17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.




# Services for Spacecraft Operations support within the ESA Space Weather Service Network

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**Abstract**

The dynamic space environment can lead to potentially hazardous and sudden effects on spacecraft that can have serious impacts on operations and service provision. The continuous real-time monitoring of space weather allows to make informed decisions related to spacecraft operations and helps with the correlation of results for future risk mitigation. Established in the frame of the ESA Space Situational Awareness programme and further strengthened in the ESA Space Safety programme, the ESA Space Weather Service Network combines European assets, including ground- and space-based space weather monitoring systems and data-processing and modelling capabilities. It builds on these in combination with expert support to develop user-tailored services, providing timely and reliable space weather information to end users. Individual products, reports, toolkits and user support are grouped into targeted services according to the needs of user communities ranging from spacecraft operators to power system operators. The network is organised around five Expert Service Centres focusing on Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather and Geomagnetic Conditions, in addition to a central Data Centre and a Coordination Centre. As part of its service evolution strategy, the network sets up user support campaigns during which tailored space weather information is proposed through prototype dashboards and/or bulletins. The campaigns focus on periods of high solar activity and help establish tailored alerting schemes. Campaign feedbacks are taken as inputs for further service developments and product improvements. This paper provides a status of the services currently offered by the ESA Space Weather Service Network Portal (https://swe.ssa.esa.int) and some lessons learned from the user campaigns. A focus is given on data products, tools and support that can help operators anticipate and possibly mitigate space weather effects. In addition, the recent user campaign performed in collaboration with the European operational satellite agency EUMETSAT for its fleet in both Low-Earth and geostationary orbits is presented.
**Keywords:** space weather, space situational awareness, service network

**Acronyms/Abbreviations**

Error Detection And Correction (EDAC)
European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)
European Space Agency (ESA)
European Space Operations Centre (ESOC)
European Space Weather Week (ESWW)
Expert Service Centre (ESC)
Geostationary Orbit (GEO)
Low-Earth Orbit (LEO)
Space Safety Programme (S2P)
Space Situational Awareness (SSA)
SSA Space Weather Coordination Centre (SSCC)

## 1. Introduction

Following the authorisation at the November 2008 ESA Ministerial Council [1] to launch its Space Situational Awareness Programme, the European Space Agency initiated the development of space weather services aiming to provide timely and reliable space weather information to their targeted end users. Since Europe already had a wealth of expertise and assets in the domain of space weather [2], the first services were established through the federation of existing and available assets or through the enhancement of already existing capabilities. The resulting preliminary service network, its web portal and its coordination centre were unveiled in 2013 [3]. Since then, the service network has substantially grown through the regular introduction of new and innovative products and the improvement of the necessary processes ensuring a reliable provision of its services. The network's growth and development continue today as part of the Space Safety Programme, succeeding to the SSA Programme since 2020 [4].

The resulting ESA Space Weather Service Network is based on a federated architecture where the service provision is carried out by a distributed network of entities in the Programme Member States, the overall provision being planned and monitored by a coordination centre, i.e., the SSA Space Weather Coordination Centre (SSCC), and five Expert Service Centres focusing on Solar Weather, Heliospheric Weather, Space Radiation Environment, Ionospheric Weather and Geomagnetic Conditions, respectively. Currently the Space Weather Service Network gathers 265 products or tools [5] provided by 52 participating groups distributed among 17 countries. However, the Space Weather Service Network is still in an intensive development phase targeting the introduction of tailored user interfaces and new key products to improve the accuracy of the information provided to the end users. Those developments target the requirements established during the SSA Programme [6][7] and are further guided by the feedback of the network user community. The programme's baseline requirements organize the Space Weather Service Network into 39 services grouped into service domains: Spacecraft Design, Spacecraft Operation, Human Space Flight, Launch Operation, Transionospheric radio link, Space Surveillance and Tracking, Power Systems Operation, Aviation, Resource Exploitation System Operation Pipeline Operation, Auroral Tourism, and General data services. For instance, the service domain Spacecraft Operation is split into five services: In-Orbit Environment and Effects Monitoring; Post-Event Analysis; In-Orbit Environment and Effects Forecast; Mission Risk Analysis; and, Space Weather in the Solar System. Appendix A provides a list of products and tools available in the network which are provided as part of the Spacecraft Operation service domain.

In the current network development, emphasis is put on the feedback of the end user community. That feedback is collected either by engaging discussions with end users during networking events such as the European Space Weather Week (see for instance [8]), by inviting some end users to a dedicated workshop, or by dialoguing with selected users on the definition of a specific interface tailored according to their needs. Such dialogue may result in the provision of dedicated space weather bulletins [9] or dashboards. Examples of the interaction with the spacecraft operation community are summarized in Section 2. Section 3 provides a more detailed description of the tailored dashboards prepared for the EUMETSAT spacecraft operators. Section 4 is dedicated to the lessons learnt and the conclusion.

## 2. End-user engagement examples

### *2.1. End-user meeting*

Typically, during the annual European Space Weather Week meeting, one or two end-user meetings are organized by the SSCC team in relation to the subject of one of the plenary sessions. For instance, such a meeting took place on October 29, 2021, in relation to the plenary session "Spacecraft operations" of the 17th ESWW [10]. After a short introduction about the relevant ongoing network developments, a discussion was initiated mainly on the desired type of products, on the risk enhancement due to large constellations, and on the space weather awareness following a relatively weak solar cycle. The discussion allowed the network to better understand the areas where improvements are expected by the spacecraft operation community. If time and budget allow, visits are paid to the end-user's premises.

### *2.2. End-user training*

On request, the SSCC team may organize a dedicated training session either online or in-person at the users' premises. For instance, such training was provided online on January 18, 2022, to ESA operators involved in Solar System Missions located at ESOC. During a training session, these topics are usually covered: the potential space weather impact, an introduction to the ESA Space Weather Service Network Portal, and some relevant use cases executed as far as possible on-line during the training. As far as possible, the use cases are adapted to the audience. Those use cases usually trigger practical questions from the participants. While the training aims to increase awareness of the products and tools available in the network, those questions help the network to capture end-user needs and identify possible gaps in the network offered services.

### *2.3. User Support Campaign*

Upon request, the SSCC may provide a tailored service during a dedicated campaign. The tailored service is based on an adaptation of the relevant service concept and is based on the products and tools available in the ESA Space Weather Service Network. Before the campaign, the SSCC iterates with the end users in order to concur on the campaign duration, the product adaptations, and the format of the tailored service. Depending on the users' needs, the tailored service could be implemented either as regular space weather bulletins, as a web page with a dashboard, as an alert message, or as a combination of those. The preparation of a campaign usually requires the support of the ESC expertise and may include several iterations with the end users in the loop. In this frame, different demonstration dashboards are being developed for ESA Mission operators and others, such as the campaign for the EUMETSAT spacecraft operators detailed in Section 3. Fig. 1 illustrates an example of space weather bulletin generated in October 2020 to support the ESA BepiColombo mission. Those user support campaigns allow to demonstrate the available capability of the network and to assess the applicability and usability of its services.

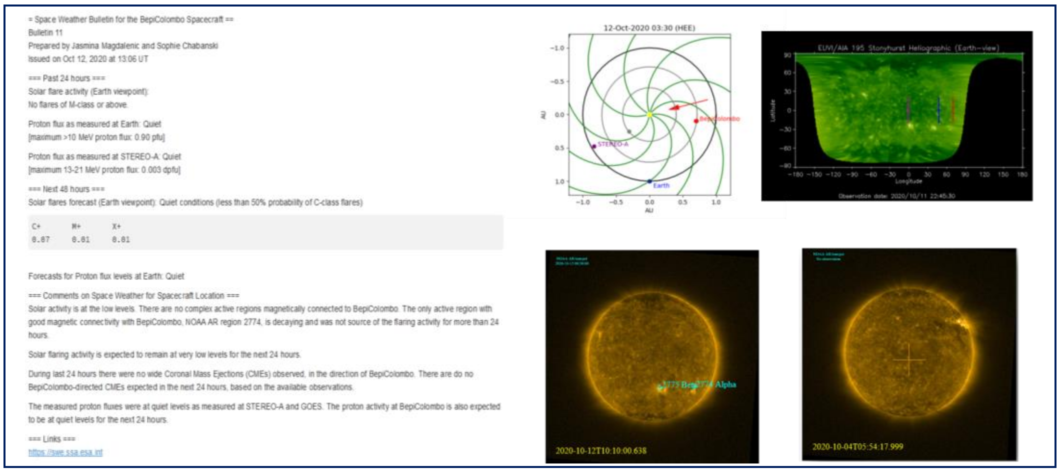

Fig. 1. Space weather bulletin prepared to support the Venus flyby of the BepiColombo mission.

## 3. Illustration of tailored dashboards

This Section describes the tailored prototype dashboard prepared by the SSCC team to support mission operations at LEO and GEO, with a focus on radiation effects, atmospheric drag and general space weather conditions. The dashboard is prepared in cooperation with EUMETSAT, which operates a fleet of satellites in geostationary and low Earth polar orbit.

Spacecraft operations can be strongly affected by space weather. Among the possible effects (depending on the orbit):

- Electrostatic discharges, due to surface and/or internal spacecraft charging by energetic electrons produced during geomagnetic (sub)storms;
- Single Event Effects, induced in microelectronic devices by energetic particles from the trapped radiation belts, Galactic Cosmic Rays, or Solar Proton Events;
- Solar panel performance degradation from displacement damage created by energetic particles or from erosion due to atomic oxygen;
- Star tracker failure during solar proton storms;
- Spacecraft communication disruptions caused by ionospheric disturbances;
- Increased spacecraft drag due to short-term atmospheric heating from solar flares or geomagnetic storms.

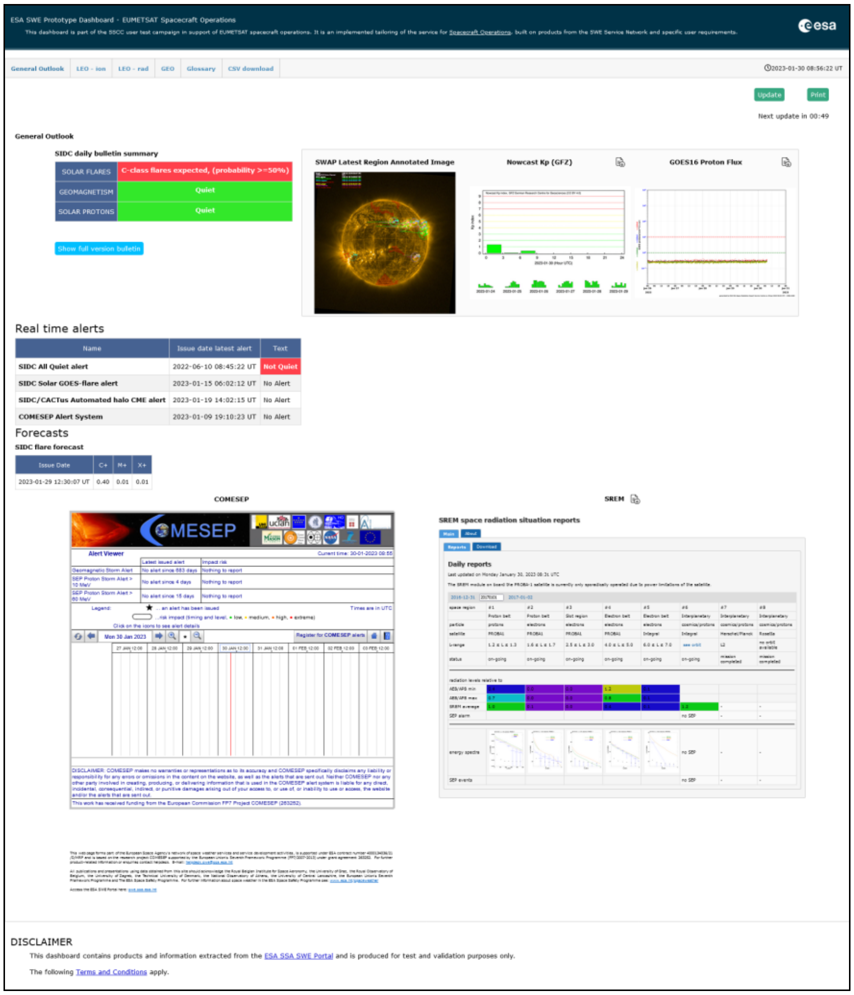


Fig. 2. Screen capture of the ESA Space Weather Service Network prototype dashboard tailored for EUMETSAT spacecraft operations

The prototype dashboard tailored for EUMETSAT operations consists of a web page with six tabs, most tabs gathering different thumbnails of the relevant products. The thumbnails are dynamically updated and designed to give a quick overview of the related product. If needed the user can easily access the full product (displayed on the network Portal) from the thumbnail. The first tab (see Fig. 2) provides a general outlook on the current space weather conditions, their forecast and the possible active alerts. The two next tabs are dedicated to the satellite fleet in polar orbit, where the second tab (see Fig. 3) covers the ionospheric conditions and atmospheric drag, and the third tab (see Fig. 4) addresses the space radiation environment. The fourth tab is dedicated to the fleet at GEO (see Fig. 5) and focusses on the radiation environment and related risks for charging and total ionising dose rate, as well as the risk of a geomagnetic storm. The two last tabs provide an extended glossary of terms used by the displayed products, and an interface to download files with the numerical data of the most relevant products.

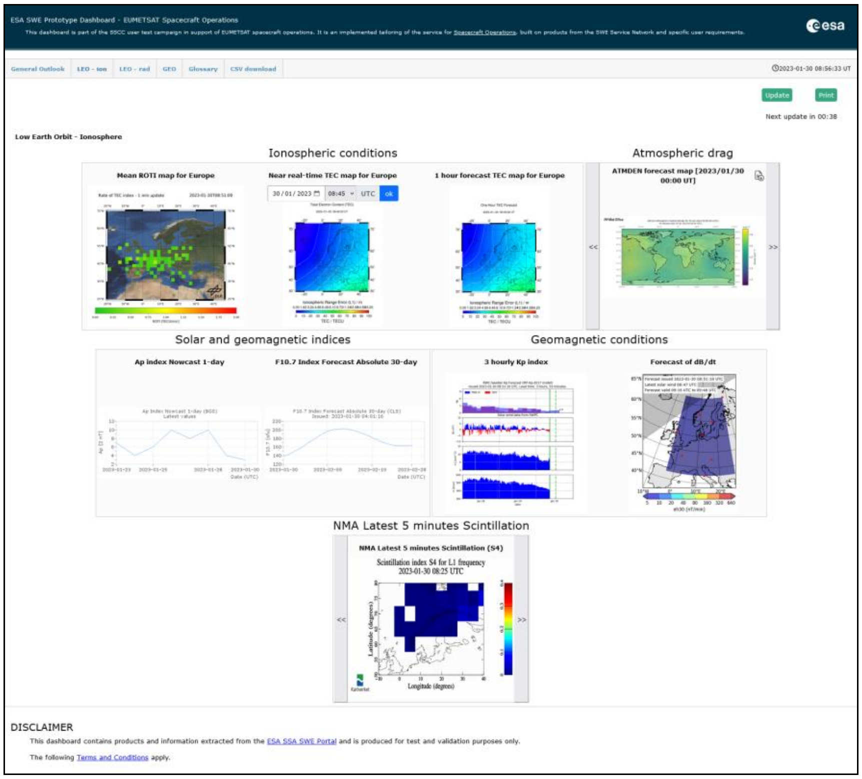


Fig. 3. Screen capture of the tab “LEO – Ionosphere” of the ESA Space Weather Service Network prototype dashboard tailored for EUMETSAT spacecraft operations

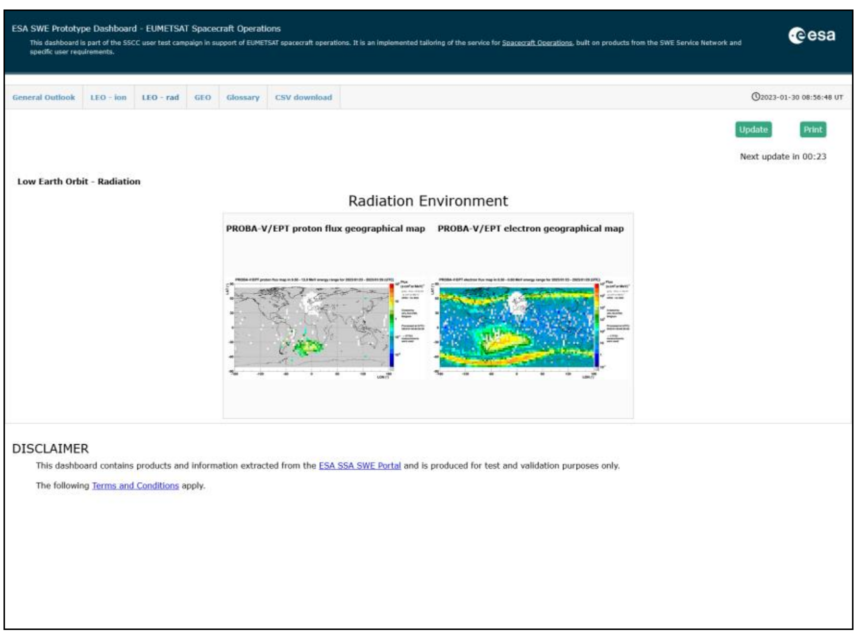


Fig. 4. Screen capture of the tab “LEO – Radiation” of the ESA Space Weather Service Network prototype dashboard tailored for EUMETSAT spacecraft operations

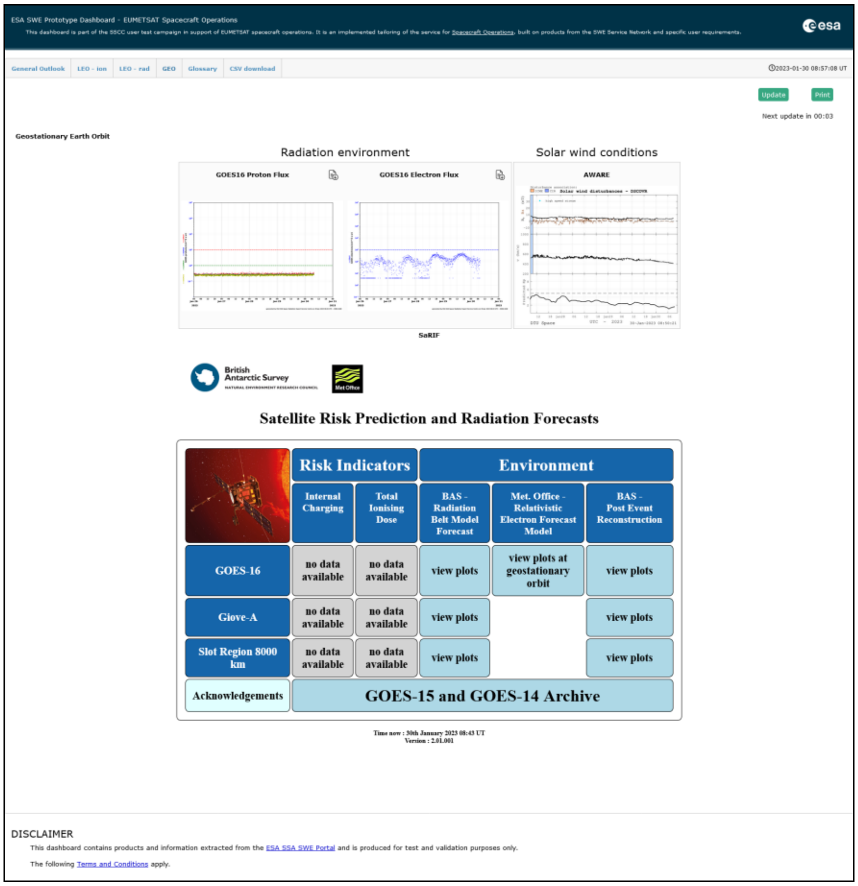

Fig. 5. Screen capture of the tab "GEO" of the ESA Space Weather Service Network prototype dashboard tailored for EUMETSAT spacecraft operations

## 4. Lessons learnt

Dialogue with end users is an important part of developing the ESA Space Weather Service Network's services. The end users and the space weather expert community do not always share the same vocabulary, the same understanding of the challenges, or the same timeline. The users generally worry more about the practical consequences on their everyday tasks, while the space weather experts may naturally tend to focus on the physical processes causing the impact. The ESA Space Weather Service Network aims to mitigate some of these challenges by encouraging dialogue, development and testing involving both the expert community participating in the ESA Space Weather Service Network and end users through some of the fora described in this paper. The end users also expect a rapid implementation of their wishes or suggestions. While some of the end-user requests and feedback received over the course of these engagements require major development work which can be lengthy, the multiplicity of channels to engage this dialogue and the implementation of demonstration prototypes allow to partly mitigate those hurdles and demonstrate increased responsiveness to user needs.

From the dialogue with the spacecraft operation community, it is evident that there is a strong interest for support to post-event analysis of recorded anomalies. What was the spacecraft space environment at the time of anomalies? May the anomalies be caused by this space environment? Did this spacecraft (or another one) experience similar space environment in the past, and did it suffer of the same impact? Another result concerns the current requirements specifying the space weather services, which are currently being updated on the basis of end-user feedback to further reflect recent developments in the sector, such as the use of electric propulsion to raise a satellite orbit to GEO, the satellite-as-a-service approach, the management of large constellations in LEO, etc.

Spacecraft operators may also want to build their own space weather report to link it with their (real) spacecraft data like occurrence of scrubbing and EDAC errors, or single-event upset induced anomalies. Hereto space weather information is desired to be provided in a format that is easy to integrate into the operators' own tools. With respect to make (basic) risk calculations for operations, spacecraft operators prefer measurements (e.g. particle fluxes) being expressed in terms of a simple normalisation against a median or nominal value.

### *4.1. Conclusion*

This paper describes how the ESA Space Weather Service Network approaches its support to the different user communities, and in particular to the Spacecraft Operation domain. The network development process is guided by regular assessments of its portfolio, with end users in the loop. The challenge of this process is to understand the user needs and to translate them into tailored services in a reasonable timeframe.

**Acknowledgements**

This work was performed in the frame of ESA Space Safety Programme 's network of space weather service development and preoperational activities and supported under ESA contract number 4000134036/21/D/MRP.

## Appendix A (Extract of the ESA Space Weather Service Network products and tools)

Table 1 provides a listing of the main products and tools of the ESA Space Weather Service Network currently implementing the services of the Spacecraft Operation domain. The products and tools are sorted by the label listed in the first column and used on the network web portal for their quick access. The label is usually an abbreviation of either the product name, the provider's name or a past project name. The second column gives the associated product codes as used in the network product catalogue [5]. The first letter of the codes corresponds to the Expert Service Centers to which the product is associated (S = Solar Weather, H = Heliospheric Weather, R = Space Radiation Environment, I = Ionospheric Weather and G = Geomagnetic Conditions). The last column of Table 1 contains the name of the product provider and the corresponding Programme Member State.

Table 1. Space weather products and tools part of the Spacecraft Operation service domain

| Label | Product Code(s) | Product description | Provider (Country) |
|---|---|---|---|
| A-Effort | S.124 | Solar-flare prediction service that monitors, evaluates, and provides advance warning of intense solar flare activity. | Research Center for Astronomy and Applied Mathematics, Academy of Athens (Greece) |
| Alert/E | H.106a | Alerts, watches, and warnings for geomagnetic and solar radiation storms in the near-Earth space. | Met Office Space Weather Operations Centre (United Kingdom) |
| ATMDEN | I.132 | Atmospheric density estimates in the altitude range 120–1500km for atmospheric drag calculation. | Met Office Space Weather Operations Centre (United Kingdom) |
| AWARE AWARE_A | H.106b, H.110b | Automated in-situ detection of interplanetary shocks, coronal mass ejections and high speed streams arriving either at the Lagrange L1 point or at the location of the STEREO-A spacecraft. | Technical University of Denmark (Denmark) |
| AWR_NXT | H.101f | Automated prediction of the potentially geo-effective solar wind disturbances at the Lagrange L1 point within the next 24 hours due to the Sun co-rotating interaction regions and the associated trailing high-speed streams. | Technical University of Denmark (Denmark) |
| COMESEP | R.134 | Automated forecasts of geomagnetic storms and solar energetic particle radiation storms based on the detection of solar flare or coronal mass ejections. | Royal Belgian Institute for Space Aeronomy (Belgium) |

| Label | Product Code(s) | Product description | Provider (Country) |
|---|---|---|---|
| DBEM<br>DBM | H.103b, H.108b | Travel and arrival time predictions of the interplanetary coronal mass ejection at an arbitrary ecliptic-plane location based on ensemble runs of a magnetohydrodynamical drag-based model | University of Graz (Austria) |
| EDID | R.107 | European Debris Impact Database providing data processing and dissemination functions from debris and meteoroid impact detector measurements. | European Space Agency (ESA) |
| EIS | I.114, I.116, I.120 | Long term prediction maps of foF2 and forecasted foF2 values for the next 24 hours over ten ionosonde stations | Ionospheric Group of the National Observatory of Athens (Greece) |
| Enlil/E (/Me, /V, /Ma) | H.101a, H.101c, H.103a, H.107a, H.108a, H.110a | Predictions of CME arrival times and solar wind speed and density near Earth (or near Mercury, Venus, Mars, resp.) based on the WSA-Enlil 3d heliospheric model. | Met Office Space Weather Operations Centre (United Kingdom) |
| EPT | R.109 – R.117, R.137 – R.141, R.160 – R.162, R.168 – R.169 | Measurements of energetic electrons, protons and helium fluxes at LEO orbit obtained from the Energetic Particle Telescope onboard PROBA-V | Center for Space Radiations (Belgium) |
| ESWF | H.101b | Forecast of background solar wind speed based on empirical relation linking the area of coronal holes to the high speed streams measured at Earth. | University of Graz (Austria) |
| ESWF24 | H.101h | Reliable short-term background solar wind speed forecast over three time windows (24h, 36h and 48h) based on the observation of coronal hole area. | University of Graz (Austria) |
| Flarecast | S.109e | Automated forecasting system for solar flares based on a machine learning algorithm. | University of Applied Sciences Northwestern Switzerland (Switzerland) |
| FORIND | I.133 | Nowcasts and forecasts of geomagnetic and solar indices needed for atmospheric modelling in support of drag calculation. | Institute of Space Science Romania (Romania) |
| Heliopropa | H.107b | 1d Magnetohydrodynamical model propagating observed plasma properties observed at Lagrange L1 point to other locations within the solar system. | Institut de Recherche en Astrophysique et Planétologie (France) |
| HESPERIA | R.158 – R.159, R.163 | Forecasts of solar energetic particle events at low and high proton energy ranges and associated notification system. | Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing (Greece) |
| HPARC/PR | H.112a | Timeline of heliospheric weather events on a month-by-month basis using inputs from the various products. | RAL Space (United Kingdom) |
| IMPC | I.103a, I.103b, I.104, I.124 | Near real-time information and data service for the current state of the ionosphere, related forecasts and warnings. | DLR Ionosphere Monitoring and Prediction Center (Germany) |

| Label | Product Code(s) | Product description | Provider (Country) |
|---|---|---|---|
| IRF | G.113,<br>G.134 – G.135 | Forecast of geomagnetic indices: Kp, Dst and dB/dt. | Swedish Institute of Space Physics (Sweden) |
| MSSL | R.131 – R.133 | Empirical electron population model at LEO, MEO and GEO as function of solar wind speed and Kp index. | Mullard Space Science Laboratory (United Kingdom) |
| PROPTOOL | H.103c | Tool assessing the propagation of coronal mass ejections, corotating interaction regions and solar energetic particles through the interplanetary medium. | Institut de Recherche en Astrophysique et Planétologie (France) |
| SaRIF | R.142 – R.148 | Colour-coded Satellite Risk Indicators Forecasts showing the risk from internal charging and total ionising dose for the outer radiation belt and slot region, as well as a reconstruction of these environments. | British Antarctic Survey (United Kingdom) |
| SEP/E | H.105a | Energetic proton fluxes from the Primary and Secondary GOES spacecraft providing indication of solar energetic particles enhancements in the near-Earth heliosphere region. | Met Office Space Weather Operations Centre (United Kingdom) |
| SEPEM | R.135 | Solar Energetic Particle Environment Modelling application providing solar energetic particle statistical analyses on an extended set of cross-calibrated data. | Royal Belgian Institute for Space Aeronomy (Belgium) |
| SIDC | S.101c, S.105c, S.109b, S.110, S.111, S.112z, S.127 | Annotated map of the solar disk (sunspots, coronal holes, filaments, etc.), probabilistic forecasts for the occurrence of X-ray flares, automated solar event detections, and daily space weather bulletin. | Solar Influences Data analysis Center (Belgium) |
| SPENVIS | R.103 | Space Environment Information System coupling several empirical and engineering models of the space environment and its effects on spacecraft or components based on a mission plan. | Royal Belgian Institute for Space Aeronomy (Belgium) |
| SPM | R.136 | Dynamical simulation providing forecasts the number density and temperature of electrons inside and outside the plasmasphere, based on predicted Kp values. | Royal Belgian Institute for Space Aeronomy (Belgium) |
| SREM | R.118– R.122 | Particle radiation environment index based on the Standard Radiation Environment Monitors onboard PROBA-1, Integral and Rosetta | P. Buehler (Austria) |
| STA+CH | H.101e | Solar wind speed forecast based on a STEREO-A persistence model | University of Graz (Austria) |
| SWE Data | — | Space Weather Data Browsing and Analysis providing access to space weather environment and monitoring data. | European Space Operations Centre (ESA) |
| SWFSC/E | H.101z | Simplified overview of all the available models to forecast solar wind speed at Earth. | RAL Space (United Kingdom) |
| UAH | G.127– G.130 | Geomagnetic indices, Dst Forecast, geomagnetic conditions and a regional geomagnetically induced currents proxy. | Universidad de Alcalá (Spain) |
| UKMO | S.109c, S.123c | Probability of solar flare occurrence, and solar active region analysis including human forecaster assessment about X-ray flares over the next 24 hours. | Met Office Space Weather Operations Centre (United Kingdom) |

| Label | Product Code(s) | Product description | Provider (Country) |
|---|---|---|---|
| UTU-SEP | R.128– R.130, R.138 | High energy Solar Energetic Particle event catalogue, and estimation of the high energy proton fluence and worst-case proton flux due to solar energetic particles for a specific mission length. | Space Research Laboratory at University of Turku (Finland) |

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