THREE DECADES OF GNSS-DERIVED GEOCENTER MOTION

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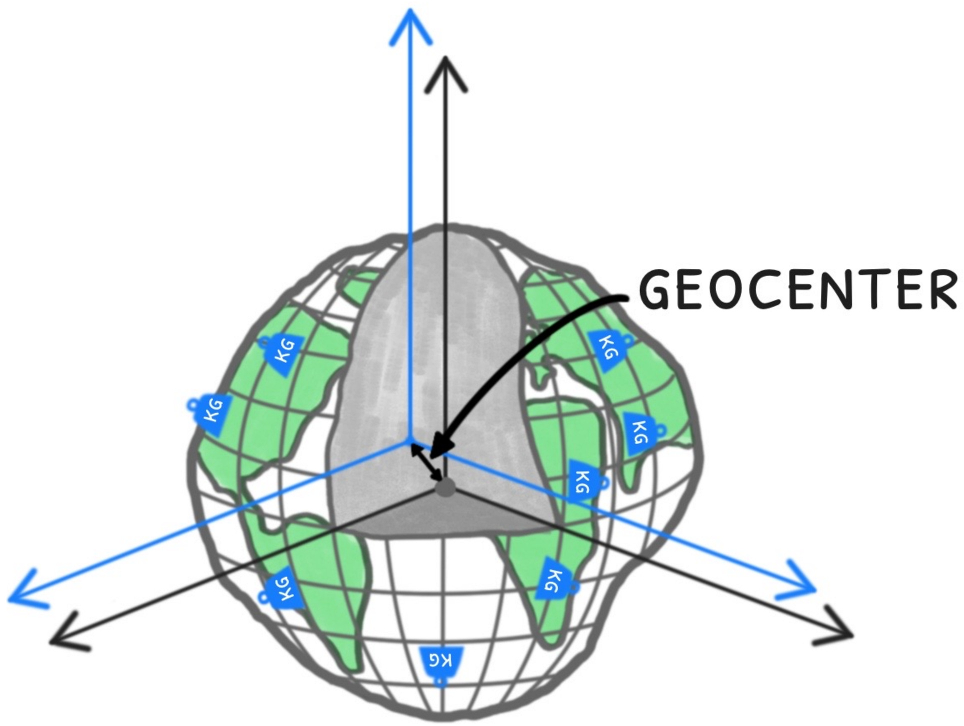
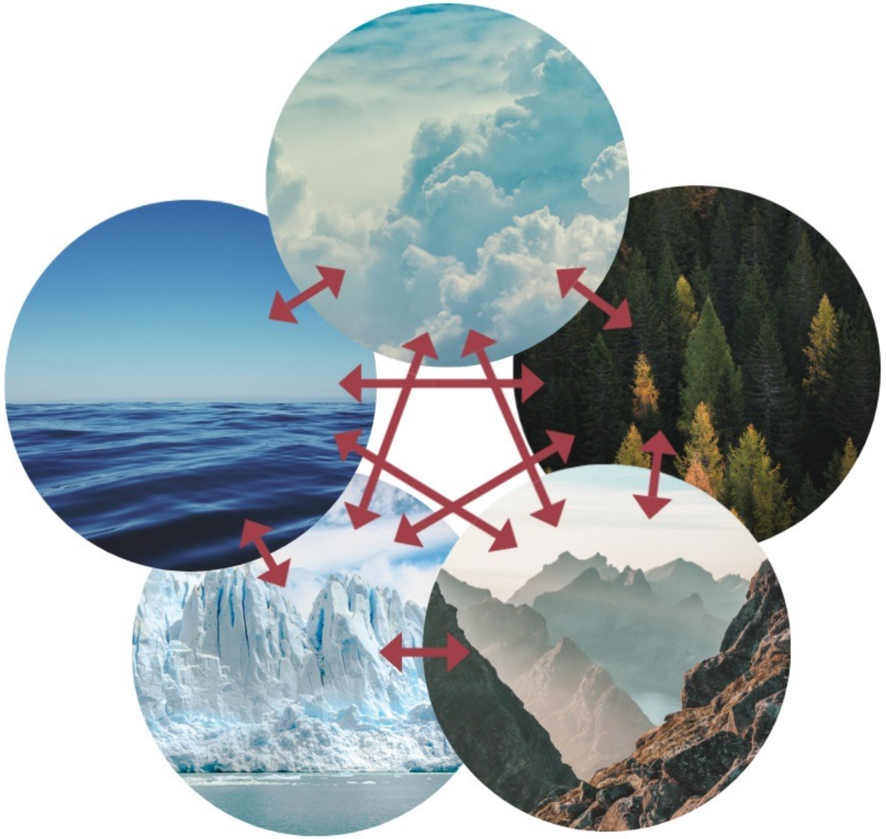
Geocenter Motion



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

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).

GNSS Excellence

Geocenter estimates from the POD-based network-shift approach **mirrors the processing quality (orbit modeling).**

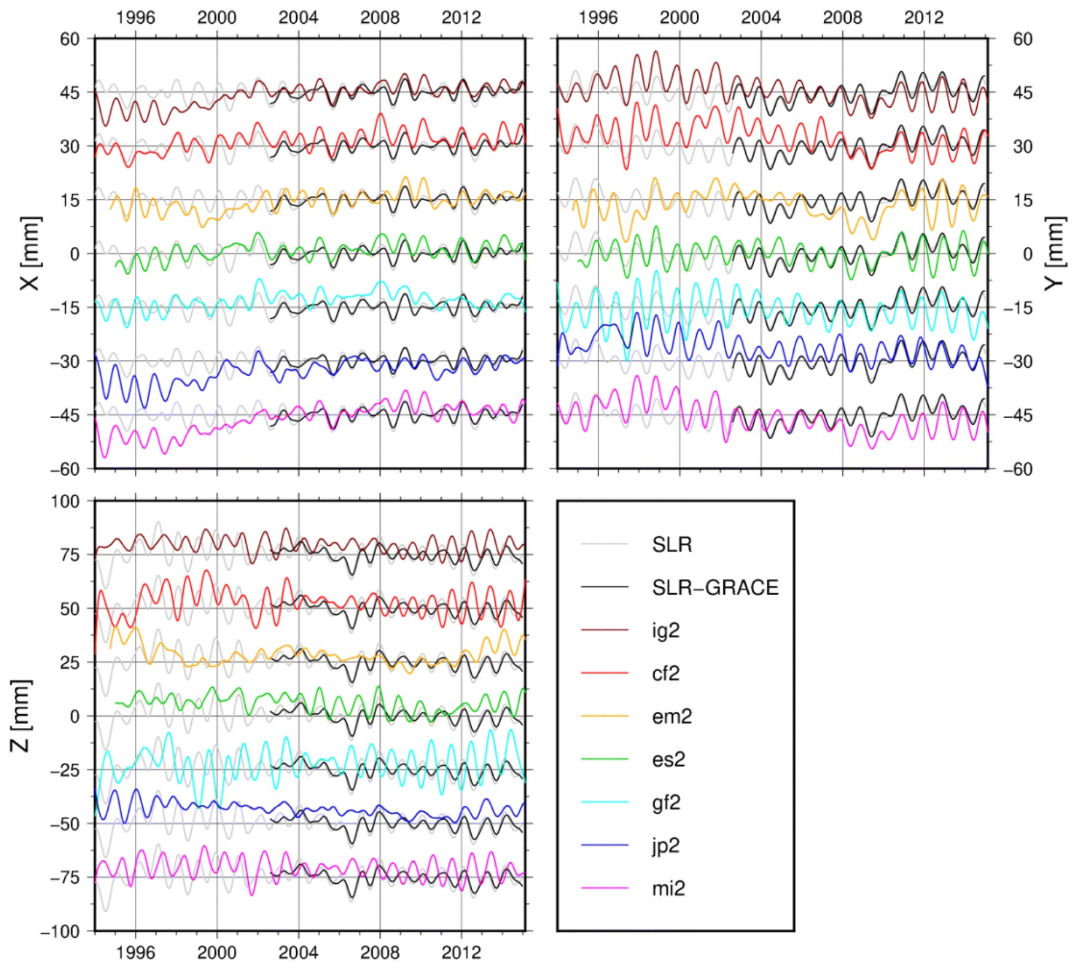
Geodetic Excellence

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

IGS Repro2 (1994 – 2015)

context of geocenter motion

- The GNSS geocenter time series **include expected seasonal variations**, but also **spurious draconitic signals**, particularly in the Z direction.
- GNSS annual geocenter motion estimates are in **reasonable agreement with SLR estimates in the X and Y directions.**
- In the Z direction, however, the annual signals derived from the IGS solutions disagree with SLR estimates.
- Inter-AC differences are substantial



Low-frequency variations of the geocenter time series (source Ma et al. 2020)

Rebischung, P., Altamimi, Z., Ray, J. *et al.* The IGS contribution to ITRF2014. *J Geod* **90**, 611–630 (2016). https://doi.org/10.1007/s00190-016-0897-6
Ma, Y., Rebischung, P., Altamimi, Z. *et al.* Assessment of geocenter motion estimates from the IGS second reprocessing. *GPS Solut* **24**, 55 (2020). https://doi.org/10.1007/s10291-020-0968-2

J Geod (2014) 88:65–85
DOI 10.1007/s00190-013-0669-5

ORIGINAL ARTICLE

A collinearity diagnosis of the GNSS geocenter determination

Paul Rebischung · Zuheir Altamimi · Tim Springer

ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 51 (2013) 1047–1064

Advances in Space Research (a COSPAR publication)

www.elsevier.com/locate/asr

Review

Geocenter coordinates estimated from GNSS data as viewed by perturbation theory

Michael Meindl *, Gerhard Beutler, Daniela Thaller, Rolf Dach, Adrian Jäggi

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Available online 9 November 2012

GPS Solutions (2021) 25:1
https://doi.org/10.1007/s10291-020-01037-3

ORIGINAL ARTICLE

Check for updates

Geocenter coordinates derived from multi-GNSS: a look into the role of solar radiation pressure modeling

Radosław Zajdel[1] · Krzysztof Sośnica[1] · Grzegorz Bury[1]

Received: 1 July 2020 / Accepted: 19 September 2020 / Published online: 7 October 2020

GPS Solutions (2026) 30:26
https://doi.org/10.1007/s10291-025-01990-x

RESEARCH

Check for updates

Geocenter motion based on GNSS: a comparison between low-degree surface load coefficients and network shift parameters

Adrian Nowak[1] · Radosław Zajdel[2,1] · Krzysztof Sośnica[1]

Received: 14 July 2025 / Accepted: 29 October 2025 / Published online: 18 November 2025

GPS Solutions (2025) 29:158
https://doi.org/10.1007/s10291-025-01920-x

RESEARCH

Check for updates

Correcting geocenter motion in GNSS solutions by combining with satellite laser ranging data

Grzegorz Bury[1] · Radosław Zajdel[1,2] · Krzysztof Sośnica[1]

Received: 7 April 2025 / Accepted: 23 June 2025 / Published online: 3 July 2025

J Geod (2018) 92:93–104
https://doi.org/10.1007/s00190-017-1047-5

CrossMark

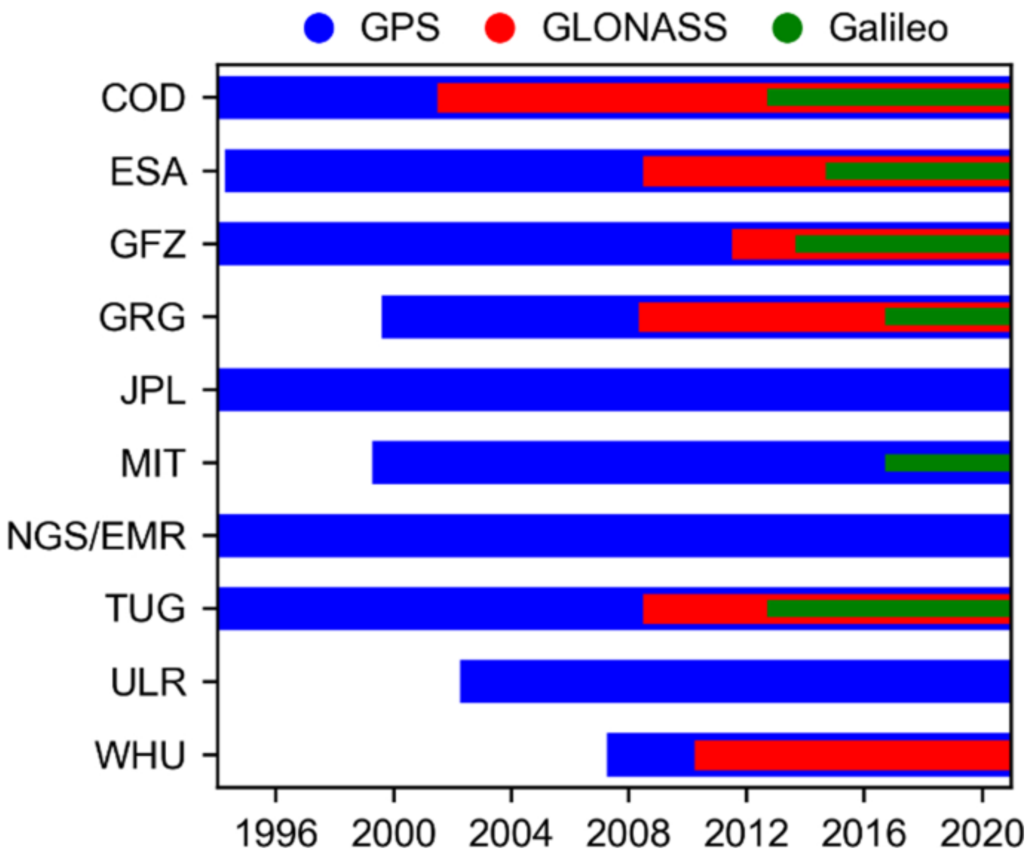
ORIGINAL ARTICLE

Dependency of geodynamic parameters on the GNSS constellation

Stefano Scaramuzza[1] · Rolf Dach[1] · Gerhard Beutler[1] · Daniel Arnold[1] · Andreja Sušnik[1] · Adrian Jäggi[1]

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 →



Journal of Geodesy (2023) 97:87
https://doi.org/10.1007/s00190-023-01777-3

ORIGINAL ARTICLE

Check for updates

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]

Received: 5 April 2023 / Accepted: 6 September 2023 / Published online: 1 October 2023

Goal of This Study

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

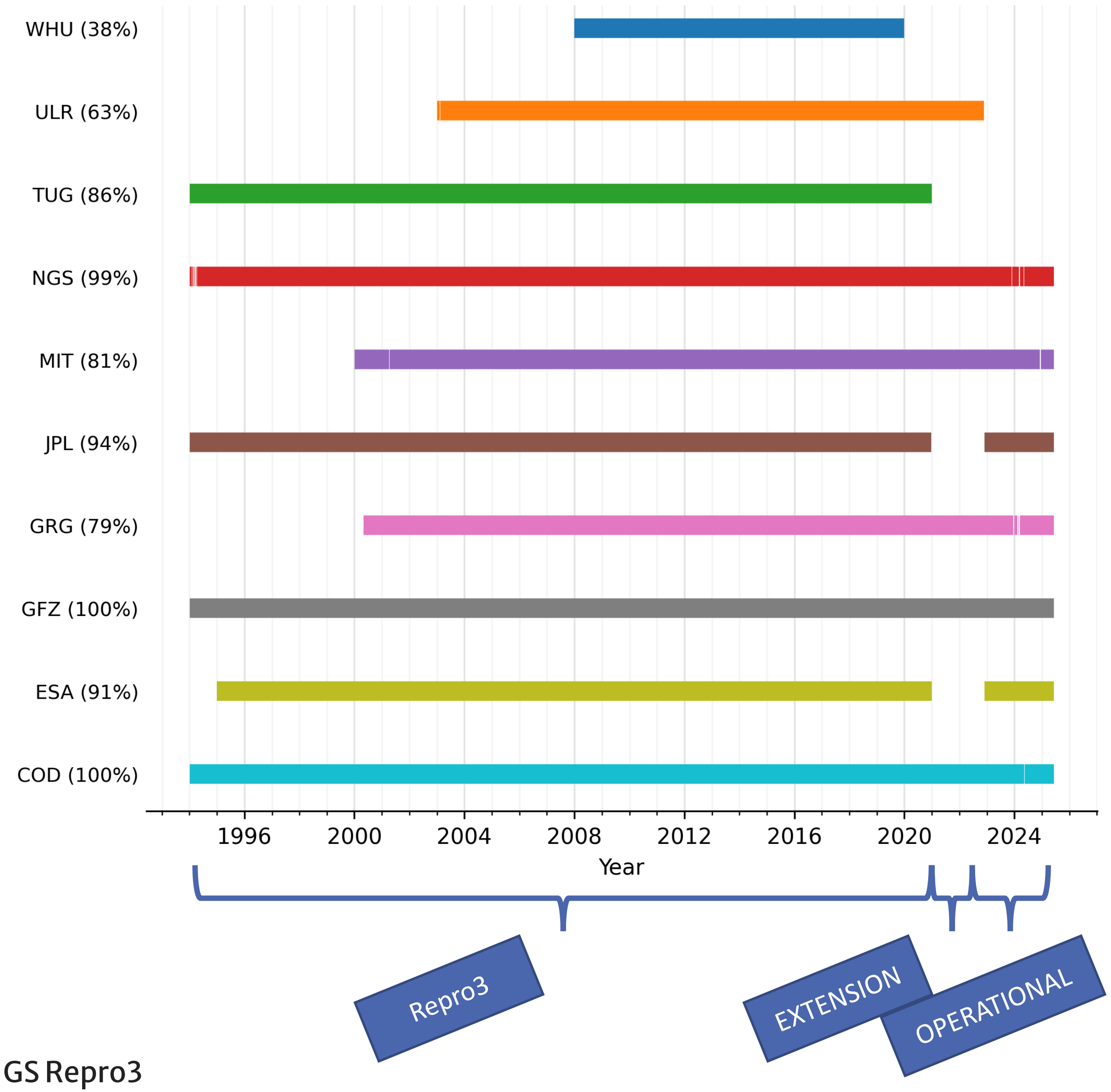
- Investigate how **GNSS-specific errors** — including orbital artifacts and draconitic effects — evolve with constellation development, assessing consistency across ACs.

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

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

GNSS dataset

- 10 Analysis Centers:
  - **Constellation differences** (GPS-only, GPS+Galileo, GPS+GLONASS, GPS+GLO+GAL).
  - **Arc length**: 24 h to multi-day solutions.
  - **SRP modeling**:
    - **Empirical parameters**: ACs estimate different sets of empirical orbit parameters.
    - **Physical vs. empirical modeling**: Different balances between force modeling and parameter estimation.
  - Station network differences



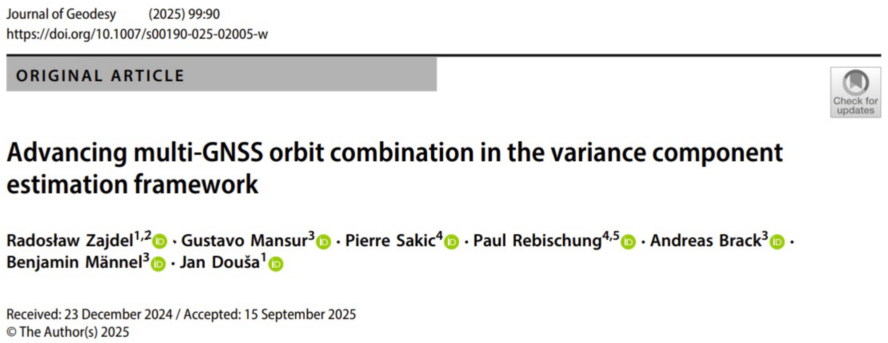
Zajdel, R., Masoumi, S., Sośnica, K. *et al.* Combination and SLR validation of IGS Repro3 orbits for ITRF2020. *J Geod* **97**, 87 (2023). https://doi.org/10.1007/s00190-023-01777-3

Combination

- Builds upon the orbit combination principles developed for GFZ's SPOCC (Zajdel et al., 2025)

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

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



Journal of Geodesy (2025) 99:90
https://doi.org/10.1007/s00190-025-02005-w

ORIGINAL ARTICLE

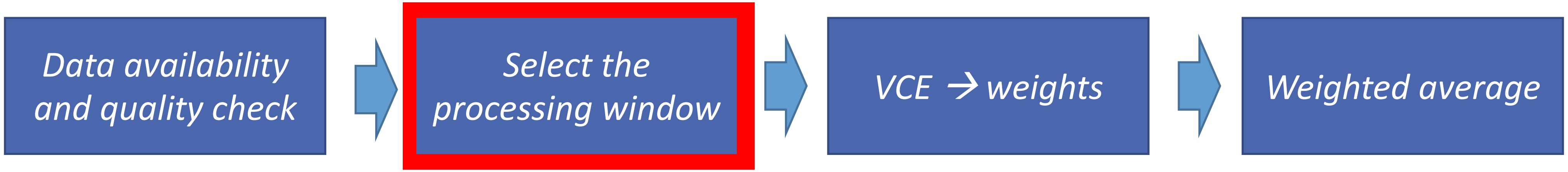
Check for updates

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]

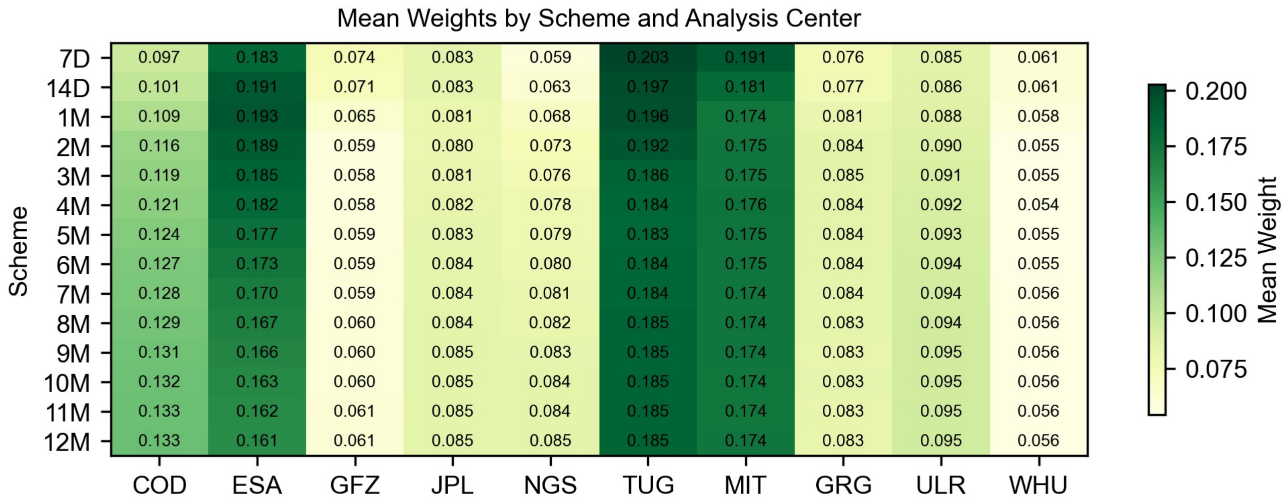
Received: 23 December 2024 / Accepted: 15 September 2025

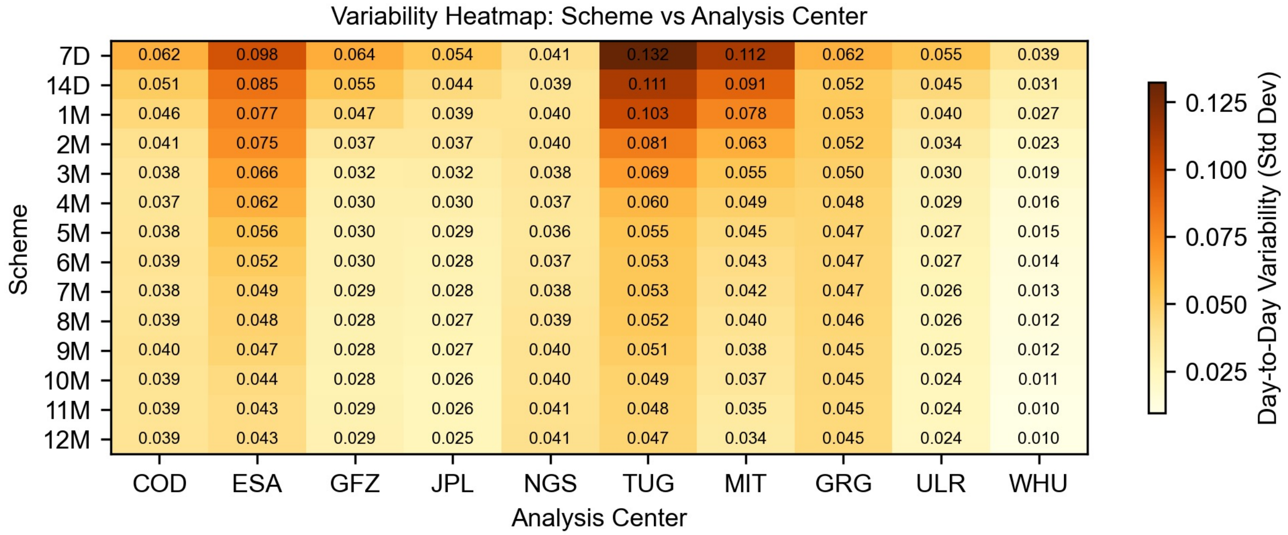
- Avoids full SINEX combination; works directly at parameter level (contrast to IGS RF → **IG3**)



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.
- **A 7-day solution (V7D)** was also analyzed to assess the impact of prioritizing minimum latency.





Reference Series

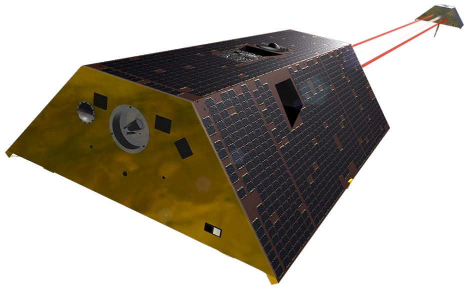
SLR	LEO	Geophysical Models

SLR

- **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.

LEO

- **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;



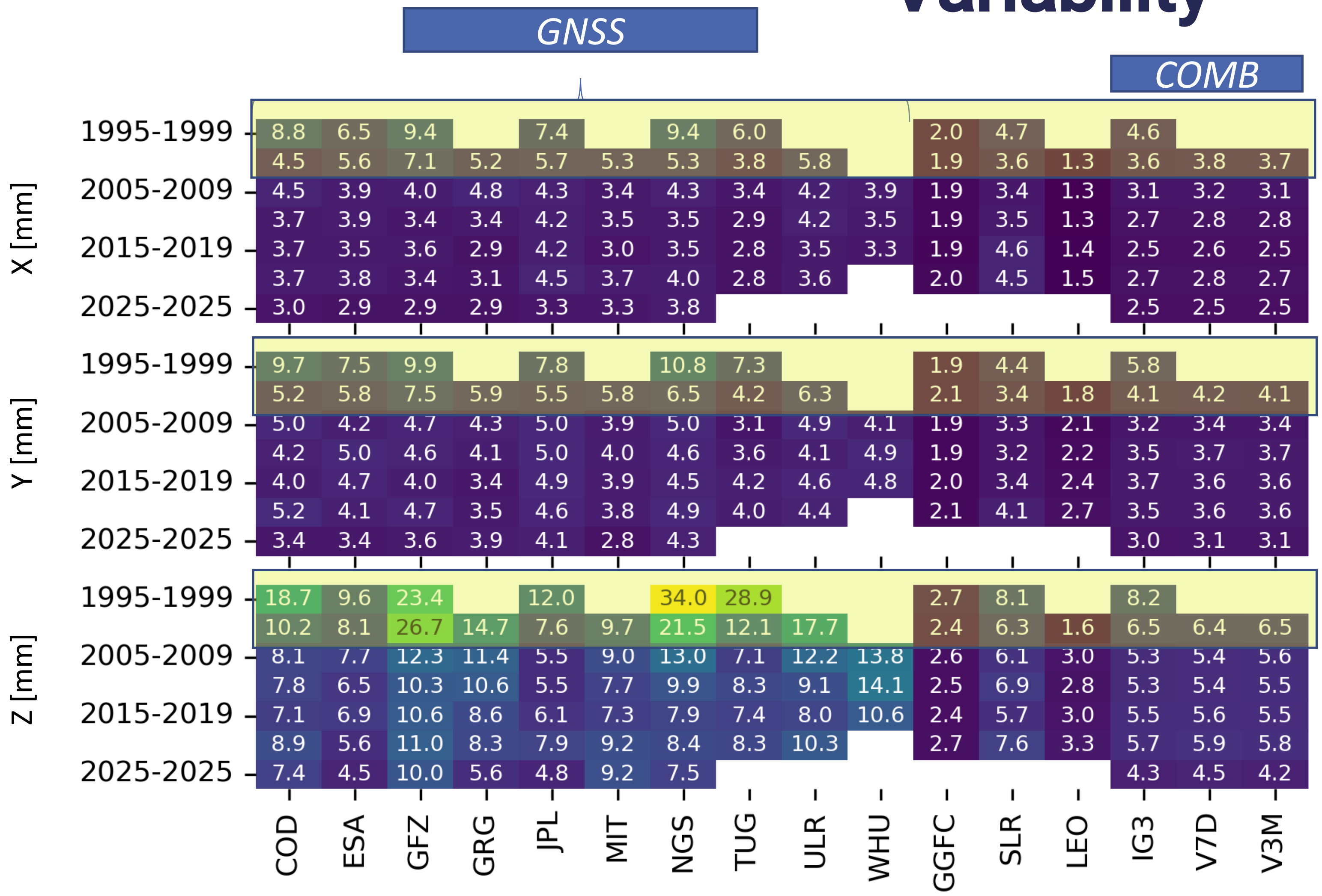
Geophysical Models

- **GGFC GCTI20** (Boy, 2021)
- **Atmosphere** (NTAL), **ocean** (NTOL), **terrestrial water storage** (HYDL).
- **All series averaged to daily for comparison with space geodesy.**

Boy J-P (2021) GGFC contribution to the ITRS 2020 realization. http://loading.u-strasbg.fr/ITRF2020/ggfc.pdf
Dill R, Dobslaw H (2013) Numerical simulations of global-scale high-resolution hydrological crustal deformations. J Geophys Res: Solid Earth 118:5008–5017. https://doi.org/10.1002/jgrb.50353
Kuang D, Desai SD, Haines BJ, Wu X (2024) Point positioning the geocenter through LEO GPS tracking and its application in geophysics. GPS Solutions 28:137. https://doi.org/10.1007/s10291-024-01680-0
Yu H, Sośnica K, Shen Y (2021) Separation of geophysical signals in the LAGEOS geocenter motion based on singular spectrum analysis. Geophys J Int 225:1755–1770. https://doi.org/10.1093/gji/ggab063

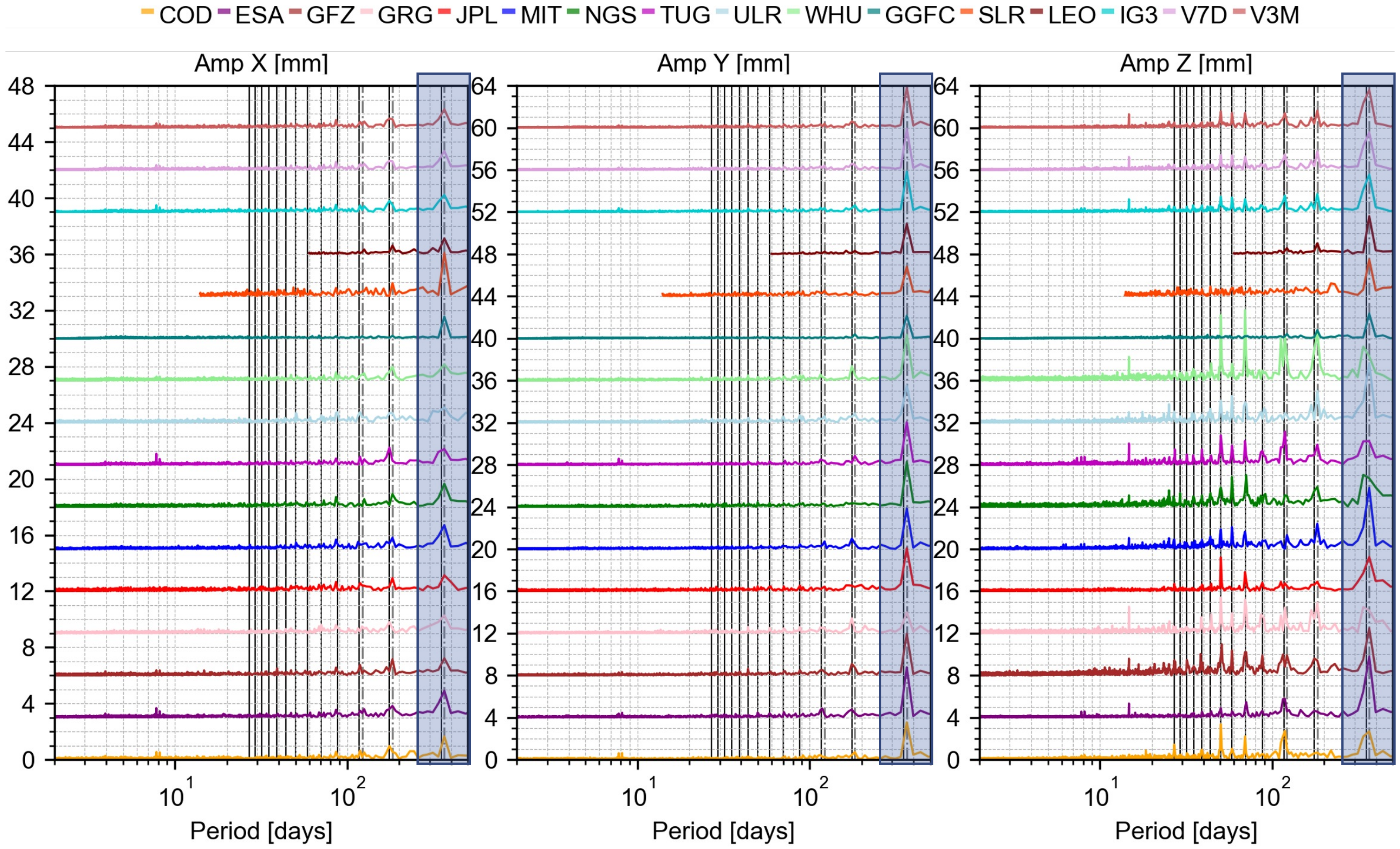
Variability

- **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.



Variability

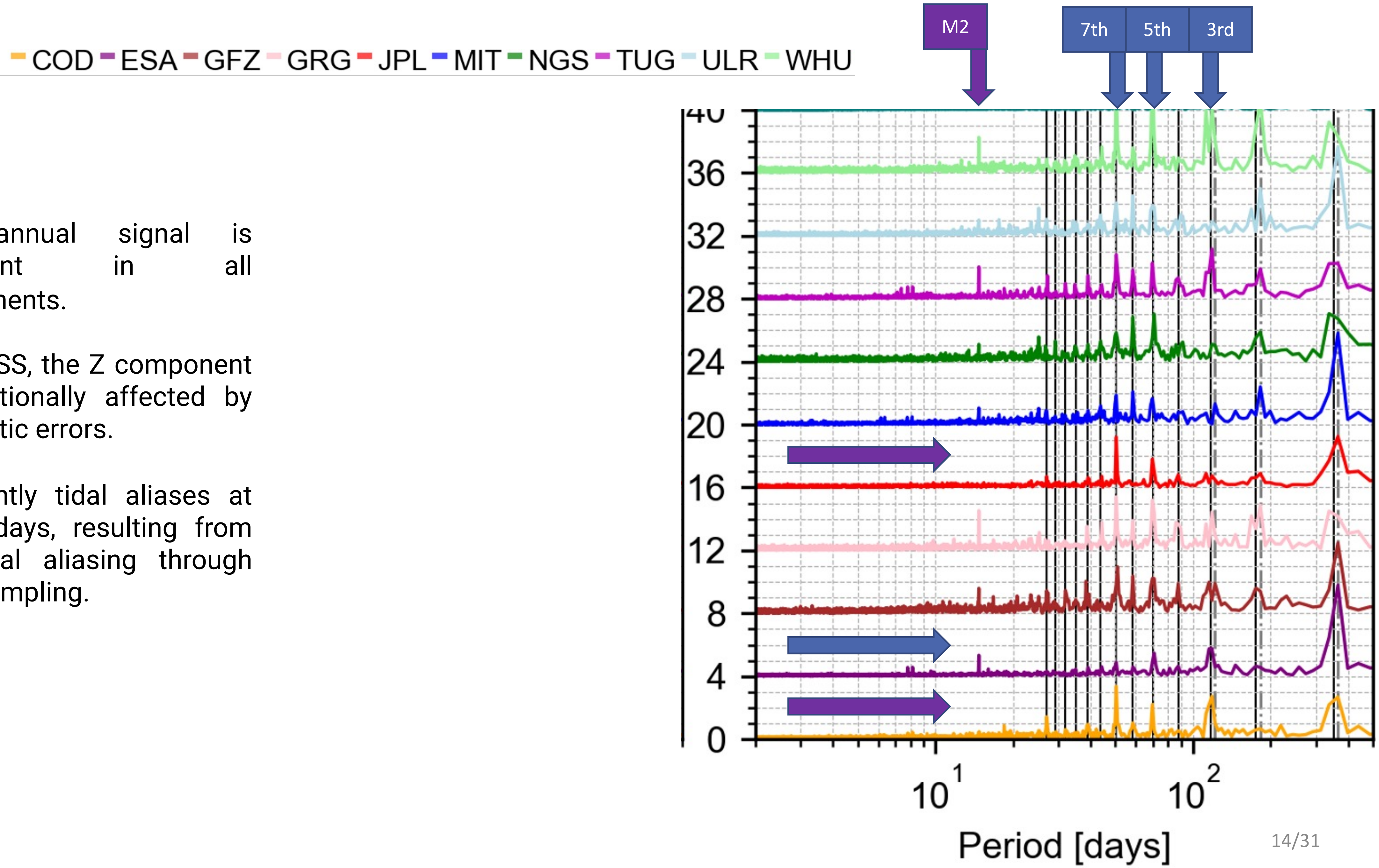
- The annual signal is dominant in all components.
- For GNSS, the Z component is additionally affected by draconitic errors.



- The annual signal is dominant in all components.

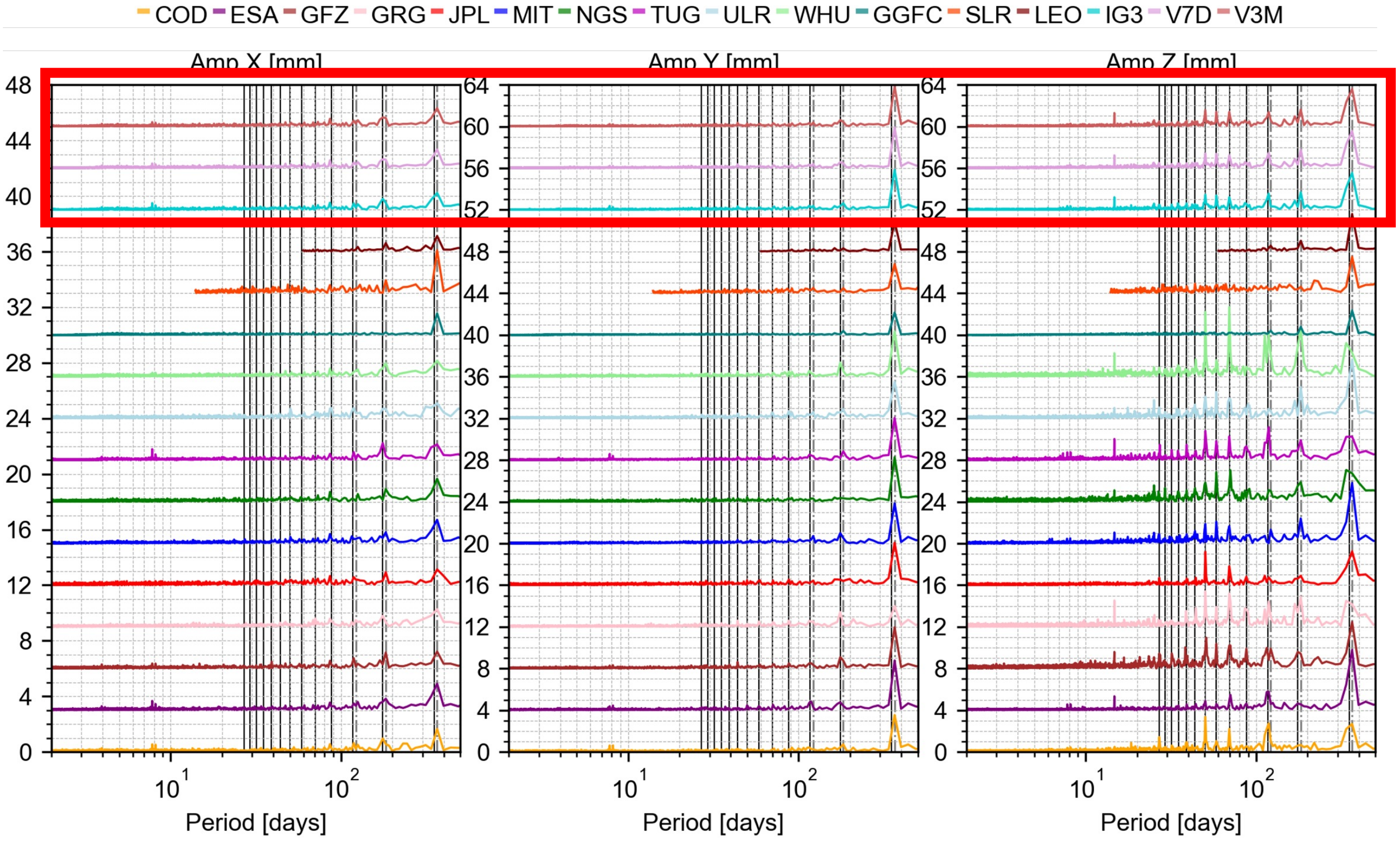
- For GNSS, the Z component is additionally affected by draconitic errors.

- Fortnightly tidal aliases at 14.76 days, resulting from M2 tidal aliasing through daily sampling.



Variability

- Combination **reduces the magnitude of the most** of the spurious signals.
- IG3 and V7D and V3M are highly consistent



Annual Signal

- **GNSS annual amplitudes are consistent to a milimeter level for X and Y and by up to 3 mm for Z.**
- **GNSS annual phases are consistent to 20°.**
- **No clear link between processing features and systematic differences in annual amplitude/phase.**
- **X:** GNSS amplitudes (V3M) align with LEO and GGFC; SLR about 3× higher.
- **Y:** GNSS amplitudes ~2 mm higher than GGFC and ~1 mm higher than SLR/LEO.
- **Z:** GNSS, SLR, LEO amplitudes mutually consistent but about 1.5 mm higher than GGFC.

	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
IGS RF COMB	IG3	1.2	-143	3.8	141	3.5	-164
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

V3M → Combined GNSS

Correlations – seasonal signals

Component	V3M–IGS	V3M–SLR	V3M–LEO	V3M–GGFC	SLR–LEO	SLR–GGFC	LEO–GGFC
X	0.999	**0.753**	**0.805**	**0.692**	0.866	0.812	0.725
Y	0.989	**0.878**	**0.940**	**0.900**	0.884	0.885	0.974
Z	0.999	**0.701**	**0.753**	**0.813**	0.749	0.826	0.917

- A band-pass filter was applied **to isolate signals with periods between 150 and 400 days (seasonal).**

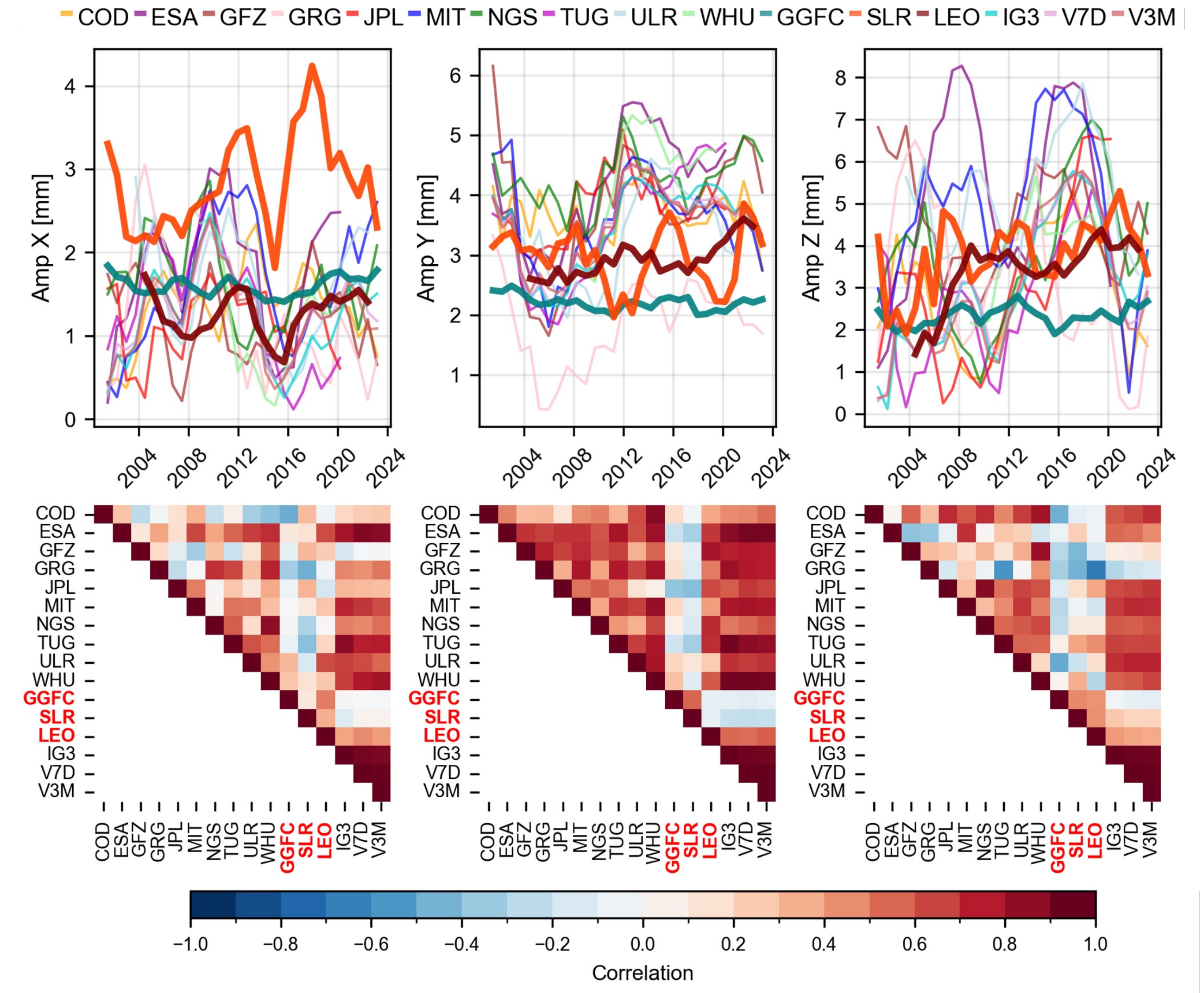
- **GNSS shows strong agreement with independent solutions** - LEO (ρ = 0.75–0.94) and SLR (ρ = 0.70–0.88).
- **The Y component is the most consistent,**
  with GNSS correlating at 0.94 with LEO, 0.90 with GGFC, and 0.88 with SLR.

- **GNSS agrees better with LEO than with SLR in all components.**

- The correlations of GNSS/SLR/LEO series with the GGFC range from 0.692 to 0.974.

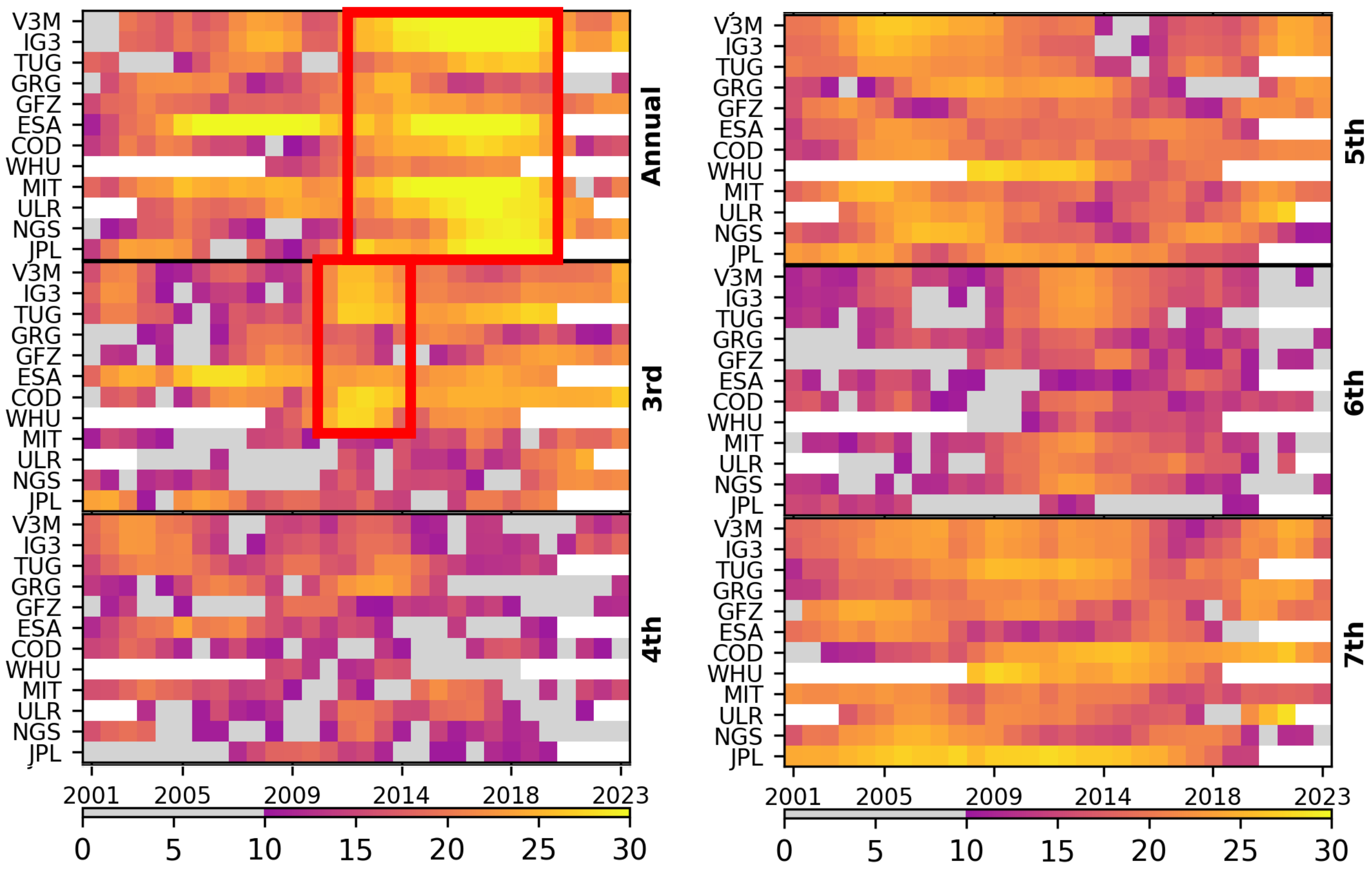
Annual Signal

- Annual variability assessed via sliding 3-year sinusoidal fits (period 365.25 days).
- **GGFC show the lowest annual amplitude variability**.
- Annual amplitudes in GNSS/LEO/SLR depend more on processing 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.
- Analysis of SNR $\mathrm{SNR} = 20\log_{10}\left(\frac{|H_i|}{\sigma_{|H_i|}}\right)$
- 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.
- Unique variability of draconitic signals in time.



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.
- 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.

Zajdel R, Balidakis K, Nowak A, et al (2025) Three decades of GNSS-derived geocenter motion: disentangling geophysical signal from systematic errors. Adv Space Res 77:74–100. https://doi.org/10.1016/j.asr.2025.11.053

Zajdel, R. (2025). Dataset for publication: "Three decades of GNSS-derived geocenter motion: disentangling geophysical signal from systematic errors" [Data set]. In Advances in Space Research (1.0). Zenodo. https://doi.org/10.5281/zenodo.16561910

Thank you!

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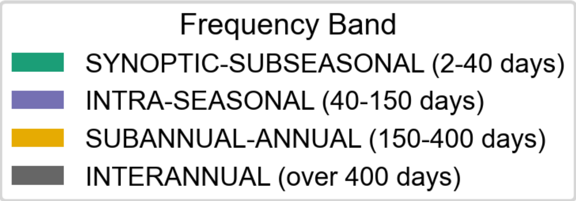
Shift in series

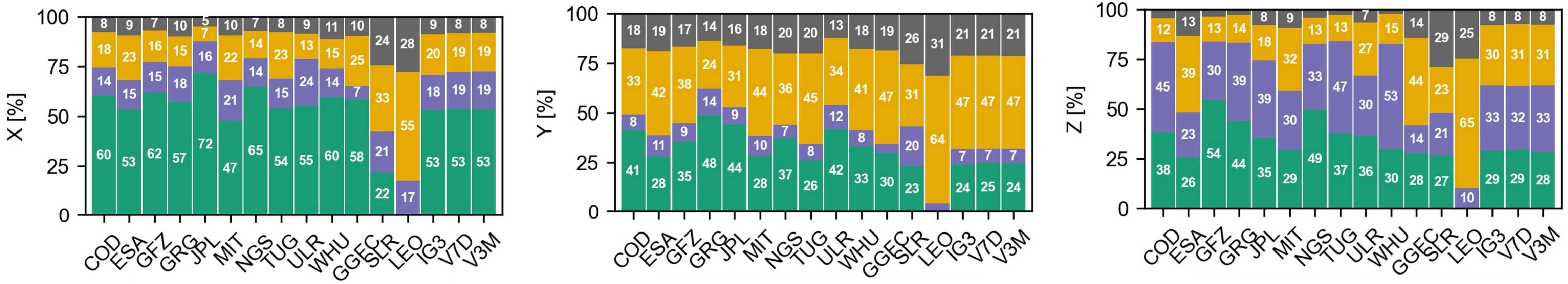
AC [mm]	1D X	7D X	30D X	182D X	365D X	1D Y	7D Y	30D Y	182D Y	365D Y	1D Z	7D Z	30D Z	182D Z	365D Z
cod	4.23	3.90	3.32	0.66	1.67	6.37	-1.06	-0.05	1.37	-0.07	-7.42	-19.80	-21.45	-4.29	2.01
gfz	1.61	-0.85	-1.45	-2.23	-0.98	4.36	-1.31	-1.85	-1.63	-0.91	-7.32	-0.41	4.18	-2.14	3.53
grg	1.54	-0.38	1.41	0.92	0.20	4.26	-3.16	-5.17	-5.99	-4.12	-6.38	-7.36	-8.29	3.13	4.83
mit	2.81	0.38	-2.90	-3.78	-1.10	6.81	0.71	0.10	-0.73	0.25	-23.48	-25.37	-18.69	-10.59	-4.59
ngs	-7.66	-5.99	-3.69	-3.73	-1.38	8.10	-1.04	-2.68	-2.66	-1.31	7.33	-3.42	-2.01	-3.50	1.25

STD [mm]	Window	Batch Period	COD	ESA	GFZ	GRG	JPL	MIT	NGS	TUG	ULR
X	NO	2020–2024	3.69	3.83	3.23	3.12	4.48	3.39	3.88	2.84	3.61
X	1D	2020–2024	3.56	3.83	3.33	3.07	4.48	3.79	4.66	2.84	3.61
X	7D	2020–2024	3.53	3.83	3.25	3.16	4.48	3.42	4.22	2.84	3.61
X	30D	2020–2024	3.48	3.83	3.30	3.07	4.48	3.55	3.83	2.84	3.61
X	183D	2020–2024	3.59	3.83	3.41	3.07	4.48	3.70	3.84	2.84	3.61
X	365D	2020–2024	3.49	3.83	3.26	3.10	4.48	3.38	3.76	2.84	3.61
Y	NO	2020–2024	4.52	4.12	4.60	4.12	4.62	3.63	4.99	4.01	4.24
Y	1D	2020–2024	6.18	4.12	5.25	5.50	4.62	5.09	6.77	4.01	4.24
Y	7D	2020–2024	4.40	4.12	4.59	3.57	4.62	3.66	4.95	4.01	4.24
Y	30D	2020–2024	4.51	4.12	4.62	3.54	4.62	3.63	5.00	4.01	4.24
Y	183D	2020–2024	4.75	4.12	4.61	3.61	4.62	3.62	5.00	4.01	4.24
Y	365D	2020–2024	4.51	4.12	4.59	3.52	4.62	3.64	4.95	4.01	4.24
Z	NO	2020–2024	8.25	5.58	9.33	8.51	7.87	10.21	8.03	8.26	10.29
Z	1D	2020–2024	9.87	5.58	10.70	9.64	7.87	10.83	8.88	8.26	10.29
Z	7D	2020–2024	14.35	5.58	9.38	9.89	7.87	11.41	8.16	8.26	10.29
Z	30D	2020–2024	15.03	5.58	9.12	10.14	7.87	9.64	8.07	8.26	10.29
Z	183D	2020–2024	9.04	5.58	9.61	8.34	7.87	8.77	8.17	8.26	10.29
Z	365D	2020–2024	8.04	5.58	9.12	8.36	7.87	9.26	8.07	8.26	10.29



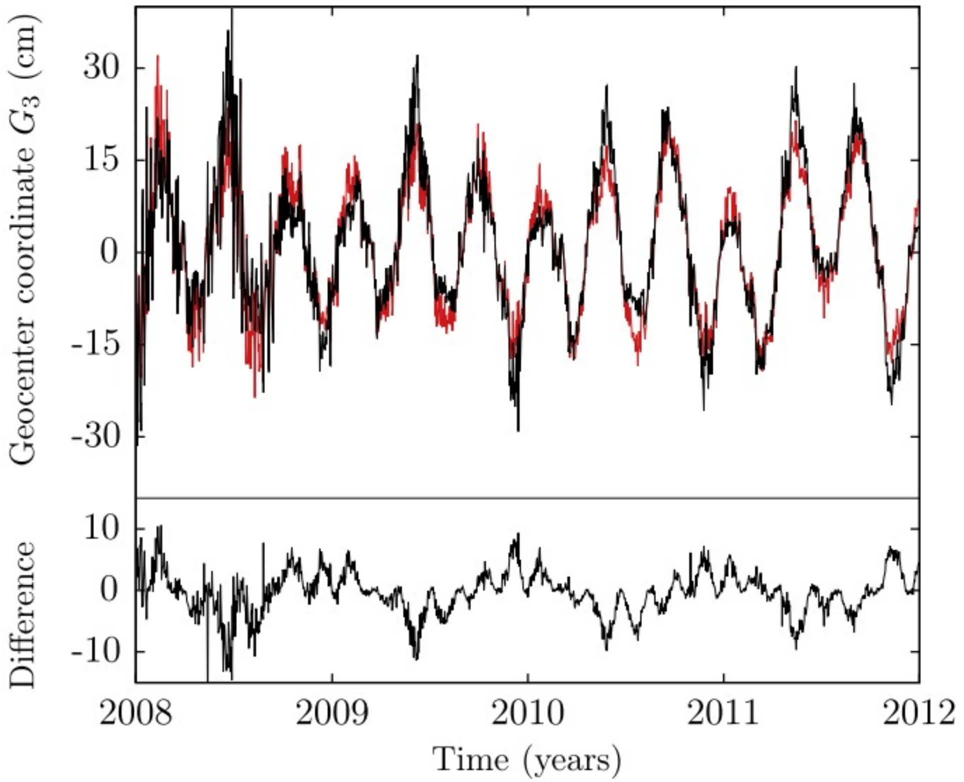
Variability

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 budgets**. *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.**

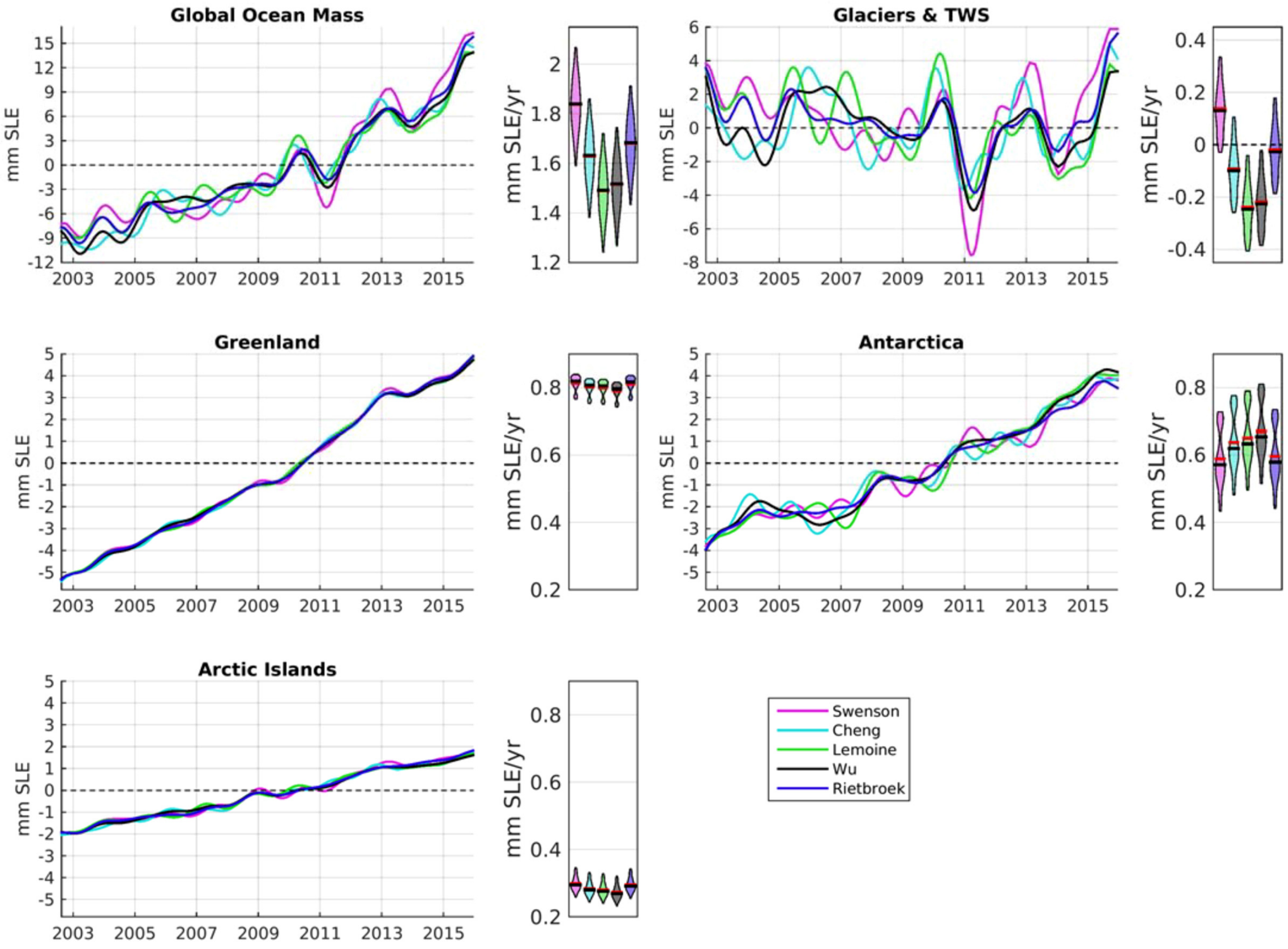
Table 1.

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	

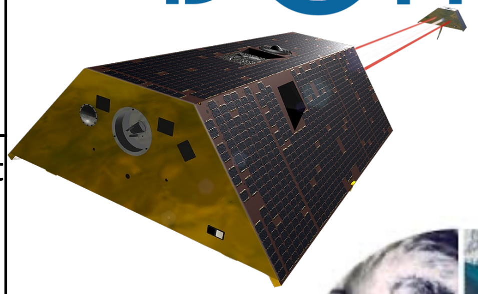
Geocenter motion – why do we care?

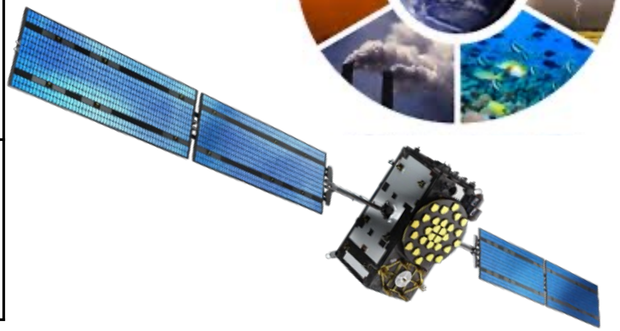
The geocenter is recognized as one of the **most significant contributors to uncertainties in global water and sea-level budgets.**



Geocenter recovery

Technique	Key Pros	Key Cons
SLR	– Superb orbit modeling of passive satellites – High precision range measurements	– Sparse ground network; – Station-specific biases
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





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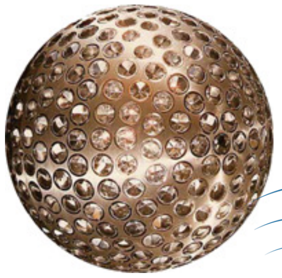
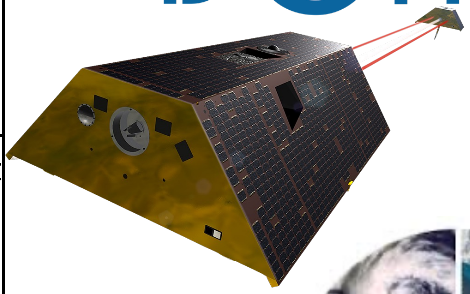
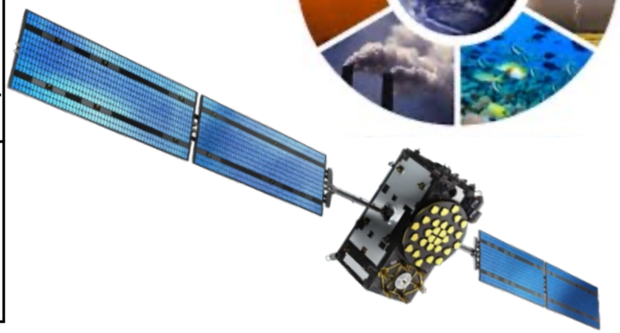
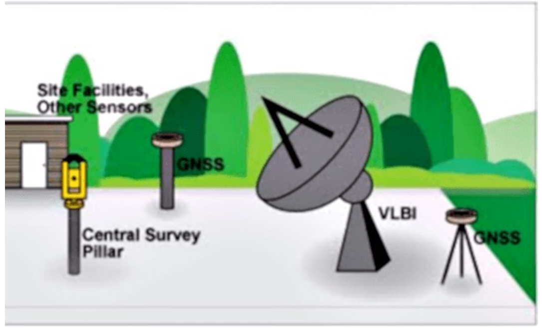


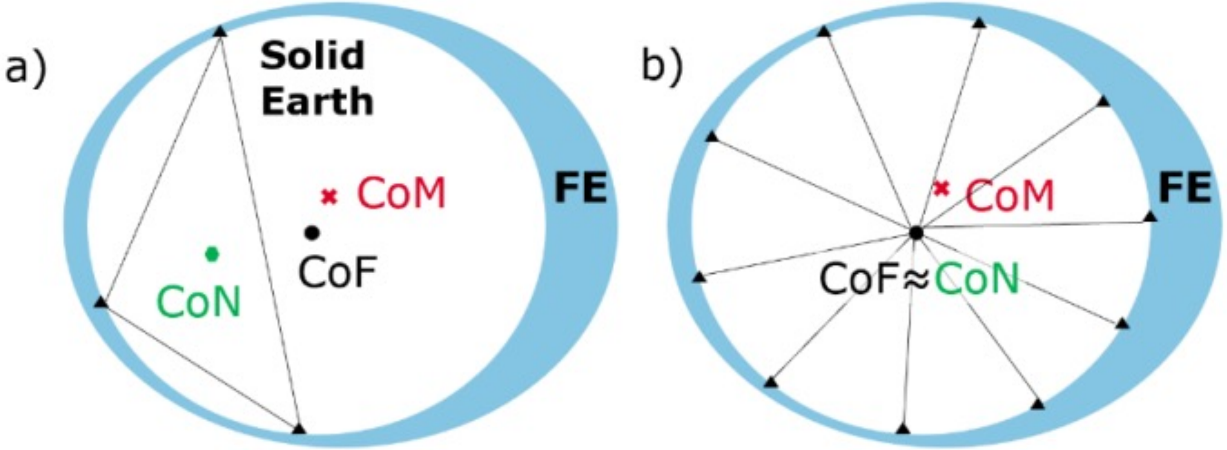


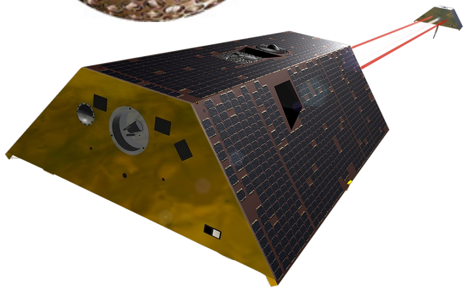


Origins of the Terrestrial Reference Frame

- **Center-of-Figure** (CoF) – Center of the solid Earth figure
- CoN (Center-of-Network) – the realization 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 center for all Earth satellites.







ITRF2020 – IGS contribution

DD – double differences; ZD – zero differences;

IF – Iono-free linear combination;

	COD	ESA	GFZ	GRG	JPL	MIT	TUG	WHU
GNSS (included from)	GPS (1994/01/02) GLO (2002/01/01) GAL (2013/01/01)	GPS (1995/01/01) GLO (2009/01/01) GAL (2015/01/01)	GPS (1994/01/02) GLO (2012/01/01) GAL (2013/12/21)	GPS (2000/05/03) GLO (2008/11/04) GAL (2016/12/31)	GPS (1994/01/02)	GPS (2000-01-02) GAL (2017-01-01)	GPS (1994/01/01) GLO (2009/01/01) GAL (2013/01/01)	GPS (2008-01-01) GLO (2010-09-28)
Orbital Arc	72h	24h	24h	30h	30h	24h + connceted SRP	24h	24h
Observable types	IF DD	IF ZD	IF ZD	IF ZD	IF ZD	IF DD	RAW (Strasser et al. 2019)	IF DD
A priori solar radiation pressure	Box-wing (Galileo)	Box-wing	-	Box-wing	GSPM13b (Sakumura et al 2017); GPS Block III: Manufacturer Table	Direct only	Box-wing	-
Empirical parameters	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S (Arnold et al. 2015) for Galileo eclipses (when |β|<12), additional parameters are estimated: D1C, D1S and Y0 (FOC only) (Sidorov et al. 2020)	(7 par) D0, Y0, B0, + B1C, B1S + Along-track 1C/1S	(9 par) D0, Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	(8 par) Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	Solar Scale and Y-Bias	(9 par - satellite/week dependent) D0, Y0, B0, B1C, B1S, D2C, D2S, D4C, D4S	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S	(7 par) D0, Y0, B0, B1C, B1S, D2C, D2S
Stochastic parameters	in radial along-track and cross-track at orbit midnight (Dach et al. 2021)	-	in radial along-track and cross-track at noon	in radial along and cross-track in eclipse	-	-	in radial along-track and cross-track at noon	-

- Most of the ACs **use either undifferenced (ESA, GFZ, GRG, JPL) or double-differenced (COD, MIT) ionospheric-free linear combinations (IF) of two selected frequencies**. **TUG is the only AC that uses raw (undifferenced and uncombined) observables from all available signal frequencies** (Strasser et al. 2019).

- The orbital arc is **typically 24 hours**, but **COD favors a long-arc solution over three days**, whereas JPL and GRG process 30 hours to obtain 6 hours of overlaps surrounding the day (3 hours on each side).

- **COD (for Galileo only), ESA, GRG, and TUG use the box-wing model as the a priori SRP model.** MIT uses the a priori SRP model to compute only the constant direct radiation pressure acting on the satellites. The JPL products rely on the GSPM13b model (Sakamura et al. 2017), which is supported by additionally estimated solar scale and Y-bias coefficients.

- **All the ACs estimate the empirical parameters; however, different sets** of these coefficients are determined by different ACs, e.g., ECOM or radial/along track.

- **Some ACs fit stochastic parameters to handle orbit modeling deficiencies**. GRG, TUG and GFZ estimate additional stochastic **parameters every noon in radial, along-track and cross-track directions**. It should be noted that GRG, unlike TUG and GFZ, estimates stochastic parameters **only in satellite eclipses**. For Repro3 products, COD developed a novel approach to estimating pseudo-stochastic parameters in orbit midnight.