DOI 10.5162/ettc2022/3.4

Performance Monitoring for Galileo and other GNSS at the Galileo Competence Center

Katharina Lutz[1], Lukasz Greda[1], Marios Smyrnaios[1], Wolfgang Dilg[1], Thomas Schilling[1], Ilinca Ioanid[1], Steffen Thölert[2], Gerardo Allende Alba[2], Martin Kriegel[3], Luca Spataro[4], Philipp Rosauer[4], Annika Meinecke[4], Rebecca Brydon[4], and Johann Furthner[1]
[1] DLR Galileo Competence Center, Oberpfaffenhofen, D-82234 Wessling, Germany,
[2] DLR Institute of Communications and Navigation, Oberpfaffenhofen, Germany,
[3] DLR Institute for Solar-Terrestrial Physics, Neustrelitz, Germany,
[4] DLR Institute for Software Technology, Cologne and Oberpfaffenhofen, Germany,

katharina.lutz-lloyd@dlr.de

Abstract:
Satellite navigation has become a vital part of our daily lives by ensuring navigation on land, in air and at sea, and by providing precise timing information for the energy, communications and finance sector. It is therefore essential to monitor the performance of the four main global navigation satellite systems (GNSS) Galileo, GPS, GLONASS and BeiDou. The Galileo Competence Center (GK), part of the German Aerospace Center (DLR), is dedicated to the further development of the European GNSS consisting of Galileo and EGNOS. Within the SigPerMon project, the GK monitors the reliability and quality of navigation signals with comparable metrics for all four GNSS, and detects deviations from the nominal state of navigation systems. Necessary data are sourced from a global network of GNSS receiver stations. These data are used to compute performance indicators to monitor and analyse the availability and health status of navigation signals, and the precision of positioning and timing solutions. In the future, machine learning models will be used to detect anomalies in the satellite signals. A summary of the results will be presented on a dedicated webpage, which provides both detailed analyses for authorized researchers and personnel, and interactive data visualizations for the general public.

Key words: Global Navigation Satellite Systems, Performance Monitoring, Machine Learning, Webpage, Receiver Network

Introduction

We present the new Global Navigation Satellite System (GNSS) performance monitoring system, which is currently being implemented at the Galileo Competence Center (GK).

The Galileo Competence Center was founded in 2019 as part of the German Aerospace Center (DLR). GK aims at furthering the development of the European GNSS Galileo and EGNOS, and at advising national and European government bodies as well as companies in the field of navigation technologies.

In this context, we are developing a comprehensive GNSS performance monitoring suite. We have started to analyse and monitor the reliability and quality of navigation signals. Furthermore, we want to detect any deviation from the nominal state of GNSS systems. In the future, we will disseminate warnings and information about detected errors to users and applications.

For each GNSS minimum performance levels have been defined by the respective governing bodies. GNSS operators regularly publish performance reports indicating how well the respective GNSS meets the minimum performance levels [1 – 4]. However, the performance indicators are at least partially different (e.g. the definition of healthy satellite signals is not identical for the four systems). In addition, the data used for the aforementioned computation are also not identical and are collected at different station locations using different equipment. Thus, a direct performance comparison of the different global navigation satellite systems is challenging and, in many cases, restricted to only a few performance indicators. Therefore, we aim to use, as far as possible, the same data processing framework to compute performance indicators for all four

DOI 10.5162/ettc2022/3.4

GNSSs and perform the computation using the same global network of ground tracking stations.

To that end, we will establish and operate a dedicated GNSS receiver network with real-time data transfer capability and global coverage. The data from this network will be used for monitoring and an extensive and fair comparison of the performance of the four global navigation satellite systems. In addition, the receiver network will support the generation of real-time corrective data for precise point positioning services. Collected data will be stored in a dedicated database.

In this paper, we will give an overview of our current performance monitoring system and present future plans.

Data collection and storage

The data necessary for performance analysis and monitoring are stored in a dedicated database. Until our own global network of monitoring stations is fully deployed, we use RINEX observation files from the International GNSS Service (IGS) stations [5]. We selected stations, such that they are distributed around the globe and that receivers are set up as homogenously as possible.

Data from these stations are stored in our database, as are daily multi-GNSS merged navigation files and other auxiliary data sets. Most of these files are accessed via Nasa's Crustal Dynamics Information System (CDDIS) archive [6]. Data sets from other external and DLR internal archives are also stored in our database. These data sets can, for example, include reference station metadata, space vehicle information, ionospheric maps, and satellite orbits from other sources. Upon collection, the data are parsed, transformed into internally defined formats and stored in PostgreSQL tables, which are organised to best serve our needs. The input RINEX files are archived as well.

The database is structured such that it allows both a long-term analysis of the performance of all four GNSS, and a simple visualisation of the most important performance indicators on our webpage. The long-term analysis might either be a classical statistical analysis of key performance indicators (KPIs) or the usage of machine learning models to detect outliers in the data. In both cases, a major challenge is the identification and removal of faulty data. Such errors might be caused by receivers during data capturing, during data conversions, coming from data traffic, from data processing tools or other sources and can result in false anomaly detections [7]. A data cleaning process or quality check for the identification of errors not coming from the navigation systems themselves but rather from other sources can be significantly sped-up via the use of the database structures.

Performance indicators and deviation analysis

In cooperation with other DLR institutes, we are implementing and validating GNSS KPI and metric evaluation algorithms. Our goal is to compute and measure these parameters for all four GNSSs, so that we can establish a monitoring framework for each GNSS. The characterisation of their performances will be carried out in real-time or in post-processing, depending on the computed parameter.

We are particularly interested in evaluating:

- the availability of a GNSS for positioning and timing applications
- the accuracy of the information (e.g. clock and orbit parameters) sent by individual satellites
- the accuracy of positioning and timing solutions

To this end we are developing a monitoring system with real-time and reporting capabilities: We use recorded data from our database for a specified time range (e.g. a month) and calculate the statistics of availability and accuracy over this time range. Furthermore, we capture real-time data streams and evaluate the current status of the GNSSs. In both cases, data would be collected by the same network of reference stations distributed around the globe. Performance reports of the different navigation systems are published every few months by the respective operators. The parameters presented in these reports are not necessarily comparable. For our performance monitoring system, we will focus on performance parameters that are calculated in a similar way for all GNSSs and are thus comparable.

In addition, we also want to know in real-time how well the GNSSs are providing their services: does a user get a reliable and good positioning or timing solution right now? To answer this question, we need to analyse GNSS signals for a sufficiently large set of GNSS monitoring stations in real-time. This analysis will include parsing a stream of incoming real-time data, reading the health

DOI 10.5162/ettc2022/3.4

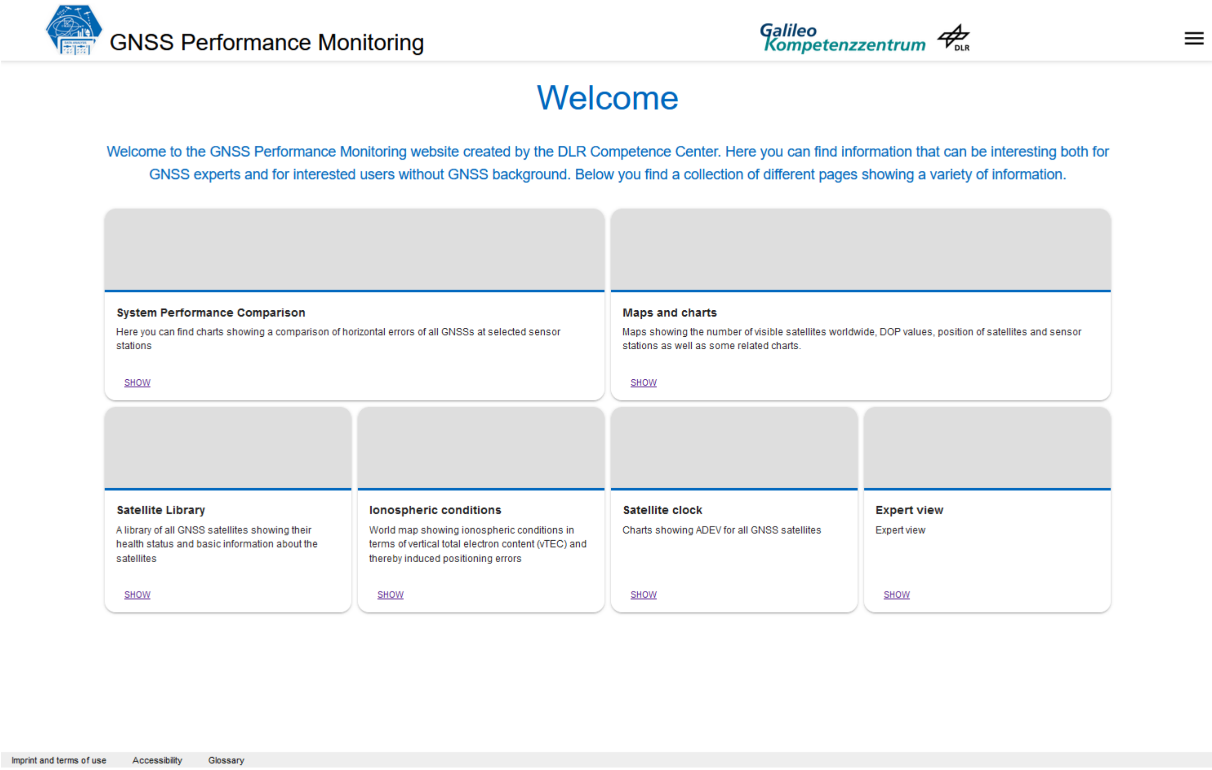

Fig. 1. Landing page with overview of available features.

status of satellites, estimating the accuracy of their orbital parameters, calculating the position of the monitoring station, and comparing that result with the reference position for that station. Since the data rate we are using is one measurement per second, our algorithms need to be fast and efficient to tackle these large amounts of data in real-time.

While some irregularities in determining timing and positioning solutions can be deduced from comparing real-time results to long term statistics, we expect to get a more comprehensive deviation analysis with the help of suitable machine learning models. The dataset to train our models on will consist not only of observed data from sensor stations, but will also need to include simulated data. The simulated data are to be provided by a GNSS simulator and signal generator. This combination of different data sources for the machine learning training dataset is vital, because for example jamming and spoofing events are rare, but still need sufficient representation in a balanced training set. Besides a supervised machine learning approach based on neural networks in a long short-term memory architecture [8], the usage of unsupervised learning methods (e.g. auto-encoders, clustering models or a combination of both) will be essential to find unexpected or little-known faulty behaviour in observed data.

In summary, we are developing a multitude of methods to monitor the performance and quality of global navigation satellite systems in real-time and for long-term statistics. This information will in part be provided on our webpage.

A dedicated performance monitoring webpage

To visualise some of the computed GNSS performance parameters, we created a dedicated user-friendly website, which reads data from our database and illustrates a selection of performance parameters of all four GNSSs.

Fig. 1 shows the landing page of the website and provides a first overview of available features:

- System Performance Comparison: a visualisation of the comparison of the horizontal positioning accuracy of the four GNSSs
- Maps and Charts: a world map, on which positions of satellites and sensor stations are shown. As overlay, dilution of precision or visible satellite count maps at a given point in time may be selected. Time series of these data may also be visualised.

- Satellite Library: a library of all GNSS satellites informing about their current health status, orbit parameters as well as some additional basic information
- Ionospheric conditions: a world map with an overlay visualising the ionospheric conditions in units of vertical total electron content and the position error subsequently induced by the ionospheric conditions
- Satellite Clocks: Charts presenting the Allan deviation of GNSS satellites. This is a measure for the stability of the clocks onboard the satellites.
- Expert view: all of the above with extended possibilities to change settings.

The functionality and design of the website are continuously evolving [9]. In the following sections, we will describe the current features in more detail and provide an outlook for future developments.

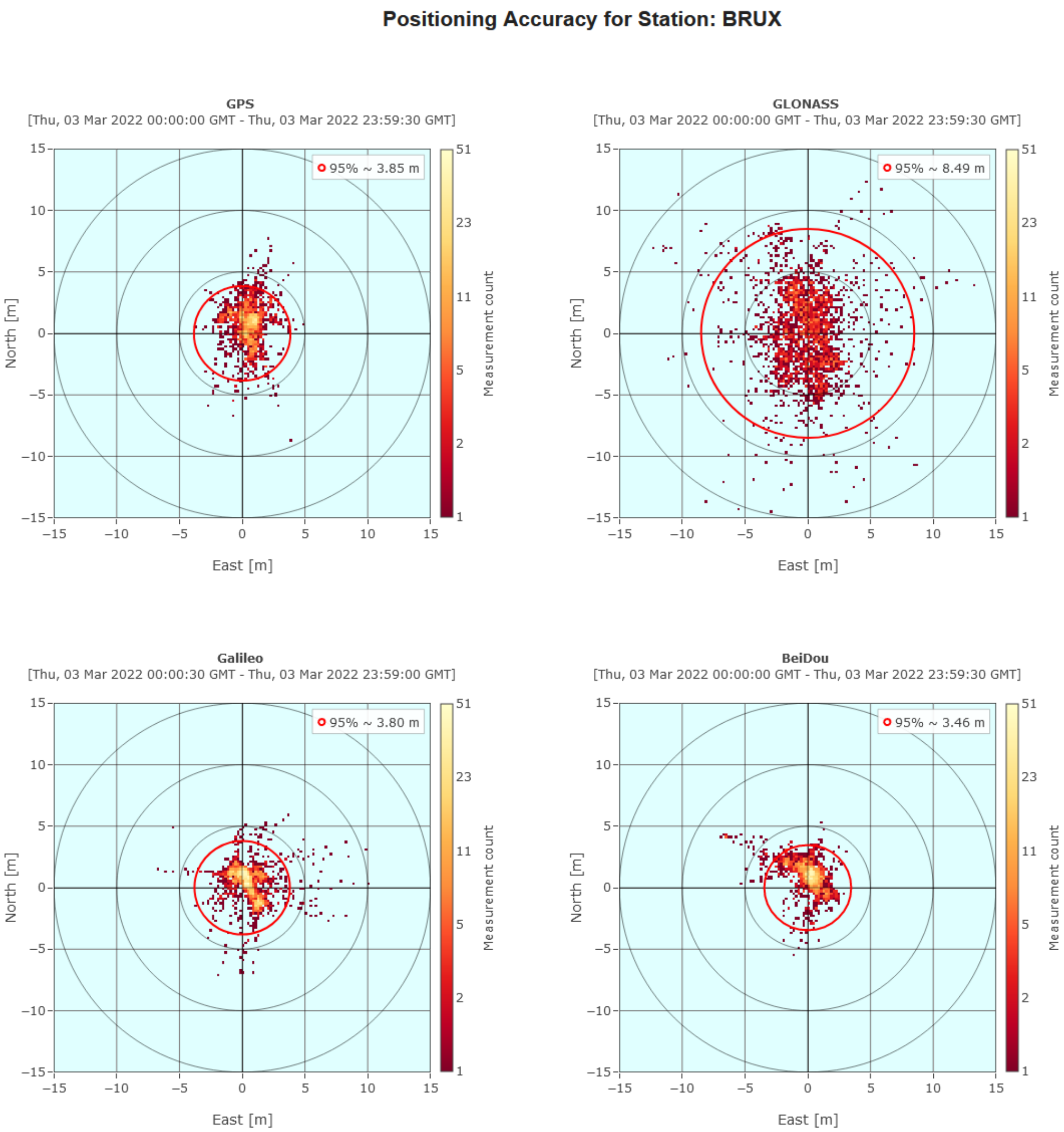

Fig. 2. Positioning accuracy in Northerly and Easterly direction for GPS, GLONASS, Galileo and BeiDou (left to right, top to bottom) at IGS station BRUX on 2022-03-03. The red circle indicates the 95th percentile of the error distribution.

DOI 10.5162/ettc2022/3.4

System Performance Comparison

To visualise the horizontal error in determining the user position, we calculate the user positions from observations in RINEX files of IGS stations. These files provide measurements for every 30 sec. The North and East-wards distance between the calculated single point position and the known, precise station position are then displayed on our website (see Fig. 2).

In the future this feature will be extended to use real-time data at a higher rate (measurements every 1 instead of 30 sec).

Fig. 3. Different Visualisations of calculated DOP values. (a) PDOP for Galileo with satellites included as soon as they rise more than 5deg above the horizon. (b) PDOP for Galileo in urban canyons, i.e. satellites are only included above elevations of 20deg. (c) Time series of all DOP values in Nuremberg over a week in April 2022.

Maps and Charts

This feature allows to visualise world maps and time series of dilution of precision (DOP) values and visible, healthy satellite counts. Moreover, positions of sensor stations and satellites are shown. Stations and satellites can be connected depending on whether or not satellites are currently visible from the sensor station given the selected elevation mask.

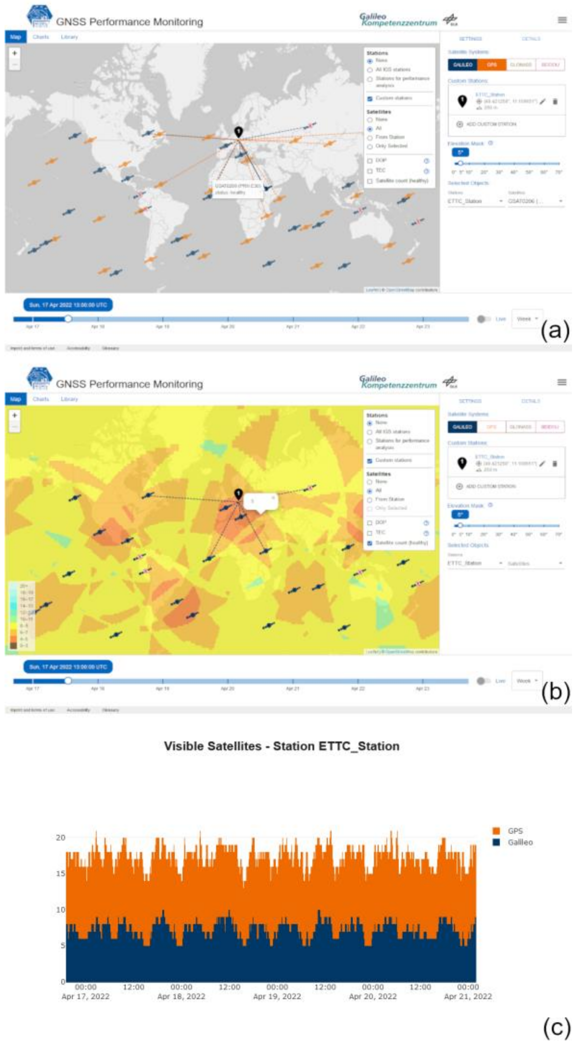

Fig. 4. Visualising satellite positions and availabilities. (a) Location of all GPS (orange) and Galileo (blue) satellite around lunch time on 2022-04-17. Satellites that are visible from Nuremberg are connected with the user-defined station marker. (b) A map of the number of visible satellites. (c) A time series of the number of satellites visible from Nuremberg during a week in April 2022.

The calculation of different DOP values (PDOP, GDOP, VDOP, HDOP, TDOP) requires the position and velocity of the GNSS satellites. These are based on orbital parameters in NORAD Two-Line Element (TLE) Set Format provided by CelesTrak [10]. For the calculation of DOP values all visible and healthy satellites are used. The user has the option to set the cut-off elevation angle and to exclude any satellite. For examples of different visualisations of the calculated DOP values see Fig. 3.

Similarly, the number of visible GNSS satellites at any point on the 2D world map is calculated using TLE data for all healthy satellites. Examples for visible satellite number and satellite position visualisation are given in Fig. 4.

Satellite Library

The satellite library aims to be a one stop shop for all information regarding single satellites. This information includes the health status of satellites, their current orbit parameters and more details such as their launch date, NORAD identifier or nicknames. An example is shown in Fig. 5.

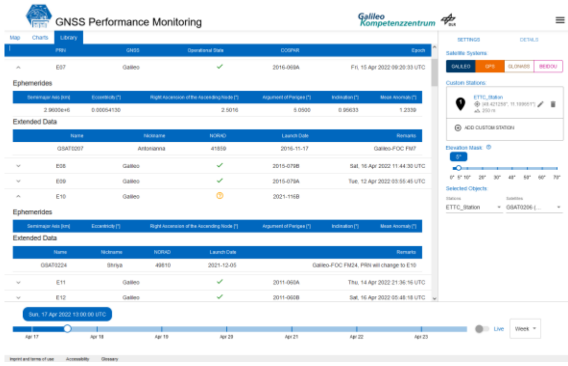

Fig. 5. The satellite library with details displayed for E07 and E10. Note how the status of newly launched GSAT0224 is still set to testing while other Galileo satellite are healthy and operational.

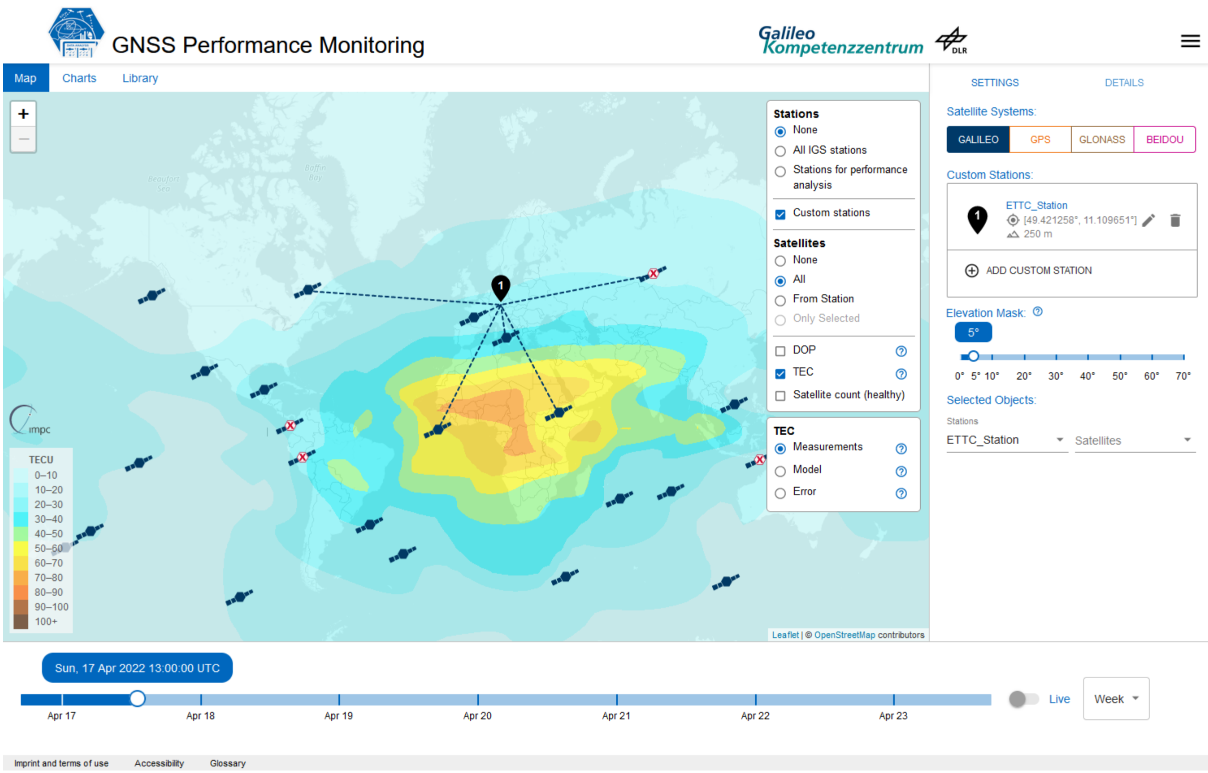

Fig. 6. Ionospheric conditions around lunch time on 2022-04-17.

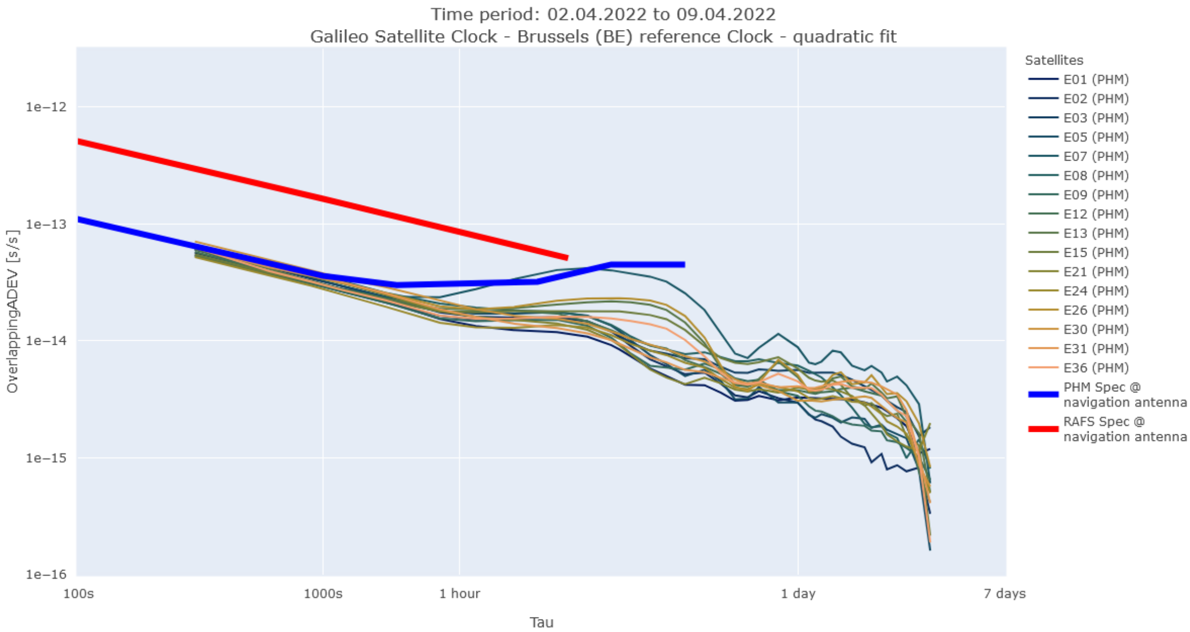

Fig. 7. The overlapping Allan Deviation for all healthy Galileo satellites for the time range from 2022-04-02 to 2022-04-09.

Ionospheric conditions

Space Weather related effects such as solar flares, coronal mass ejections (CMEs) and radio bursts can severely affect GNSS performance by causing rapid changes of the Earth's geomagnetic and atmospheric conditions (e.g. increased ionization, strong plasma density irregularities and associated gradients) at various temporal and spatial scales. To monitor ionospheric conditions, the website offers a two-dimensional visualisation of vertical total electron content (vTEC) on a world map. The user can switch between measured, modelled and error data (see Fig. 6). The vTEC data are provided in near real-time by DLR's Ionosphere Monitoring and Prediction Center (IMPC) [11], with an update rate of 5 minutes.

Satellite Clocks

The frequency stability of a clock can be characterised by measuring its overlapping Allan deviation. We obtain these measurements for GNSS satellite clocks using precise clock corrections from GFZ Potsdam [12]. The calculations are run with a Python script making use of the package AllanTools [13].

Expert View

While the above views will be limited to only a few user settings, we will also offer an expert view. The expert view is aimed at users, who work in the field of satellite navigation and need very detailed analyses. We want the expert users to be able to select options that are most suitable for their use case. In other words, the expert view is envisioned as a contrast to the other views, which come with many pre-set options and should make the usage of the website easy for the interested public and political decision makers. Furthermore, detailed analyses will be made available, which are not necessarily useful or helpful for users from outside the field of satellite navigation.

Outlook

The new performance monitoring system will not be limited to pure provision of KPIs. It will also include newly developed algorithms for error detection and analysis using advanced methods for detection metrics. One example is the use of machine learning for the automated detection of known and still unknown GNSS errors or anomalies. This also includes key parameters for characterising the impact of Space Weather on GNSSs which are currently being developed at the DLR Institute for Solar-Terrestrial Physics and can be included in the future.

In the coming years, we will combine the navigation signal monitoring at user level, as described in this paper, with more detailed raw signal analysis using the DLR 30 m parabolic reflector high gain antenna. As very large amounts of data will be gathered by recording I/Q data for all GNSS satellites, we will use appropriate machine learning algorithms for error detection, distinguishing between nominal and abnormal signal states and determination of ageing effects. Based on the combined evaluation of all data, possible errors can then be analysed extremely reliably and with high precision.

We expect the webpage to be available end of May 2022 under www.GNSS-Monitoring.dlr.de .

References

[1] Galileo Performance Reports, [Online]. Available: https://www.gsc-europa.eu/electronic-library/galileo-serviceperformance-reports [Accessed: 2022-02-07].

[2] GPS performance, [Online]. Available: https://www.gps.gov/systems/gps/performance/ [Accessed: 2022-02-07].

[3] BeiDou Monitoring and Eval., [Online]. Available: http://en.beidou.gov.cn/SYSTEMS/Monitoringandevaluation/ [Accessed: 2022-02-07].

[4] GLONASS System documents, [Online]. Available: https://www.glonass-iac.ru/en/documents/ [Accessed: 2022-02-07].

[5] G. Johnston, A. Riddell, G. Hausler, The International GNSS Service. *Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed.)*, 967-982 (2017). Cham, Switzerland: Springer International Publishing; doi: 10.1007/978-3-319-42928-1

[6] C. Noll, The Crustal Dynamics Data Information System: A resource to support scientific analysis using space geodesy, *Advances in Space Research*, 45, 1421-1440 (2010); doi: 10.1016/j.asr.2010.01.018

[7] L. Heng, G. X. Gao, T. Walter, and P. Enge, GPS Signal-in-Space Anomalies in the Last Decade: Data Mining of 400,000,000 GPS Navigation Messages, *Proceedings of the 23rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2010)*, *Portland, OR*, 3115-3122 (2010); doi: NA

[8] S. Hochreiter and J. Schmidhuber, 'Long Short-Term Memory, *Neural Computation*, 9, 1735–1780 (1997); doi: 10.1162/neco.1997.9.8.1735

[9] L. Greda et al., Performance Analysis for Galileo and other GNSS at DLR Galileo Competence Center, *Proceedings of NAVITEC 2022*, 41 (2022); doi: NA

[10] CelesTrak, [Online]. Available: http://celestrak.com/NORAD/elements/ [Accessed: 2022-02-07]

[11] DLR’s Ionosphere Monitoring and Prediction Center (IMPC). [Online]. Available: https://impc.dlr.de [Accessed: 2022-04-21]

[12] B. Männel, A. Brandt, T. Nischan, A. Brack, P. Sakic, M. Bradke, GFZ rapid product series for the IGS, *GFZ Data Services*, (2020); doi: 10.5880/GFZ.1.1.2020.003

[13] A. E. E. Wallin, D. Price, C. G. Carson, F. Meynadier, Y. Xie, E. Benkler, AllanTools, [Online] Available: https://allantools.readthedocs.io [Accessed 2022-04-20]