



HAL
open science

Performance indicator development to mitigate space weather impact on GNSS

Paul David, Martin Kriegel, Jens Berdermann, Kirsti Kauristie, Stanley Jacobsen, Vincent Fabbro, Hannah Laurens, Ralf Keil

► **To cite this version:**

Paul David, Martin Kriegel, Jens Berdermann, Kirsti Kauristie, Stanley Jacobsen, et al.. Performance indicator development to mitigate space weather impact on GNSS. 11th IAASS Conference "Managing Risk in Space", International Association for the Advancement of Space Safety, Oct 2021, Rotterdam, Netherlands. pp.740-747. hal-03533166

HAL Id: hal-03533166

<https://hal.science/hal-03533166>

Submitted on 31 Jan 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PERFORMANCE INDICATOR DEVELOPMENT TO MITIGATE SPACE WEATHER IMPACT ON GNSS

Paul David⁽¹⁾, Martin Kriegel⁽¹⁾, Jens Berdermann⁽¹⁾, Kirsti Kauristie⁽²⁾, Knut Stanley Jacobsen⁽³⁾, Vincent Fabbro⁽⁴⁾, Hannah Laurens⁽⁵⁾, Ralf Keil⁽⁵⁾

⁽¹⁾ Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute for Solar-Terrestrial Physics, Kalkhorstweg 53, 17235 Neustrelitz, Germany, Email: Paul.David@dlr.de

⁽²⁾ Finnish Meteorological Institute (FMI), 00101 Helsinki, Finland, Email: Kirsti.Kauristie@fmi.fi

⁽³⁾ Norwegian Mapping Authority (NMA), PO 600 Sentrum, 3507 Hønefoss, Norway, Email: Knut.Stanley.Jacobsen@kartverket.no

⁽⁴⁾ ONERA/DEMR, Université de Toulouse, 31055 Toulouse, France, Email: vincent.fabbro@onera.fr

⁽⁵⁾ RHEA System GmbH for ESA/ESOC, Darmstadt, Germany, Email: Hannah.Laurens@esa.int, Ralf.Keil@esa.int

ABSTRACT

The ESA Space Weather Service Network identifies the development of performance indicators for the Global Navigation Satellite System (GNSS) 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 requirements of different user domains in this field. The goal of the Space Weather Impact on GNSS Performance Indicator Application Development (SWIGPAD) project is to develop GNSS performance indicators built on existing data provided by various European research institutes through the ESA Space Weather Service Portal (available at <https://swe.ssa.esa.int>) and representative use cases derived from industry and government experts that have been established through dedicated meetings. The performance application 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 provided 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 first results of the project.

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. 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 of power networks, pipelines and degradation of radio communications. [9]

It can be the case however, that users from various domains 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 Figure 1.

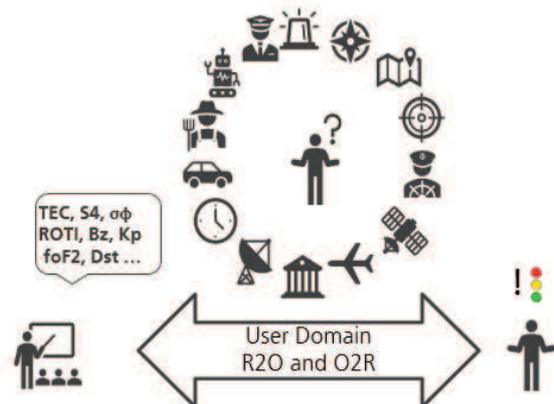


Figure 1. The objective of SWIGPAD is the transfer of Space Weather products provided by the ESA Space Weather Service Network to a wide range of PNT-related user domains with different requirements by providing GNSS Performance Indicators

A key objective of the SWIGPAD project is therefore to develop a simple-to-use indicator allowing users to enter their position via an interactive map and makes use of colour-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 from the local to the global scale [8], provided by federated expert groups through different interfaces (e.g. see Fig. 2-6).

2. USER GROUPS

The user groups identified for this project follow the definitions provided by the ESA Space Weather Service Networks service domain *Transionospheric Radio Link* (available at

https://swe.ssa.esa.int/web/guest/tio_dashboard)

following the SSA Customer Requirements Document. [1] Thus, the application will support the six user groups shown in Table 1.

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. EGNOS user)
SWE-CRD-TIO-USR-03	Users of multi-frequency GNSS systems with average multifrequency accuracy, no integrity (commercial 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, 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 (UHF - C-band radars, GNSS-R altimetry, UHF/low microwave radioastronomy and deep space communications)

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 European Geostationary Navigation Overlay Service (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 estimate 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 will provide 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 (PRS). 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 utilise 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 ($\sigma\phi$), the SWIGPAD performance indicator can warn users on situations of enhanced ionospheric turbulence implying exceptionally long integration times for high precision results.

SWE-CRD-TIO-USR-01 the relevant metrics are focused on TEC, ionosphere inhomogeneity, scintillation indices (S4, ROTI, $\sigma\phi$), Kp and PNT errors. The users desire to be able to access near real-time data, archived data for the last 24 hours and if possible forecasts of up to 24 hours 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 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, AATR, $\sigma\phi$), 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 are required. A value representing the uncertainty of the computed value is also desired. Similar to user group 1 the data should be 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, $\sigma\phi$), 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

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 ultra-high frequency (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 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 will be 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.

3.1. For

provided. 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, $\sigma\phi$), solar flares and radio burst information. Near real-time and archived data as well as forecasts for up to 8 minutes 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, $\sigma\phi$) and radio burst information. Near real-time data, archived data for the last 24 hours and forecast of up to 24 hours are required. The indicator shall provide global and regional coverage. Additionally, an uncertainty for the calculated performance indicator should be provided. 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, $\sigma\phi$), 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 conclusion, all user groups except SWE-CRD-TIO-USR-01, which aims for less than 5, preferentially less than 1 meter, aim for spatial accuracies below decameter scales.

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 unanimous 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, σ_ϕ , 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 minutes.

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

CRD-TIO-USR-02, SWE-CRD-TIO-USR-05 and SWE-CRD-TIO-USR-06.

Forecasts of up to 24 hours would be welcome in several user domains. Also forecasts with shorter lead times (from 8 minutes to 12 hours) 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 will be mainly based on scintillation indices S4, ROTI and σ_ϕ as well as TEC and Kp.

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

- 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 Figure 2
- IMPC 1 hour forecast of the Total Electron Content (TEC) worldwide
- RTIM VTEC maps (Northern Europe)
- Swarm Total Electron Content (TEC) and Rate of TEC (ROT) as presented in Figure 6

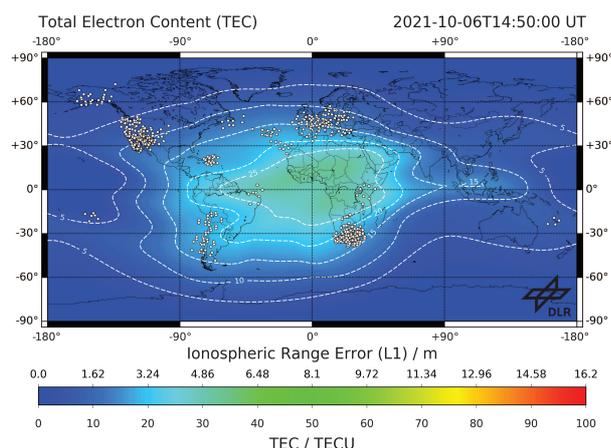


Figure 2. Near-real-time global map of the Total Electron Content (TEC) provided by IMPC [4].

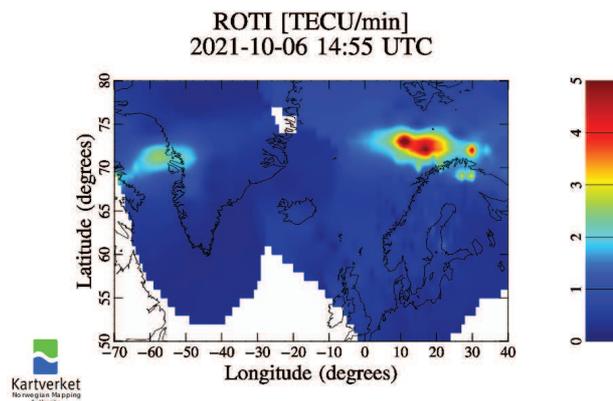


Figure 3. RTIM ROTI maps (Northern Europe) provided by NMA.

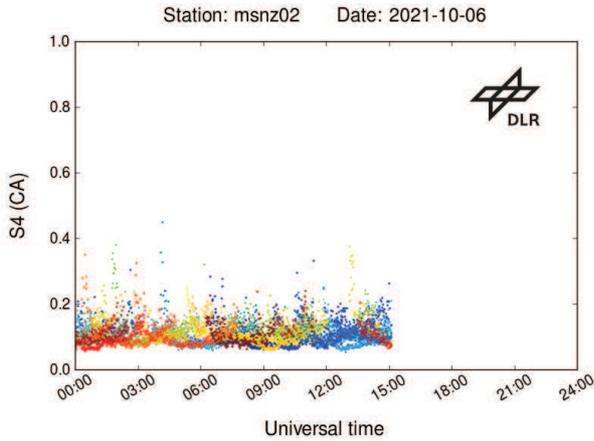


Figure 4. IMPC Local scintillation index S_4 for Neustrelitz (Germany) provided by IMPC [4].

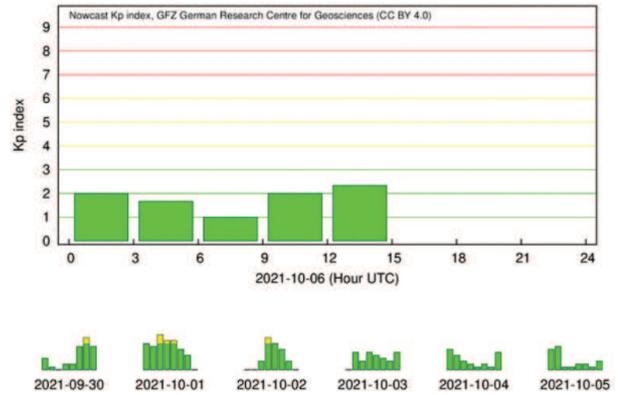


Figure 5. Nowcast of the Kp Index provided by GFZ.

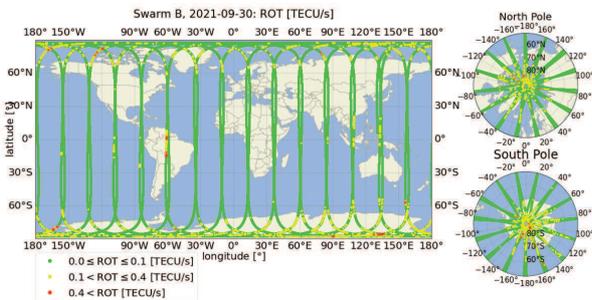


Figure 6. Swarm Rate of TEC (ROT) provided by GFZ.

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

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

Additionally, $\sigma\phi$ and S_4 can be used. The following products or even combinations of these can be leveraged for this purpose:

- RTIM $\sigma\phi$ maps (Northern Europe)
- IMPC Local scintillation indices S_4 & $\sigma\phi$ for Kiruna (Sweden)
- IMPC Local scintillation indices S_4 & $\sigma\phi$ for Neustrelitz (Germany) as shown in Figure 4
- IMPC Local scintillation indices S_4 & $\sigma\phi$ for Svalbard (Norway)
- IMPC Local scintillation indices S_4 & $\sigma\phi$ for Laguna (Tenerife/ Spain)
- IMPC Local scintillation indices S_4 & $\sigma\phi$ for Toulouse (France)

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

- BGS Global activity indices nowcasts (Kp)
- GFZ Nowcast Kp index as seen in Figure 5
- GFZ Kp and Ap index archive
- IRF Forecast of Kp

5. PROCESSING

To compute the SWIGPAD performance indicator, the eligible products from the list described in the previous section will be chosen based on the location, time and use case given by the user. For each product type (ROTI, TEC, S_4 , $\sigma\phi$ and Kp) a dedicated indicator in form of a numerical value, color-coded by thresholds based on each user group, will be calculated. The final performance indicator is then given by combining those using a weighted average. The weights for this method will be defined and preset by the SWIGPAD team, while a future development goal will allow users to customize these weights to their individual needs.

The S_4 -based indicator will be classified similar to the classification proposed by the International Telecommunication Union. [3] Thus, the threshold values are shown in Table 2.

Table 2. Table of performance indicator value based on S_4 scintillation index.

Performance indicator value S_4 index (no unit)	Description	Color
0	"No data."	Grey
$0 < S_4 < 0.3$	"No amplitude scintillation to weak amplitude scintillation."	Green
$0.3 \leq S_4 < 0.6$	"Mean/moderate amplitude scintillation intensity."	Yellow
$S_4 \geq 0.6$	"Strong amplitude scintillation."	Red

The $\sigma\phi$ -based indicator will be classified using the following thresholds defined in Table 3. [5][6]

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

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

The values of ROTI typically vary between 0 TEC Units per minute (TECU/min) (no scintillation) and can reach values above 5 TECU/min in case of high scintillation activity. Thus, the ROTI-based performance indicator uses the classification presented in Table 4. [7]

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

Performance indicator value ROTI (TECU/min)	Description	Color
0	"No data."	Grey
$0 < \text{ROTI} < 1$	"Low activity. No adverse effects expected."	Green
$1 \leq \text{ROTI} < 3$	"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
$3 \leq \text{ROTI} < 5$	"Moderate activity. Users may have difficulty getting a good coordinate solution."	Yellow
$\text{ROTI} \geq 5$	"High activity. Users will have difficulty getting a good coordinate solution. Network base stations may lose lock on satellites."	Red

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

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

Performance indicator value dTEC (TECU)	Description	Color
0	"No data."	Grey
$0 < \text{dTEC} <$	"Correct estimation of TEC."	Green

dTECmax		Green
$\text{dTEC} \geq \text{dTECmax}$	"Incorrect estimation of TEC."	Red

Additionally, an indicator based on the positioning error will be provided. This indicator will be derived from the modelled probability of the positioning error, which was determined on the basis of ROTI according to [2] and will be classified as presented in Table 6.

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

Performance indicator value, probability in %	Description	Color
0	"No data."	Grey
$p < 75.7\%$	"Positioning error variability lower than criterion."	Green
$p \geq 75.7\%$	"Positioning error variability higher than criterion."	Red

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

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

Performance indicator value Kp	Description	Color
0	"No data."	Grey
$Kp < 4$	"Low magnetic activity or normal activity."	Green
$Kp \geq 4$	"High magnetic activity, indicating a geomagnetic storm."	Red

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 business need. The services will be loosely coupled using a common interface and protocol standards and will therefore act as individual entities. As a result, each service will be small and can be tested, developed, and scaled independently. This also allows for technological heterogeneity, so that each service or component can be implemented using different technologies that are perfectly suited to the application at hand. In addition, each service or component is easier for the developer to maintain and understand due to its smaller 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 load.

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

The API uses messages in JSON format for input and output. It accepts user requests, validates the provided input parameters and handles communication with the 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 the 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 Figure 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 SSA/S2P Space Weather Service Network, caching and locally storing frequently requested products.

Since the application will also be available in the ESA SSA/S2P Space Weather Service Network, it will be 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.

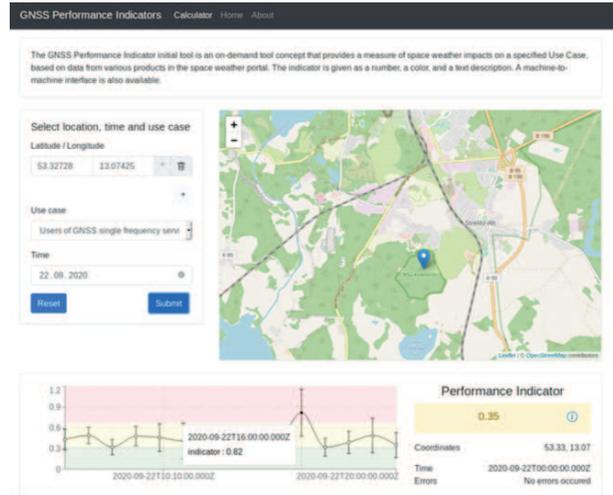


Figure 7. Design mock-up of the Graphical User Interface

7. OUTLOOK

At the time of writing the project is still in the implementation phase, which is expected to be completed in January of 2022. The application will be validated and integrated into the ESA SSO system and deployed to the ESA Space Weather Service Portal as a federated page under the provision of the IMPC. A dedicated user test campaign following the deployment to the ESA Space Weather Service Portal will be organized to collect relevant feedback. Finally, the SWIGPAD performance indicator application will provide detailed information of the GNSS service performance for different applications and help to mitigate Space Weather related disturbances on our modern security.

8. ACKNOWLEDGEMENTS

Work has been performed in the frame of ESA Space Safety Programme's network of Space Weather Service development and pre-operational activities, supported under ESA Contract 4000131051/2 0/D/CT.

9. REFERENCES

1. ESA SSA Team (2011). Space Situational Awareness - Space Weather Customer Requirements Document (SSA-SWE-RS-CRD-1001), Iteration 4, Revision 5a, p59. https://swe.ssa.esa.int/DOCS/SSA-SWE/SSA-SWE-CRD-1001_i4r5a.pdf.
2. Fabbro, V., Jacobsen, K. S., Andalsvik, Y. L., & Rougerie, S. (2021). GNSS positioning error forecasting in the Arctic: ROTI and Precise Point Positioning error forecasting from solar wind measurements. *Journal of Space Weather*

- and Space Climate, 11, 43.
<https://doi.org/10.1051/swsc/2021024>
3. ITU-R (2019). Ionospheric propagation data and prediction methods required for the design of satellite services and systems. Recommendation ITU-R P.531-14.
 4. Kriegel, M., & Berdermann J. (2021). Ionosphere Monitoring and Prediction Center, 2020 European Navigation Conference (ENC), 2020, pp. 1-10.
<https://doi.org/10.23919/ENC48637.2020.9317443>
 5. Prikryl, P., Ghoddousi-Fard, R., Weygand, J. M., Viljanen, A., Connors, M., Danskin, D. W., Jayachandran, P. T., Jacobsen, K. S., Andalsvik, Y. L., Thomas, E. G., Ruohoniemi, J. M., Durgonics, T., Oksavik, K., Zhang, Y., Spanswick, E., Aquino, M., & Sreeja, V. (2016). GPS phase scintillation at high latitudes during the geomagnetic storm of 17–18 March 2015. Journal of Geophysical Research: Space Physics, 121(10).
<https://doi.org/10.1002/2016ja023171>
 6. Aquino, M., Dodson, A., Souter, J., & Moore, T. (2007). Ionospheric Scintillation Effects on GPS Carrier Phase Positioning Accuracy at Auroral and Sub-auroral Latitudes. In Dynamic Planet (pp. 859–866). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-49350-1_121
 7. Jacobsen, K. S., & Dähnn, M. (2014). Statistics of ionospheric disturbances and their correlation with GNSS positioning errors at high latitudes. Journal of Space Weather and Space Climate, 4, A27.
<https://doi.org/10.1051/swsc/2014024>
 8. Borries, C., Wilken, V., Jacobsen, K. S., García-Rigo, A., Dziak-Jankowska, B., Kervalishvili, G., Jakowski, N., Tsagouri, I., Hernández-Pajares, M., Ferreira, A. A., & Hoque, M. M. (2020). Assessment of the capabilities and applicability of ionospheric perturbation indices provided in Europe. Advances in Space Research, 66(3), 546–562.
<https://doi.org/10.1016/j.asr.2020.04.013>
 9. Berdermann, J., Kriegel, M., Banyś, D., Heymann, F., Hoque, M. M., Wilken, V., Borries, C., Heßelbarth, A., & Jakowski, N. (2018). Ionospheric Response to the X9.3 Flare on 6 September 2017 and Its Implication for Navigation Services Over Europe. Space Weather, 16(10), 1604–1615.
<https://doi.org/10.1029/2018sw001933>