covering 1994–2020, delivered as the official IGS contribution to ITRF2020
- For the first time, **Repro3 provides consistent multi-GNSS products, including GPS, GLONASS, and Galileo**
- Based on updated models, standards, and processing strategies, ensuring long-term homogeneity of the IGS time series
- Fundamental improvement in terms of orbit modeling →
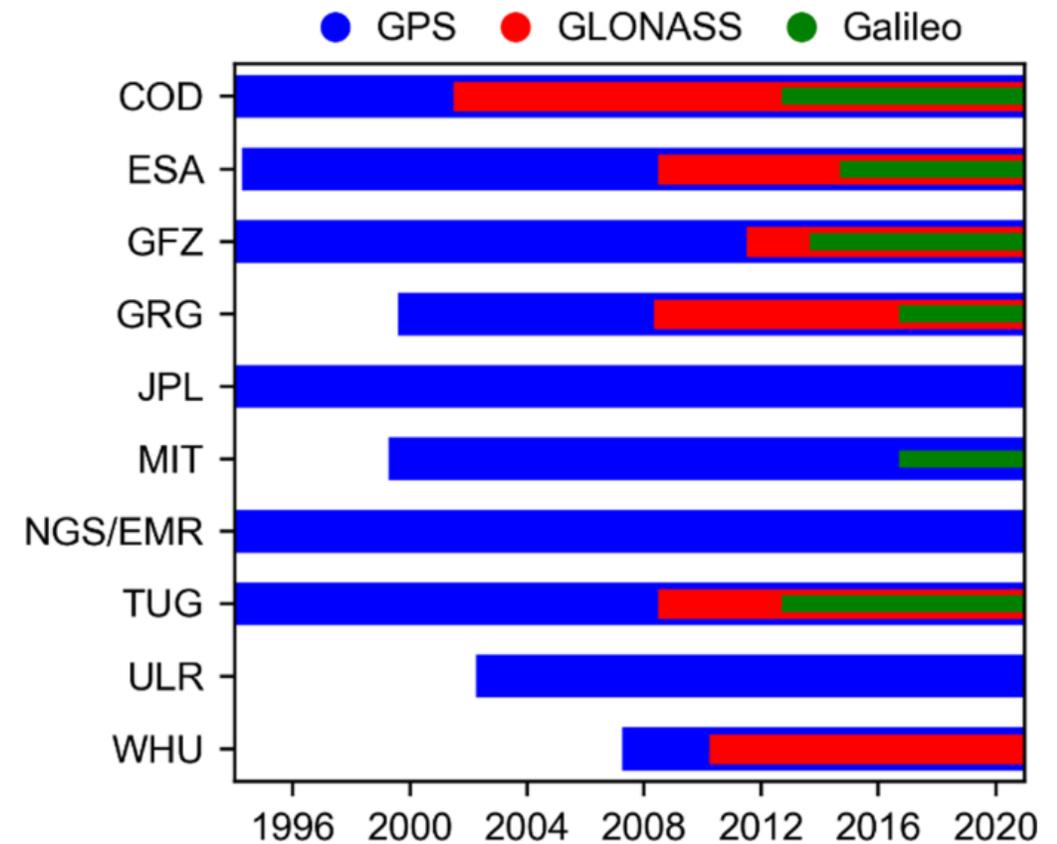
ORIGINAL ARTICLE

Combination and SLR validation of IGS Repro3 orbits for ITRF2020

Radosław Zajdel[1] · Salim Masoumi[2] · Krzysztof Sośnica[1] · Filip Gałdyn[1] · Dariusz Strugarek[1] · Grzegorz Bury[1]

Goal of this study

- **explore the individual behavior of IGS geocenter series through the last 30 years.**

- investigates how **GNSS-specific errors** – including orbital artifacts and draconitic effects – evolve with constellation development, assessing consistency across ACs.

- **cross-compare the results with independent estimates** from geophysical fluid models, LAGEOS-based SLR solutions (Yu et al., 2025), and GPS-based Low-Earth-Orbit (LEO) satellite positioning (Kuang et al., 2024).

- **Provide the combined GNSS based geocenter product.**

Geocenter motion from GNSS

- 10 Analysis Centers: Constellation differences (GPS-only, GPS+Galileo, GPS+GLONASS, full multi-GNSS).
- Orbit modeling differences / station network distribution
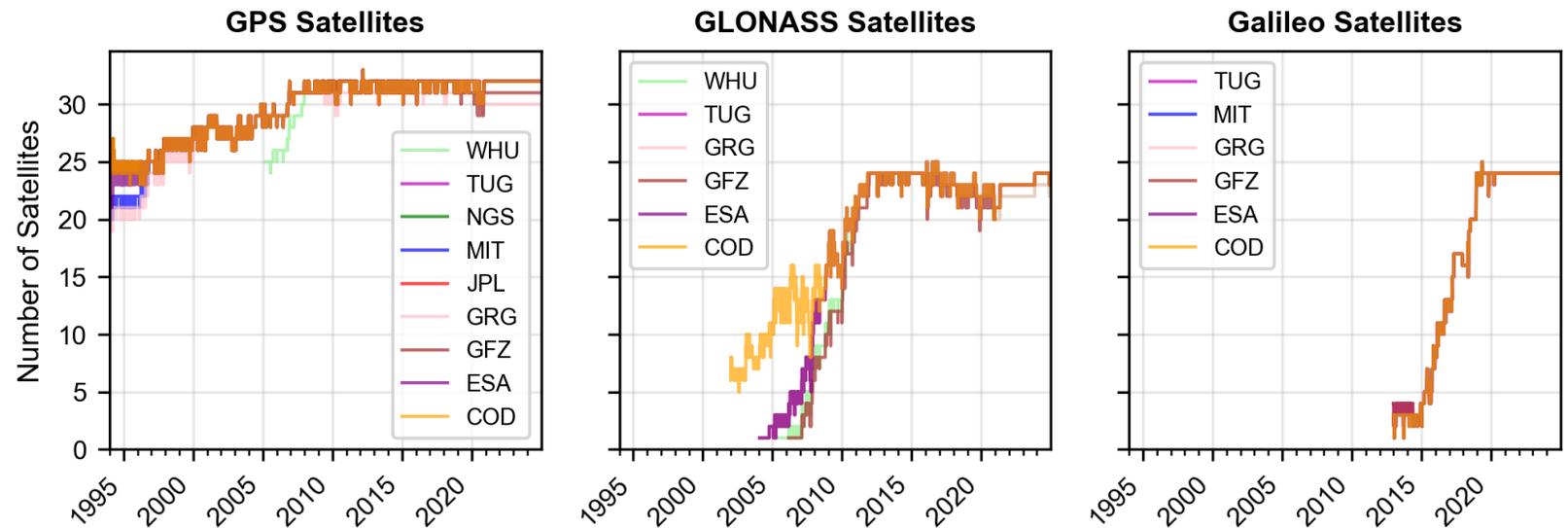
- IGS Repro3 contributions: 1994-01-02 to 2020-12-31
- IGS Repro3 extension: 2021-01-01 to 2022-11-26
- IGS operational products (after switch to IGS20 reference frame): 2022-11-27 to 2025-06-01

Combination

- Builds upon IGS combination principles for orbits/clocks (Zajdel et al. 2025)

ORIGINAL ARTICLE

- Aim to **improve resilience** against AC-specific artifacts.

Advancing multi-GNSS orbit combination in the variance component estimation framework

Radosław Zajdel[1,2] · Gustavo Mansur[3] · Pierre Sakic[4] · Paul Rebischung[4,5] · Andreas Brack[3] · Benjamin Männel[3] · Jan Douša[1]

- **Förstner VCE** computes optimal AC weights.

- Avoids full SINEX combination; works directly at parameter level (contrast to IGS combination)

| *Data availability and quality check* | → | *Select the processing window* | → | *VCE → weights* | → | *Weighted average* |
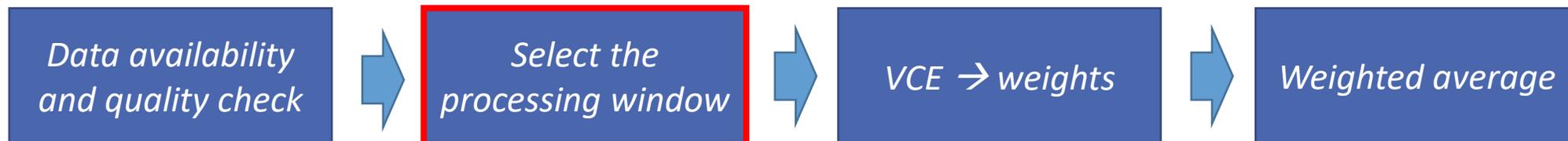
Reference series

SLR	LEO	Geophysical Models

- **LAGEOS-1/2 only** (single satellite type to avoid target-change artifacts) (Yu et al. 2025).
- **Considered a highly suitable technique for sensing GCC:** simple orbit modeling and independence from GNSS-specific errors.

- **Derived from GPS-based POD of LEOs, including GRACE, GRACE-FO, and seven additional missions** (Kuang et al., 2024).
- GCC sensed directly by LEO orbital motion;
- **Provides monthly GCC time series.**
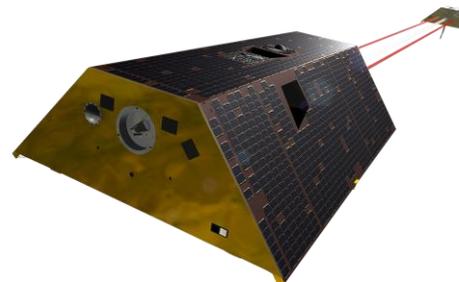
- Two loading model suites: **GGFC GCTI20** (Boy, 2021) and **ESMGFZ** (Dill & Dobslaw, 2013).
- **Atmosphere** (NTAL), **ocean** (NTOL), **terrestrial water storage** (HYDL).
- **All series averaged to daily for comparison with space geodesy.**

Variability

- **GNSS scatter high before 2000** (incomplete constellations, sparse tracking); variability drops after 2005 (window to window std differences become lower than 1–2 mm).

- **GNSS scatter at the level of 3-5 mm** for X and Y, while about **5-14 mm** for the Z geocenter component.

- SLR and GNSS exhibit greater variability than LEO and GGFC/ESM.

GNSS / COMB heatmap of variability values [mm]

X [mm]

	COD	ESA	GFZ	GRG	JPL	MIT	NGS	TUG	ULR	WHU	GGFC	SLR	LEO	IG3	V7D	V3M
1995-1999	8.8	6.5	9.4		7.4		9.4	6.0			2.0	4.7		4.6		
	4.5	5.6	7.1	5.2	5.7	5.3	5.3	3.8	5.8		1.9	3.6	1.3	3.6	3.8	3.7
2005-2009	4.5	3.9	4.0	4.8	4.3	3.4	4.3	3.4	4.2	3.9	1.9	3.4	1.3	3.1	3.2	3.1
	3.7	3.9	3.4	3.4	4.2	3.5	3.5	2.9	4.2	3.5	1.9	3.5	1.3	2.7	2.8	2.8
2015-2019	3.7	3.5	3.6	2.9	4.2	3.0	3.5	2.8	3.5	3.3	1.9	4.6	1.4	2.5	2.6	2.5
	3.7	3.8	3.4	3.1	4.5	3.7	4.0	2.8	3.6		2.0	4.5	1.5	2.7	2.8	2.7
2025-2025	3.0	2.9	2.9	2.9	3.3	3.3	3.8							2.5	2.5	2.5

Y [mm]

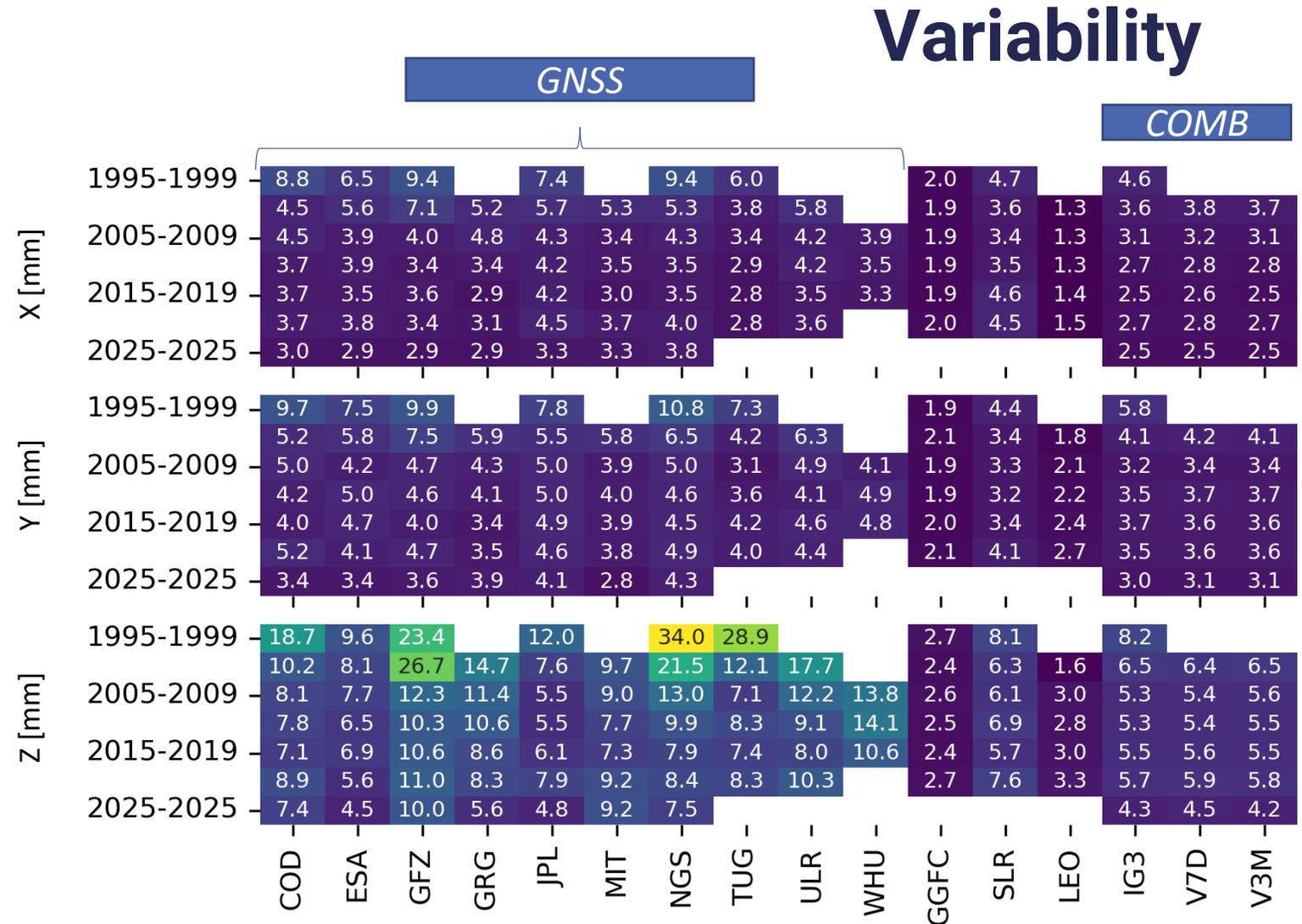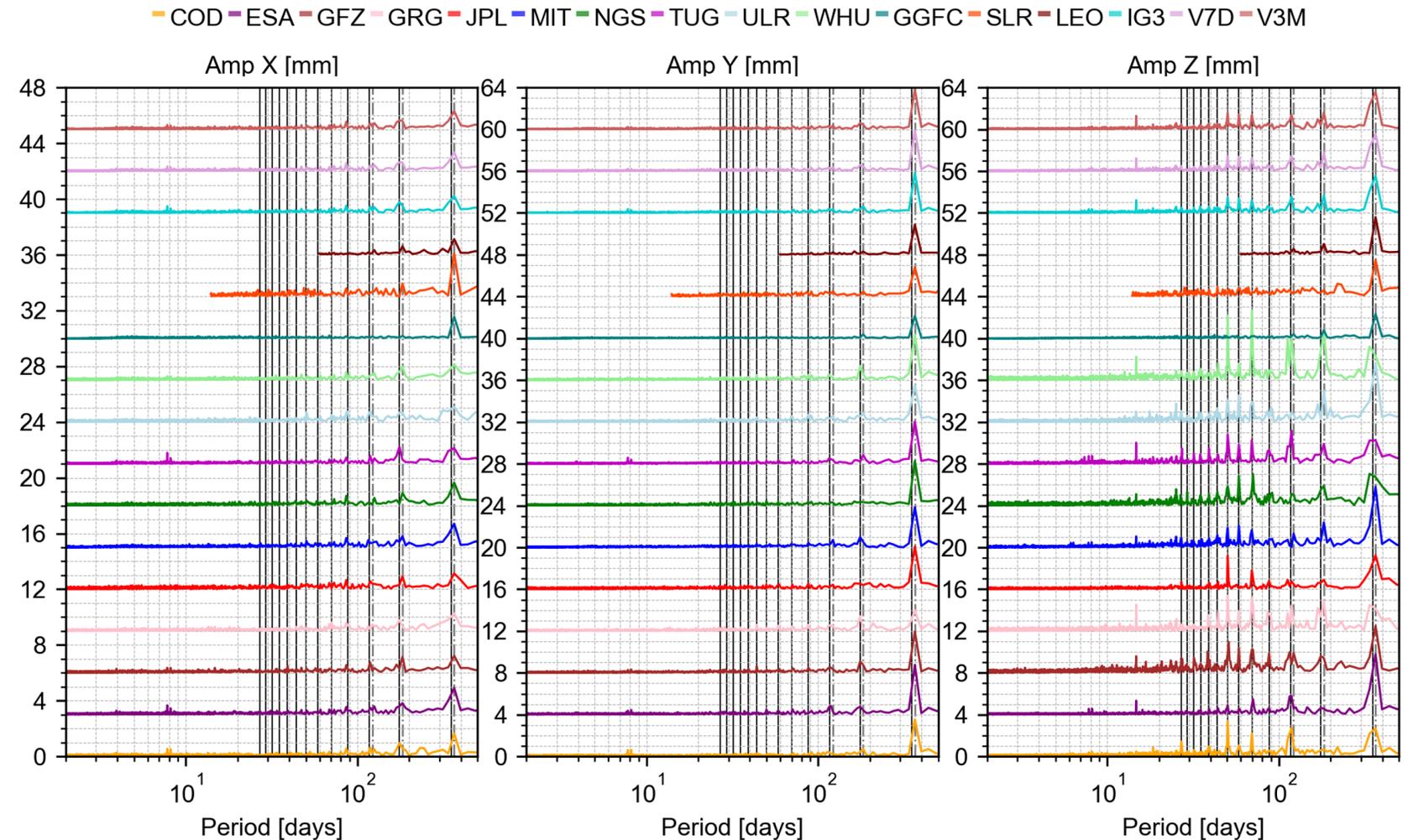|	COD	ESA	GFZ	GRG	JPL	MIT	NGS	TUG	ULR	WHU	GGFC	SLR	LEO	IG3	V7D	V3M
1995-1999	9.7	7.5	9.9		7.8		10.8	7.3			1.9	4.4		5.8		
	5.2	5.8	7.5	5.9	5.5	5.8	6.5	4.2	6.3		2.1	3.4	1.8	4.1	4.2	4.1
2005-2009	5.0	4.2	4.7	4.3	5.0	3.9	5.0	3.1	4.9	4.1	1.9	3.3	2.1	3.2	3.4	3.4
	4.2	5.0	4.6	4.1	5.0	4.0	4.6	3.6	4.1	4.9	1.9	3.2	2.2	3.5	3.7	3.7
2015-2019	4.0	4.7	4.0	3.4	4.9	3.9	4.5	4.2	4.6	4.8	2.0	3.4	2.4	3.7	3.6	3.6
	5.2	4.1	4.7	3.5	4.6	3.8	4.9	4.0	4.4		2.1	4.1	2.7	3.5	3.6	3.6
2025-2025	3.4	3.4	3.6	3.9	4.1	2.8	4.3							3.0	3.1	3.1

Z [mm]

	COD	ESA	GFZ	GRG	JPL	MIT	NGS	TUG	ULR	WHU	GGFC	SLR	LEO	IG3	V7D	V3M
1995-1999	18.7	9.6	23.4		12.0		34.0	28.9			2.7	8.1		8.2		
	10.2	8.1	26.7	14.7	7.6	9.7	21.5	12.1	17.7		2.4	6.3	1.6	6.5	6.4	6.5
2005-2009	8.1	7.7	12.3	11.4	5.5	9.0	13.0	7.1	12.2	13.8	2.6	6.1	3.0	5.3	5.4	5.6
	7.8	6.5	10.3	10.6	5.5	7.7	9.9	8.3	9.1	14.1	2.5	6.9	2.8	5.3	5.4	5.5
2015-2019	7.1	6.9	10.6	8.6	6.1	7.3	7.9	7.4	8.0	10.6	2.4	5.7	3.0	5.5	5.6	5.5
	8.9	5.6	11.0	8.3	7.9	9.2	8.4	8.3	10.3		2.7	7.6	3.3	5.7	5.9	5.8
2025-2025	7.4	4.5	10.0	5.6	4.8	9.2	7.5							4.3	4.5	4.2

GNSS

COMB

Variability

- For the GNSS series, the annual signal dominate in all the components but the Z component is influenced also by draconitic errors.

Variability
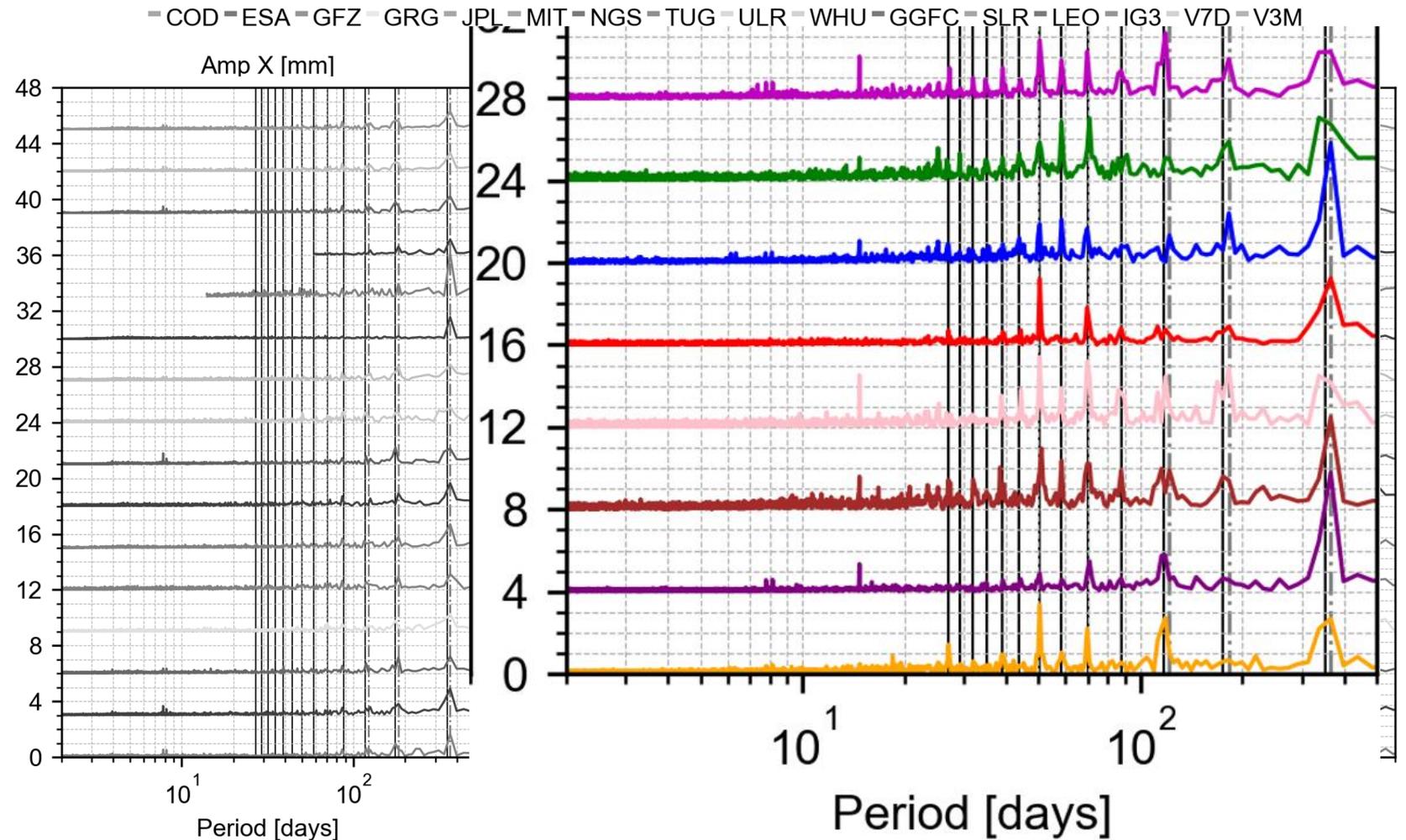
- For the GNSS series, the annual signal dominate in all the components but the Z component is influenced also by draconitic errors.
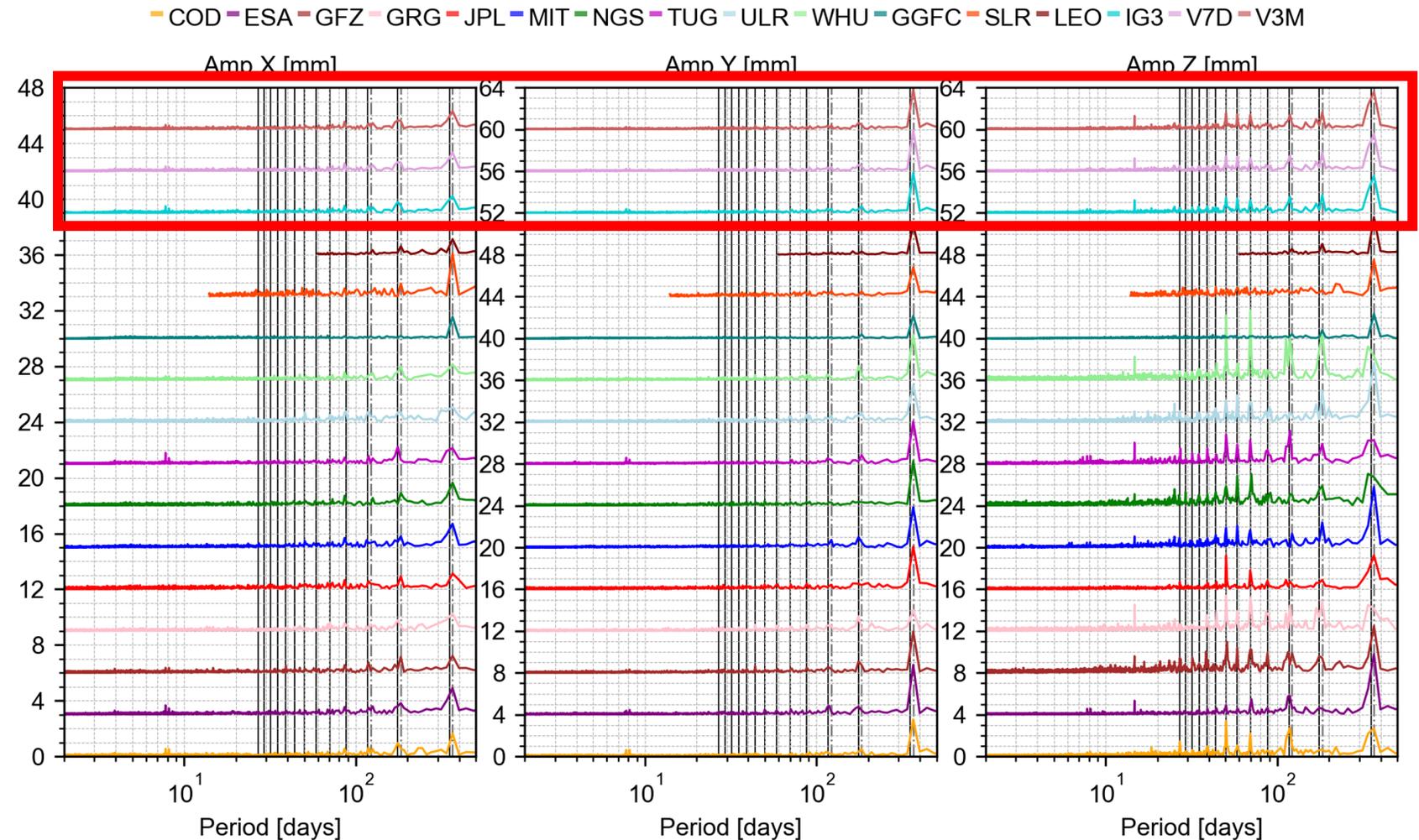
Variability

- For the GNSS series, the annual signal dominate in all the components but the Z component is influenced also by draconitic errors.

- Combination **mitigates most** of the spurious signals.

- IG3 and V7D and V3M are highly consistent

- **Correlation matrix (upper triangle) and standard deviations of differences in mm (lower triangle).**

- In the high-frequency band (2−40 days), individual AC solutions show moderate to weak correlations.

- The draconitic band (40−150 days) exhibits correlations generally higher, ranging from 0.4 to 0.8.

- At seasonal timescales (150−400 days), the correlation patterns reveal the strongest inter-solution agreement across all solution types. Individual AC correlations typically exceed 0.6−0.8, with the highest of 0.92 for the pair NGS and MIT. The latter indicates that annual geophysical signals dominate over processing-specific errors at these frequencies.
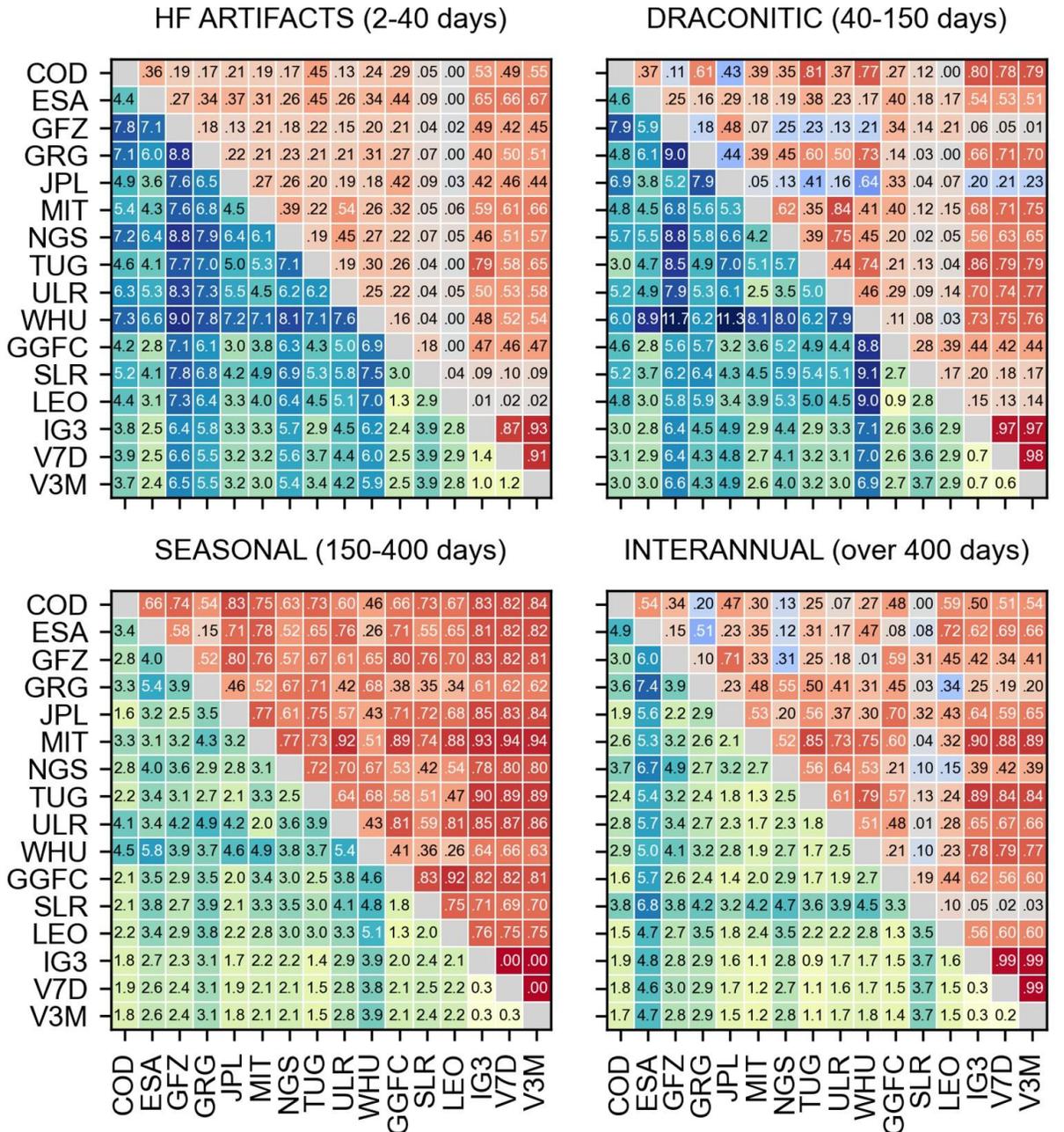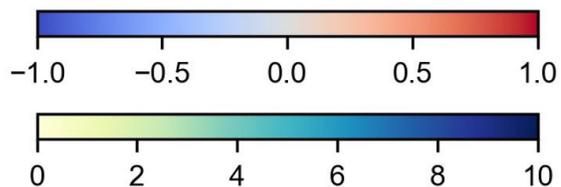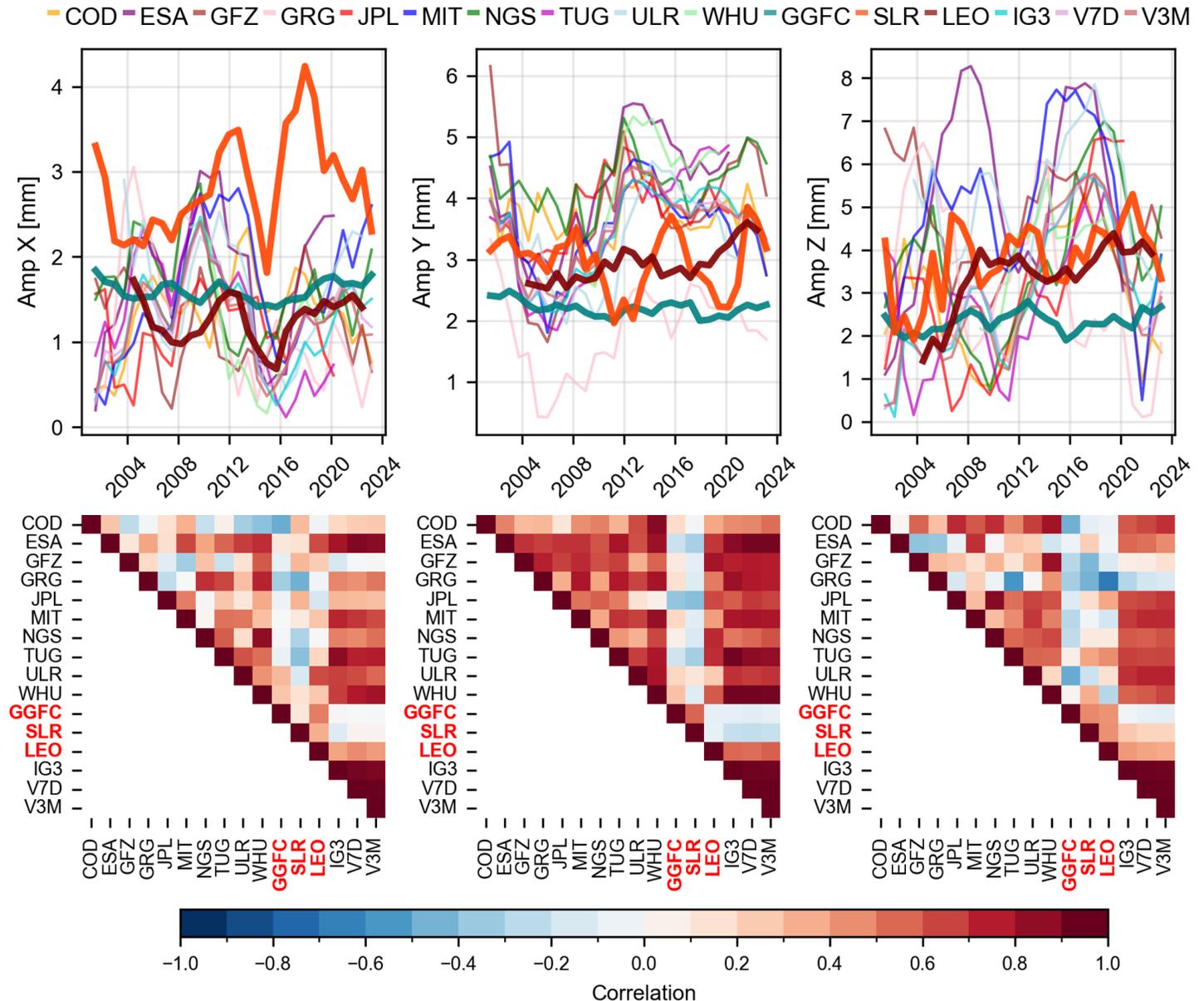
Annual signal

- GNSS annual amplitudes are consistent to a milimeter level for X and Y and by up to 5 mm for Z.

- GNSS annual phases are consistent to 20.

- No clear link between GNSS constellation choices and systematic differences in annual amplitude/phase.

- X: **GNSS amplitudes (V3M) align with LEO and GGFC/ESM**; SLR about 3× higher.
- Y: GNSS amplitudes (V3M) ~2 mm higher than GGFC/ESM and ~1 mm higher than SLR/LEO.
- Z: GNSS (V3M), SLR, LEO amplitudes mutually consistent but about 1.5 mm higher than GGFC/ESM, again indicating greater Z sensitivity to technique errors.

	SOL	X		Y		Z	
		A [mm]	P [°]	A [mm]	P [°]	A [mm]	P [°]
GPS	JPL	1.0	-112	3.9	147	3.4	-162
	NGS	1.5	-102	4.3	143	2.9	-166
	ULR	1.1	-178	3.5	140	5.6	-181
GPS+GAL	MIT	1.7	-165	3.9	133	5.6	-165
GPS+GAL+GLO	WHU	1.1	-122	4.4	142	2.3	-112
	COD	1.6	-128	3.6	136	2.7	-154
	ESA	1.9	-141	4.7	150	5.4	-195
	GFZ	1.2	-105	4.1	147	4.4	-135
	GRG	1.2	-130	2.0	135	2.1	-105
	TUG	1.1	-145	4.1	140	2.4	-160
GNSS COMB	V3M	1.3	-139	3.8	142	3.5	-169
LAGEOS	SLR	3.1	-131	2.8	145	3.8	-141
LEO	LEO	1.2	-123	2.9	154	3.7	-159
NTAL+NTOL+HYDL	GGFC	1.6	-155	2.2	164	2.4	-158
NTAL+NTOL +HYDL+SLEL	ESM	1.8	-126	2.2	134	2.2	-133
NTAL	NTAL	0.4	169	1.0	175	1.0	170
NTOL	NTOL	0.6	-163	0.1	138	0.1	-136
HYDL	HYDL	0.8	-99	1.2	97	1.1	-106
SLEL	SLEL	0.6	-93	0.3	137	0.7	-106

Annual signal

- Annual variability assessed via sliding 3-year sinusoidal fits (period 365.25 days).

- **GGFC and ESM show the lowest annual amplitude variability**; stable benchmarks.

- Annual amplitudes in GNSS/LEO/SLR depend more on processing strategies than exposing the responses to geophysical phenomena.

- **GNSS solutions agree better with each other than with external models** (notably in Y); X and Z show more complex patterns.

Variability of draconitic signals

- Analysis of Z component as being mostly affected by draconitic signals.

- Looking for the explanation in the change of the annual signal in the general change of other draconitic signals.

- No correlation found between the increase of the draconitics and annual signal amplitude.
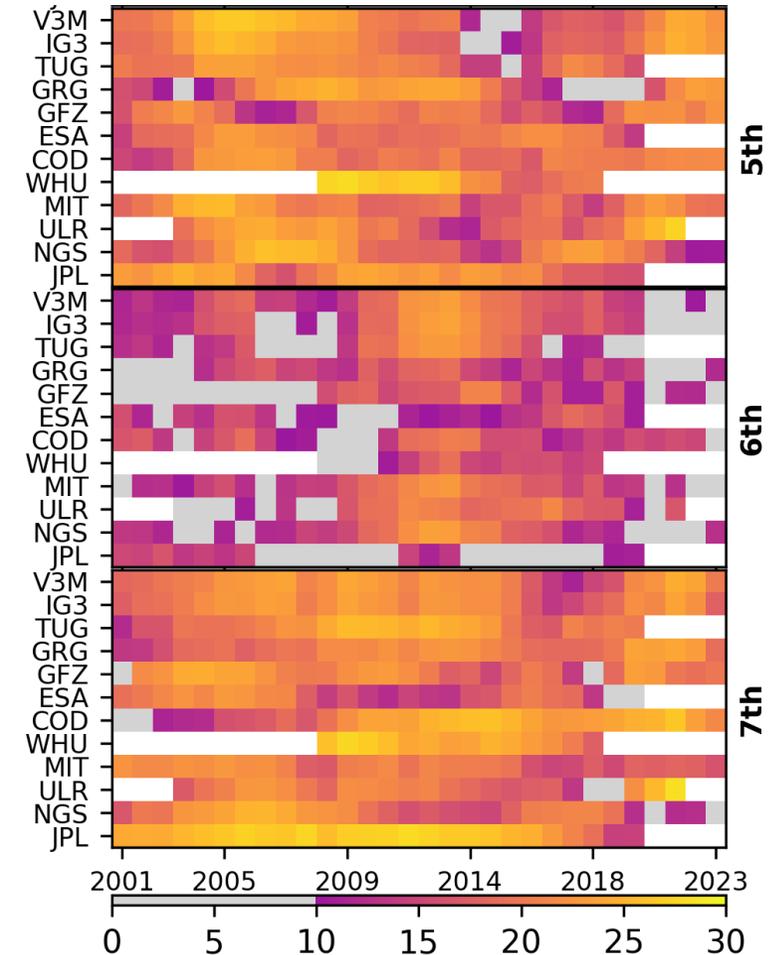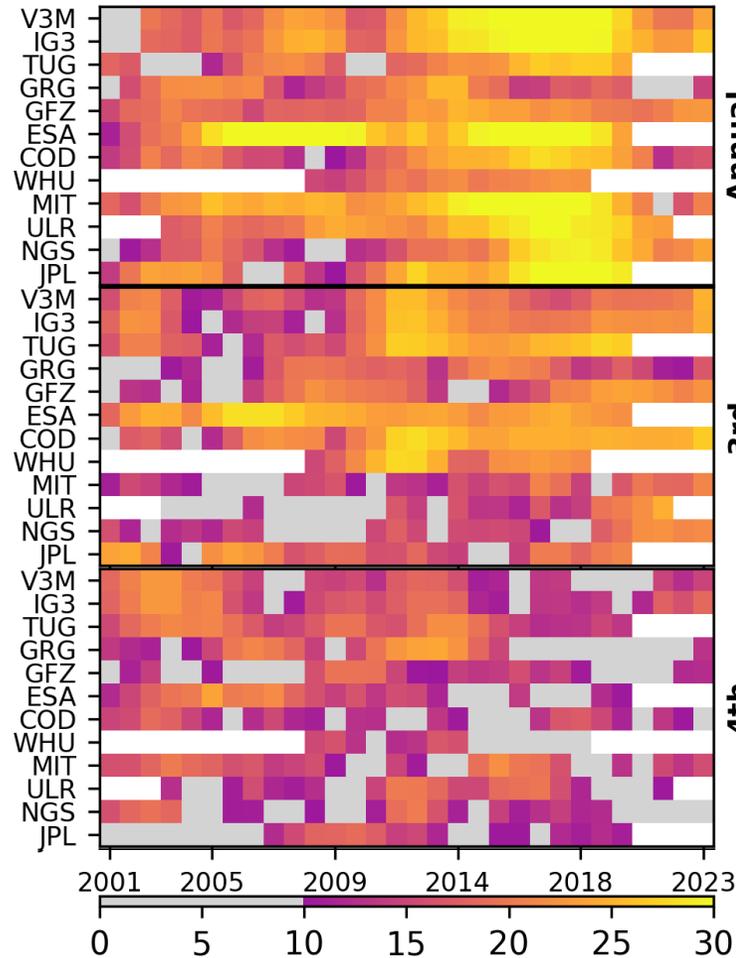
Conclusions

- The study provides **detailed characterization of systematic errors across** temporal frequency bands and establishes accuracy benchmarks for a direct geocenter recovery from GNSS POD processing.

- **Combining individual GNSS solutions significantly reduces scatter**: 40–50% improvement in the high-frequency band (2–40 days) and 35–40% in the draconitic band (40–150 days).

- The parameter-level combination method used is effective, achieving quality comparable to the full SINEX combination methods used by the IGS.

- GNSS solutions show strong agreement (correlations >0.8) with independent datasets (SLR to LAGEOS, LEO POD, geophysical models) at seasonal timescales, confirming the geophysical origin of annual variations.

- The seasonal component accounts for only 20–35% of the total variance, highlighting the dominance of GNSS-related artifacts. The time-variability of the annual signal is not consistent between the techniques.

Thank you!

Contact:

radoslaw.zajdel@pecny.cz

http://orcid.org/0000-0002-1634-388X

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Advances in Space Research xx (2025) xxx-xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Three decades of GNSS-derived geocenter motion: disentangling geophysical signal from systematic errors

Radosław Zajdel[a,*], Kyriakos Balidakis[b], Adrian Nowak[c], Tomasz Kur[c], Krzysztof Sośnica[c], Jan Douša[a]

[a]Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný (GOP), Ústecká 98, Zdiby, 250 66, Czechia
[b]Federal Agency for Cartography and Geodesy (BKG), Richard-Strauss-Allee 11, Frankfurt am Main, 60598, Germany
[c]Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Grunwaldzka 53, Wroclaw, 50-357, Poland

Combination – Choice of temporal window

- The selection involves a trade-off between the latency of the combination availability and the stability of the weight estimation.

- Longer windows yield more stable variance estimates but reduce the ability to capture rapid changes in solution quality.

- We suggest a 3-month solution (V3M) as the optimal window.

- Extending the window beyond 3 months provided no significant change

- shorter windows (e.g., 7 days) tend to concentrate weights on specific analysis centers like ESA and TUG. A 7-day solution (V7D) was also analyzed to assess the impact of prioritizing minimum latency.

Mean Weights by Scheme and Analysis Center

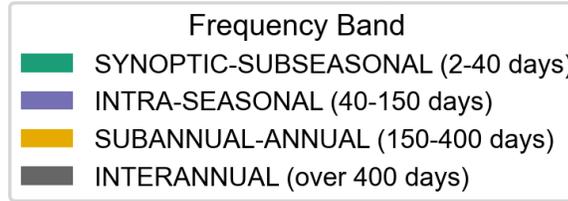| Scheme	COD	ESA	GFZ	JPL	NGS	TUG	MIT	GRG	ULR	WHU
7D	0.097	0.183	0.074	0.083	0.059	0.203	0.191	0.076	0.085	0.061
14D	0.101	0.191	0.071	0.083	0.063	0.197	0.181	0.077	0.086	0.061
1M	0.109	0.193	0.065	0.081	0.068	0.196	0.174	0.081	0.088	0.058
2M	0.116	0.189	0.059	0.080	0.073	0.192	0.175	0.084	0.090	0.055
3M	0.119	0.185	0.058	0.081	0.076	0.186	0.175	0.085	0.091	0.055
4M	0.121	0.182	0.058	0.082	0.078	0.184	0.176	0.084	0.092	0.054
5M	0.124	0.177	0.059	0.083	0.079	0.183	0.175	0.084	0.093	0.055
6M	0.127	0.173	0.059	0.084	0.080	0.184	0.175	0.084	0.094	0.055
7M	0.128	0.170	0.059	0.084	0.081	0.184	0.174	0.084	0.094	0.056
8M	0.129	0.167	0.060	0.084	0.082	0.185	0.174	0.083	0.094	0.056
9M	0.131	0.166	0.060	0.085	0.083	0.185	0.174	0.083	0.095	0.056
10M	0.132	0.163	0.060	0.085	0.084	0.185	0.174	0.083	0.095	0.056
11M	0.133	0.162	0.061	0.085	0.084	0.185	0.174	0.083	0.095	0.056
12M	0.133	0.161	0.061	0.085	0.085	0.185	0.174	0.083	0.095	0.056

Variability Heatmap: Scheme vs Analysis Center

| Scheme	COD	ESA	GFZ	JPL	NGS	TUG	MIT	GRG	ULR	WHU
7D	0.062	0.098	0.064	0.054	0.041	0.132	0.112	0.062	0.055	0.039
14D	0.051	0.085	0.055	0.044	0.039	0.111	0.091	0.052	0.045	0.031
1M	0.046	0.077	0.047	0.039	0.040	0.103	0.078	0.053	0.040	0.027
2M	0.041	0.075	0.037	0.037	0.040	0.081	0.063	0.052	0.034	0.023
3M	0.038	0.066	0.032	0.032	0.038	0.069	0.055	0.050	0.030	0.019
4M	0.037	0.062	0.030	0.030	0.037	0.060	0.049	0.048	0.029	0.016
5M	0.038	0.056	0.030	0.029	0.036	0.055	0.045	0.047	0.027	0.015
6M	0.039	0.052	0.030	0.028	0.037	0.053	0.043	0.047	0.027	0.014
7M	0.038	0.049	0.029	0.028	0.038	0.053	0.042	0.047	0.026	0.013
8M	0.039	0.048	0.028	0.027	0.039	0.052	0.040	0.046	0.026	0.012
9M	0.040	0.047	0.028	0.027	0.040	0.051	0.038	0.045	0.025	0.012
10M	0.039	0.044	0.028	0.026	0.040	0.049	0.037	0.045	0.024	0.011
11M	0.039	0.043	0.029	0.026	0.041	0.048	0.035	0.045	0.024	0.010
12M	0.039	0.043	0.029	0.025	0.041	0.047	0.034	0.045	0.024	0.010

Analysis Center

Variability

Power distribution of the specific **spectral** band as a percentage of the total power.
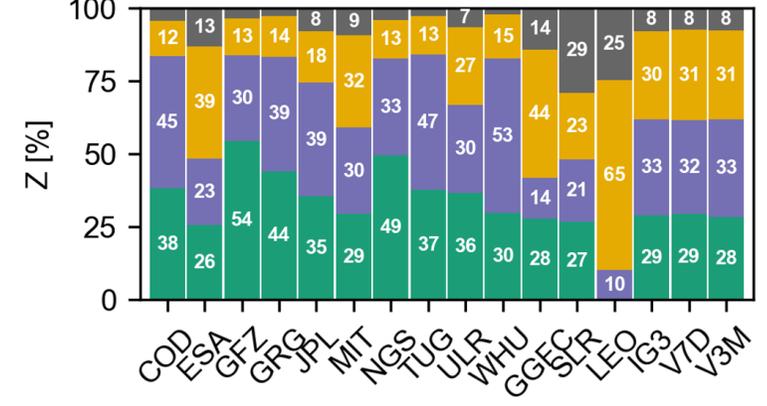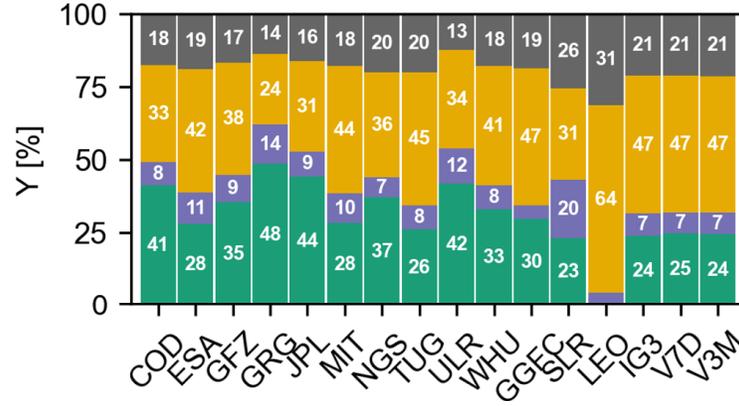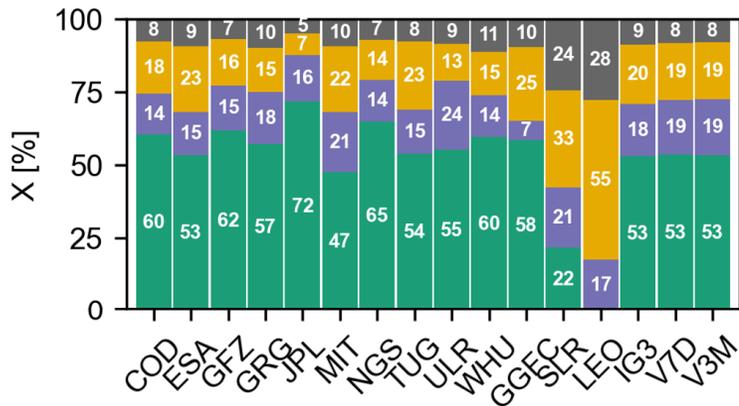
- **Strong high-frequency artifacts for GNSS** (notably X from orbital errors); **elevated intra-seasonal power in Z (draconitic errors)**.

- Combined GNSS solution (V3M) boosts annual/semiannual bands and suppresses high-frequency/intra-seasonal bands (periods < 150 days)

- SLR/LEO series have both coarser sampling; signal power concentrated in subannual–interannual bands.

Geocenter motion − Meindl et al. (2013)
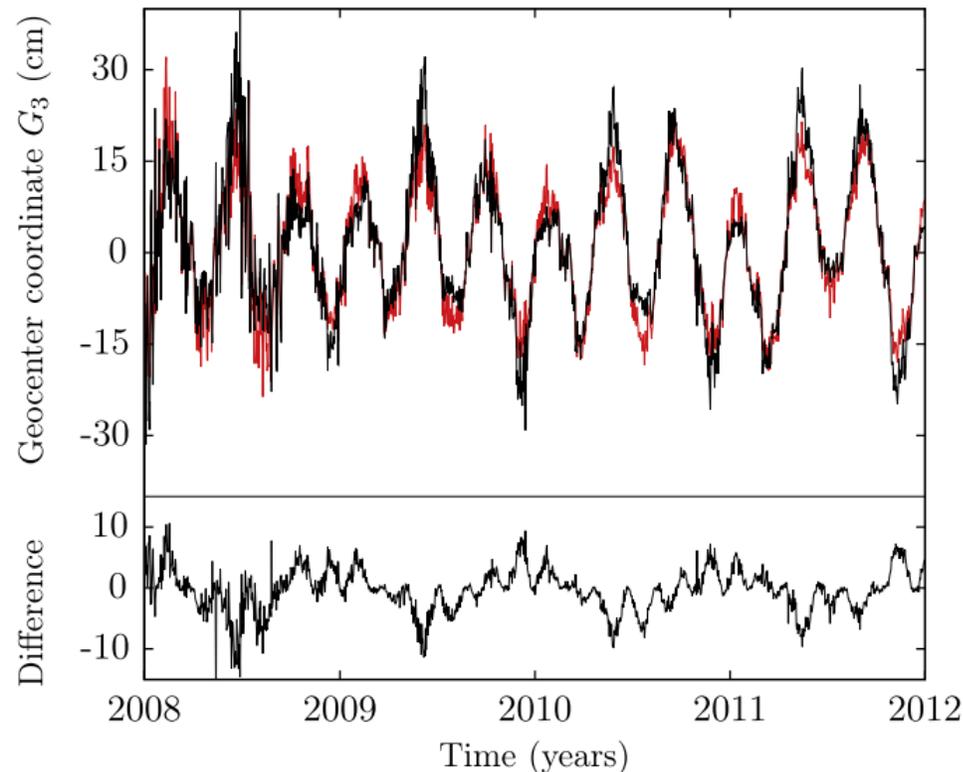
The total theoretical shift dz of the geocenter induced by the plane-specific direct SRP in the satellite-sun direction (ΔD); of all p orbital planes, is:

$$\delta z = \frac{\sum_{\ell=1}^{p} \Delta D_{\ell} \sin \beta_{s\ell}}{n^2 \cos i},$$

Where, n is the mean motion, i is the inclination, β is the Sun elevation angle above the orbital plane.

The **red** and the **black** curves correspond to the estimated and calculated GCC-z values.

Geocenter motion – why do we care?

Blazquez, A., Meyssignac, B., Lemoine, J., Berthier, E., Ribes, A., & Cazenave, A. (2018). **Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: Implications for the global water and sea level budget**s. *Geophysical Journal International*, *215*(1), 415–430. https://doi.org/10.1093/gji/ggy293

The geocenter is recognized as one of the **most significant contributors to uncertainties in global water and sea-level budgets.**

Table 1.

Uncertainties in trend over 2005–2015 of GRACE estimates of the global water budget components ($mm\ yr^{-1}$).

($mm\ yr^{-1}$ SLE)	Ocean mass		Greenland		Antarctica		Arctic islands		Glacier & TWS	
Mean trend	1.63		0.80		0.63		0.29		−0.09	
Processing centre	0.09	(5 per cent)	0.02	(2 per cent)	0.06	(9 per cent)	0.01	(3 per cent)	0.12	(137 per cent)
Geocentre motion	0.21	(13 per cent)	0.01	(2 per cent)	0.05	(8 per cent)	0.02	(5 per cent)	0.23	(255 per cent)
$C_{2,0}$	0.02	(1 per cent)	<0.01	(<1 per cent)	0.02	(3 per cent)	<0.01	(1 per cent)	<0.01	(6 per cent)
Filtering	0.02	(1 per cent)	0.03	(3 per cent)	0.01	(1 per cent)	0.02	(8 per cent)	<0.01	(10 per cent)
Leakage correction	0.08	(5 per cent)	<0.01	(<1 per cent)	<0.01	(<1 per cent)	<0.01	(1 per cent)	0.09	(103 per cent)
GIA	0.12	(7 per cent)	<0.01	(<1 per cent)	0.12	(19 per cent)	0.01	(4 per cent)	0.03	(30 per cent)
Total uncertainty	0.27		0.04		0.15		0.04		0.27	
Quadratic sum of individual uncertainties	0.27		0.04		0.15		0.04		0.27	
Interaction	<0.01		<0.01		<0.01		<0.01		<0.01	

Geocenter motion – why do we care?

The geocenter is recognized as one of the **most significant contributors to uncertainties in global water and sea-level budgets.**