Space Weather Bulletins as part of a User Test Campaign for GNSS service users

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Abstract: *ESA Space Weather Service Network supports end users in a wide range of affected sectors, in mitigating the effects of space weather on their systems, reducing costs and improving reliability. In this network, space weather products and tools are developed and federated in services, that are suitable for operational implementation to meet the end user needs.*
In the aim to establish a close relationship with the end users of space weather services, the SSA Space Weather Coordination Centre (SSCC) organizes user support campaigns to build tailored space weather bulletins. During the campaign, the SSCC works together with the user in order to compile dedicated space weather forecast notifications.
We highlight here the SSCC user support campaign for a group of test users within the GNSS community.

1. Introduction

Space Weather is defined as the set of all conditions – on the Sun, and in the solar wind, magnetosphere, ionosphere and thermosphere – that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life [1]. In the frame of its Space Safety programme (following the Space Situational Awareness programme or SSA), the European Space Agency (ESA) is establishing a Space Weather (SWE) Service Network [2] to support end users, in a wide range of affected sectors including Global Navigation Satellite System (GNSS) service users, in mitigating the effects of space weather on their operational systems, reducing costs and improving reliability. In building this network, Space Weather products/tools are developed and federated in services targeting end user needs.

ESA Space Weather Service Network is based on a federated architecture built on five Expert Service Centers (ESCs), the SSA Space Weather Coordination Centre (SSCC) that provides first line support to the user, and a Data Centre. The ESCs collect assets and expertise from all over Europe into five different domains depending on their focus: Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather and Geomagnetic Conditions. These centres are responsible for the provision and maintenance of the current service level as well as introducing new, complimentary products to the network. Over time, this ensures the enhancement of the network as current products evolve and new products are developed and incorporated into the system, filling identified service capability gaps. In their current status, all services serve as a basis to collect feedback from the different user communities to evaluate and improve the service development.

2. Space weather effects on the GNSS community

The effects of Space Weather on GNSS applications can present themselves in different ways [1]:

- Increase in the time required to fix the GNSS signal phase ambiguities
- Phase and amplitude fluctuations
- Decreased reference network model integrity
- Discrepancies between "processed" and "solved" GNSS satellites

GNSS users need to rely on a GNSS reference network to achieve a high level of precision and calculate required ionospheric corrections. One of the main factors limiting the performance of such reference networks is the time needed to determine the phase ambiguities. The variability of the ionosphere strongly affects the capabilities of such network services [1].

The phase and amplitude fluctuations are due to ionospheric disturbances and occur especially at polar or equatorial areas. They are caused by refractive and diffracting scattering linked to ionospheric plasma irregularities. This could lead to cycles slips or tracking losses due to scintillations [3].

The Network Model Integrity is also an important operational parameter used in the GNSS reference network software to control both the integrity and the quality of the satellite positioning services [1] . The ionospheric linear influence on GNSS signals is usually defined and removed by applying an ionospheric and geometric correction on the raw data. However, in case of an ionospheric disturbance, the residuals ionospheric impacts can not be considered linear. Solving these nonlinear effects need a more complex process and, if the disturbance is large, the fixing of these ambiguities can take longer times and increase the inaccuracies.

Global Navigation Satellite System signals are also directly affected by solar radio bursts. Intense Solar Radio Bursts (SRB), related to solar flares, may enhance the radio flux in the L-band (1-2 GHz) and directly interfere with GNSS signals. The output of this could be a reduction of the signal-to-noise ratio (SNR) and the number of tracked GNSS satellites. Instantaneous or long-period loss of lock (LOL) on GNSS signals may occur with complete loss of positioning information. [4]

The effect of Space Weather on GNSS depends very much on the type of application. In particular, applications that require real-time results are much more sensitive to Space Weather conditions. Within our campaign, the focus is on differential positioning (affected by medium to large-scale gradients in the Total Electron Content (TEC)) and precise relative positioning (degraded by smaller-scale ionospheric variability due to scintillations, TEC noise-like behavior and Travelling Ionospheric Disturbances). The test users in our campaign are situated in the field of real-time kinematic (RTK) positioning and differential GNSS positioning.

3. Space Weather Bulletins as part of a User Test Campaign

To establish a close relationship with the end users and to demonstrate the current capability of the ESA SWE Service Network to support them, the SSCC, which is the first contact point for the user in the SWE Service Network, organizes user support test campaigns. During the campaign, the SSCC works closely with the end user in order to compile tailored space weather bulletins to be delivered on an agreed time schedule. Products/tools from the SWE Service Network are tailored to address the specific end user needs and are combined in a dashboard from which dedicated Space Weather forecast notifications are generated. We present here the user support test campaign that the SSCC is running in support of GNSS service users with regard to the impact of Space Weather on precise GNSS positioning. SWE Services defined in the network that are relevant to GNSS users are:

- the provision near real-time Total Electron Content (TEC) maps
- the provision of forecast TEC maps
- the provision of a quality assessment of ionospheric correction
- the provision of near real-time ionospheric scintillation maps
- the monitoring and forecast of ionospheric disturbances.

Ionospheric perturbations can affect GNSS applications and cause rapid phase and amplitude fluctuations of the satellite signals. This can therefore lead to a degradation of the accuracy, reliability and performances of the system [5]. Ionospheric perturbations on the GNSS signals are either due to dispersion or scintillation caused by plasma density irregularities. They are observed in signal amplitude scintillation, signal phase scintillation, and the variation of the TEC in a column extending through the overhead ionosphere. Scintillations cause signal fades and receivers may lose lock on signal if the scintillations are sufficiently strong. The number of tracked satellites may become too small to estimate a precise position. Amplitude scintillations are measured by specialized GNSS receivers and are given by the index S4, the normalized standard deviation in the signal strength. Phase scintillations, also measured by specialized receivers, are categorized by the parameter $\sigma\varphi$, the standard deviation in the signal phase.

In order to provide the test user with a comprehensive overview of actual and expected conditions in space and related possible impacts on the ionosphere, a dashboard is built on basis of operational products (plots, animated maps, alerts, etc.) available in the ESA SWE Service Network. Most information is displayed in graphical and tabular format, complementing the textual information that is sent to the user by SMS and email in case ionospheric disturbances are expected and/or observed. To structure the information, the dashboard is organised in different sections/tabs with respect to solar weather conditions, ionospheric conditions and geomagnetic conditions.

As illustrated in Figure 1 the dashboard includes near real-time information and forecasts on the space weather conditions with expected impacts in case of increased solar activity. A summary table provides a quick look on the current observed solar and geomagnetic activity, and also for the next 24h if available. A color code is used such that the user can rapidly identify an unusual situation. Additional information (refresh rate, units, precision, etc.) about the products is displayed when clicking on the product title, also including the url link to the product webpage on the SWE Portal [2]. The dashboard can be exported in html or pdf format (3) if a user wishes to record the activity at any given time. An automatic archive is also recorded if any of the monitored conditions exceeds a threshold that has been agreed with the campaign test users. The GNSS user community can therefore use this archive for post event analysis. To make sure that the latest data is shown, the dashboard is refreshed each 5 min (4) and the date/time of the last update is displayed (5). Information on the adopted thresholds, references and products is included in the information icon at the top right of the tables (6).

Figure 1: general outline of the dashboard

The thresholds that we are currently using have been established based on the feedback of our test users and are describes in Table 1. They are closely related to their specific needs related to their fieldwork and could be adapted based on the requirements of different communities.

Table 1: Criteria for establishing the impact level of ionospheric disturbance

	minor	moderate	severe
F10.7 (sfu)	<140	140	300
Kp	<4	4	7
Dst (nT)	>-50	-50	-100
VTEC (TEC units)	<125	125	175
S4	<0.5	0.5	0.8
σ_φ (radians)	<0.4	0.4	0.7
X-ray Solar flare	M1 – X1	X1	X10

The impact of solar flares on the dayside of the ionosphere is immediate and may last for several minutes to hours. The solar activity dashboard tab is partially illustrated by Figure 2. The probabilistic flare forecasts (for the next 24h) are shown as produced by the Athens Effective Solar Flare Forecasting (A-EFFort) monitoring service, in combination with a forecast from the Solar Influences Data analysis Center (SIDC) that is based on statistical techniques and expert judgement on the evolution of active regions on the solar disk. An SIDC forecast of the F10.7 radio flux as it is expected to be observed over the next 3 days is also included. Advanced warnings (1 – 4 days) of upcoming geomagnetic storms due to the impact of solar wind structures (e.g. Earth-directed solar coronal mass ejections (CMEs)) are generated on basis of the 3D MHD WSA-Enlil Models. The video shows the time evolution of the solar wind plasma density and radial velocity at three locations: Earth, STEREO A and STEREO B.

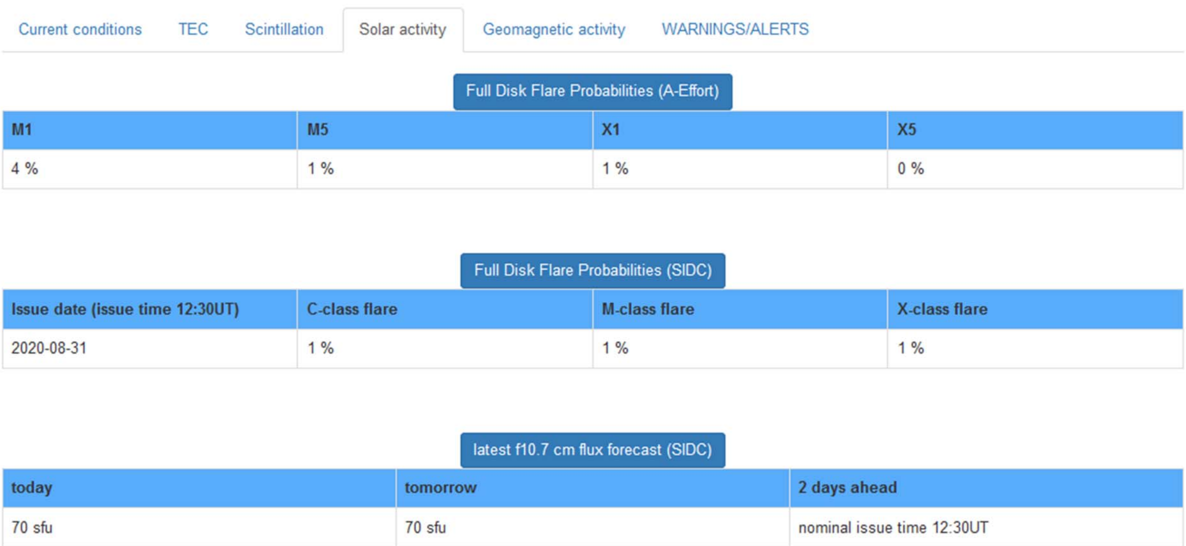

Figure 2: Partial overview of the Solar weather section

The response of the ionosphere to the impact of a solar flare is reflected in sudden changes in the TEC. The dashboard tab, presented by Figure 3 collects near real-time and forecast global

TEC maps as well as TEC maps for the European region together with the mean Rate-Of-TEC Index (ROTI) map for Europe. The ROTI is a measure of ionospheric turbulence whereby higher values indicate more noise in the phase observables of the GNSS signals and in position resolution. Regional maps of the scintillation indices S4 and σ_φ, which are measured by specialized receivers and correspond to the most severe error sources for GNSS signals, are also displayed on the dashboard in the scintillation section of Figure 4. The maps are provided in the network by the Ionosphere Monitoring and Prediction Center (IMPC), the Norwegian Mapping Authority (NMA) and ESOC's Ionosphere Monitoring Facility (IONMON). Next to the TEC maps, a 30-days forecast of the F10.7 cm solar radio flux is given, which are often correlated [6]. In addition, the time evolution of the daylight GNSS-based estimated EUV flux rate and the number of GPS rays available in the sunlit region is shown as generated respectively by the SOLERA-drift and SISTED network products.

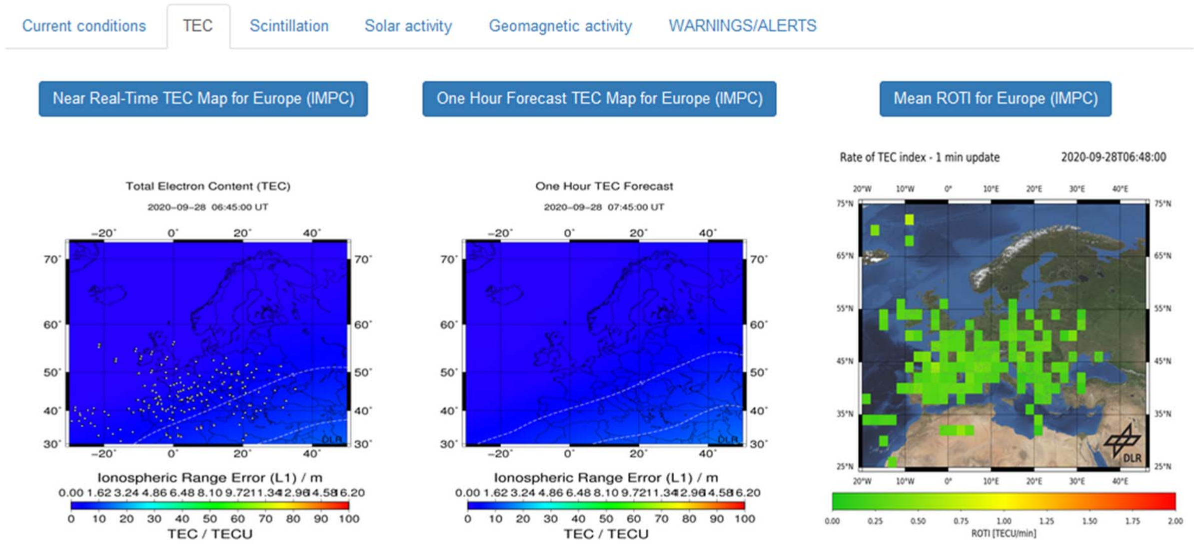

Figure 3: Partial overview of the TEC section

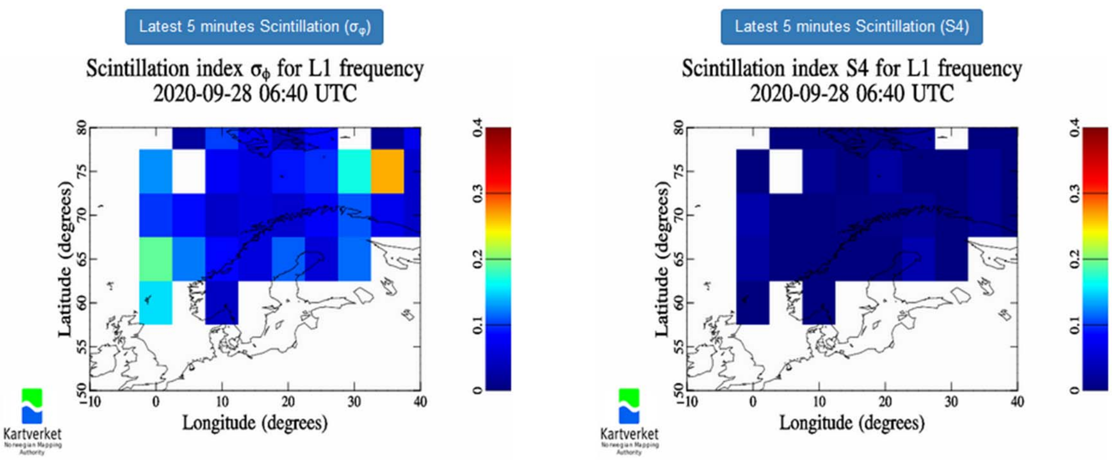

Figure 4: Partial overview of the scintillation section

Information on the geomagnetic activity is captured in a nowcast/forecast of the Kp and Dst index which is given in combination with the solar wind conditions at L1 as illustrated in Figure 5. A table also offers a quick look of the situation and in case of an event.

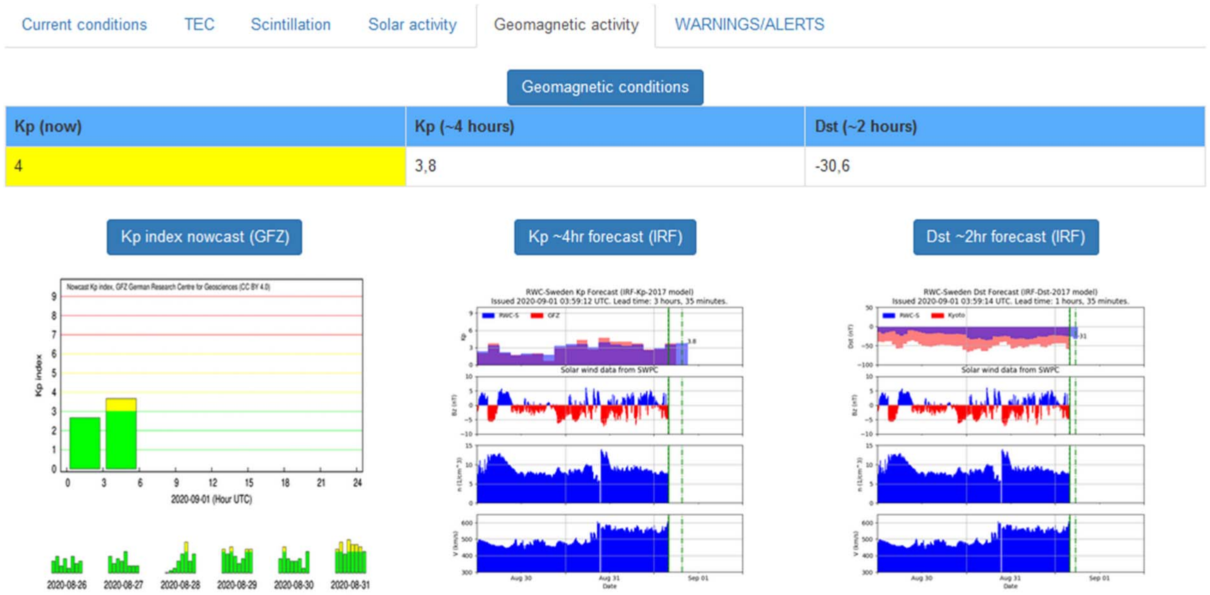

Figure 5: Overview of the geomagnetic activity section

Finally, the dashboard is linked to the following alerts which are directly relevant to ionospheric disturbances:

- ➢ Period of expected high space weather activity in the next 48 hours
- ➢ Human based alert system of solar or geomagnetic activity in case where automated processes have failed or are late as well as follow up and complementary information on the automated alerts.
- ➢ Occurrence of X-ray flares of classes M5 and up in near-real-time
- ➢ Ionospheric alerts based on the implementation of the Solar Wind driven autoregression model for Ionospheric short-term Forecast (SWIF)

Their status, last occurrence and details are included. The first three alerts are provided by the SIDC and the last by the Ionospheric Group of the National Observatory of Athens (NOA/EIS).

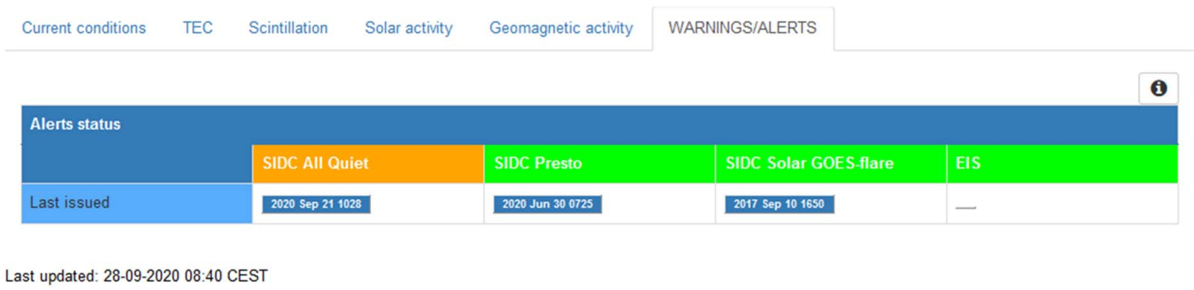

Figure 6: Overview of the alerts/warnings section

All the products used to construct this dashboard and offer a global and quick overview of the ionospheric impact on GNSS users are listed in Table 2.

Table 2: List of the SWE Portal products presented on the GNSS dashboard (by section)

Product name	**URL**
Current conditions	
Forecast of Kp	http://swe.ssa.esa.int/web/guest/irf-federated
Forecast of Dst	http://swe.ssa.esa.int/web/guest/irf-federated
AWARE_NEXT Enhanced 24 hour solar wind forecast	http://swe.ssa.esa.int/web/guest/dtu-aware-next-federated
TEC	
TEC map (Europe), current	http://swe.ssa.esa.int/web/guest/swaci-federated
TEC map (Europe), 1hr forecast	http://swe.ssa.esa.int/web/guest/swaci-federated
ROTI maps for Europe	http://swe.ssa.esa.int/web/guest/upc-federated
IONMON TEC maps	https://swe.ssa.esa.int/ionmon/
TEC map (Global), current	http://swe.ssa.esa.int/web/guest/swaci-federated
TEC map (Global), 1hr forecast	http://swe.ssa.esa.int/web/guest/swaci-federated
SISTED	http://swe.ssa.esa.int/web/guest/upc-federated
SOLERA drift	http://swe.ssa.esa.int/web/guest/upc-federated
Nowcasts and Forecasts of Geomagnetic and Solar Indices	http://swe.ssa.esa.int/web/guest/forind-federated
Scintillation	
S4 maps (Northern Europe)	http://swe.ssa.esa.int/web/guest/rtim-federated
σφ maps (Northern Europe)	http://swe.ssa.esa.int/web/guest/rtim-federated
Local scintillation indices S4 & σφ Neustrelitz	http://swe.ssa.esa.int/web/guest/swaci-federated
Local scintillation indices S4 & σφ Kiruna	http://swe.ssa.esa.int/web/guest/swaci-federated
Local scintillation indices S4 & σφ Tenerife	http://swe.ssa.esa.int/web/guest/swaci-federated
Local scintillation indices S4 & σφ Toulouse	http://swe.ssa.esa.int/web/guest/swaci-federated
Solar activity	
A-EFFort Solar flare forecast	http://swe.ssa.esa.int/web/guest/rcaam-federated
SIDC Solar flare forecast	http://swe.ssa.esa.int/web/guest/sidc-S109b-federated
SIDC 10.7cm Solar radio flux (F10.7) forecast	http://swe.ssa.esa.int/web/guest/sidc-S109a-federated
SIDC Daily space weather bulletin	http://swe.ssa.esa.int/web/guest/sidc-S110-federated
Near-Earth solar wind forecasts (WSA-Enlil + Ensemble)	http://swe.ssa.esa.int/web/guest/metoffice-enlil-e-federated
Geomagnetic activity	
Forecast of Kp	http://swe.ssa.esa.int/web/guest/irf-federated
Forecast of Dst	http://swe.ssa.esa.int/web/guest/irf-federated
Nowcast Kp index	http://swe.ssa.esa.int/web/guest/gfz-kp-federated
Warnings/Alerts	

Product name	URL
SIDC All quiet alert	http://swe.ssa.esa.int/web/guest/sidc-S113-federated
SIDC Human operator alert moderation	http://swe.ssa.esa.int/web/guest/sidc-S112z-federated
SIDC Solar GOES-flare alert	http://swe.ssa.esa.int/web/guest/sidc-S112a-federated
Alerts for ionospheric disturbances in the European sector	http://swe.ssa.esa.int/web/guest/dias-federated

All of the key products in the dashboard are automatically monitored and the table describing the impacts is always pre-filled based on the thresholds defined in Table 1 for those products. It will give in near real-time the impact level showing a general overview of the current situation. The forecast analysis and the detailed information on the impacted area or duration need manual input from an operator. In case any unusual activity is detected, an alert will first be sent to the on-duty SSCC operator. He will analyze the space weather conditions and provide a more detailed estimation of the impact with additional information on the onset of the event, its location and duration.

At this point and on basis of all the information gathered in the dashboard by the SSCC operator, the users will be personally contacted. Warning and alert messages for expected/observed ionospheric disturbances with possible GNSS interference are issued and delivered to the end user by SMS and an email that includes a screenshot of the dashboard. To classify the impact level as low, moderate and severe, ad hoc thresholds are adopted as they may depend on the type of application.

It should be mentioned that at this stage the main interest of the test users involved in establishing this test campaign, is in being aware of the current SWE conditions and possible impacts on GNSS when an event is predicted or ongoing. Other use-cases could be foreseen in the future based on the results of this campaign and/or participation of additional users with different needs.

4. Summary and outlook

This paper is focused on the relationship between Space Weather events and impacts on ionospheric disturbances affecting the GNSS community. In the frame of its Space Safety programme, the European Space Agency is establishing a Space Weather Service Network to support end users in mitigating the effects of space weather on their systems, reducing costs and improving reliability. The SSCC is at the forefront of this action by developing an end user campaign targeting specifically the GNSS community.

A dashboard has been designed together with a SWE bulletin tailored according to the needs of GNSS service users. Both are updated regularly on basis of user feedback and new products being integrated into the network. This system provides the user with alerts/warnings by SMS/emails whenever an impact on GNSS systems is expected based on the monitoring of products issued from the SSA SWE Service Network.

Currently the campaign is focused on requirements from test users active in the field of real-time kinematic (RTK) positioning and differential GNSS positioning.

Access to the GNSS dashboard and SMS/email service is currently restricted to the group of test users, but we welcome GNSS end user communities to contribute with feedback and recommendations. For further information, please contact the helpdesk by email (helpdesk.swe@ssa.esa.int).

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