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Performance indicator development addressing mitigation of the space weather impacts on GNSS

Paul David[a,*], Martin Kriegel[a], Jens Berdermann[a], Kirsti Kauristie[b], Knut Stanley Jacobsen[c], Vincent Fabbro[d], Hannah Laurens[e], Ralf Keil[e]

[a] *Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute for Solar-Terrestrial Physics, Kalkhorstweg 53, Neustrelitz 17235, Germany*
[b] *Finnish Meteorological Institute (FMI), Helsinki 00101, Finland*
[c] *Norwegian Mapping Authority (NMA), PO 600 Sentrum, Hønefoss 3507, Norway*
[d] *ONERA/DEMR, Université de Toulouse, Toulouse 31055, France*
[e] *RHEA System GmbH for ESA/ESOC, Darmstadt, Germany*

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ABSTRACT

Within the European Space Agency's (ESA) Space Weather Service Network, the development of performance indicators for the Global Navigation Satellite System (GNSS) has been identified as essential to meet the growing needs of end users for Space Weather information in the field of navigation. This requires a targeted analysis of Space Weather-related disturbances of technical systems and services in the field of satellite-based navigation, considering the growing requirements of all the different users in this domain. The goal of the Space Weather Impact on GNSS Performance: Application Development (SWIGPAD) project is to develop GNSS performance indicators (GPI) based on Space Weather data provided by European research institutes through the ESA Space Weather Service Portal (available at https://swe.ssa.esa.int) with the aim to fulfill representative use cases derived from dedicated meeting with industry and government experts. The application that serves the GPI will provide the user with information about current and expected effects of Space Weather on positioning at their respective location. Additionally, end users in the various GNSS application domains shall be assisted with an overall numerical and graphical estimate of the positioning uncertainty resulting from ionospheric conditions and its evolution over time. The intent of this article is to present the results of the project and the capabilities of the GPI application.

1. Introduction

Space Weather refers to solar processes as well as varying conditions in the solar wind, the Earth's magnetosphere, ionosphere and thermosphere that may affect space-and ground-based technological systems in their performance and reliability [1]. Monitoring and forecasting of potential impacts on technological systems is important, since Space Weather effects are observed in the degradation of spacecraft communications, performance, reliability, and lifetime. In addition, Space Weather effects can lead to enhanced risks to human health on manned space missions. Space Weather also has numerous effects on aviation and ground-based systems, e.g., enhanced radiation dose, damage to power networks, pipelines and degradation of radio communications [2].

The effects of Space Weather are not well known in our society and even industrial users from various domains affected often lack the expertise on how to interpret the collection of Space Weather products provided by the ESA Space Weather Service Portal, as illustrated in Fig. 1.

Therefore, a key objective of the SWIGPAD project is to provide a simple-to-use indicator tool, allowing users to enter their position via an interactive map and creating color-coded thresholds to reflect the inaccuracy of GNSS positioning solutions due to Space Weather effects. These developments require the harmonization of a wide range of products from different observation areas with different spatial and temporal resolutions ranging from local to the global scale [3] and are provided by federated expert groups through different interfaces (e.g. see Figs. 2–6).

* Corresponding author.
E-mail address: Paul.David@dlr.de (P. David).

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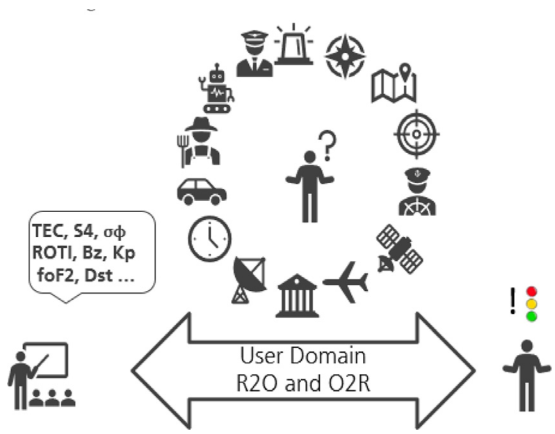

Fig. 1. The objective of SWIGPAD is the transfer of Space Weather products provided by the ESA Space Weather Service Network to a wide range of Positioning, Navigation and Timing (PNT)-related user domains with different requirements by providing GNSS Performance Indicators.

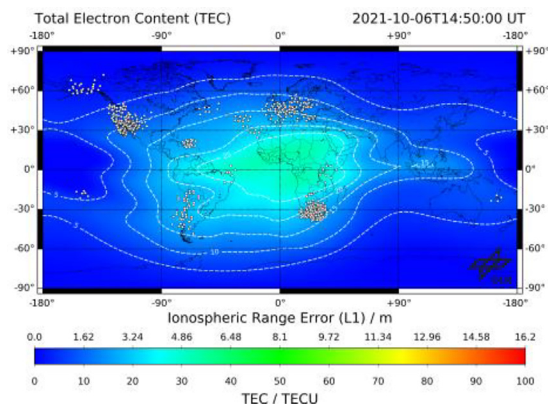

Fig. 2. Near-real-time global map of the Total Electron Content (TEC) provided by IMPC [6].

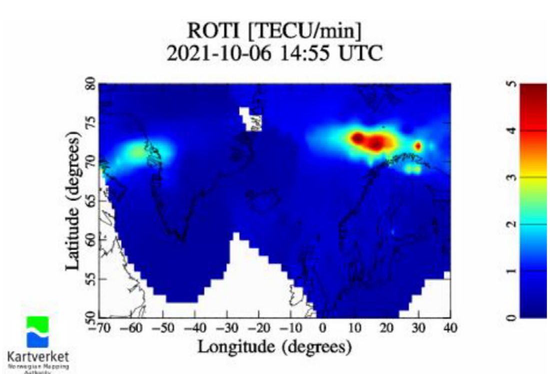

Fig. 3. RTIM ROTI maps (Northern Europe) provided by NMA.

2. USER groups

The user groups identified for this project follow the definitions provided by the ESA Space Weather Service Network within the service domain *Transionospheric Radio Link* (available at https://swe.ssa.esa.int/web/guest/tio_dashboard) following the Space Situational Awareness (SSA) Customer Requirements Document [4]. Thus, the application supports the six user groups shown in Table 1.

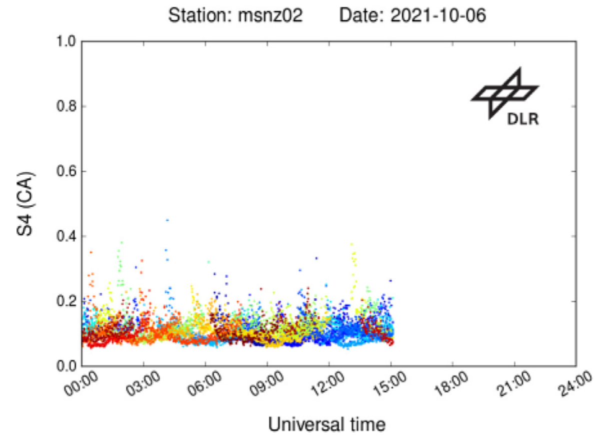

Fig. 4. IMPC Local scintillation index S4 for Neustrelitz (Germany) provided by IMPC [6].

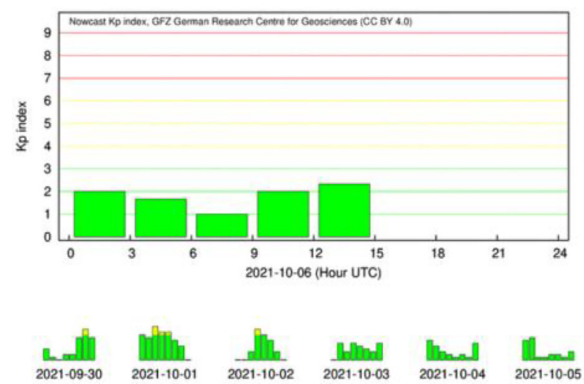

Fig. 5. Nowcast of the Kp Index provided by GFZ.

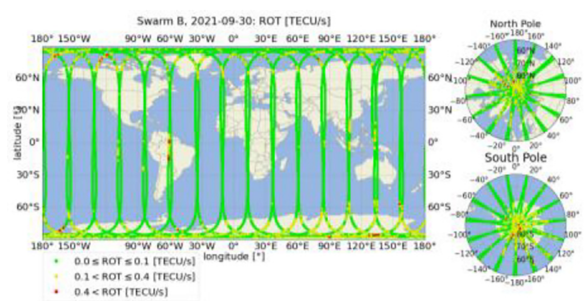

Fig. 6. Swarm Rate of TEC (ROT) provided by GFZ.

2.1. SWE-CRD-TIO-USR-01

This user group contains users of GNSS single frequency services with average accuracy, not using integrity, which typically includes GNSS mass-market users. This user group is expected to benefit from the service by avoiding safety critical situations in navigation (e.g. transport) or high costs due to unfeasible expeditions (e.g. land surveying).

2.2. SWE-CRD-TIO-USR-02

This user group includes users of GNSS single frequency services with average accuracy, using integrity. The most popular example of this kind of service is the EGNOS. Using a wide area network of GNSS receivers, it provides an additional data stream that is transmitted to the users, e.g. aircrafts during landing approaches, via geostationary satellites. The transmitted data includes an esti-

Table 1
User groups of the ESA space weather service networks transionospheric radio link service domain defined in the SSA customer requirements document.

USER GROUP	DESCRIPTION
SWE-CRD-TIO-USR-01	Users of GNSS Single frequency services with average accuracy, no integrity (e.g. typical GNSS mass market user)
SWE-CRD-TIO-USR-02	Users of GNSS Single frequency services with average accuracy, using integrity (e.g. European Geostationary Navigation Overlay Service (EGNOS) user)
SWE-CRD-TIO-USR-03	Users of multi-frequency GNSS systems with average multifrequency accuracy, no integrity (commercial services, Public Regulated Services (PRS))
SWE-CRD-TIO-USR-04	Users of multi-frequency GNSS systems with average accuracy, integrity (aeronautical multifrequency)
SWE-CRD-TIO-USR-05	Users of multi-frequency GNSS systems with very high accuracy (e.g. GNSS geodetic users, Real-time kinematic positioning (RTK))
SWE-CRD-TIO-USR-06	Users of satellite data communications with high availability / continuity (e.g. Search-and-Rescue, Air Traffic Control/Management via Satellite, high availability/continuity data networks such as Galileo Ground Segment Data Network) and other space-based services/products users affected by the ionosphere (Ultra-high frequency (UHF) - C-band radars, GNSS reflectometry (GNSS-R) altimetry, UHF/low microwave radio astronomy and deep space communications)

mate of ionospheric Vertical Total Electron Content (VTEC) and an error bound for that estimate, called Grid Ionospheric Vertical Error (GIVE). Since VTEC is already used to provide corrections of the ionospheric delay in positioning estimates, the main parameters of interest for this user group are the satellite usability and the related ionospheric conditions.

The SWIGPAD application provides a tool that enables the users to extract VTEC/GIVE information in formats tailored for their own services and to get information on the time evolution of disturbed periods.

2.3. SWE-CRD-TIO-USR-03

This user group targets users of multi-frequency GNSS systems with average accuracy, not using integrity, which typically involves commercial GNSS users and the users of the Public Regulated Service. For commercial services in particular, it is important for users to know that the performance of GNSS-based navigation can be affected by Space Weather effects. The performance indicator developed in this project is a good approach to address the problems caused by these influences. While PRS users are typically aware of the potential shortcomings of GNSS, SWIGPAD will help to distinguish Space Weather-related discrepancies in the service from anthropogenic error sources.

2.4. SWE-CRD-TIO-USR-04

This user group covers users of multi-frequency GNSS systems with average accuracy, using integrity. An important example of this user domain is the Ground Based Augmentation System (GBAS), which is a landing system for aircrafts based on a Differential GNSS (DGNSS) architecture. While this enables the system to transmit corrections to GNSS signal propagation estimates and integrity parameters, leading to a very accurate positioning solution inside the aircraft, the DGNSS architecture relies on the assumption that the ionosphere is homogeneous in the paths of the ground-based reference station and the moving receiver. However, since the ionosphere is also showing irregularities at times that lead to a significant change of the experienced ionospheric delay over rather short distances, the SWIGPAD performance indicators can be used to warn DGNSS users on the situations where the ionosphere is expected to be exceptionally turbulent.

2.5. SWE-CRD-TIO-USR-05

This user group represents users of multi-frequency GNSS systems with very high accuracy, which typically represent professional and commercial users such as surveying, mapping and construction. Often, these users rely on additional data streams by a Network Real-Time Kinematic (NRTK) service. A service like this collects data from a network of fixed receivers with coordinates known to very high accuracy and that utilize high-quality equipment. On this basis, it generates a data stream that user equipment can use to correct for much of the error in the measurements, including ionospheric propagation delays. Therefore, exceptionally large VTEC levels or their spatial gradients do not affect NRTK, but rapid temporal fluctuations are of concern.

By relying on parameters that are linked to those rapid fluctuations, such as Rate of TEC Index (ROTI) and phase scintillation ($\sigma\varphi$), the SWIGPAD performance indicator can warn users on situations of enhanced ionospheric turbulence implying exceptionally long integration times for high precision results.

2.6. SWE-CRD-TIO-USR-06

This user group is dedicated to users of satellite data communications with high availability and continuity requirements. This does not only include Search-and-Rescue applications such as Search and Rescue Satellite Aided Tracking (SARSAT), Air Traffic Control/Management via Satellite and high availability/continuity data networks such as Galileo Ground Segment Data Network, but also other space-based services and products like UHF – C-Band radars, GNSS-R altimetry and deep space communications.

The main ionospheric distortions or parameters that influence the users in this domain are Total Electron Content (TEC) gradients, ionospheric scintillations and inhomogeneities, which cause image and positioning distortions as well as loss of lock or loss of signal in strong cases.

To raise awareness of these challenges, the SWIGPAD performance indicators are based on the mentioned parameters.

3. Results of end user discussions

The requirements for each of the use cases were derived from direct input of expert-users from industry and government. This section provides a consolidated summary of the conducted interviews.

For SWE-CRD-TIO-USR-01 the relevant metrics are focused on TEC, ionosphere inhomogeneity, scintillation indices (S4, ROTI, $\sigma\varphi$), Kp and PNT errors. The users desire to be able to access near real-time data, archived data for the last 24 h and if possible forecasts of up to 24 h in advance with a global, European and regional coverage are required. Additionally, an uncertainty for the calculated performance indicator should be provided. The data should be accessible in an automated manner using an Application Programming Interface (API) and also a dedicated website, presenting numerical results and visualizations.

The relevant metrics for SWE-CRD-TIO-USR-02 resolve around TEC, scintillation indices (S4, ROTI, Along Arc TEC Rate (AATR), $\sigma\varphi$), Kp and PNT errors. The users of this group also require near real-time data, archived data and if possible forecasts of up to one hour in advance providing global, regional and local coverage. A value representing the uncertainty of the computed value is also desired.

Similar to user group 1 the data should be provided in an automated manner using an API and also a dedicated website, presenting numerical results and visualizations.

The key parameters for SWE-CRD-TIO-USR-03 are scintillation indices (S4, ROTI, $\sigma\varphi$), radio burst characterization and PNT errors. Near real-time data is required during strong events. Additionally, archived data and if possible, forecasted warnings should be provided too. The users expressed interest to access the data in an automated manner using an API and also a dedicated website, presenting numerical results and visualizations.

For SWE-CRD-TIO-USR-04 the relevant metrics are focused on TEC, scintillation indices (S4, ROTI, $\sigma\varphi$), solar flares and radio burst information. Near real-time and archived data as well as forecasts for up to 8 min during radiation events and up to 1 day for quiet conditions are required. Additionally, an uncertainty for the computed performance indicator should be provided. For the users of this group the data should be accessible in an automated manner using an API and also a dedicated website, presenting numerical results and visualizations.

The relevant metrics for SWE-CRD-TIO-USR-05 are focused on scintillation indices (S4, ROTI, $\sigma\varphi$) and radio burst information. Near real-time data, archived data for the last 24 h and forecast of up to 24 h are required. The indicator shall provide global and regional coverage. Additionally, an uncertainty for the calculated performance indicator should be given. The data should be accessible in an automated manner using an API and also a dedicated website, presenting numerical results and visualizations.

The key parameters for SWE-CRD-TIO-USR-06 resolve around scintillation indices (S4, ROTI, $\sigma\varphi$), TEC gradients, TEC, vertical variation of electron density and Kp. The users of this group only require archived data with global coverage. Furthermore, an uncertainty value of the computed performance indicator should be given. The users of this group expressed interest to access the data in an automated manner using an API and also a dedicated website, presenting numerical results and visualizations.

In addition, almost all user groups aim for spatial accuracies below the decimeter range. The only exception here is the user group SWE-CRD-TIO-USR-01, which in general aims for less than 5 m, but preferably less than 1 meter.

Many users assume the positioning errors to have a Gaussian distribution and use its standard deviation to characterize tolerable errors and cases of fatal outages. Both near-real time and archived Space Weather information are found valuable in most user groups with near-real time information being of particular interest in SWE-CRD-TIO-USR-02 and SWE-CRD-TIO-USR-04 and archived information being unanimously supported in SWE-CRD-TIO-USR-01, SWE-CRD-TIO-USR-02, SWE-CRD-TIO-USR-05 and SWE-CRD-TIO-USR-06.

Particularly maps are a welcome format for Space Weather information in all user groups.

The most interesting Space Weather parameters vary much across groups. The parameters S4, $\sigma\varphi$, ROTI, TEC, and Kp get enhanced weight factors in many user groups. On the other hand, solar radio bursts get single supporting votes across a broad range of the different user groups.

The target for Space Weather service latencies should be less than 1 hour, preferentially less than 5 min.

The targeted spatial resolution for a Space Weather service for SWE-CRD-TIO-USR-01 should be better than 5°, preferably better than 1°. Resolutions better than 1° are necessary in SWE-CRD-TIO-USR-02, SWE-CRD-TIO-USR-05and SWE-CRD-TIO-USR-06.

Forecasts of up to 24 h would be welcome in several user domains. Also forecasts with shorter lead times (from 8 min to 12 h) are considered useful.

Whether a Space Weather service should avoid fake positives (i.e. giving false alarms) or fake negatives (i.e. missing significant events) depends much on its application. Avoiding fake positives seems to be important for SWE-CRD-TIO-USR-05, while in SWE-CRD-TIO-USR-02 and SWE-CRD-TIO-USR-04 both options are desired.

4. Data used

As described in the previous section the performance indicator is based on scintillation indices S4, ROTI and $\sigma\varphi$ as well as TEC and Kp. These are crucial parameters to consider when assessing the impact of space weather on GNSS users [1,5]. The Earth's ionosphere contains free electrons that can delay the propagation of GNSS signals. TEC quantifies the total number of electrons along the signal path between the satellite and receiver which introduces a delay in the signal arrival time, affecting the accuracy of position calculations. By monitoring TEC, GNSS users can account for ionospheric delays and correct for them in their positioning solutions. Additionally, space weather events, such as solar flares or geomagnetic storms (indicated by Kp Index), can cause disturbances in the ionosphere, resulting in irregularities in the TEC distribution. These irregularities can also lead to signal scintillation, which refers to rapid and random fluctuations in the amplitude and phase of GNSS signals. Severe scintillation can disrupt the GNSS signal tracking and degrade positioning accuracy. Finally, sudden changes in TEC, particularly during space weather events, can also affect receiver performance, leading to loss of signal lock or extended time for signal acquisition. Therefore, monitoring TEC and incorporating TEC products into the GPI application helps to assess the GNSS error budget due to ionospheric disturbances, which is one of the major sources of error related to GNSS positioning.

To compute the TEC performance indicator, at least one of the following data sources is required:

- Ionosphere Monitoring and Prediction Center (IMPC) Near-real-time map of the Total Electron Content (TEC) for the European region
- IMPC 1 hour forecast of the Total Electron Content (TEC) for the European region
- IMPC Near-real-time global map of the Total Electron Content (TEC) as seen in Fig. 2.
- IMPC 1 hour forecast of the Total Electron Content (TEC) worldwide
- Real-Time Ionosphere Monitor (RTIM) VTEC maps (Northern Europe)
- Swarm Total Electron Content (TEC) and Rate of TEC (ROT) as presented in Fig. 6.

To process the ROTI based performance indicator, one of the following data sources is required:

- RTIM ROTI maps (Northern Europe) as shown in Fig. 3
- RTIM ROTI@Ground maps (Fennoscandia)
- IMPC Rate of change of TEC index (ROTI) maps for Europe

Additionally, $\sigma\varphi$ and S4 can be used. The following products or even combinations of these products can be utilized for this purpose:

- RTIM $\sigma\varphi$ maps (Northern Europe)
- IMPC Local scintillation indices S4 & $\sigma\varphi$ for Kiruna (Sweden)
- IMPC Local scintillation indices S4 & $\sigma\varphi$ for Neustrelitz (Germany) as shown in Fig. 4
- IMPC Local scintillation indices S4 & $\sigma\varphi$ for Svalbard (Norway)
- IMPC Local scintillation indices S4 & $\sigma\varphi$ for Laguna (Tenerife/Spain)
- IMPC Local scintillation indices S4 & $\sigma\varphi$ for Toulouse (France)

Furthermore, to include information on geomagnetic activity, the Kp index is required. Thus, the use of the following products is feasible:

Table 2
Table of performance indicator value based on S4 scintillation index.

1Performance indicator value S4 index (no unit)	Description	Color
0	"no data."	gray
$0 < S4 < 0.3$	"No amplitude scintillation to weak amplitude scintillation."	Green
$0.3 \leq S4 < 0.6$	"Mean/moderate amplitude scintillation intensity."	Yellow
$S4 \geq 0.6$	"Strong amplitude scintillation."	Red

Table 3
Table of performance indicator value based on $\sigma\varphi$ scintillation index.

Performance indicator value $\sigma\varphi$ (rad)	Description	Color
0	"no data."	Gray
$0 < \sigma\varphi < 0.1$	"No phase scintillation."	Green
$0.1 \leq \sigma\varphi < 0.25$	"Weak phase scintillation."	Green
$0.25 \leq \sigma\varphi < 0.5$	"Moderate phase scintillation intensity."	Yellow
$\sigma\varphi \geq 0.5$	"Strong phase scintillation."	Red

Table 4
Table of performance indicator value based on ROTI scintillation index.

Performance indicator value ROTI (TECU/60 s)	Description	Color
0	"no data."	Gray
$0 < ROTI < 1$	"Low activity. No adverse effects expected."	Green
$1 \leq ROTI < 3$	"Normal activity. For most users, this level of activity will not cause problems. A slight increase in position error may be detected in high-accuracy applications."	Green
$3 \leq ROTI < 5$	"Moderate activity. Users may have difficulty getting a good coordinate solution."	Yellow
$ROTI \geq 5$	"High activity. Users will have difficulty getting a good coordinate solution. Network base stations may lose lock on satellites."	Red

- British Geological Survey (BGS) Global activity indices nowcasts (Kp)
- German Research centre for Geosciences (GFZ) Nowcast Kp index as seen in Fig. 5
- GFZ Kp and Ap index archive
- Swedish Institute of Space Physics (IRF) Forecast of Kp

5. Processing

To compute the SWIGPAD performance indicator, the eligible products from the list described in the previous section are chosen based on the location, time and use case given by the user. For each product type (ROTI, TEC, S4, $\sigma\varphi$ and Kp) a dedicated indicator in form of a numerical value, color-coded by thresholds based on each user group, are calculated. The final performance indicator is then given by combining those using a weighted average. The weights for this method are defined and preset by the SWIGPAD team, while a future development goal will allow users to customize their own weights suitable for their individual needs.

In addition to the performance indicator, an uncertainty value is calculated, which provides information about the quality of the result. This uncertainty value is based on the number of available products for the selected input parameters.

The S4-based indicator is classified similar to the classification proposed by the International Telecommunication Union [7]. Thus, the threshold values are shown in Table 2.

The $\sigma\varphi$-based indicator is classified using the following thresholds defined in Table 3 [8,9].

The values of ROTI typically vary between 0 TEC Units per minute (TECU/60 s) (no scintillation) and can reach values above 5 TECU/60 s in case of high scintillation activity. Thus, the ROTI-based performance indicator uses the classification presented in Table 4 [10].

The TEC-based performance indicator is based on the variability of TEC in time (here called dTEC) and is checked with respect to a maximum value (here called dTECmax). Therefore, the classification is given in Table 5.

Additionally, an indicator based on the positioning error is provided. This indicator is derived from the modelled probability of the positioning error, which was determined on the basis of ROTI according to [11] and will be classified as presented in Table 6.

The Kp-based indicator is classified as seen in Table 7.

6. System design

The system is designed using a distributed, service-oriented architecture based on microservices. Thus, the application is divided into a collection of interconnected services, with each service fulfilling only one specific task. The services are loosely coupled using a common interface and protocol standards and will therefore act as individual entities. As a result, each service is small and can be tested, developed, and scaled independently. This also allows for technological heterogeneity, so that each service or component can be implemented with different technologies that are best suited for the particular application. In addition, each service or component is easier for the developer to maintain and understand, due to reduced size and complexity, as well as better fault isolation compared to a monolithic application. Another major advantage is the ability to scale individual services or components horizontally based on current workload.

The central entry points for the user to use the system are a Graphical User Interface (GUI) and a Hypertext Transfer Protocol (HTTP) API.

The API handles messages in JavaScript Object Notation (JSON) format for input and output. It accepts user requests, validates the provided input parameters and executes communication with the

Table 5
Table of performance indicator value based on TEC variability.

Performance indicator value dTEC (TECU)	Description	Color
0	“no data.”	Gray
0 < dTEC < dTECmax	"Correct estimation of TEC."	Green
dTEC ≥ dTECmax	"Incorrect estimation of TEC."	Red

Table 6
Table of performance indicator value based on positioning error probability $1 \times \sigma$ and Gaussian distribution of error.

Performance indicator value probability in%	Description	Color
0	“no data.”	Gray
$p < 68.3\%$	"Positioning error variability lower than criterion."	Green
$p \geq 68.3\%$	"Positioning error variability higher than criterion."	Red

Table 7
Table of performance indicator value based on Kp index.

Performance indicator value Kp	Description	Color
0	“no data.”	Gray
Kp < 4	"Low magnetic activity or normal activity."	Green
Kp ≥ 4	"High magnetic activity, indicating a geomagnetic storm."	Red

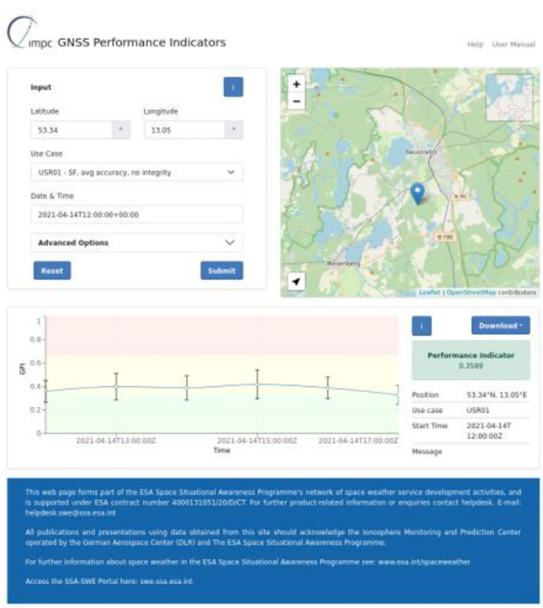

Fig. 7. Graphical user Interface of the system.

processing backend. This also includes handling and returning the processing results or errors that eventually occurred to the user.

The GUI is a convenient tool that enables the user to interactively work with the system. It provides forms for the input parameters like time and use case as well as the user’s location, which can be entered using an input form, an interactive map or optionally automations to fetch the position from the user’s device. Additionally, the GUI offers a numerical representation of the performance indicator and a visualization in form of interactive time series charts presenting the timely evolution as well as a detailed view, which shows additional information like the products used for computation. A design mock-up of the GUI can be seen in Fig. 7.

Internally the GUI uses the API Service to communicate with the system.

The already mentioned Processing Service is designed with horizontal scalability in mind, which enables the system to be adjusted to the incoming load.

For the computation of the performance indicator, the Processing Service has to acquire the required products. To reduce latency the Caching Service acts as a proxy between the Processing Service and the ESA Space Weather Service Network, caching and locally storing frequently requested products.

Since the application is available in the ESA Space Weather Service Network, it is connected to the ESA Single Sign-On (SSO) Service to authenticate user requests to the SWIGPAD application via the usage of the Web Service. Depending on the requested endpoint it routes successfully authenticated requests to the API Service or delivers the static files needed to render the GUI.

Finally, to ensure the systems functionality and availability, the system uses a unified logging format. The logs will then get stored centrally using the Monitoring Service.

7. Outlook

At the time of writing the project has finished its implementation phase, by having successfully passed acceptance testing in participation of ESA Space Safety Programme (S2P) team. It was successfully integrated into the ESA SSO system and made available on the ESA Space Weather Service Portal as a federated site under the provisions of IMPC with release 3.5 on October 11, 2022. A dedicated user test campaign following the deployment to the ESA Space Weather Service Portal is being organized to collect relevant feedback. Finally, the SWIGPAD application provides detailed information of the GNSS service performance for different applications and help mitigate Space Weather related disturbances on our modern security. Therefore, the SWIGPAD application will be an important tool to assess the space weather impact on the GNSS performance, which is especially important during the upcoming phase of increased solar activity with its expected maximum in 2025/2026.

Declarations of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Paul David: Conceptualization, Software, Validation, Visualization, Writing – original draft. **Martin Kriegel:** Conceptualization, Software, Validation, Project administration, Supervision, Visualization, Writing – review & editing. **Jens Berdermann:** Project administration, Supervision, Visualization, Writing – review & editing. **Kirsti Kauristie:** Conceptualization, Formal analysis, Resources, Visualization, Writing – review & editing. **Knut Stanley Jacobsen:** Conceptualization, Software, Formal analysis, Resources, Writing – review & editing. **Vincent Fabbro:** Conceptualization, Formal analysis, Investigation, Data curation, Resources, Writing – review & editing. **Hannah Laurens:** Resources, Supervision, Project administration, Visualization, Writing – review & editing. **Ralf Keil:** Resources, Supervision, Project administration, Writing – review & editing.

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