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Geocenter coordinates and Earth rotation parameters

from GPS, GLONASS, Galileo, and the combined GPS+GLONASS+Galileo solutions

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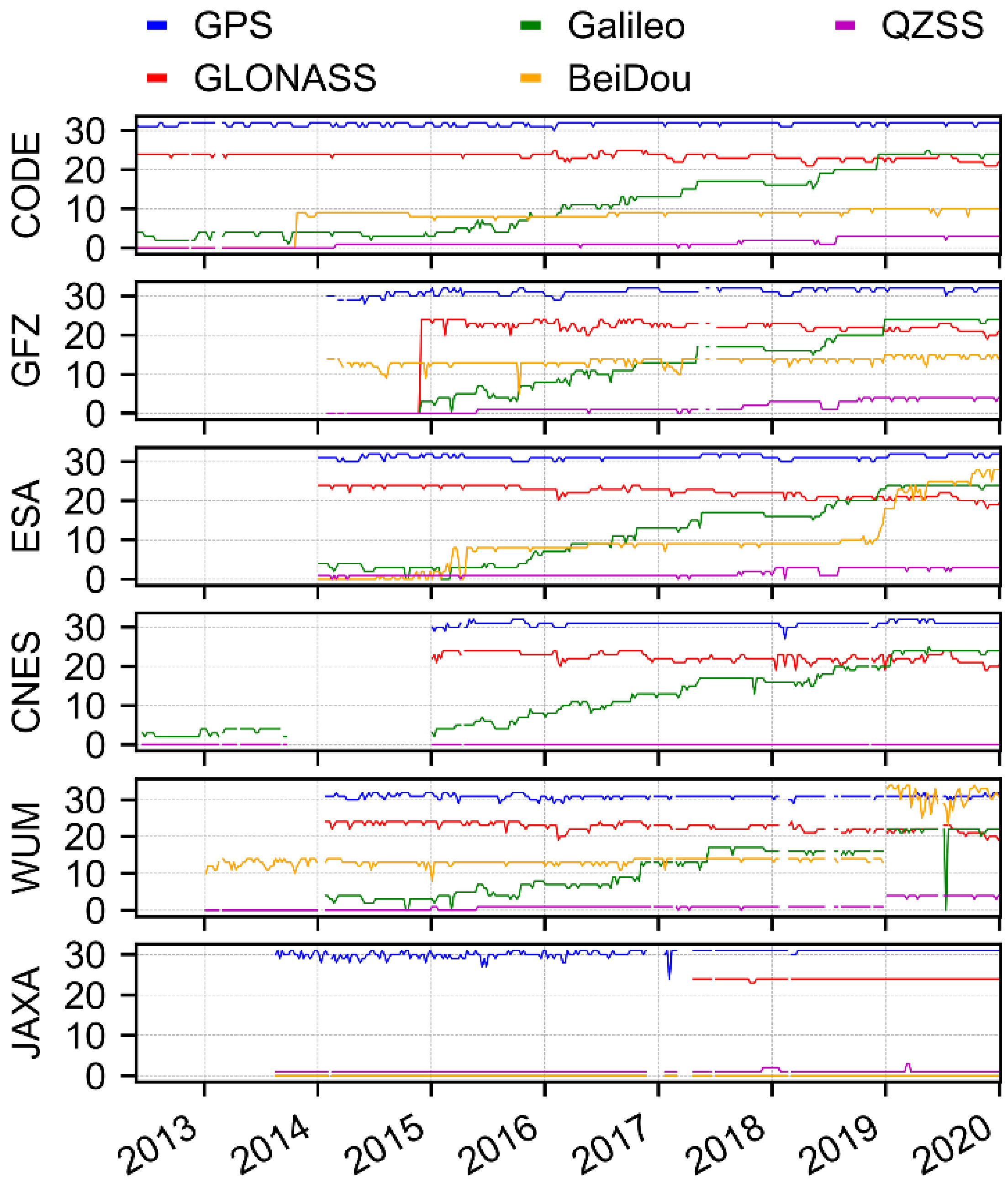
Motivation

- **GNSS** is the **primary technique** for deriving Earth rotation parameters (ERPs): polar motion and lenght-of-day (LoD),
- In the combined **IERS-C04 series** the IGS solutions are considered which are **mostly based on GPS results** with a minor contribution from GLONASS,
- GPS satellites are in a deep 2:1 resonance with Earth rotation, which generates some issues for ERPs estimates
- **GNSS** is **NOT the primary technique** for deriving **geocenter** coordinates, however, the horizontal components from GNSS agree well with SLR-based results,
- **The geocenter motion from GLONASS with 3 orbital planes is completely unrealistic** (especially the Z component)
- **In 2019 GPS, GLONASS, Galileo, and BeiDou reached the number of 24 active satellites**

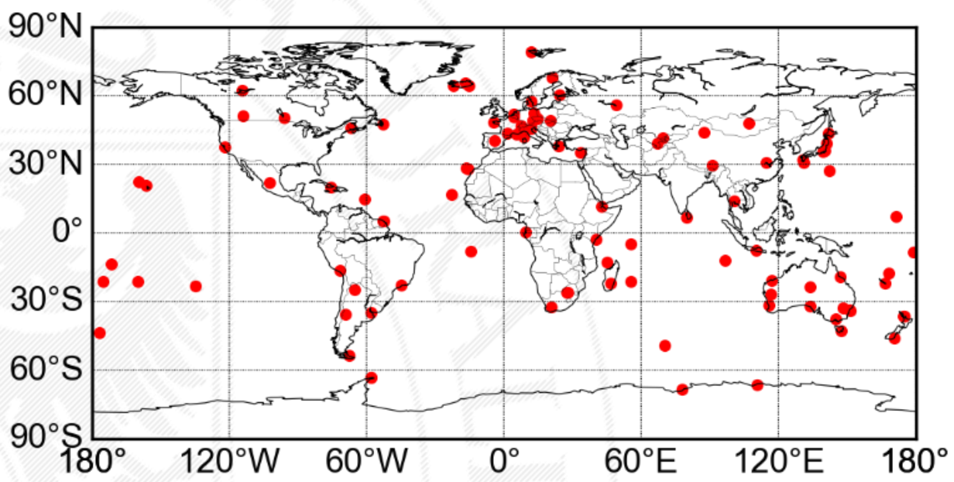


Number of satellites in multi-GNSS solutions

In this study, we address the following questions:

- What is the **added value for ERPs and geocenter from** considering **Galileo**?
- Does **Galileo** show the same **errors** as observed in **GLONASS** results due to **3 orbital planes**? Are they caused by orbital resonances?
- How sensitive are ERPs and geocenter coordinates to **the GNSS orbit model?** Are the empirical models or the box-wing models better?
- What is the origin of **spurious signals seen in GPS, GLONASS, and Galileo-based time series**?
- Can we remove **system-specific errors** by combining **GPS+GLONASS+Galileo**? That is three systems with three different revolution periods and different resonance periods with Earth rotation.

Processing strategy



Solution	Systems	Orbit modeling
GRE	GPS+Galileo +GLONASS	ECOM2 (7 par)
GPS	GPS	ECOM2 (7 par)
GLO	GLONASS	ECOM2 (7 par)
GAL	Galileo	ECOM2 (7 par)
GAB	Galileo	box-wing & D_0, Y_0, B_0 Based on Galileo metadata

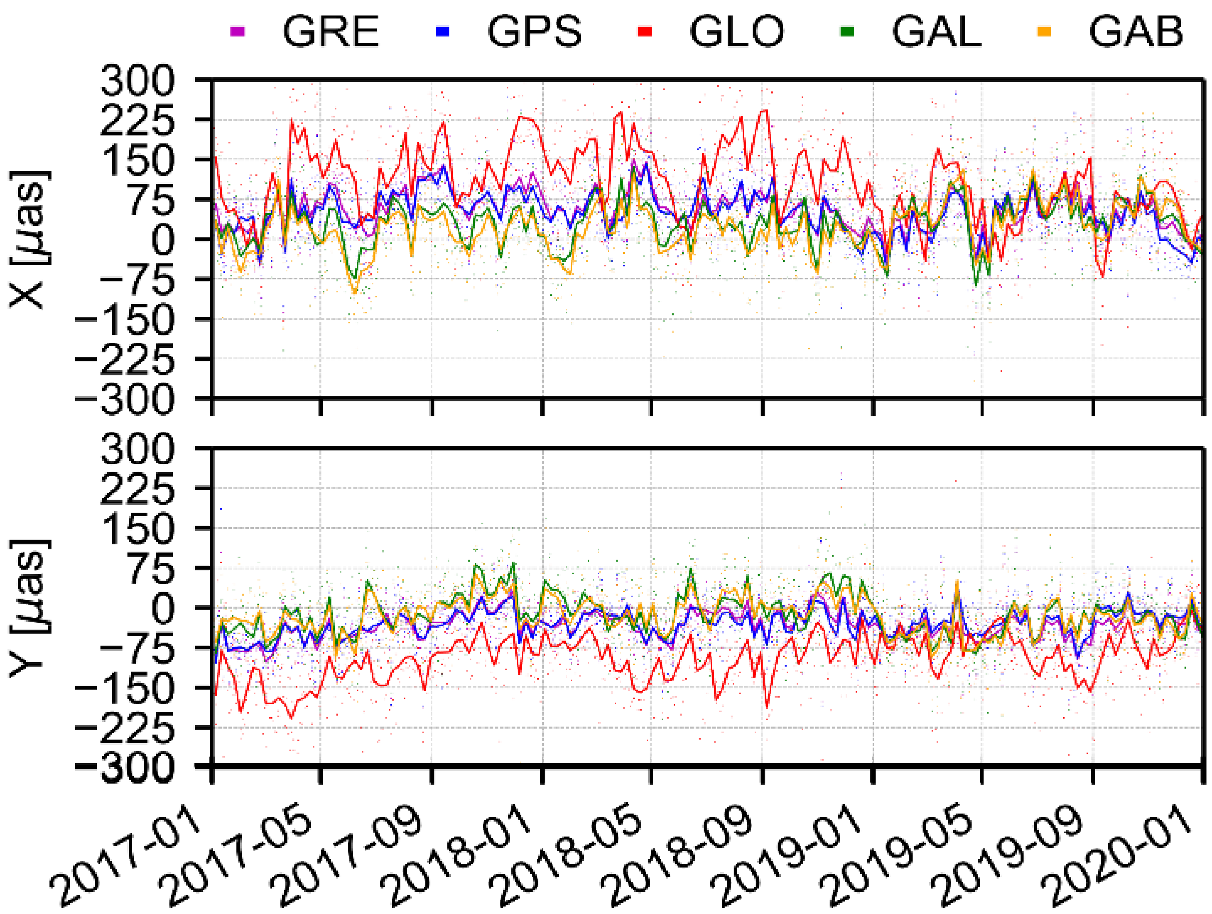
Software: Bernese GNSS Software

Processing feature	Adopted processing strategy
GNSS considered	GPS, GLONASS, Galileo (up to 80 satellites)
Time Span	Three years: 2017.0-2020.0
Number of stations	~100 stations (all track GPS, GLONASS, Galileo)
Processing scheme	Double-difference network processing (observable: phase double differences, ionospheric-free linear combination), ambiguity fixing for GPS, GLONASS, and Galileo
Signals	GPS (L1+L2), GLONASS (G1+G2), Galileo (E1+E5a)
A priori reference frame	IGS14
Rec. antenna model	GPS, GLONASS: IGS14 Galileo: adopted from GPS L1 and L2
Sat. antenna model	PCO and PCV for GPS and GLONASS; PCO for Galileo; based on CODE MGEX ANTEX
Earth orientation	A priori ERPs: IERS-C04-14 The sub-daily variations in ERP and effects of the tidal deformations on earth rotation are modeled consistently with the IERS 2010 Conventions
Pseudo stochastic pulses (sigma)	Every noon and midnight epochs in the along-track (10^{-5} m/s), cross-track (10^{-8} m/s), radial (10^{-6} m/s)

Earth rotation parameters

Polar motion from GPS, GLONASS, Galileo w.r.t. IERS-C04-14

	X [μas]		Y [μas]	
	Mean	RMS	Mean	RMS
GRE	54	54	-33	41
GPS	49	56	-30	41
GLO	107	91	-95	63
GAL	31	66	-12	57
GAB	23	66	-15	52



Galileo provides the 1-day pole coordinates of almost the same quality as the **GPS** does and much better quality than that from **GLONASS.**
Galileo is the only system not considered in IERS-C04 series, thus, fully independent.

GPS resonance 2:1
GLONASS resonance 17:8
Galileo resonance 17:10

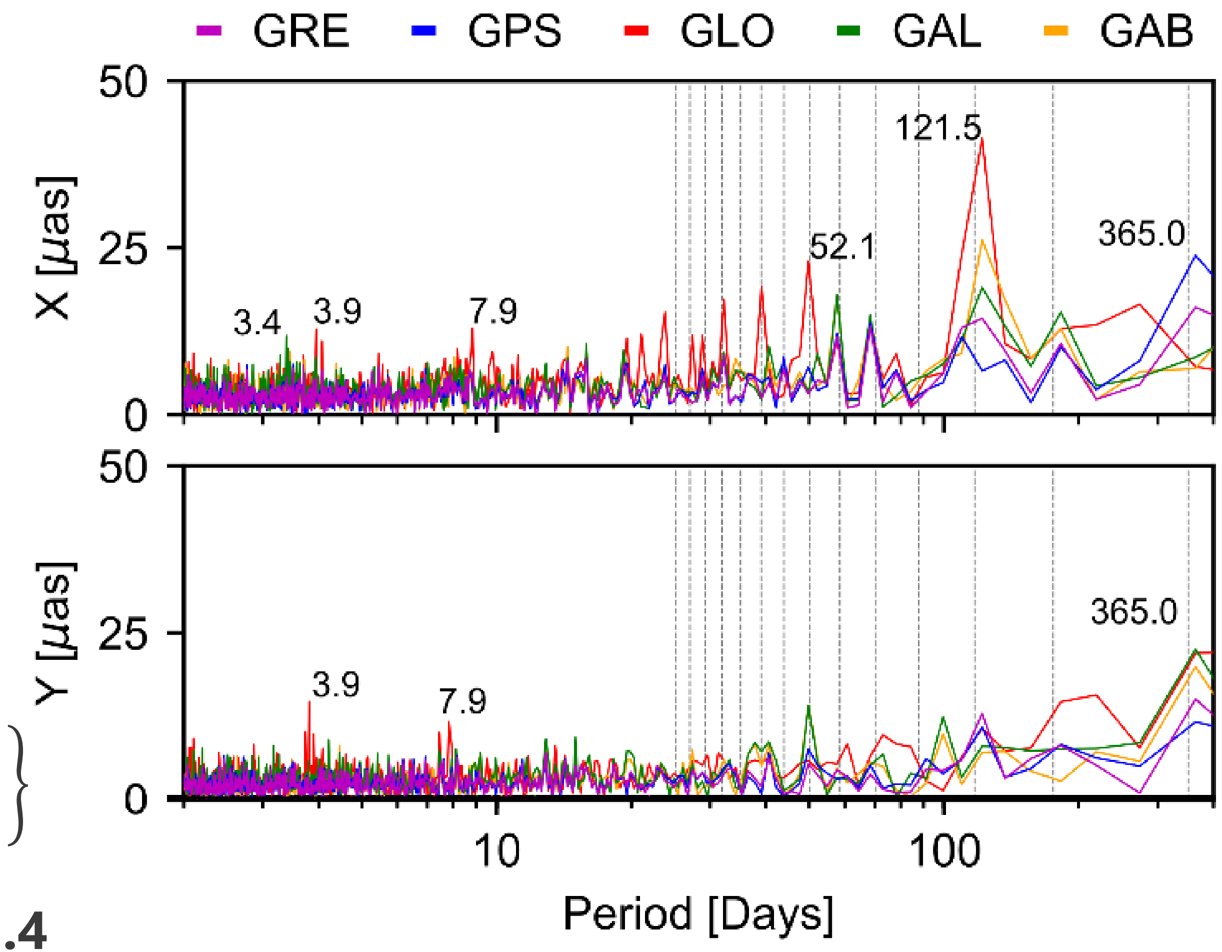
Polar motion from GPS, GLONASS, Galileo w.r.t. IERS-C04-14

The spectral analysis reveals 2 error sources:

- **Harmonics of the draconitic year** (351 days for GLO, 352 days for GPS, 355 days for GAL): 1/3, 1/5, 1/7, 1/9, 1/11, 1/15, etc.
- **Resonances** between Earth rotation and satellite revolution period (constelation repeatability). When f_E and f_S are the frequency of Earth rotation and satellite revolution, respectively, then we have:

$$\left|\frac{1}{n * f_S + m * f_E}\right|, \text{with } n, m = \{\dots, -4, -3, -2, -1, 0, 1, 2, 3, 4, \dots\}$$

For **Galileo**-based solutions: **2.5 days** (n=2, m=-3), **3.4 days** (n=1, m=-2), **10 days** (n=3, m=-5)
For **GLONASS**-based solutions: **2.6 days** (n=3, m=-6), **3.9 days** (n=2, m=-4), **7.9 days** (n=1, m=-2)



	GPS	GLONASS	Galileo
$rev.$	11h58m	11h16m	14h05m
f_S [1/h]	0.0836	0.0888	0.0708

Polar motion from GPS, GLONASS, Galileo w.r.t. IERS-C04-14

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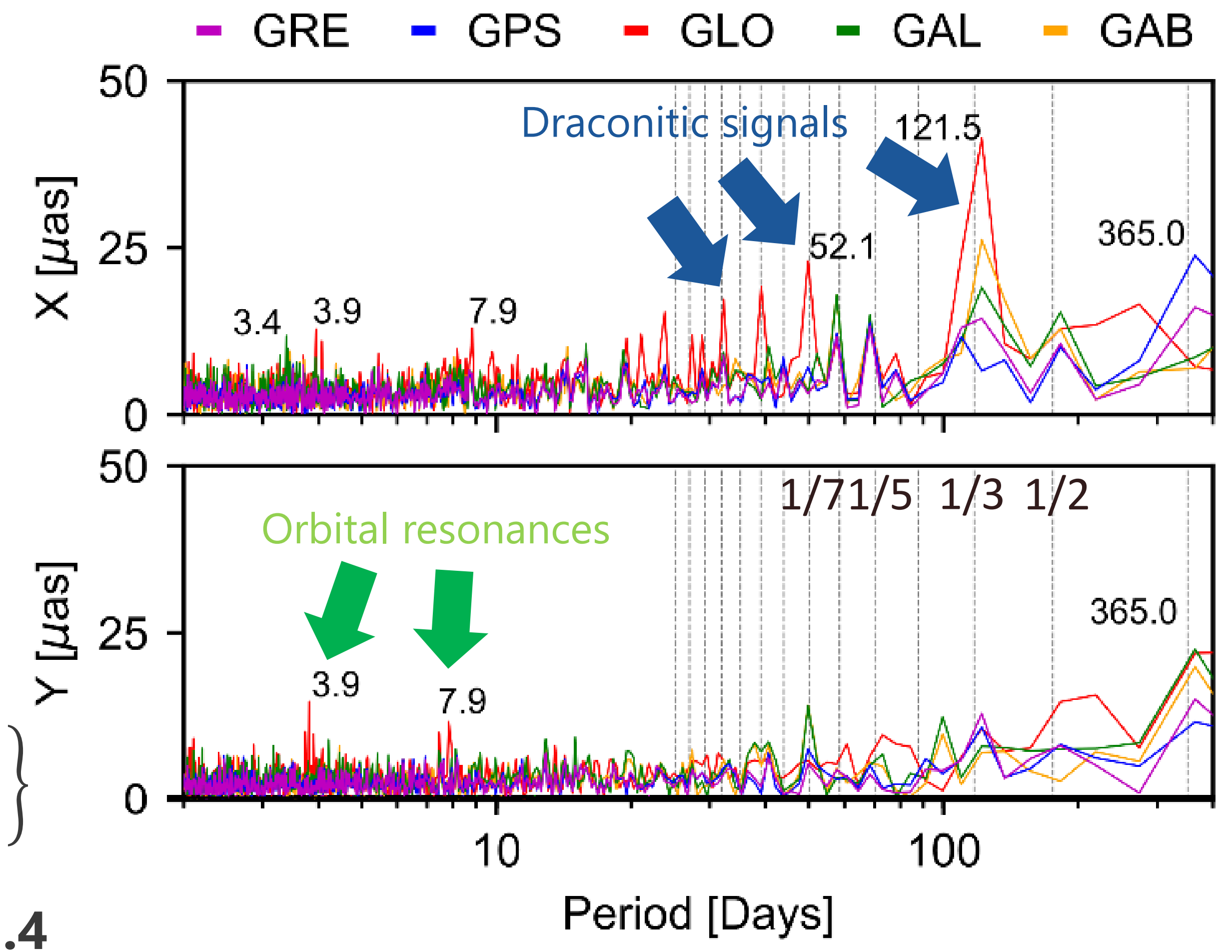

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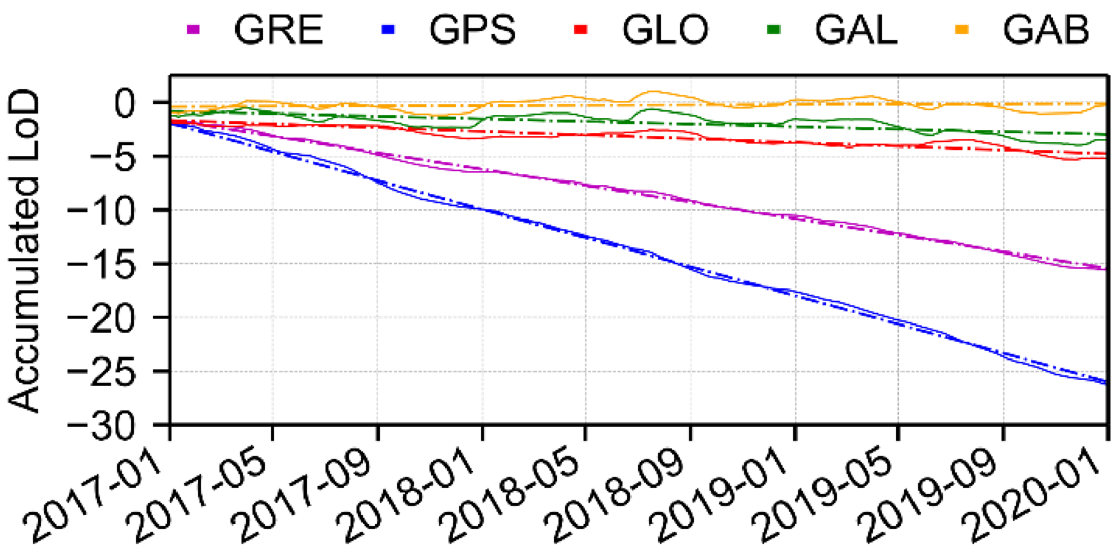
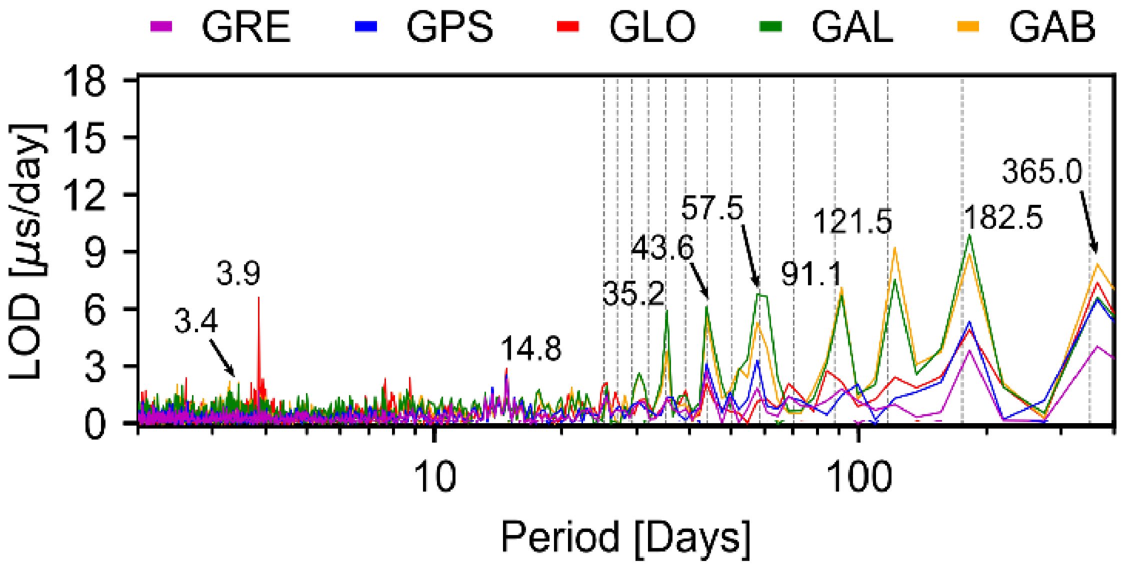
LoD w.r.t. IERS-14-C04

Three types of errors can be distinguished in LoD:

- Draconitic errors
- Orbital resonances
- **Aliasing periods with sub-daily ERP tidal models: 14.8 days (M_2),** 14.2 days (O_1)
  -> visible in all solutions independently of the constellation (solutions based on sub-daily models from the IERS Conventions 2010)

	LoD [µs/d]	
	mean	RMS
GRE	-13	10
GPS	-22	12
GLO	-3	16
GAL	-2	22
GAB	1	21





LoD w.r.t. IERS-14-C04

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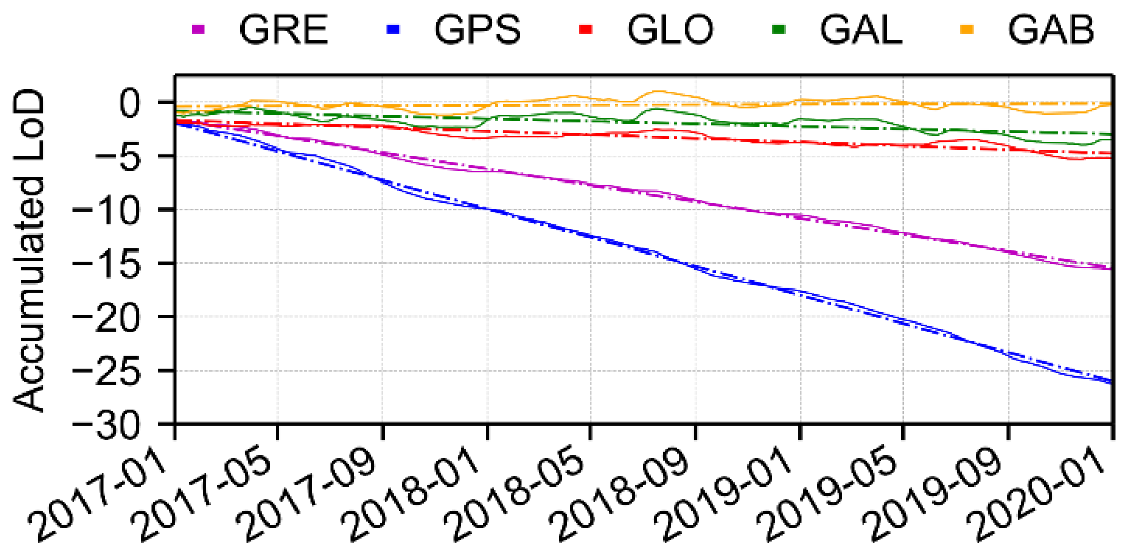
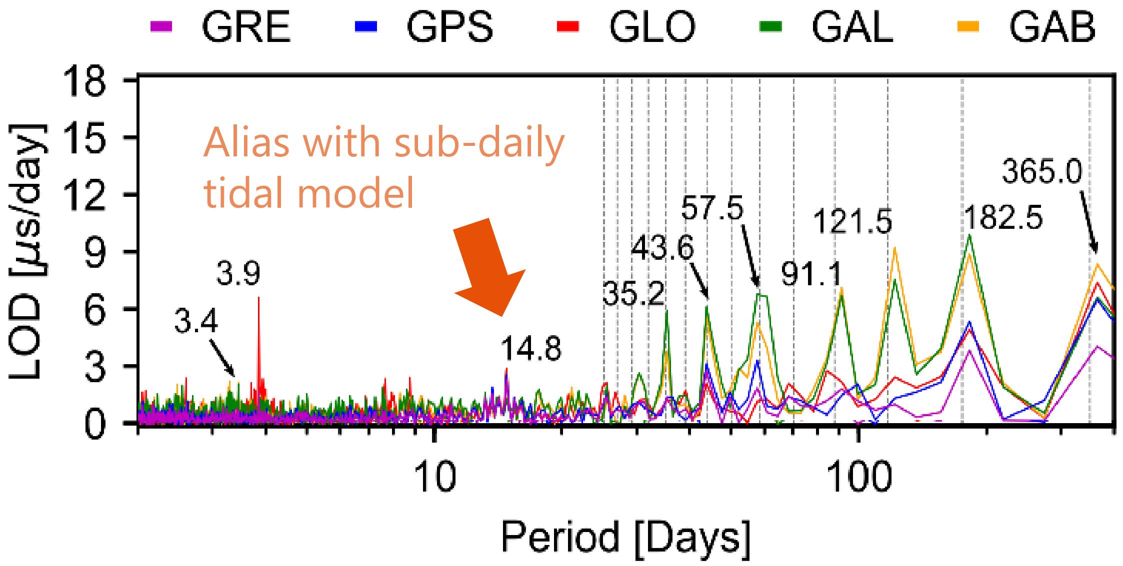
GPS has a large secular drift of the accumulated LoD in 1-day solutions due to orbital resonances.

GLONASS and Galileo have much smaller drifts, however, **the combined solution is dominated by GPS**.

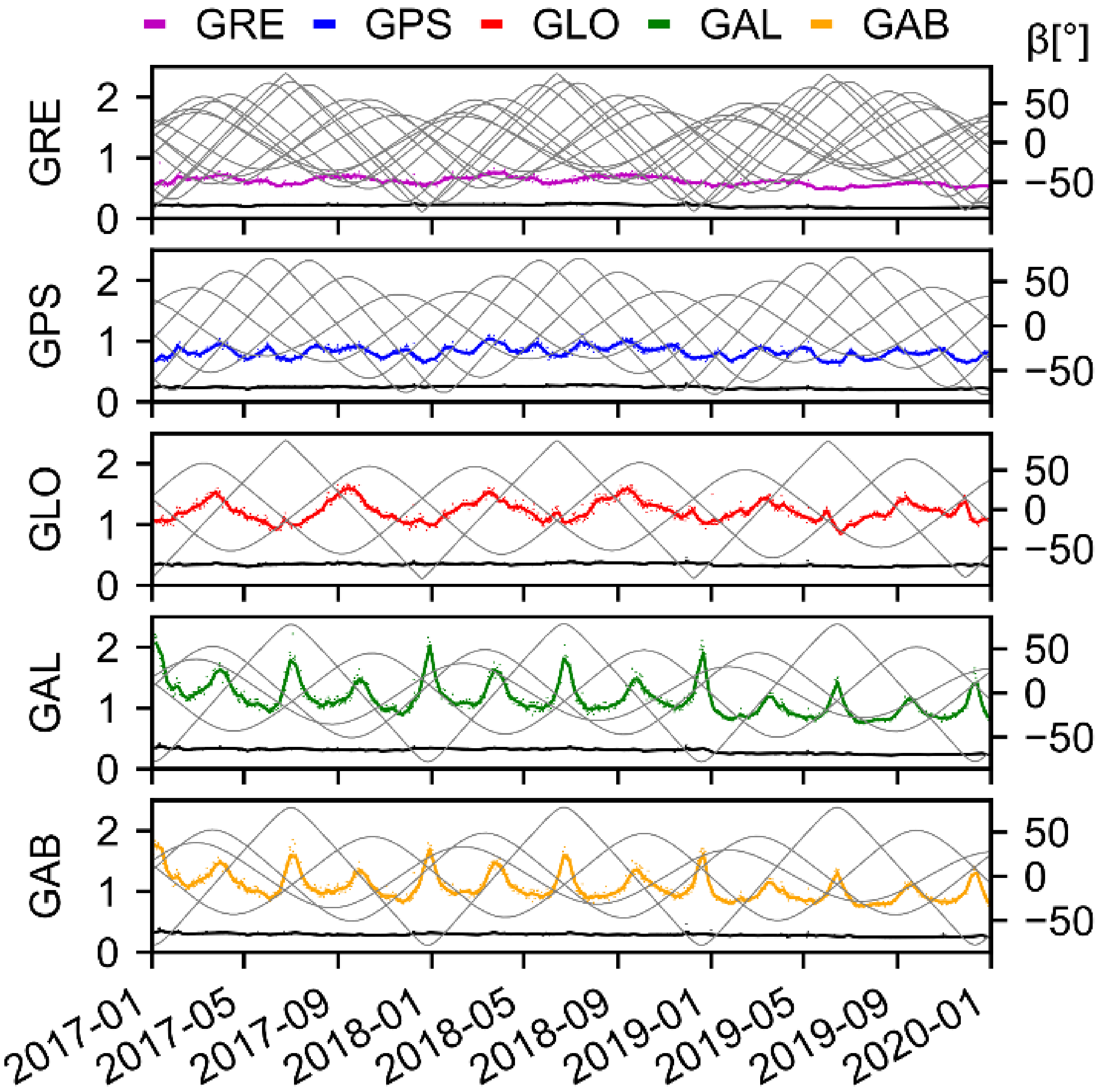




Formal errors of ERPs

The errors of estimated ERPs:

- Strongly depend on the **orientation of the orbital planes w.r.t. the Sun** (measured by **β-angle** – the elevation of the Sun above the orbital plane – gray lines)
- Variations of errors are greater for **GLONASS and Galileo** because they comprise **3 orbital planes** as opposed to **GPS with 6 planes**
- Errors are maximum for **eclipsing seasons** (|β|<12-14°) and when orientation of 2 planes is the same w.r.t. the Sun. **Major signal: 4 times a year for Galileo; 2 times a year for GLONASS; 6 times a year for GPS**
- Errors decrease in 2019 in Galileo solutions (late 2018: 24 active Galileo satellites)
- The combined solution GRE mitigates the time-variable errors

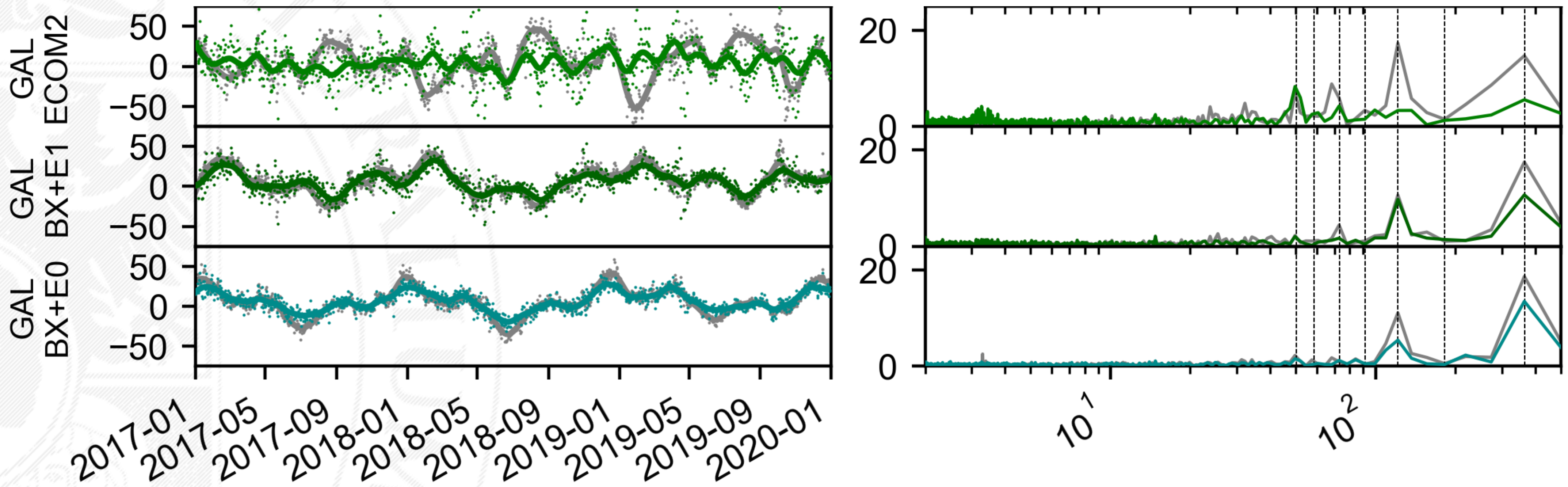


LoD formal errors

Geocenter coordinates

Z geocenter component from Galileo-only

1-day arcs in green
3-day arcs in gray



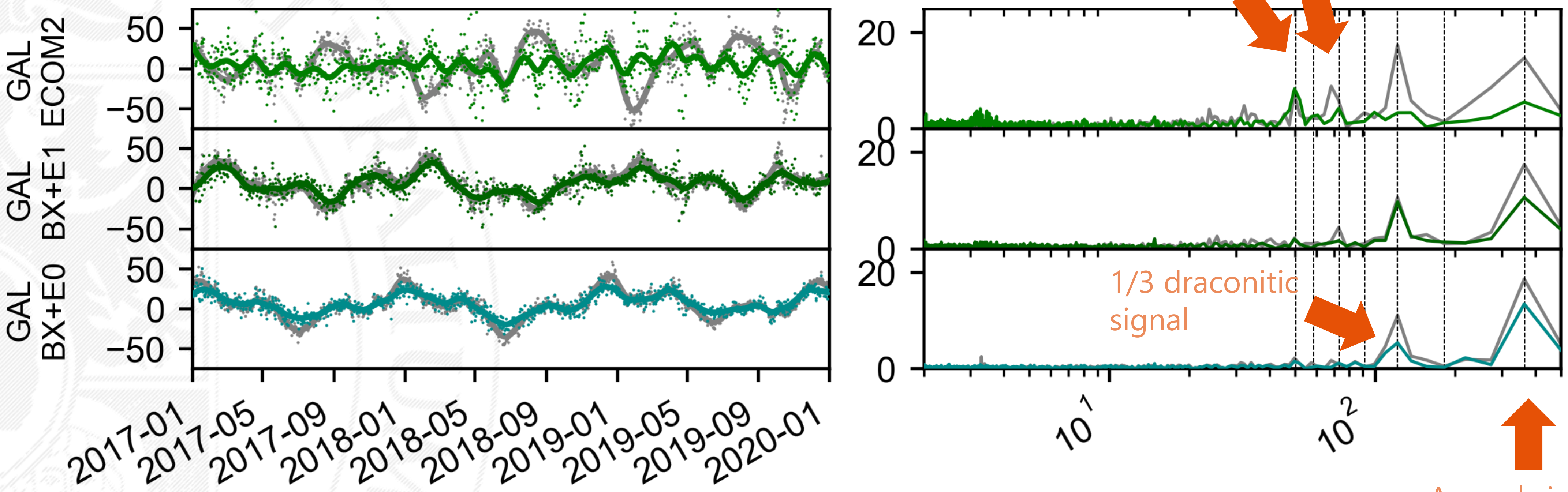
Galileo-only geocenter motion with different orbit modelining:

ECOM2: 7 empirical orbit parameters (no a priori box-wing)
BX+E1: a priori box-wing model + 5 empirical ECOM1 parameters)
BX+E0: a priori box-wing model + 3 constant D_0, Y_0, B_0 ECOM parameters

Z geocenter component from Galileo-only

In ECOM2, 1/5 and 1/7 signals

1-day arcs in green
3-day arcs in gray



Annual signal larger than expected (3-5 mm from SLR)

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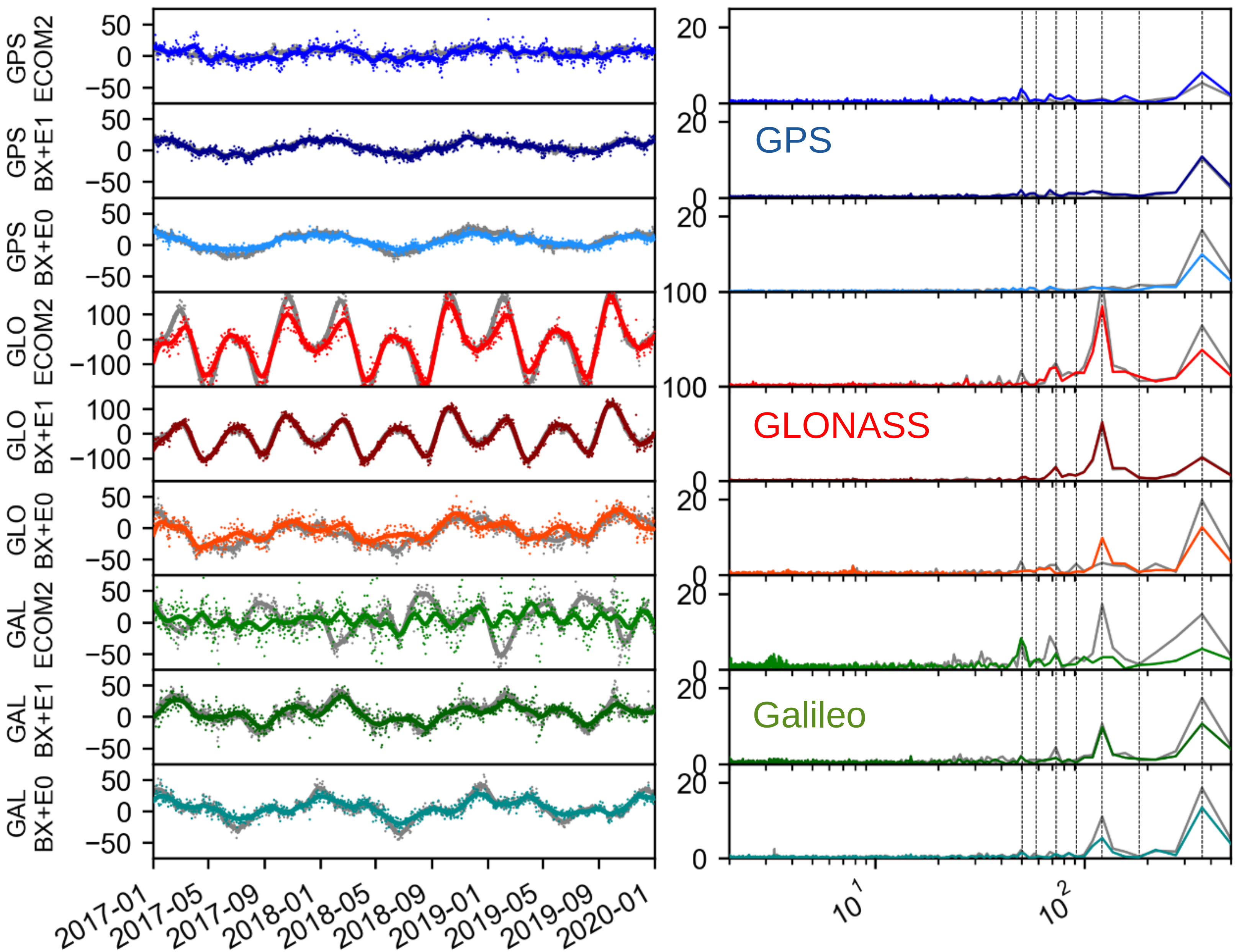
Z geocenter component

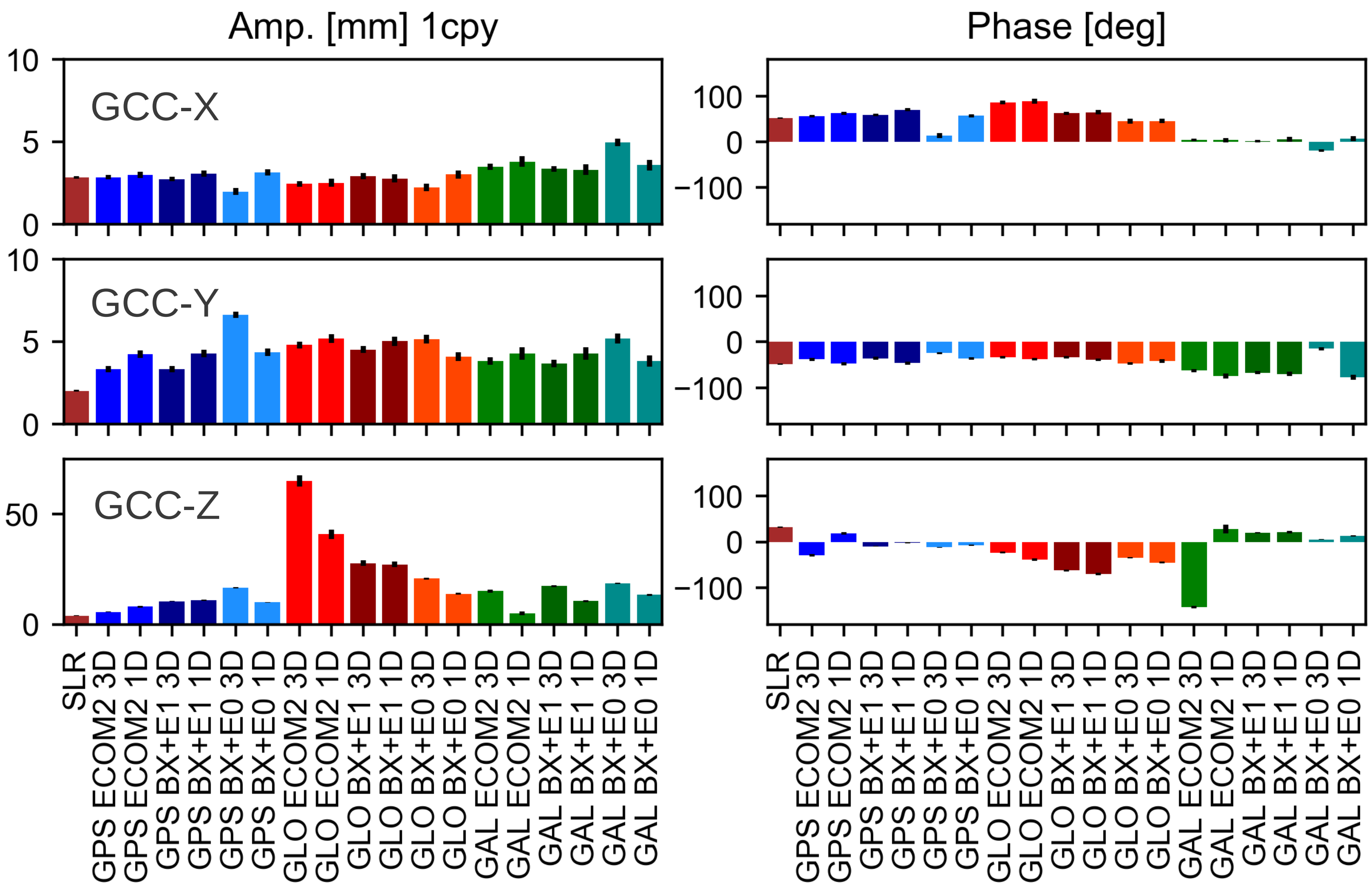
- **ECOM2 is insufficient for GLONASS and Galileo** (unrealistic signal)
- The **Z component from Galileo is much better than that from GLONASS** despite having also 3 orbital planes
- In all ECOM2 solutions, the 1/7th and 1/5th harmonics are visible
- **The 1/7th and 1/5th harmonics disappear in box-wing solutions (BX)**
- **GLONASS is strongly improved when no periodic terms are estimated** (BX+E0 – box-wing + constant par.)
- **3-day arcs** increase the amplitude of the annual signal in most cases, which suggests the **amplified impact of orbit modeling errors** in longer orbital arcs

Low-pass cut-off 40 day filter used; box-wing (BX) for GPS and GLONASS based on assumed proporties



Geocenter from GNSS

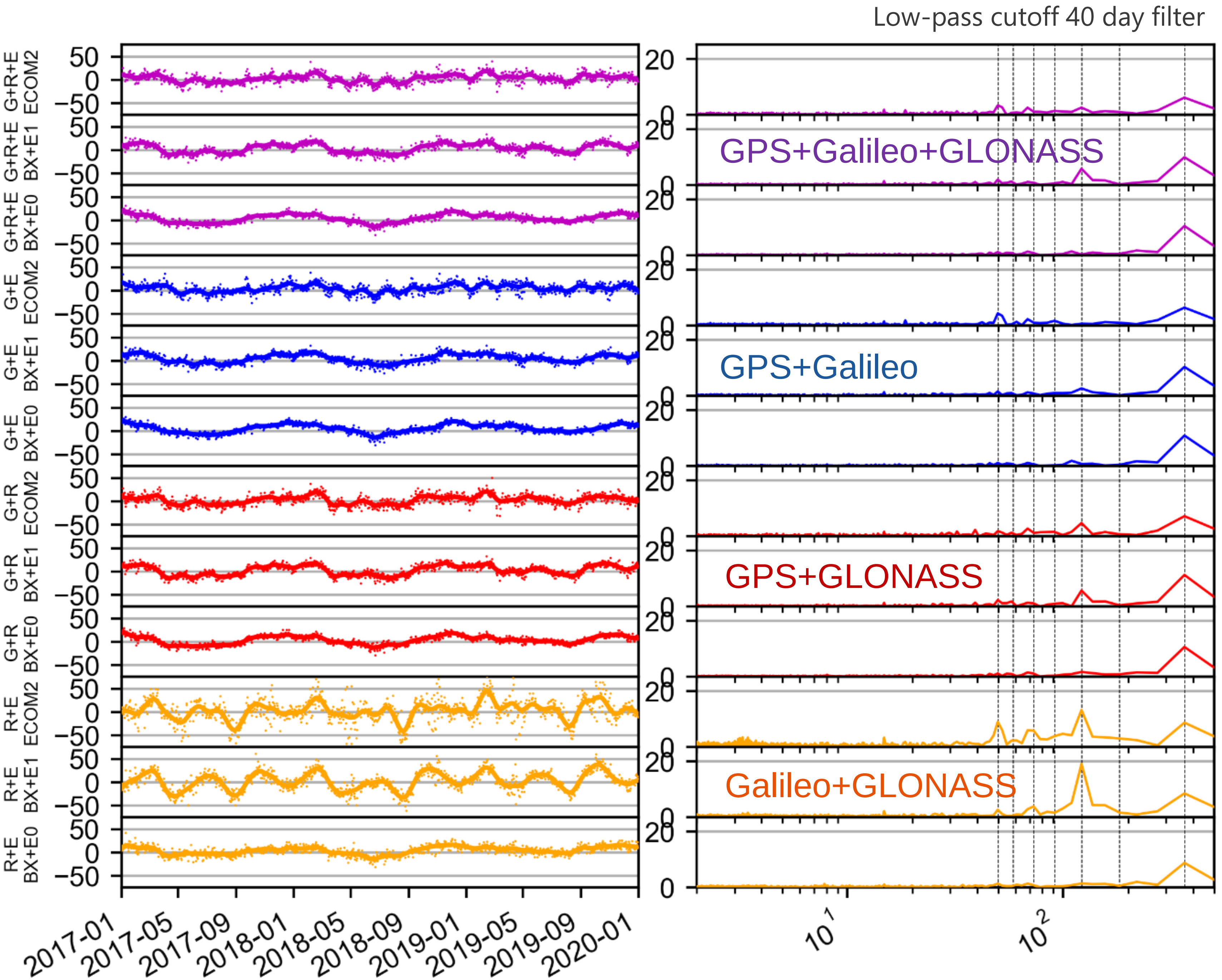
- Good agreement in the **phase for the X and Y** w.r.t. SLR,
- Good agreement in the amplitude for the X, especially in GPS and GLONASS solutions,
- Phase shifted for X in Galileo by 45 deg (1.5 month)
- **3-day arc increases the amplitude for GLO and GAL**, however, decreases the amplitude for GPS ,
- **All GLO results with estimated periodic terms** (ECOM2+E1) **are unrealistic for the Z component,**
- For GAL, the best results w.r.t. SLR are for **1D BX+E1** and **1D ECOM2**, however, the latter has large 1/5th draconitic signal (see the previous slide).



Amplitudes and phases of the annual signal from 1-day and 3-day arcs. Individual GNSS solutions

Combinations

- GLONASS has 1/3 draconitic term when periodic terms are estimated (no matter with or without the a priori box-wing)
- GLONASS+Galileo solution quite good if box-wing (BX) with no periodic terms estimated (E0)
- GPS+Galileo is better than the combined GRE solution, when estimating periodic terms (reduction of the 1/3 harmonic). From the analysis of the orbit quality we know, however, that periodic terms ECOM1 (E1) should be estimated. Thus, E0 is not the best solution for other GNSS-based parameters.



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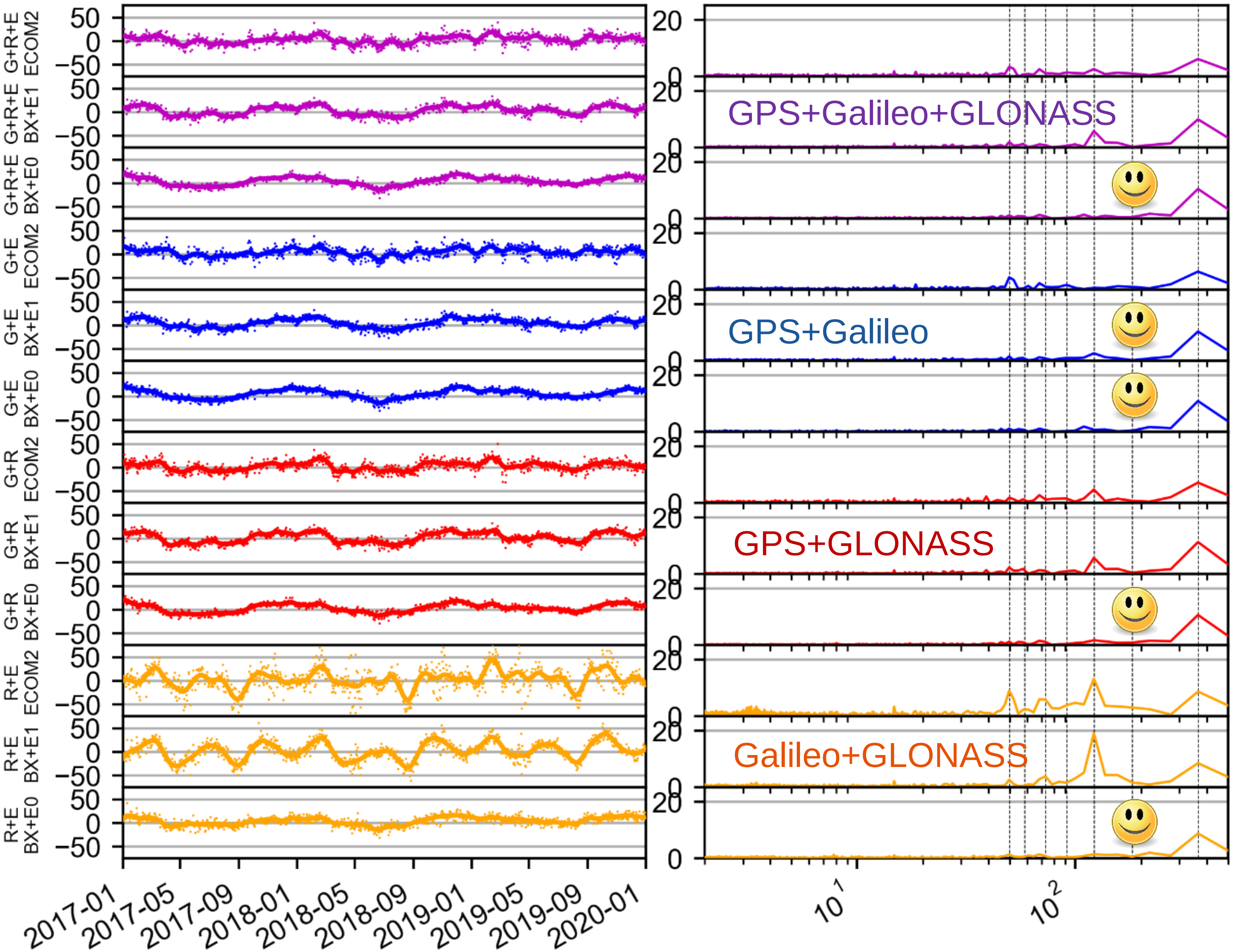
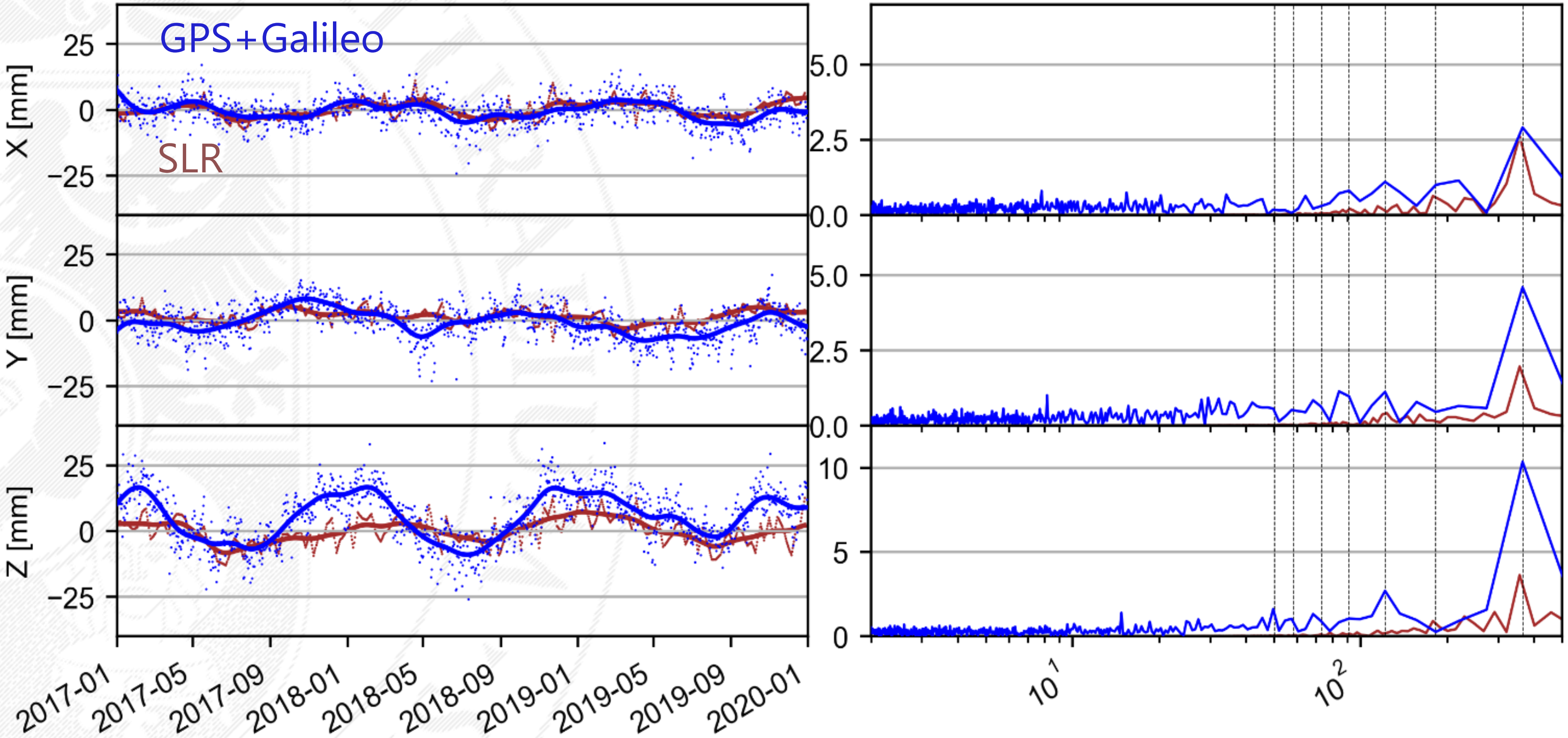
Low-pass cutoff 40 day filter



Best GNSS geocenter solution: GPS+Galileo

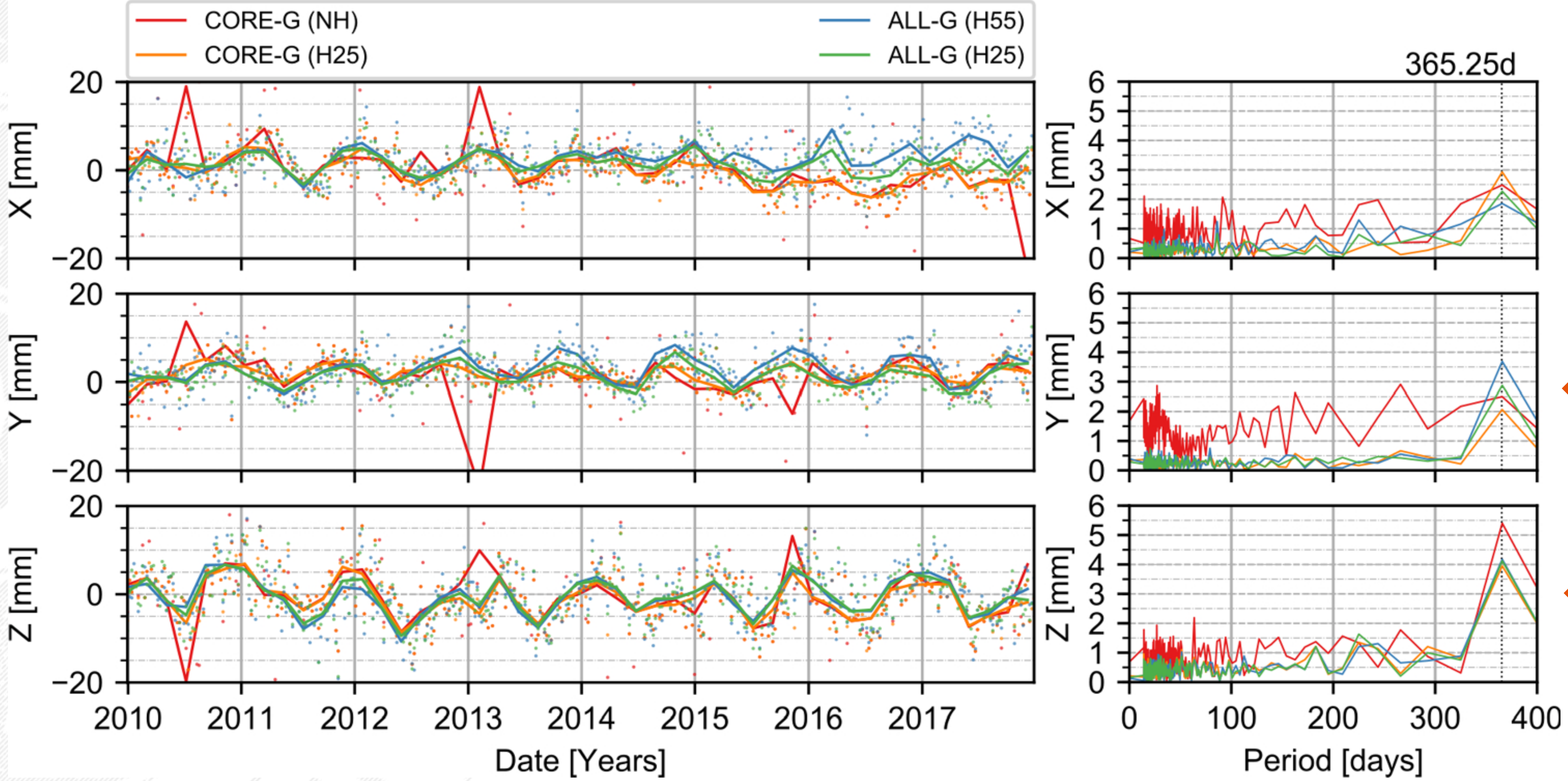


	SLR		GPS+GAL	
	Phase [deg]	Ampl [mm]	Phase [deg]	Ampl [mm]
X	52	2.8	60	3.1
Y	311	2.0	303	4.2
Z	32	3.9	3	10.3

GPS+Galileo BX+E1:
A priori box-wing + 5 ECOM1 parameters estimated
GLONASS excluded!

- **Very good agreement** in the amplitude and phase **for the X component**
- Amplitude of the Y and Z components overestimated in GNSS w.r.t. SLR
- **Draconitic signals do not dominate the Z component anymore (!),** and the phases agree

…. however, SLR-derived geocenter is not errorless ….



Zajdel R., Sośnica K., Drożdżewski M., Bury G., Strugarek D. (2019) ***Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS***
Journal of Geodesy, Vol. 93 No. 11, Berlin Heidelberg, Germany 2019, pp. 2293-2313
DOI: 10.1007/s00190-019-01307-0

Amplitude of the annual signal from 2.0 to 3.7 mm depending on the network

Amplitude of the annual signal from 3.8 to 5.5 mm

Dependency of LAGEOS-based geocenter motion on the selection of SLR sites.
CORE SLR sites, ALL SLR sites with different outlier rejection - station stability of 25 mm (H25), 55 mm (H55), and no rejection (NH).

Summary

1. Polar motion derived from Galileo is characterized by a **comparable quality to GPS** results.

2. Secular drift of **accumulated LoD** is much **smaller for Galileo and GLONASS** than for GPS solutions.

3. The **best** results of **geocenter** coordinates are obtained from the combination of **GPS+Galileo** (excluding GLONASS) and **with the a priori box-wing model** and 5-parameter ECOM. Galileo-based geocenter is much better than the GLONASS-based despite 3 orbital planes in both systems.

4. Three main error sources (spurious signals) can be identified in GNSS-derived ERPs and geocenter:

a) **Harmonics** of the **draconitic year** (repeatability of the orientation of orbital planes w.r.t. the Sun): 177 days, 118 days, 88.5 days, 70.8 days, 59.0 days, 50.6 days, 35.4 days, etc.

b) **Resonances** (common repeatabilities) of the **Earth rotation** (sidereal day) and the **revolution period** of the constellations. Galileo: 2.5 days, 3.4 days, 10 days; GLONASS: 2.6 days, 3.9 days, 7.9 days.

c) **Aliasing with sub-daily ERP tides** (common for all GNSS independently from the revolution period): 14.2 days, 14.8 days.

Literature on multi-GNSS ERPs, geocenter, and network effects

Zajdel R., Sośnica K., Bury G., Dach R., Prange L., (2020)
System-specific systematic errors in earth rotation parameters derived from GPS, GLONASS, and Galileo
GPS Solutions (available this week)
DOI: https://doi.org/10.1007/s10291-020-00989-w

Zajdel R., Sośnica K., Dach R., Bury G., Prange L., Jäggi A. (2019)
Network effects and handling of the geocenter motion in multi-GNSS processing
Journal of Geophysical Research-Solid Earth, Vol. 124 No. 6, Washington, DC, USA 2019, pp. 5970-5989
DOI: https://doi.org/10.1029/2019JB017443

Zajdel R., Sośnica K., Drożdżewski M., Bury G., Strugarek D. (2019) ***Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS***
Journal of Geodesy, Vol. 93 No. 11, Berlin Heidelberg, Germany 2019, pp. 2293-2313
DOI: https://doi.org/10.1007/s00190-019-01307-0

Literature on GNSS orbit modeling and the box-wing model

Bury G., Sośnica K., Zajdel R., Strugarek D. (2020)
Toward the 1-cm Galileo orbits: challenges in modeling of perturbing forces
Journal of Geodesy, Vol. 94 No. 16, Berlin Heidelberg, Germany 2020, pp. 1-19
DOI: https://doi.org/10.1007/s00190-020-01342-2

Bury G., Zajdel R., Sośnica K. (2019)
Accounting for perturbing forces acting on Galileo using a box-wing model
GPS Solutions, Vol. 23 No. 74, Berlin - Heidelberg 2019, pp. 1-12, DOI: https://doi.org/10.1007/s10291-019-0860-0

Sośnica K., Zajdel R., Bury G., Bosy J., Moore M., Masoumi S. (2020) ***Quality assessment of experimental IGS multi-GNSS combined orbits***
GPS Solutions, Vol. 24 No. 54, Berlin - Heidelberg 2020, pp. 1-14, DOI: https://doi.org/10.1007/s10291-020-0965-5

Journal of Geodesy (2020) 94:16
https://doi.org/10.1007/s00190-020-01342-2

ORIGINAL ARTICLE

Toward the 1-cm Galileo orbits: challenges in modeling of perturbing forces

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

GPS Solutions (2019) 23:74
https://doi.org/10.1007/s10291-019-0860-0

ORIGINAL ARTICLE

Accounting for perturbing forces acting on Galileo using a box-wing model

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

GPS Solutions (2020) 24:54
https://doi.org/10.1007/s10291-020-0965-5

ORIGINAL ARTICLE

Quality assessment of experimental IGS multi-GNSS combined orbits

Krzysztof Sośnica[1] · Radosław Zajdel[1] · Grzegorz Bury[1] · Jarosław Bosy[1] · Michael Moore[2] · Salim Masoumi[2]

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Abstract
The International GNSS Service (IGS) Analysis Center Coordinator initiated in 2019 an experimental multi-GNSS orbit combination service by adapting the current combination software that has been used for many years for IGS GPS and GLONASS combinations. The multi-GNSS orbits are based on individual products generated by IGS and multi-GNSS Pilot Project analysis centers. However, the combinations are not yet considered to be the final products at this time. The goal of this research is to provide a quality assessment of the very first IGS experimental multi-GNSS combined orbits based on Satellite Laser Ranging (SLR) observations and the mean position errors from the orbit combinations. The errors available in the combined orbit files provide information about the consistency between orbits from different analysis centers, whereas SLR provides independent orbit validation results even for those satellites which are considered only by one analysis center, and thus, the quality of the combination is not provided in the orbit files. We found that the BeiDou-3 satellites manufac-

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Thank you for your attention

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