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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 <sub>0</sub> , Y <sub>0</sub> , B <sub>0</sub> 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
	A priori ERPs: IERS-C04-14
Earth orientation	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 <sup>-5</sup> m/s), cross-track (10 <sup>-8</sup> m/s), radial (10 <sup>-6</sup> m/s)

# **Earth rotation parameters**

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

	X [µ	ias]	4] Y	ias]
	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 WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

## 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 (constellation repeatability). When f<sub>E</sub> and f<sub>S</sub> 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
<i>f<sub>s</sub></i> [1/h]	0.0836	0.0888	0.0708

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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<sub>2</sub>), 14.2 days (O<sub>1</sub>)
   -> 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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GAB	1	21

GPS has a large secular driftImage of the accumulated LoD in1-day solutions due to<br/>orbital resonances.Image of the accumulated LoD inGLONASS and Galileo have<br/>much smaller drifts, however,<br/>the combined solution is dominated<br/>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</li>
- Errors decrease in 2019 in Galileo solutions (late 2018: 24 active Galileo satellites)
- The combined solution GRE mitigates the time-variable errors



# **Geocenter coordinates**

### Z geocenter component from Galileo-only

## 1-day arcs in green3-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<sub>0</sub>, Y<sub>0</sub>, B<sub>0</sub> ECOM parameters



Galileo-only geocenter motion with different orbit modelining:

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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

### Low-pass cutoff 40 day filter

## **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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## **Best GNSS geocenter solution: GPS+Galileo**



- 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

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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

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Journal of Geodesy (2019) 93:2293-2313 https://doi.org/10.1007/s00190-019-01307-0 **ORIGINAL ARTICLE** Impact of network constraining on the terrestrial reference frame

realization based on SLR observations to LAGEOS

R. Zajdel<sup>1</sup> · K. Sośnica<sup>1</sup> · M. Drożdżewski<sup>1</sup> · G. Bury<sup>1</sup> · D. Strugarek<sup>1</sup>

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### **JGR** Solid Earth

RESEARCH ARTICLE 10.1029/2019JB017443

Network Effects and Handling of the Geocenter Motion in Multi-GNSS Processing

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· Using the No-Net-Translation constraint in global multi-GNSS processing is beneficial for station coordinate estimates · Galileo constellation can provide geocenter coordinates whose quality corresponds to that from GPS

· Inhomogeneous distribution of GNSS stations leads to systematic effects in geocenter coordinates delivered from GNSS

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EARTHAND

Abstract Both, the network configuration and the way of terrestrial reference frame (TRF) realization affect the global geodetic products delivered from the Global Navigation Satellite Systems (GNSS) data processing. The purpose of this study is to analyze the differences in GNSS products, such as station coordinates, Earth rotation parameters, geocenter coordinates (GCC), and satellite orbits delivered from the double-difference multi-GNSS (GPS, GLONASS, and Galileo) processing, which may arise from (1) using a homogeneous and inhomogeneous network of multi-GNSS stations, (2) different approaches to the TRF realization using minimum constraint conditions, and (3) different approaches to handling of GCC in GNSS global processing. The questionable quality of GCC delivered from the global GNSS solutions is described with a special attention to network effects and system-specific parameters. We found that Galileo can provide GCC, whose quality corresponds to the GPS series. Moreover, the GCC from Galileo is of a better quality than those based on GLONASS data, despite the same number of nominal orbital planes and a much lower number of active satellites. When the No-Net-Translation constraint is not applied on the GNSS network, the station coordinate repeatability is worsened by about 70%, 55%, and 25% for the north, east, and up components, respectively, compared to the solution when applying No-Net-Translation and when having the network origin consistent with the international TRF. We thus infer that the No-Net-Translation condition is mandatory in global GNSS solutions.

#### 1. Introduction

Global coverage of the Global Navigation Satellite Systems (GNSS) network is essential for the proper representation of the geometry of the Earth figure and for deriving proper Earth rotation parameters (ERPs; Plag & Pearlman, 2009). In addition to the coverage, the spatial distribution of stations may lead to obvi-

## Literature on GNSS orbit modeling and the box-wing model

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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

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GPS Solutions, Vol. 24 No. 54, Berlin - Heidelberg 2020, pp. 1-14, DOI: https://doi.org/10.1007/s10291-020-0965-5

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Rec © T Ab In ma the mc wh var pla 25 the par pla the	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 <sup>1</sup> • Radosław Zajdel <sup>1</sup> • Grzegorz Bury <sup>1</sup> • Jarosław Bosy <sup>1</sup> • Michael Moore <sup>2</sup> • Salim Masoumi Received: 3 December 2019 / Accepted: 25 February 2020 / Published online: 7 March 2020 • The Author(s) 2020  Abstract The International GNSS Service (IGS) Analysis Center Coordinator initiated in 2019 an experimental multi-GNSS or combination service by adapting the current combination software that has been used for many years for IGS GPS a
Rec © T Ab In ma the mc wh var pla 25 the par pla the	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 <sup>1</sup> • Radosław Zajdel <sup>1</sup> • Grzegorz Bury <sup>1</sup> • Jarosław Bosy <sup>1</sup> • Michael Moore <sup>2</sup> • Salim Masoumi Received: 3 December 2019 / Accepted: 25 February 2020 / Published online: 7 March 2020 • The Author(s) 2020 Abstract The International GNSS Service (IGS) Analysis Center Coordinator initiated in 2019 an experimental multi-GNSS or combination service by adapting the current combination software that has been used for many years for IGS GPS a GLONASS combinations. The multi-GNSS orbits are based on individual products centerated by IGS and multi-GNSS orbits
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# Thank you for your attention

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