Galileo Open Service Navigation Performance Monitoring Supported by RIGTC/GOP

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Abstract

Geodetic Observatory Pecný (GOP) of the Research Institute of Geodesy, Topography and Cartography (RIGTC) contributes to the monitoring navigation performance of the Galileo Open Service Signal in Space within the Member States support of the Galileo Reference Centre. GOP contribution consists of the three main tasks: 1) monitoring the quality of multi-GNSS data stemming from about 65 reference stations, 2) generating consolidated navigation files and reference GPS and Galileo satellites orbit and clock products with a latency of 6 and 42 hours, and 3) estimating key-parameter indicators for the Galileo OS navigation performance monitoring. The GOP chain of monitoring processes and all mandatory inputs is independent from other contributions in terms of the tools (G-Nut software), reference products rapid precise satellite orbits and clocks), and consolidated broadcast navigation data (BRDC files).

Keywords 1

GNSS, Galileo, satellite orbits and clocks, navigation data quality, performance monitoring

1. Introduction

The Galileo system is going to provide various services to billions of users around the world, hence there is a strong need for a continuous performance monitoring of the service components. Since October 2018, the Geodetic Observatory Pecný (GOP) of the Research Institute of Geodesy, Topography and Cartography (RIGTC) has contributed to an independent monitoring of the Galileo Open Service (OS) Signal in Space (SIS) navigation performance. This activity has been performed within the Member States supporting (GRC-MS project) the Galileo Reference Centre (GRC) established by the European GNSS Agency (GSA) in Noordwijk, the Netherlands [1], [2]. The paper describes an implementation of tasks performed at GOP contributing to the GRC-MS, namely:

- Monitoring the quality of multi-GNSS data from about 65 reference stations
- Providing reference products:
    a. Consolidated broadcast navigation data (BRDC) files [3]
    b. Precise GPS and Galileo orbits and clock corrections for active satellites
- Monitoring the performance of the Galileo Open Service navigation:
    a. Service volume availability
    b. Site-measured positioning service accuracy

The Galileo navigation performance monitoring at GOP has been designed fully independent from the system or any other monitoring services. Figure 1 shows a scheme of a full chain of the processes performed at GOP, inputs and outputs, and processing dependencies. All the processes are still dependent on observations and navigation data collected from several networks of global stations (grey boxes). The service volume and site-measured performance monitoring indicators (yellow boxes) relay then on both input observations and GOP reference products (green boxes). The GOP products are

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generated on a daily basis in early-rapid and rapid processing mode, i.e. targeting a delivery within 48 hours and 6 hours, respectively. For a maximum independency, in-house developed or extended tools are mainly exploited for generating reference products (green boxes), monitoring of station data quality (blue box), estimating station reference coordinates (red box), and monitoring navigation performance indicators (yellow boxes):

- G-Nut/Anubis tool originally designed for a multi-GNSS data quality control and further enhanced for estimating site-measured horizontal and vertical positioning indicators using specific signals and navigation data,
- G-Nut/Aset tool originally designed for the evaluation of satellite orbits and clocks, but additionally enhanced for merging, filtering and quality control of multi-GNSS navigation records,
- G-Nut/Geb tool implementing precise coordinate estimates using the Precise Point Positioning (PPP) method and precise orbit and clock products,
- G-Nut/Sothis tool for estimating GPS and Galileo precise satellite clock corrections, and
- Bernese GNSS software Version 5.2 driven by an autonomous processing system developed at GOP for determining precise orbits in the rapid and early-rapid modes.

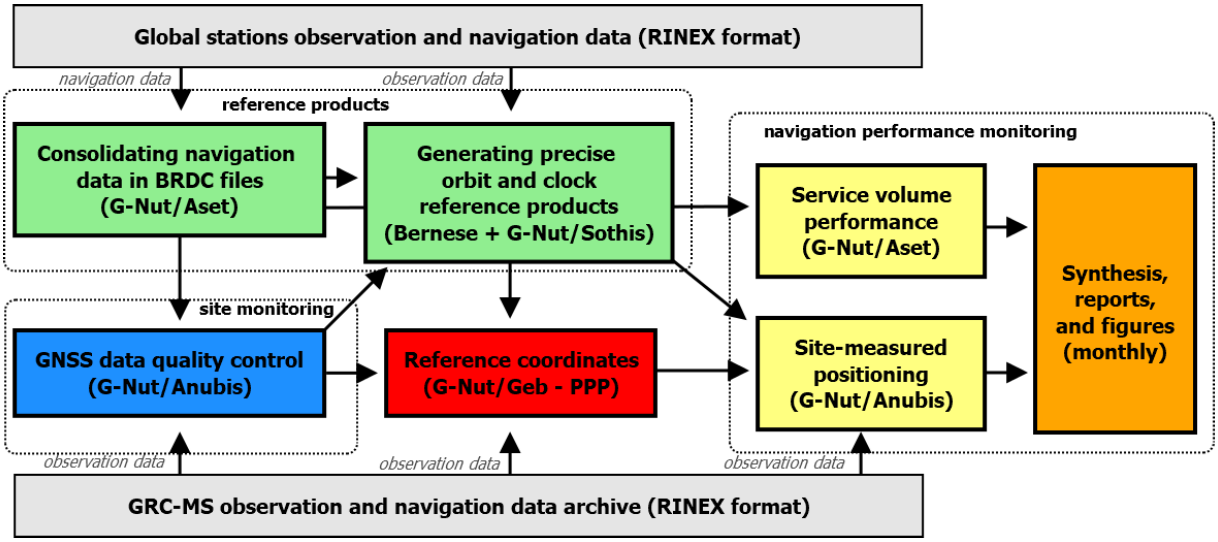

Figure 1: Complete chain of monitoring procedures, inputs and software implemented at GOP

2. Consolidated navigation data (BRDC files)

The GOP consolidated navigation BRDC files [3][1] are generated using the G-Nut/Aset software and inputs from real-time streams and hourly/daily RINEX files of about 300 global multi-GNSS stations of the IGS Multi-GNSS Experiment (MGEX) [4], [5] and the GRC-MS networks. The GOP BRDC product contains navigation data for all the GNSS constellations and regional augmentations. The RINEX 2 and 3 files are provided repetitively over past three days with a delay of 2-72 hours.

The GOP consolidation procedure consists of merging, filtering, and data quality control of navigation records collected from an extensive number of global multi-GNSS stations. In support of the ultra-fast delivery, it requires neither reference products nor external a priori information. In order to guarantee a high reliability of the consolidated files, it relays on autonomous methods: a) time-series analysis for selected parameters (values, differences), b) range check (record pre-filtering), c) statistical analysis, d) majority vote, e) penalty system, f) identification and correction of issues from specific receivers.

The parameter range check is applied for filtering out obviously incorrect navigation records. An analysis of selected navigation parameter time-series monitors absolute values and their changes in time. This procedure is completed with a penalty system using adaptable thresholds for identifying and rejecting outliers. Signal group delays and satellite health status are evaluated statistically along with autonomously detecting (and eliminating) problematic receiver types. Header data are selected according to a majority vote. All the methods applied within the concatenation and the quality-control processes are performed at several levels when selecting a group of navigation files from available global stations.

From the four types of navigation messages provided by the Galileo system [6] the two are currently supported: 2) F/NAV navigation message transmitted on channel E5a-I at a rate of 25 bps and 2) I/NAV navigation message transmitted on both E1B and E5b-I channels at a rate of 125 bps. Figure 2 and Figure 3 display total numbers of satellites per individual GNSS (top) and mean numbers of navigation messages per satellite for each GNSS (bottom) as available in the GOP BRDC files in the years 2017-2021. The top plot shows new satellites included in the Galileo system and reaching 22 (+2 eccentric) satellites in February 2018. The bottom plot indicates several periods with a low number of navigation data (per satellite) in a day. Two from all recognizable events occurred in 2018 (November 7-8) and in 2019 (July 11-17), i.e. during the GRC-MS monitoring period, and these were also reported as outages in the Notice Advisory to Galileo Users (NAGU) 2018027-031 and 2019025-028, respectively.

Figure 4 then displays daily percentages of healthy navigation records per day for all individual satellites (the y-axis) using Galileo F/NAV data. The I/NAV data performs usually in a similar way. The value 100% and 0% represents healthy and unhealthy satellites, respectively. Some days/satellites show mixed healthy and unhealthy signal status records. Note that Galileo health status is combined from the Signal Health Status (SHS), the Data Validity Status (DVS) and the Signal-in-Space Accuracy (SISA) flags defined in the Galileo OS Service Definition Document [7]. The plot also shows the two Galileo eccentric satellites (E14 and E18) becoming active on November 30, 2020 (NAGU 2020019-020) and eventually providing 24 Galileo active (+2 permanently inactive) satellites. Another event occurred on December 14, 2020, when the Galileo F/NAV and I/NAV OS SIS was not healthy during 4 and 6 hours (NAGU 2020021), respectively. This was due to the SISA providing the status 'No Accuracy Prediction Available' (NAPA) as visible in dark blue color in Figure 5. The SISA=NAPA (negative value) is the most frequent reason observed behind short-term unhealthy statuses of Galileo satellites.

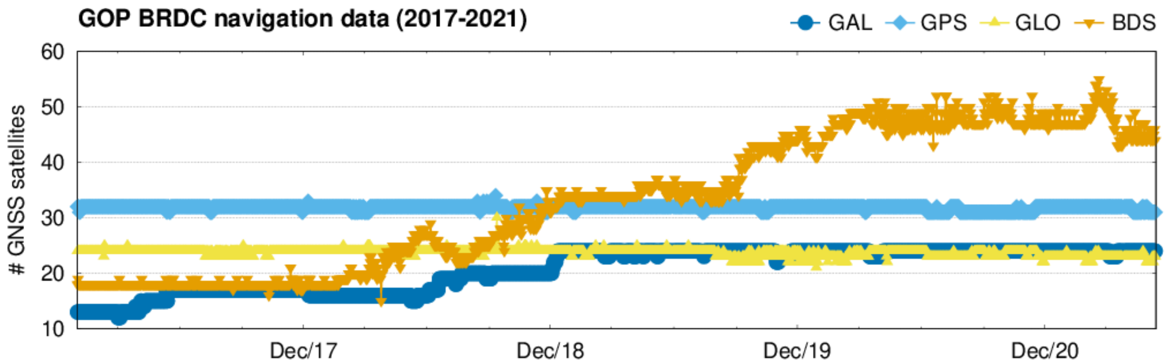

Figure 2: Number of satellites per GNSS system

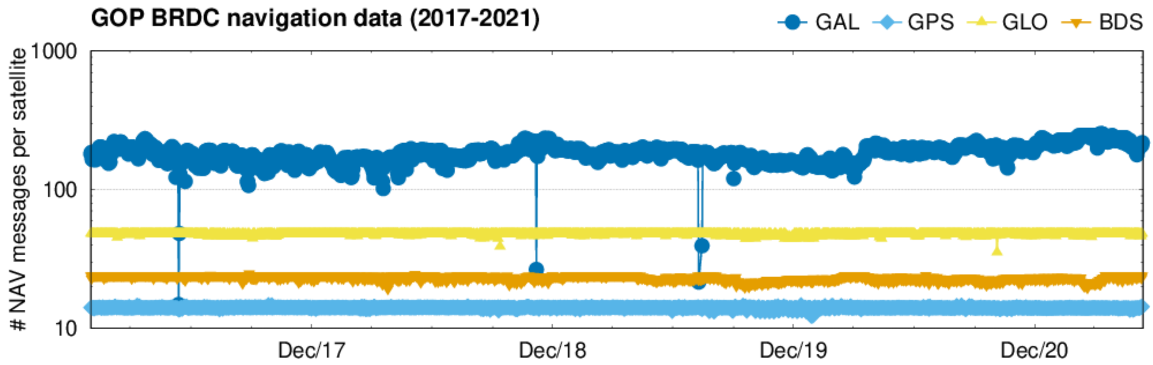

Figure 3: Number of navigation records per satellite

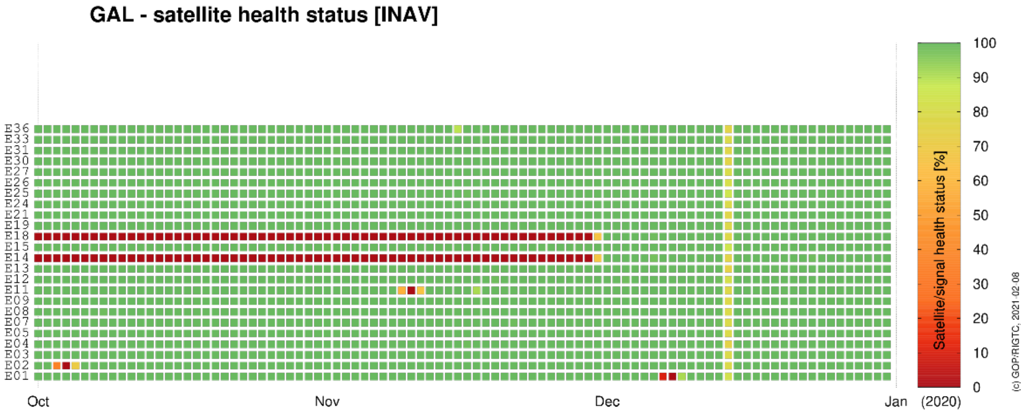

Figure 4: Daily percentages of Galileo F/NAV healthy navigation records; y-axis: satellites

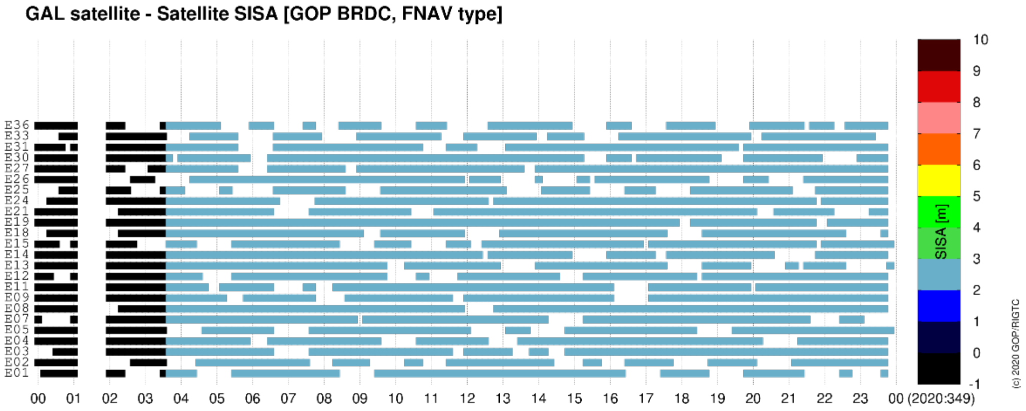

Figure 5: Galileo SISA values on Dec 14, 2020 for I/NAV data records, x-axis: ToC

3. Reference satellite orbit and clock products

The GOP uses the Bernese GNSS Software V5.2 software [8] for generating precise orbits when exploiting double-difference observations from a network of more than 120 global stations. The processing strategy was derived from the GOP ultra-rapid orbits procedure contributing to IGS [9] [10], however, now including the Galileo besides the GPS system. Two solutions are provided according to IGS standard delivery timeliness: 1) rapid one with a latency of 2 days, and 2) early-rapid one with a latency of 6 hours. The latter is a trade-off between the standard IGS ultra-rapid production (6 hour latency, 4 times/day), supporting mainly (near) real-time data processing, and the rapid production – the early-rapid is generated once a day (as rapids), but has low latency and includes a 1-day orbit prediction (as ultra-rapids).

The orbit product results from combining normal equations of two consecutive days, thus generating a 2-day arc solution. The orbit model includes 6 Kepler orbital parameters, 9 solar radiation pressure parameters of the Extended Center for Orbit Determination in Europe Model (ECOM) Version 2 [11], and 3 stochastic pulses introduced every 12 hours. The orbit determination is initialized exploiting the GOP BRDC files. The procedure consists of two main iterations while additional ones may be triggered anytime when handling specific problems due to individual satellites, stations, or baselines. Satellite-specific orbit accuracy codes provided within the header of the extended Standard Product version 3 format (SP3) are estimated when exploiting a variety of information such as parameter formal errors, day-to-day orbit comparisons, short-/long-arc combinations, and other internal control procedures.

Station coordinates and Earth rotation parameters (X-/Y-Pole, X-/Y-Pole rates, length of a day) are estimated along with satellite orbits on a daily basis too. Other parameters, such as tropospheric delays, ionospheric corrections, and initial phase ambiguities, are handled within individual processing steps with an effective time resolution. The models used in the processing are compliant with the International

Earth Rotation and Reference System Service (IERS) 2010 conventions [12]. The absolute antenna type calibrations for phase center offsets and variations follows the IGS14 model updates.

The GOP precise satellite clock corrections are estimated on a daily basis using the G-Nut/Sothis software and introducing the GOP early-rapid (or rapid) satellite orbits and station coordinates. The processing strategy exploits the ionosphere-free linear combination, however, mixing zero- and epoch-difference observations. Epoch clock variations are estimated by using epoch-differenced carrier-phase observations. Initial clock biases (ICBs) for each individual satellite are then estimated by using zero-differenced code observations [13]. The method is both efficient and robust thanks to the elimination of initial phase ambiguities and reducing a possible negative impact of cycle slips. Satellite and receiver clock corrections are estimated epoch-by-epoch in a stochastic process (the Kalman filter) as a sum of epoch-differenced clock corrections and corresponding initial clock bias. For accurate ICB estimates, the procedure is supported with differential code biases from DLR MGEX quarterly files [14]. The clock datum is defined using the common clock satellite datum and the strategy developed at GOP focusing on real-time applications [15]. The clock corrections are estimated at a 5-min sampling rate for all healthy GPS and Galileo satellites and provided consistently in SP3 and clock RINEX files.

The GOP orbits and clocks are regularly compared to the IGS MGEX products, in particular CODE [16], [17] and CNES solutions [18].The comparison is performed on a daily basis using the G-Nut/Aset software and a 15-min time resolution. Such an orbit comparison includes the calculation of 7 Helmert parameters between both solutions in a global scale, and on a daily basis, when removing problematic satellites, if any. The satellite clock comparison is performed on a double-difference basis, the first eliminating the clock datum definition within individual products (accessible as a common clock error in a single epoch) and, the second eliminating initial satellite clock biases corresponding to satellite-specific code biases at the initial epoch. The clock differences are also reduced by the radial position error – for this case transformed into time domain by applying the speed of light – for the corresponding satellite, because the actual clocks also include the compensation of errors in the radial component.

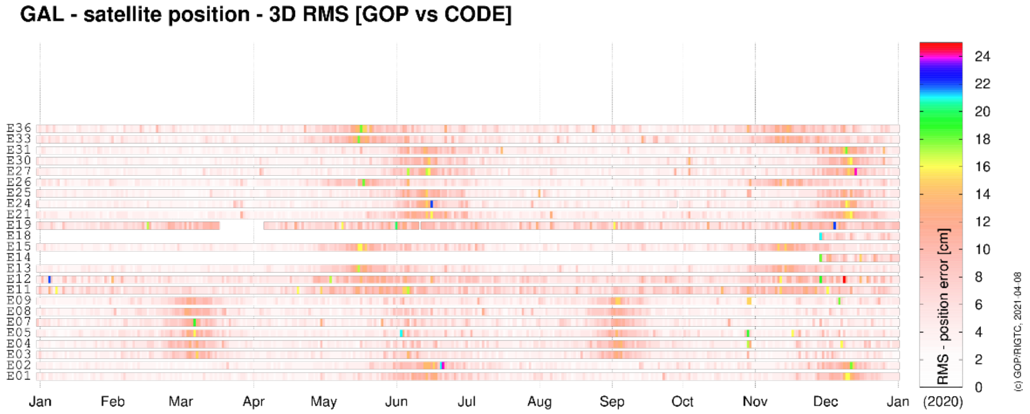

Figure 6: Comparison of GOP rapid and CODE final Galileo satellite orbits

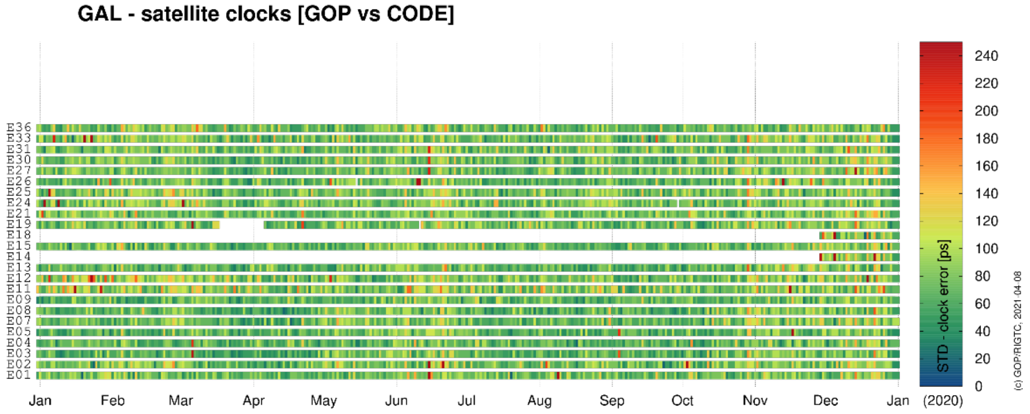

Figure 7: Comparison of GOP rapid and CODE final Galileo satellite clock products

Figure 5 and Figure 7 show results of GOP rapid Galileo satellite orbits and clock corrections, respectively, compared to the final products of the Center of Orbit Determination in Europe (CODE). The plots correspond to the year 2020 when the two Galileo elliptic satellites were estimated by GOP immediately after becoming active on November 30, 2020. A slightly worse performance of the GOP orbit comparison to CODE (but not so for CNES) revealed for the satellites with a low beta angle (the angle between the Sun and the corresponding orbital planes), compare Figure 8. The reason is related to a recent update of the orbit model at CODE considering the effect of thermal radiators [19]. Some isolated issues at individual days (a vertical view) or satellites (a horizontal view) are usually associated with the lack of optimal coverage of Galileo data in a global scope within a short latency of the analysis. A temporal or spatial lack of data then affects even more significantly satellite clock estimates. Figure 9 shows a general agreement of GOP rapid orbits to the final products of CODE and CNES (French Space Agency) with a RMS of 3 cm and 6 cm for GPS and Galileo, respectively.

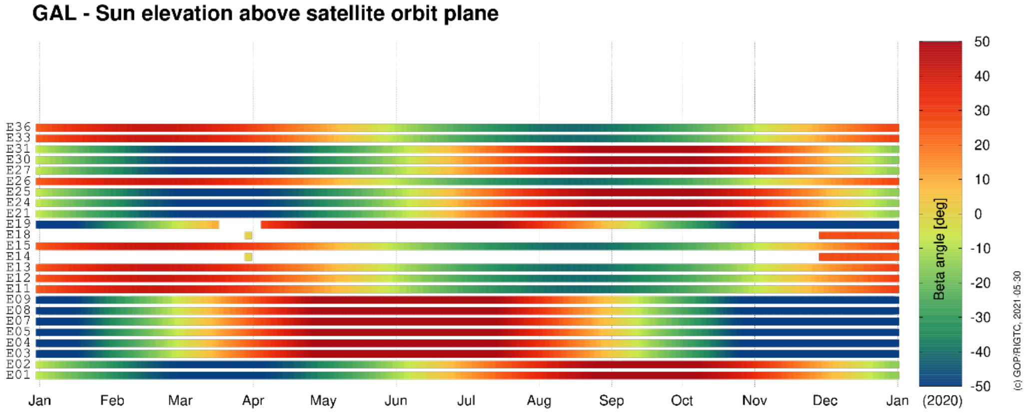

Figure 8: Angles of the Sun from the Galileo satellite orbital planes

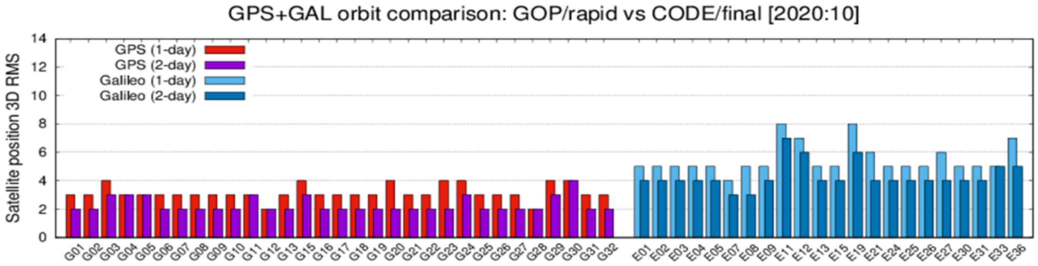

Figure 9: Statistics of GOP rapid orbits compared to CODE final orbits

4. Service volume availability

A monitoring of the Galileo Open Service volume, e.g. such as the availability of at least one dual-frequency OS SIS and 3D DOP < 6, is performed globally using navigation data only. The service volume approach does not consider any errors stemming from environmental effects or user equipment. We estimate service volume Key Parameter Indicators (KPIs) using a regular grid of ‘user’ points with a horizontal resolution of 10×10 degrees, and a 900 seconds sampling interval. For each grid point and time epoch, the availability of the dual-frequency OS SIS is checked and the Position DOP (PDOP) is calculated using healthy satellites above the elevation angle cut-off 5 degrees. The healthy satellites are considered according to SHS, DVS, SISA flags and the ephemeris validity period [13].

The service volume availability KPIs are estimated using the G-Nut/Aset software and GOP BRDC files on a monthly basis. Monthly percentages of at least one dual-frequency OS SIS is obtained from the Worst User Location (WUL) on the globe. Figure 10 shows the evolution of the KPI during October 2018 and May 2021 for I/NAV data. An event of July 11-17, 2019 can be clearly observed with the KPI decreasing down to 81.08%. Two other smaller events can also be observed: November 7-8, 2018 and December 14, 2020, discussed at other places in the paper.

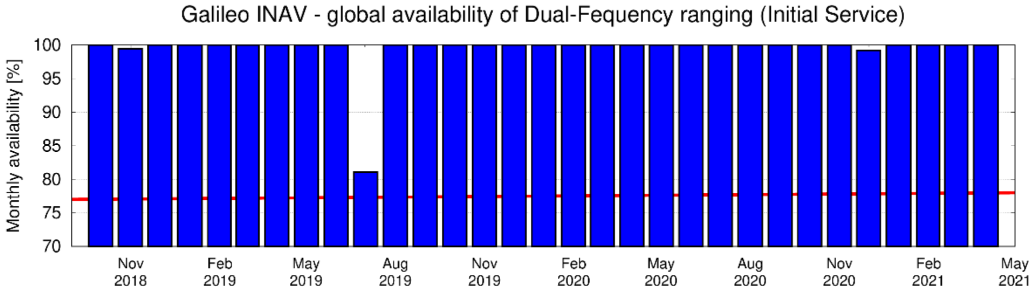

Figure 10: Availability of dual-frequency observations for October 2018 – May 2021 and I/NAV data

Monthly percentages of available PDOP < 6 is then represented as a weighted mean (with respect to the latitude) over all grid points. Figure 11 shows the monthly KPI for mean availability of PDOP < 6 during the period. On February 11, 2019, a total number of 22 satellites became active for Galileo and, obviously, the Initial Service achieved low PDOP values at any time of a day enabling a continuous positioning at any place on the Earth. Hence, monthly KPIs increased to values higher than 99%, with a single exception of 87% occurring during the event in July 2019. The Minimum Performance Levels (MPL) defined in the Galileo OS-SIS SDD [7] is 77% which has been satisfied continuously.

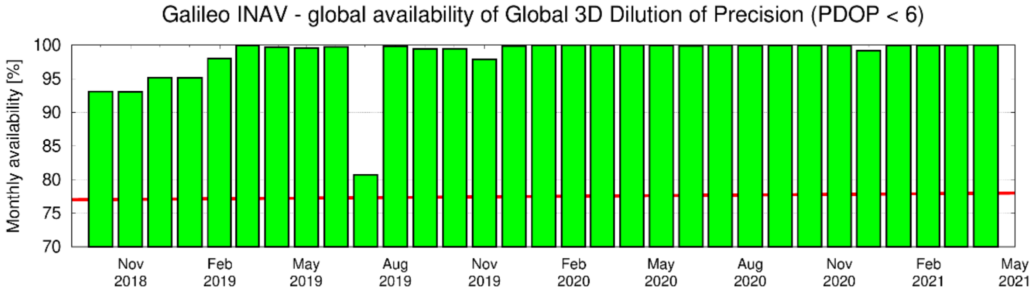

Figure 11: Mean availability of PDOP < 6 for October 2018 – May 2021 and I/NAV data

Figure 12 displays samples of global maps with monthly PDOP KPIs for December 2020 using F/NAV (left) and I/NAV (right) broadcast navigation data types. This month includes the event from December 14, 2020 and shows a small difference in KPIs between F/NAV and I/NAV data when these were not available for all the satellites during 4h and 6h hours, respectively. However, the performance still achieved values above 98% in both cases, and was a single such an event in 2020.

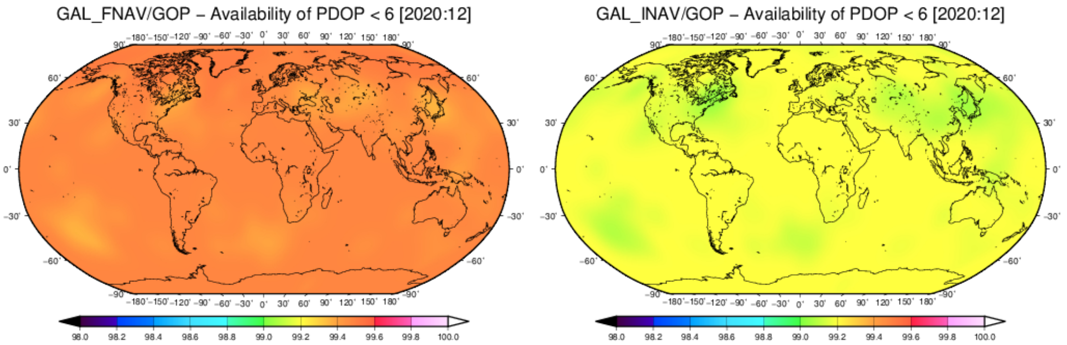

Figure 12: Mean availability of PDOP<6 on December 2020, F/NAV (left) and I/NAV (right)

5. Site measured positioning performance

A site-measured positioning performance exploits real data of selected stations, and thus includes implicitly atmospheric, user equipment, and site environment errors. At GOP, the Galileo horizontal and vertical positioning performance is thus monitored using 14 selected sites distributed globally, and those providing Galileo E1, E5a and E5b signals. Reference coordinates are estimated in the first step with the Precise Point Positioning (PPP) [20] method on a daily basis, using the G-Nut/Geb software [21], [22], and GOP rapid products. A Single Point Positioning (SPP) method is then performed on a daily basis using the G-Nut/Anubis software [23], exploiting code observations only from the selected stations, and GOP consolidated navigation files. Two independent positioning solutions uses the ionosphere-free linear combinations of E1+E5a and E1+E5b. The Galileo F/NAV and I/NAV broadcast navigation type is used for the former and the latter linear combination. The SHS, DVS, SISA, and the ephemeris validity period are considered prior using any satellite contributing to the performance monitoring. All healthy satellites above the 5-degree elevation angle cut-off are then used. Station coordinates, tropospheric path delays, and receiver clock offsets are estimated simultaneously epoch by epoch at a 30-sec sampling interval provided the PDOP is below 6.

Figure 13 displays several example time-series of horizontal and vertical positioning errors using E1+E5a supported with F/NAV navigation data. The horizontal error, absolute vertical error and PDOP are displayed in blue, green and yellow colors. A very good results can be observed at the AREG station (top-left plot) during November 2020. An impact of a reduced number of Galileo satellites before February 11, 2018 can be observed at the JFNG station (top-right plot) which resulted in regular periods of a global unavailability of Galileo OS positioning during a day. The incident of unplanned discontinuity of navigation data for all the satellites over 27 hours November 7-8, 2018 (reported with NAGU 2018027-028), and including an impact of degrading OS SIS prior the outage on horizontal and vertical positioning, are displayed for the AREQ station (bottom-left plot). The data quality may also affect the positioning in the site-measured performance monitoring as it is visible in a period of frequent degradations at the URUM station during August 2019.

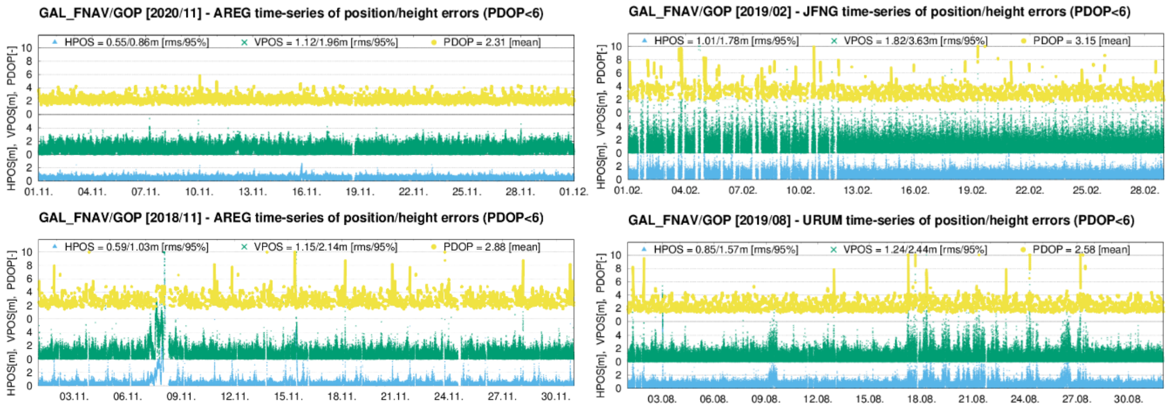

Figure 13: Sample time-series of horizontal and vertical positioning errors using E1+E5a with F/NAV at several stations showing different situations occurring in the site-measured position monitoring

Table 1: 95th percentiles of horizontal and absolute vertical positioning errors at 14 sites (2020/Q4)

	95% Horizontal Position Error [m]						95% Vertical Position Error [m]					
	E1+E5a with F/NAV			E1+E5b with I/NAV			E1+E5a with F/NAV			E1+E5b with I/NAV		
Station	**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**
AREG	0.67	0.67	0.64	0.68	0.68	0.65	1.66	1.66	1.71	1.46	1.45	1.48
ASCG	1.55	1.52	1.46	1.76	1.73	1.66	2.71	2.63	2.61	2.94	2.94	2.82
GAMG	0.97	1.19	0.91	1.06	1.28	1.00	2.01	2.25	1.86	2.09	2.29	1.91
HARB	0.80	0.78	-	0.86	0.85	-	1.91	1.99	-	1.93	2.04	-
JFNG	1.29	1.31	1.41	1.47	1.45	1.47	2.73	2.67	2.88	3.18	3.07	3.05
KOUG	0.94	0.93	0.91	1.05	1.02	1.00	2.17	2.25	2.20	2.39	2.48	2.40
MATE	0.83	0.84	0.81	0.90	0.90	0.87	1.49	1.48	1.47	1.57	1.58	1.54
MAYG	1.40	1.62	1.35	1.53	1.73	1.49	2.63	2.66	2.63	2.85	2.86	2.77
METG	0.88	0.90	0.91	0.98	1.00	1.01	1.26	1.29	1.32	1.35	1.39	1.37
OWMG	1.20	1.45	1.04	1.33	1.55	1.13	2.31	2.48	1.98	2.43	2.55	2.04
POTS	1.52	1.48	1.48	1.67	1.62	1.62	2.01	1.96	2.00	2.16	2.12	2.13
STJ3	1.04	1.00	0.95	1.14	1.11	1.05	1.85	1.73	1.62	1.94	1.85	1.74
URUM	1.19	1.14	1.31	1.35	1.33	1.54	1.88	1.78	1.64	1.96	1.86	1.85
YEL2	0.86	0.78	0.86	0.95	0.84	0.93	1.55	1.41	1.51	1.63	1.50	1.58
Mean	**1.08**	**1.11**	**1.08**	**1.20**	**1.22**	**1.19**	**2.01**	**2.02**	**1.96**	**2.13**	**2.14**	**2.05**

Finally, Table 1 shows a typical monthly performance of Galileo horizontal and vertical positioning errors at the 95th percentiles during 4th quarter of 2020. The best three global stations (AREG, METG, and YEL2) achieved 0.6-1.0m and 1.3-1.8m horizontal and vertical errors respectively, and the worst three stations (ASCG, JFNG, and MAYG) achieved 1.3-1.8m and 2.5-3.5m, respectively. This results is typical for solutions using either F/NAV or I/NAV data during 2019 and 2020 with more or less stable constellation and, currently, it is the best performance from all other GNSS systems.

6. Conclusion

The Galileo OS SIS performance monitoring at GOP comprises of a fully independent chain of processes including the exploited software as well as input reference products. The GOP solution is also performed in a rapid mode (or shorter), i.e. providing all results within 1-2 days after the last observation. It is based on the GOP fast consolidation of global navigation files, early generation of GPS and Galileo reference products and key-parameter indicators estimated using the G-Nut software tools. The solution can be easily extended to additional indicators, other GNSS or to a real-time mode.

During the period (2018/Q4 – 2020/Q4), the Galileo OS SIS performed very well in terms of all the positioning aspects monitored at GOP and satisfied the MPL defined in the OS SIS SDD. However, few events have been observed, those related to the positioning performance analysed at GOP, reported to the GRC and GSA on a quarterly basis, and some of them briefly discussed in this paper:

- 2018, Nov 7-8 – unplanned discontinuity of navigation data for all the satellites over 27 hours (reported with NAGU 2018027-028).
- 2019, Feb 11 – activated new Galileo satellites (E13, E15, E33 and E36), and firstly achieving 24-hour continuous Galileo PDOP < 6 in a global scope.
- 2019, July 11-17 – unplanned unavailability of OS SIS over 6 days for all the satellites (reported with NAGU 2019025-027).
- 2019, Sept 2-3 – satellite on-board navigation data provision only (i.e. without ground update) for all satellites over 12 hours.
- 2019, Oct 29 – short-term E11 satellite clock degradation (followed by the satellite deactivation) with a 30-min impact on positioning around the South-East Africa.
- 2020, Dec 14 – 4h and 6h provision of on-board navigation data for all satellites and F/NAV and I/NAV, respectively.
- 2020, Oct 30 – activating the two eccentric Galileo satellites (E14 and E18).

7. Acknowledgements

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