



Multi-GNSS Analyses in the Time and Frequency Domains

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Agenda

1. Introduction
2. GNSS Interoperability (Time Domain)
3. Doppler Analysis (Frequency Domain)
4. Monthly Results
5. Conclusions

Introduction

- The University of Padova is one of the partners that participate in the SG3 – Galileo activities: 25 partners among the 27, from 14 EU Member States+ Norway.
- The proposal from the GEMOP (Galileo and EGNOS Monitoring of Performances) consortium was the response to the EUSPA invitation to submit a proposal for the third specific grant (SG3) related to the support from the Member States to Galileo performance monitoring activities in the frame of the Framework Partnership Agreement (FPA) EUSPA/GRANT/03/2021.
- The objectives of this proposal are in line with those mentioned in the Strategic Action Plan.
 - Support to the GRC-core with data from a worldwide network, reference products, KPIs and expertise;
 - Wide-range of high-end data and products;
 - Independence of the means and people involved in GEMOP with respect to Galileo systems and operations;
 - Monitoring of the Galileo services (OS, HAS, OSNMA)
 - GNSS abnormal events investigations
 - Use of Member States means and resources.

Introduction

UPAD (WPG3.5) Description of work:

- **Required inputs**

- Data & files: RINEX 3.03 (and following versions) data and navigation daily files from GEMOP/EPN/IGS reference network. 37 different stations covering Europe and Eastern Asia were selected as the stations of our test network.
- MultiGNSS analysis software (as described in GPS Solutions 2015 19(2) pp. 297-307).

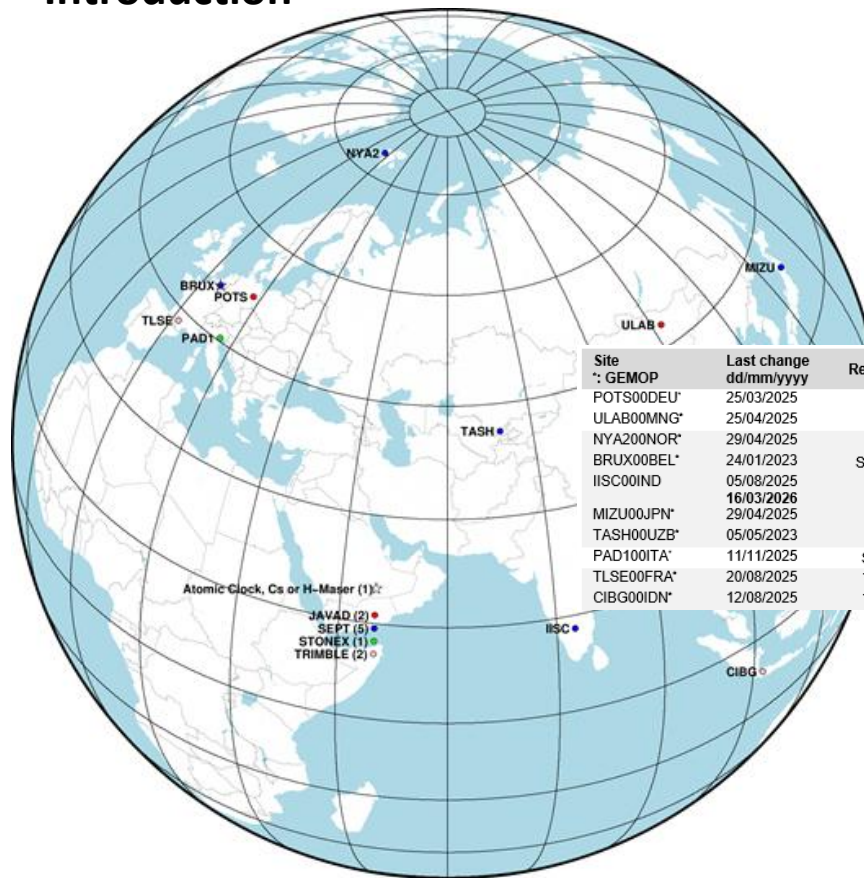
- **Tasks to carry out**

- For Interoperability/Doppler/GTRF Analysis:
 - Monitoring network.
 - Data collection and management.
 - Data processing and analysis.
 - Result reporting

Three different solutions are computed for Galileo (I/NAV, F/NAV and E1B (single frequency))

All the Global GNSS (GPS, GLO, GAL, BDS) + Regional (QZSS, NAV, and GAG) are included.

Introduction



Site	Last change	Rec. Type	FW	Rec. SN	Antenna type + radome	External clock	BIPM receiver
Site : GEMOP	dd/mm/yyyy						
POTS00DEU*	25/03/2025	JAVAD TRE_3	4.5.00-241014	4171773	JAVRINGANT_G5T NONE		
ULAB00MNG*	25/04/2025	JAVAD TRE_3	4.5.00-241014	1480898	JAVRINGANT_G5T NONE		
NYA200NOR*	29/04/2025	SEPT POLARX5	5.5.0	3051453	JAVRINGANT_G5T NONE		
BRUX00BEL*	24/01/2023	SEPT POLARX5TR	5.5.0	3057609	JAVRINGANT_DM SCIS	IMASER 3000	YES (OR5Z)
IISC00IND	05/08/2025	SEPT POLARX5	5.6.0	3013572	ASH701945E_M NONE		
	16/03/2026	SEPT POLARX5	5.7.0				
MIZU00JPN*	29/04/2025	SEPT POLARX5	5.6.0	3051468	SEPCHOKE_B3E6 NONE		
TASH00UZB*	05/05/2023	SEPT ASTERX4	4.10.0	3046856	SEPCHOKE_B3E6 NONE		
PAD100ITA*	11/11/2025	STONEX SC2200	2.12.251031-STX	SC22E2061002G	STXSA1200 STXR		
TLSE00FRA*	20/08/2025	TRIMBLE ALLOY	6.401	6139R40106	TRM59800.00 NONE		
CIBG00IDN*	12/08/2025	TRIMBLE ALLOY	6.40	6023R40127	LEIAR25.R4 NONE		

GNSS Interoperability (Time Domain)

According to the Galileo Open Service Definition Document, interoperability can be understood as the **capability for user equipment to exploit available navigation signals of different GNSS and to produce a combined solution that generally exhibits performance benefits** (e.g., better accuracy, higher availability) with respect to the standalone system solution. **The TIME offsets of the different GNSS must be computed and accounted for.**

- Analysis of SiS performance: Analysis of the intersystem clock biases (GPS to Galileo Clock offsets)
 - Daily processing of RINEX observations and broadcast navigation files
 - Estimate epochwise (900 s):
 - Time offset and time drift to GPS time for each available GNSS (Glonass, Galileo, BeiDou, QZSS, NAVIC, GAGAN), depending on the receiver tracking capabilities, available ephemeris and the station's geographical location
 - TZD (Tropospheric Zenith Delay)
 - Coordinates and velocities (Doppler analysis)
 - Postfit range residuals and post-fit doppler residuals computed
 - IGS CAS DCB corrections applied (Galileo, GLONASS, GPS, and QZSS).
 - TGD1 corrections for BDS (C2I and C6I signals)

GNSS Interoperability (Time Domain)

Least squares solution:

$$H^T H \Delta x = H^T y \rightarrow \Delta x = [H^T H]^{-1} H^T y$$

$$y = H \Delta x + \varepsilon$$

Every epoch (900 sec):

- 3 coordinates
- 1 clock per tracked system
- 1 tropospheric estimate

The model of the pseudorange $p^i(t)$ is described in (1)-(3):

$$p^i(t) = \left[\begin{aligned} &range^i + c \cdot dt^i(t') \\ &+ c \cdot (TSC_X + dT_{REC,X}) + \frac{TZD}{\sin(E^i)} + DCB^i \end{aligned} \right] \quad (1)$$

$$range^i = \sqrt{\begin{aligned} &[X^i(t') + \omega_e \cdot Y^i(t - t') - x]^2 + \\ &[Y^i(t') - \omega_e \cdot X^i(t - t') - y]^2 + \\ &[Z^i(t') - z]^2 \end{aligned}} \quad (2)$$

$$dt^i(t') = \left[\begin{aligned} &a_0 + a_1 \cdot (t' - T_{oc}) + a_2 \cdot (t' - T_{oc})^2 \\ &- \frac{2\sqrt{\mu a}}{c^2} e \cdot \sin(E(t')) + LS \end{aligned} \right] \quad (3)$$

$$H = \begin{bmatrix} -\frac{x_{1G} - x_0}{\rho_{1G}} & -\frac{y_{1G} - y_0}{\rho_{1G}} & -\frac{z_{1G} - z_0}{\rho_{1G}} & 1 & 0 & 0 & 0 & 0 \\ -\frac{x_{2G} - x_0}{\rho_{2G}} & -\frac{y_{2G} - y_0}{\rho_{2G}} & -\frac{z_{2G} - z_0}{\rho_{2G}} & 1 & 0 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\frac{x_{nG} - x_0}{\rho_{nG}} & -\frac{y_{nG} - y_0}{\rho_{nG}} & -\frac{z_{nG} - z_0}{\rho_{nG}} & 1 & 0 & 0 & 0 & 0 \\ -\frac{x_{1R} - x_0}{\rho_{1R}} & -\frac{y_{1R} - y_0}{\rho_{1R}} & -\frac{z_{1R} - z_0}{\rho_{1R}} & 0 & 1 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\frac{x_{nR} - x_0}{\rho_{nR}} & -\frac{y_{nR} - y_0}{\rho_{nR}} & -\frac{z_{nR} - z_0}{\rho_{nR}} & 0 & 1 & 0 & 0 & 0 \\ -\frac{x_{1E} - x_0}{\rho_{1E}} & -\frac{y_{1E} - y_0}{\rho_{1E}} & -\frac{z_{1E} - z_0}{\rho_{1E}} & 0 & 0 & 1 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\frac{x_{nE} - x_0}{\rho_{nE}} & -\frac{y_{nE} - y_0}{\rho_{nE}} & -\frac{z_{nE} - z_0}{\rho_{nE}} & 0 & 0 & 1 & 0 & 0 \\ -\frac{x_{1C} - x_0}{\rho_{1C}} & -\frac{y_{1C} - y_0}{\rho_{1C}} & -\frac{z_{1C} - z_0}{\rho_{1C}} & 0 & 0 & 0 & 1 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\frac{x_{nC} - x_0}{\rho_{nC}} & -\frac{y_{nC} - y_0}{\rho_{nC}} & -\frac{z_{nC} - z_0}{\rho_{nC}} & 0 & 0 & 0 & 1 & 0 \\ -\frac{x_{1S} - x_0}{\rho_{1S}} & -\frac{y_{1S} - y_0}{\rho_{1S}} & -\frac{z_{1S} - z_0}{\rho_{1S}} & 0 & 0 & 0 & 0 & 1 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ -\frac{x_{nS} - x_0}{\rho_{nS}} & -\frac{y_{nS} - y_0}{\rho_{nS}} & -\frac{z_{nS} - z_0}{\rho_{nS}} & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

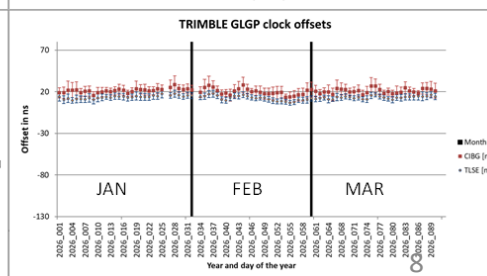
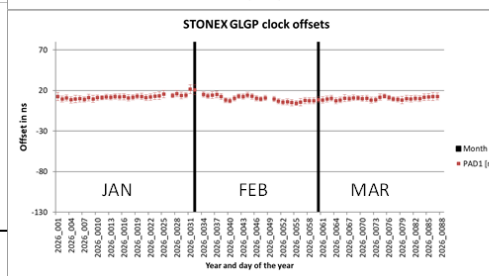
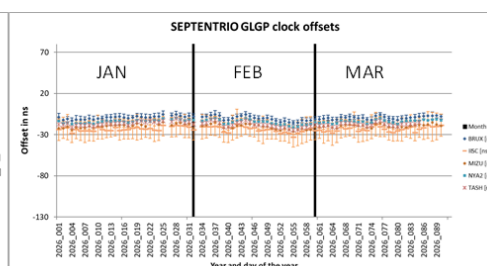
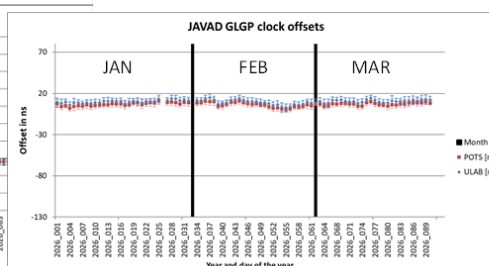
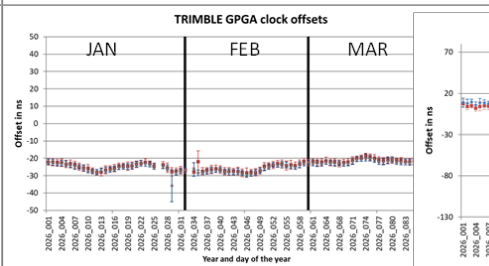
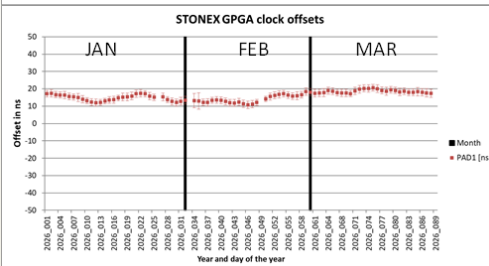
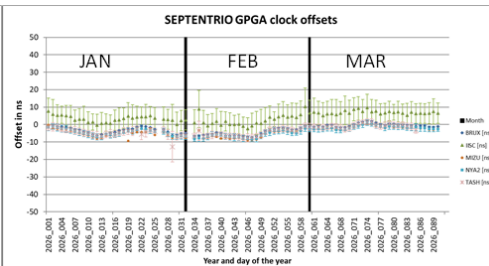
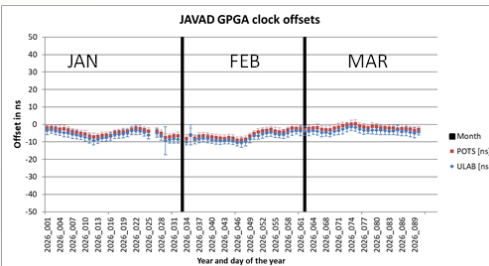
$$\Delta x = \begin{bmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \\ rcvrbias + TimeSystemCorr_GPS \\ rcvrbias + TimeSystemCorr_GLO \\ rcvrbias + TimeSystemCorr_GAL \\ rcvrbias + TimeSystemCorr_BeiDou \\ rcvrbias + TimeSystemCorr_SBAS \end{bmatrix}$$

GNSS Interoperability (Time Domain)

GNSS Time Offsets (by receiver/GNSS) related to GPS

Time offset	Definition
GPGA*	$(TSC_G + dT_{REC,G}) - (TSC_E + dT_{REC,E})$
GLGP*	$(TSC_R + dT_{REC,R}) - (TSC_G + dT_{REC,G})$
BDGP*	$(TSC_C + dT_{REC,C}) - (TSC_G + dT_{REC,G})$
QZGP*	$(TSC_J + dT_{REC,J}) - (TSC_G + dT_{REC,G})$
NAGP*	$(TSC_I + dT_{REC,I}) - (TSC_G + dT_{REC,G})$
GNGP*	$(TSC_N + dT_{REC,N}) - (TSC_G + dT_{REC,G})$

* $dT_{REC,x}$ depends not only on the receiver, but on the constellation too.

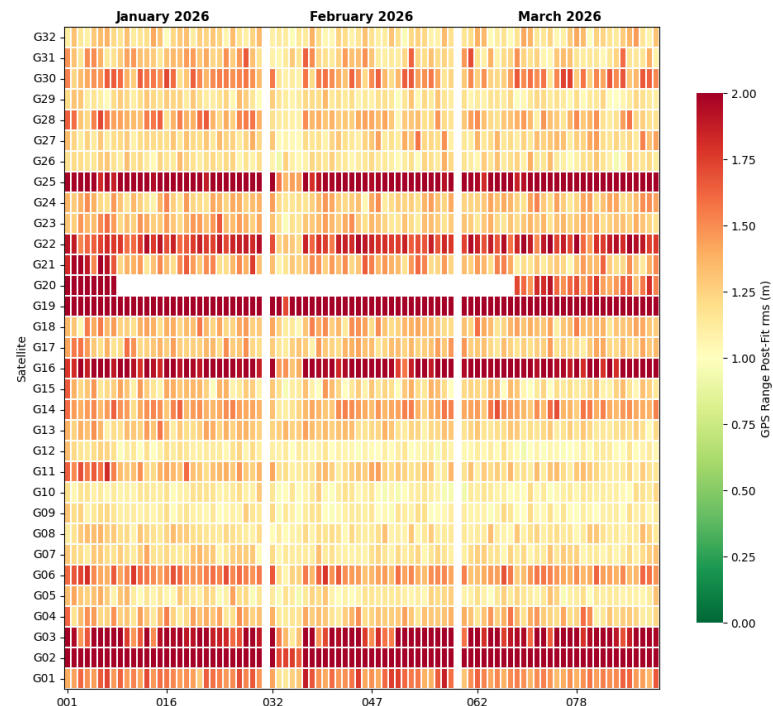
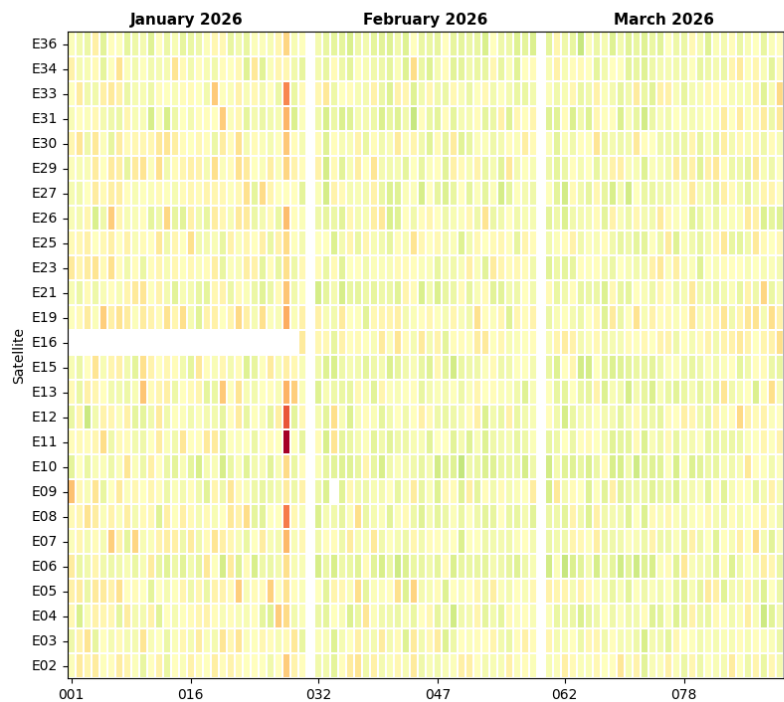


GNSS Interoperability (Time Domain)

GNSS performance based on the post-fit residual analysis (SiS MPL: ± 2.0 m)

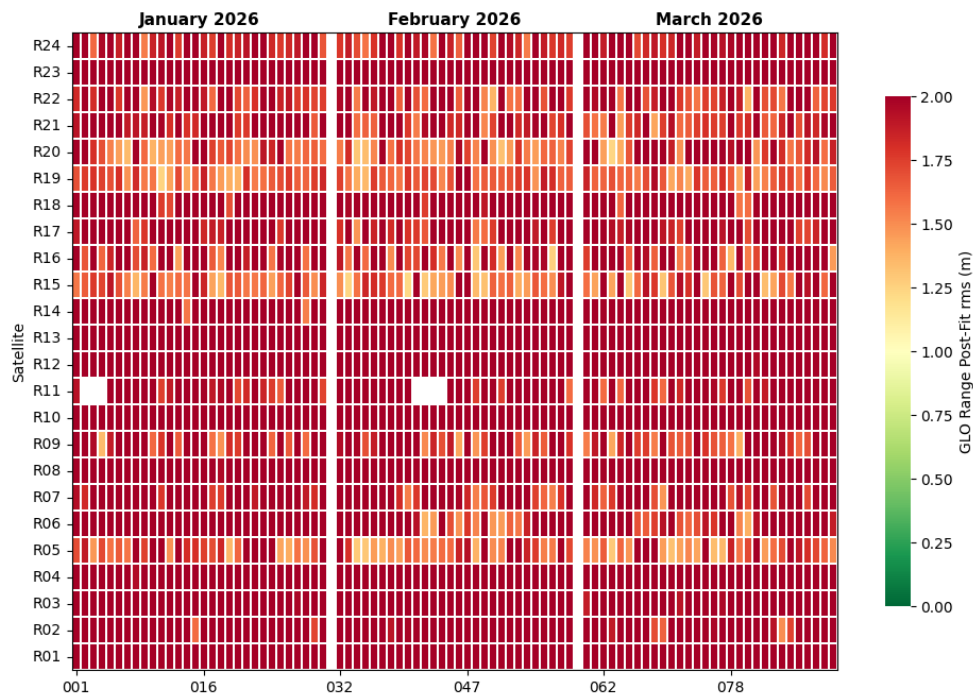
GAL (I/NAV) Satellite Range Residual RMS

GPS Satellite Range Residual RMS

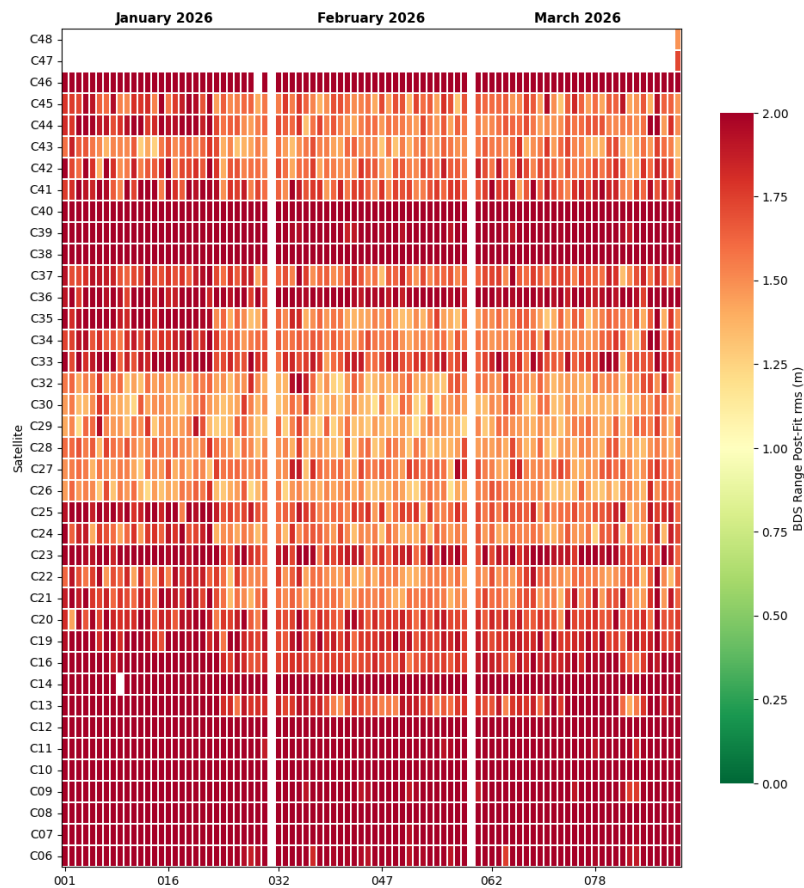


GNSS Interoperability (Time Domain)

GLO Satellite Range Residual RMS

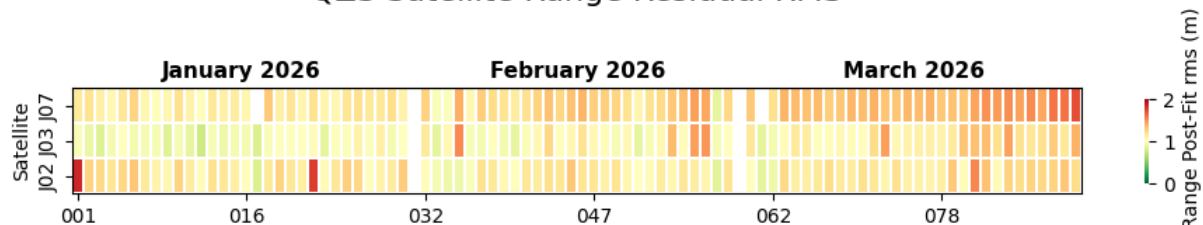


BDS Satellite Range Residual RMS

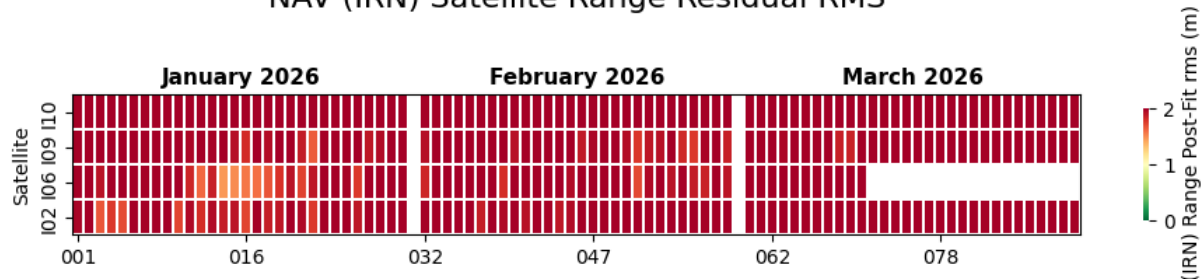


GNSS Interoperability (Time Domain)

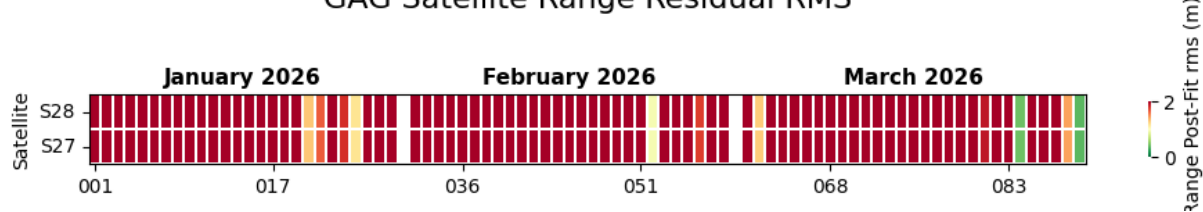
QZS Satellite Range Residual RMS



NAV (IRN) Satellite Range Residual RMS



GAG Satellite Range Residual RMS

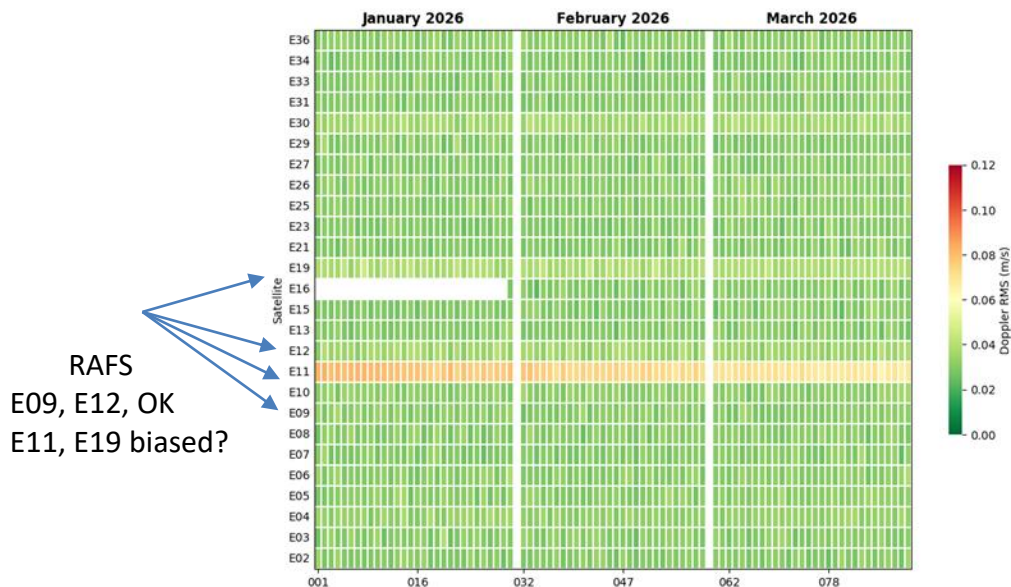


Doppler Analysis (Frequency Domain)

The design matrix (H) for the Doppler analysis is the same as for interoperability, with no ZTD component (negligible ZTD rate vs sampling rate is considered). The O – C values are computed as:

$$D^i = -(\vec{V}^i - \vec{v}) \cdot \overline{\text{los}}^i + c \cdot \left[\frac{\partial TSC_X}{\partial t} + dT_{REC,X} \right] \quad (4)$$

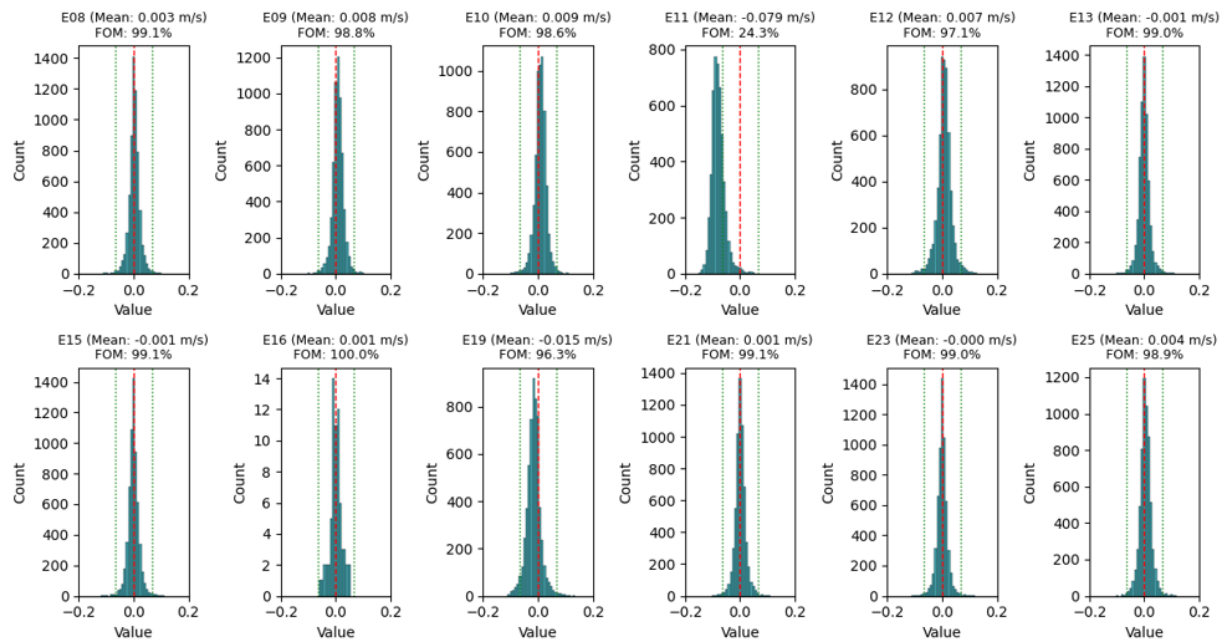
GAL Combined Doppler Residual RMS



Time drift	Definition
$\frac{\partial}{\partial t}(\text{GPGA})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_E) + dT_{rec} \right]$
$\frac{\partial}{\partial t}(\text{GLGP})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_R) + dT_{rec} \right]$
$\frac{\partial}{\partial t}(\text{BDGP})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_C) + dT_{rec} \right]$
$\frac{\partial}{\partial t}(\text{QZGP})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_J) + dT_{rec} \right]$
$\frac{\partial}{\partial t}(\text{NAGP})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_I) + dT_{rec} \right]$
$\frac{\partial}{\partial t}(\text{GNGP})$	$\left[\frac{\partial}{\partial t}(TSC_G) + dT_{rec} \right] - \left[\frac{\partial}{\partial t}(TSC_N) + dT_{rec} \right]$

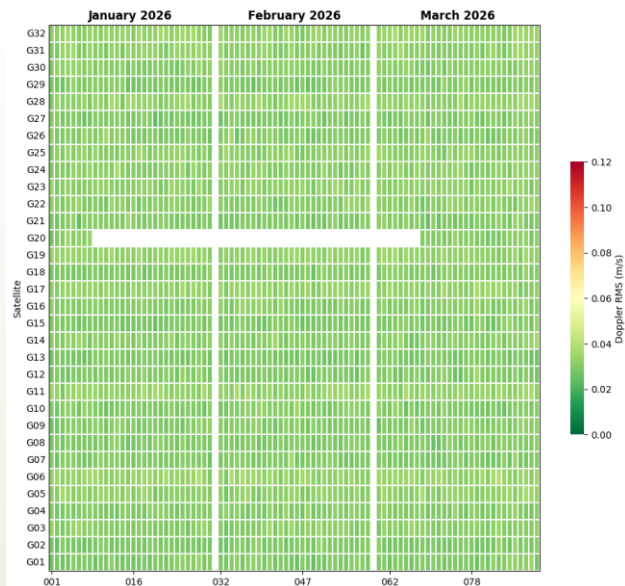
Doppler Analysis (Frequency Domain)

The E11 and E19 clock rates are biased related to the other Galileo:

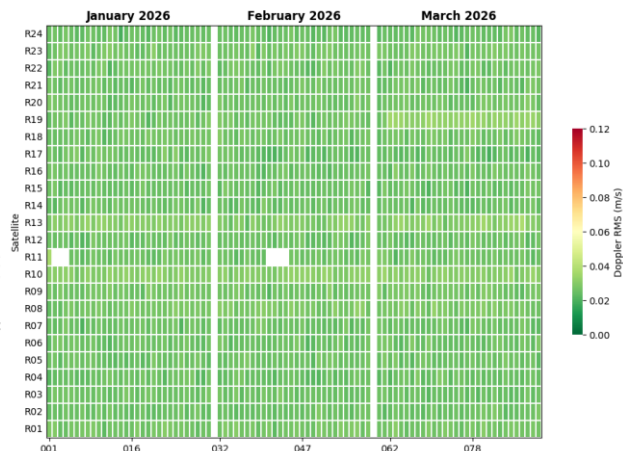


Doppler Analysis (Frequency Domain)

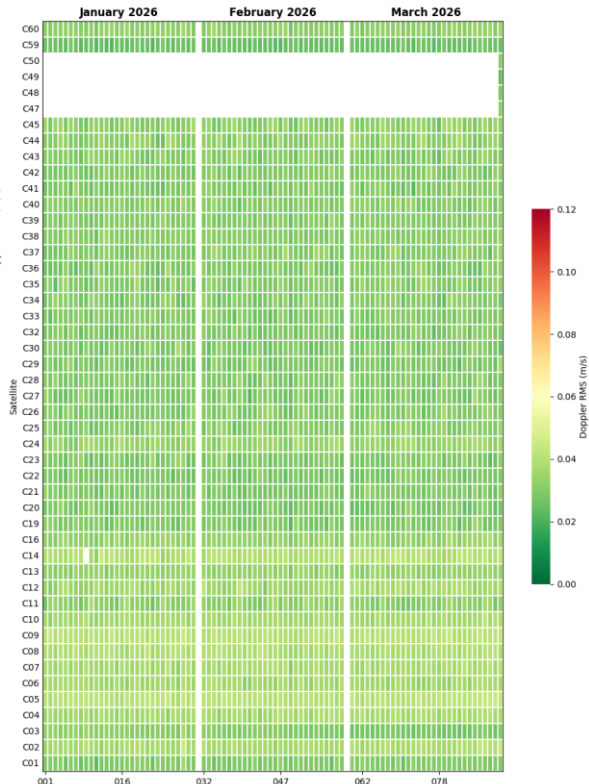
GPS Combined Doppler Residual RMS



GLO Combined Doppler Residual RMS

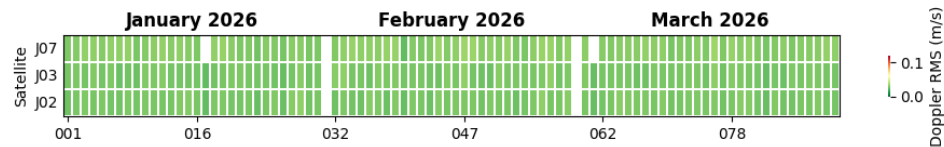


BDS Combined Doppler Residual RMS

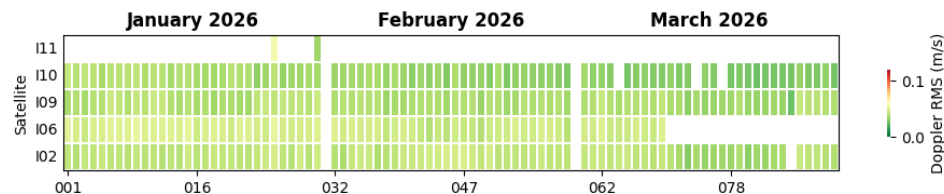


Doppler Analysis (Frequency Domain)

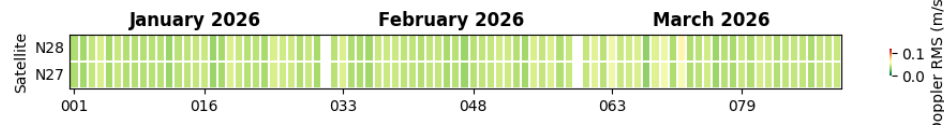
QZS Combined Doppler Residual RMS



IRN Combined Doppler Residual RMS

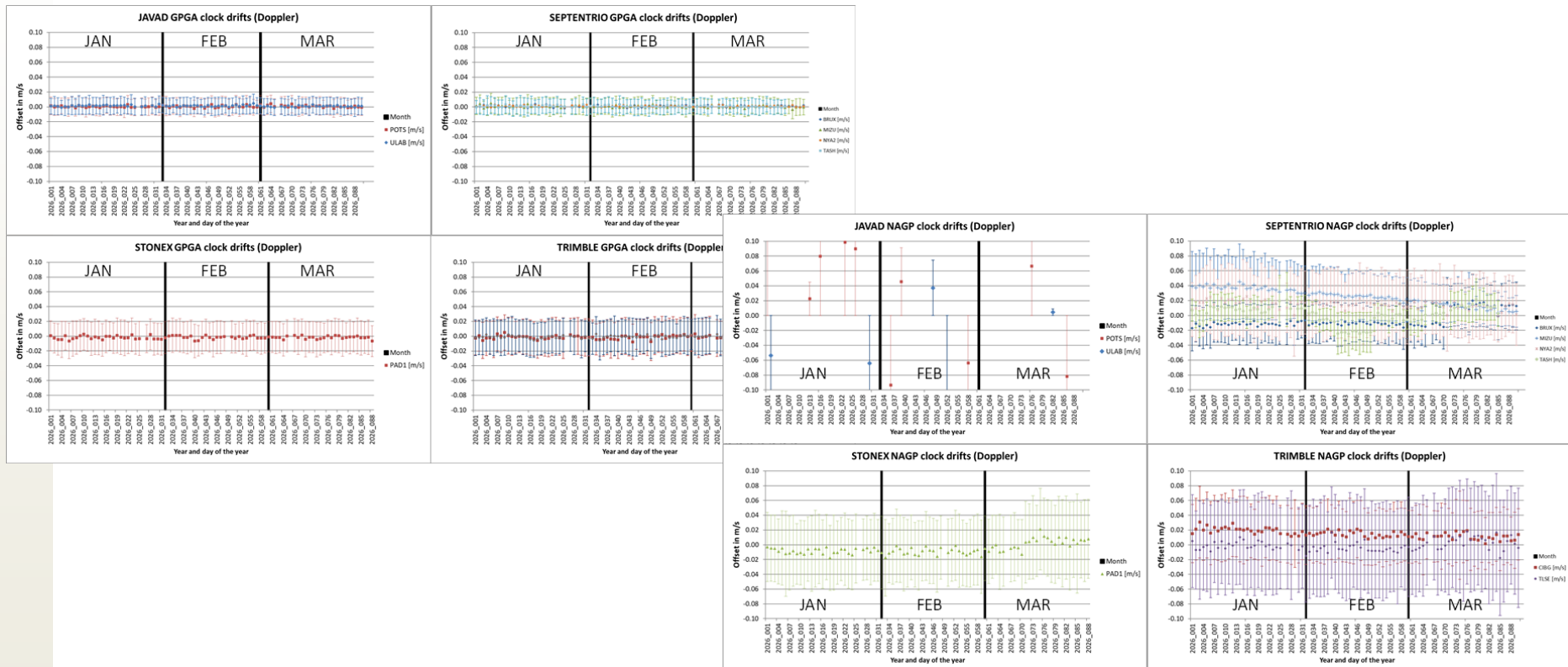


GAG Combined Doppler Residual RMS



Doppler Analysis (Frequency Domain)

Receiver Clock Drift estimation vs GPS: GPS to Galileo and Navic to GPS



Monthly Results

multiGNSS (post-fit range residuals)

Expected for Normal Distribution: Skewness ≈ 0.0 (ideally -0.5 to 0.5), Kurtosis ≈ 3.0 (ideally from 2 to 4)

System	Original Filename	Num Samples	Mean (m)	Median (m)	RMS (m)	KPI(%)	Skewness	Kurtosis
BDS	26001_26031_BDS	292654	0.021	-0.178	2.232	62.43	0.20	2.73
GAG	26001_26031_GAG	174	0.000	0.000	2.900	43.68	0.00	2.12
GAL E5b+E1B	26001_26031_GAL	180912	-0.000	0.018	1.009	94.83	-0.14	5.10
GAL E1B	26001_26031_GAL_E1B	179079	-0.005	0.075	1.844	73.44	-0.11	3.19
GAL E5a+E1B	26001_26031_GAL_E5a	180962	-0.000	0.013	0.975	95.42	-0.06	5.35
GLO	26001_26031_GLO	156618	-0.017	-0.087	2.534	53.98	0.10	2.41
GPS	26001_26031_GPS	221764	-0.002	-0.192	1.644	79.38	0.49	3.44
NAV	26001_26031_IRN	47193	-0.005	-0.099	2.103	66.43	0.16	2.92
QZS	26001_26031_QZS	22556	-0.005	0.019	1.097	93.14	-1.12	24.00

Expected for Normal Distribution: Skewness ≈ 0.0 (ideally -0.5 to 0.5), Kurtosis ≈ 3.0 (ideally from 2 to 4)

System	Original Filename	Num Samples	Mean (m)	Median (m)	RMS (m)	KPI(%)	Skewness	Kurtosis
BDS	26032_26059_BDS	352934	0.037	-0.009	1.886	72.83	0.07	3.30
GAG	26032_26059_GAG	274	0.000	0.000	3.397	35.04	0.00	1.78
GAL E5b+E1B	26032_26059_GAL	217220	-0.000	0.023	0.957	95.64	-0.17	5.70
GAL E1B	26032_26059_GAL_E1B	213003	-0.010	0.031	1.928	71.81	-0.02	3.20
GAL E5a+E1B	26032_26059_GAL_E5a	217273	-0.000	0.016	0.921	96.18	-0.09	5.94
GLO	26032_26059_GLO	183533	-0.019	-0.163	2.464	55.73	0.17	2.47
GPS	26032_26059_GPS	257992	-0.002	-0.155	1.541	82.41	0.47	3.67
NAV	26032_26059_IRN	52536	-0.002	-0.048	2.186	63.66	0.08	2.79
QZS	26032_26059_QZS	26639	-0.009	-0.007	1.146	92.29	-1.02	18.04

Expected for Normal Distribution: Skewness ≈ 0.0 (ideally -0.5 to 0.5), Kurtosis ≈ 3.0 (ideally from 2 to 4)

System	Original Filename	Num Samples	Mean (m)	Median (m)	RMS (m)	KPI(%)	Skewness	Kurtosis
BDS	26060_26090_BDS	320461	0.036	-0.022	1.951	70.83	0.07	3.17
GAG	26060_26090_GAG	188	0.000	0.000	3.200	39.36	0.00	1.94
GAL E5b+E1B	26060_26090_GAL	202059	-0.000	0.021	0.968	95.54	-0.11	5.74
GAL E1B	26060_26090_GAL_E1B	196907	-0.015	-0.002	2.013	69.41	0.03	3.07
GAL E5a+E1B	26060_26090_GAL_E5a	201861	-0.001	0.012	0.936	96.04	-0.04	6.12
GLO	26060_26090_GLO	166518	-0.018	-0.137	2.477	55.07	0.14	2.45
GPS	26060_26090_GPS	239134	-0.001	-0.172	1.576	81.24	0.48	3.55
NAV	26060_26090_IRN	33086	-0.007	-0.081	2.427	57.11	0.08	2.54
QZS	26060_26090_QZS	24134	-0.009	-0.020	1.251	89.66	-0.28	8.89

Doppler (post-fit range residuals)

MONTH	SYSTEM	MEAN (m/s)	RMS (m/s)	FOM (%)
January 2026	BDS	-0.0000	0.0220	98.72%
February 2026	BDS	-0.0000	0.0218	98.76%
March 2026	BDS	-0.0000	0.0218	98.72%
January 2026	GAG	0.0000	0.0409	89.39%
February 2026	GAG	0.0001	0.0422	88.23%
March 2026	GAG	-0.0002	0.0446	86.12%
January 2026	GAL	0.0000	0.0262	96.25%
February 2026	GAL	-0.0000	0.0258	96.36%
March 2026	GAL	0.0000	0.0251	96.81%
January 2026	GLO	0.0000	0.0192	98.95%
February 2026	GLO	0.0000	0.0191	98.99%
March 2026	GLO	0.0000	0.0194	99.01%
January 2026	GPS	0.0000	0.0207	98.78%
February 2026	GPS	0.0000	0.0206	98.80%
March 2026	GPS	0.0000	0.0206	98.82%
January 2026	NAV	0.0000	0.0353	96.15%
February 2026	NAV	-0.0000	0.0307	97.87%
March 2026	NAV	0.0000	0.0269	98.84%
January 2026	QZS	-0.0000	0.0172	99.72%
February 2026	QZS	-0.0000	0.0171	99.67%
March 2026	QZS	-0.0000	0.0173	99.64%

Conclusions

- We have shown the results for multiGNSS solutions (using code and Doppler observations) for a test network of 10 stations distributed over the world.
- Several tests to assess the quality of the various GNSS were driven for pseudoranges (time alignment) and also for Doppler (frequency stability).
- The inter-system time offsets show the same picture regardless the receiver type (and FW) and location.
- The multiGNSS **post-fit residuals** confirm that Galileo is the best performer, followed by GPS/BDS. GLONASS is the worst performer of the Global GNSS and QZSS is an excellent system (best after Galileo), but with limited coverage. NaVIC and GAGAN are the worst ones.
- Regarding the **Doppler analyses**, the frequency differences (clock rate differences) are very stable for all the GNSS except for GAGAN (the location plays a important role), where we find unexplained jumps, not always synchronized, in different receivers.
- QZSS is the best performer, followed by GLONASS. Galileo easily meets the MPL (0.066 m/sec at the 95% of the cases) and improves when RAFS clocks are excluded.



Thanks
Questions/Comments/Suggestions