New Data Products and Tools Available in Services for Spacecraft Operations Support within the ESA Space Weather Service Network

Lenka Zychová[a]*, Norma Crosby[b], Erwin De Donder[c], Mark Dierckxsens[d], Alexi Glover[e], Ralf Keil[f], Martin Kriegel[g], Michel Kruglanski[h], Hannah Laurens[i], Corentin Liber[j], Alice Michel[k], Jennifer O'Hara[l]

[a] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, lenka.zychova@aeronomie.be*
[b] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, norma.crosby@aeronomie.be*
[c] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, erwin.dedonder@aeronomie.be*
[d] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, mark.dierckxsens@aeronomie.be*
[e] *ESA Space Weather Office, Darmstadt, Germany, alexi.glover@esa.int*
[f] *Starion Deutschland GmbH, Darmstadt, Germany, ralf.keil@ext.esa.int*
[g] *German Aerospace Center, Cologne, Germany, martin.kriegel@dlr.de*
[h] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, michel.kruglanski@aeronomie.be*
[i] *Starion Deutschland GmbH, Darmstadt, Germany, hannah.laurens@ext.esa.int*
[j] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, corentin.liber@aeronomie.be*
[k] *Royal Belgian Institute for Space Aeronomy, Uccle, Belgium, alice.michel@aeronomie.be*
[l] *Royal Observatory of Belgium, Uccle, Belgium, jennifer.ohara@oma.be*
* Corresponding Author

Abstract

The dynamic space environment can pose significant risks to spacecraft operations, making continuous space weather monitoring essential for informed decision-making and risk mitigation. The ESA Space Weather Service Network, developed under the Space Situational Awareness and Space Safety programs, integrates European assets, including ground- and space-based monitoring, data processing, and expert support, to deliver tailored services for various user communities. Organized around five Expert Service Centres, a Data Centre, and a Coordination Centre, the network provides real-time space weather information via the ESA Space Weather Portal. This paper presents an update on available services, highlighting new data products, tools, and use cases demonstrating their application in spacecraft operations. Additionally, it discusses how user feedback, gathered through targeted test campaigns and dedicated dashboards, informs service improvements and key recommendations from a recent network review.

Keywords: Space Weather, Spacecraft Operations, Risk Mitigation, Spacecraft Charging, Single Event Effects, Radiation Effects

Acronyms/Abbreviations

- ACE – Advanced Composition Explorer
- API – Application Programming Interface
- ATMDEN – Atmospheric Density
- BAS-RBM – British Arctic Survey – Radiation Belt Monitoring
- BLEO – Beyond Low Earth Orbit
- BIRA-IASB – Belgian Institute for Space Aeronomy
- CMEs – Coronal Mass Ejections
- CNES – Centre National d'Études Spatiales
- COMESEP - COronal Mass Ejections and Solar Energetic Particles
- CSR – Center for Space Radiations
- DBEM – Drag-Based Ensemble Model
- DICTAT – Dielectric Internal Charging Threat Assessment Tool
- DTM2013 – Drag Temperature Model 2013
- EDRS-C – European Data Relay System-C
- EPAM – Electron Proton Alpha Monitor
- EPHIN – Electron Proton Helium Instrument
- EPT – Energetic Particle Telescope
- ESA – European Space Agency
- ESD – Electrostatic Discharge

- ESC – Expert Service Centre
- ESOC – European Space Operations Centre
- GEO – Geostationary Orbit
- GIOVE-A – Galileo In-Orbit Validation Element A
- GNSS – Global Navigation Satellite System
- GOES – Geostationary Operational Environmental Satellite
- GOES-16 – Geostationary Operational Environmental Satellite-16
- GRACE – Gravity Recovery and Climate Experiment
- HESPERIA – High-Energy Solar Particle Event Risk Assessment
- HESPERIA REleASE – HESPERIA Relativistic Electron Alert System for Exploration
- ICME – Interplanetary Coronal Mass Ejection
- ICEA – Internal Charging Environment Analysis
- IGAM – Institute of Physics, University of Graz
- KPI – Key Performance Indicator
- Kp – Geomagnetic index used to measure solar activity
- Kp index – Planetary K-index
- LEO – Low Earth Orbit
- MEO – Medium Earth Orbit
- NASA – National Aeronautics and Space Administration
- NGRM – Next Generation Radiation Monitor
- NOA/IAASARS – National Observatory of Athens, Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing
- ONERA – Space Radiative Environment Research Group
- PROBA-V – Project for On-Board Autonomy – Vegetation
- RAL – Rutherford Appleton Laboratory
- RB-FAN – Radiation Belt Forecast and Alert
- REFM – Relativistic Electron Forecast Model
- ROB – Royal Observatory of Belgium
- SAA – South Atlantic Anomaly
- SEB – Single Event Burnout
- SEE – Single Event Effects
- SEL – Single Event Latch-up
- SEP – Solar Energetic Particles
- SEU – Single Event Upset
- SIDC – Solar Influences Data analysis Center
- SOHO – Solar and Heliospheric Observatory
- SODA – Satellite Orbit DecAy
- SPARC – Space Applications and Research Consultancy
- SREM - Standard Radiation Environment Monitor
- SSA – Space Situational Awareness
- SSCC – SSA Space Weather Coordination Centre
- STFC – Science and Technology Facilities Council
- STRV-1C – Space Technology Research Vehicle-1C
- SWE – Space WEather
- UKMO – UK Met Office
- UMA – University of Málaga
- UNIGRAZ – University of Graz

1. Introduction

The space environment is dynamic and can adversely affect spacecraft operations, leading to potential disruptions in service provision and operation. Continuous real-time monitoring and forecasting of space weather enable informed decision-making for spacecraft operations and assist in identifying causes of experienced effects for future risk mitigation. The European Space Agency (ESA) has established the Space Weather Service Network to provide timely and reliable space weather information to end users. This paper provides an update on the services currently available through the network portal, highlighting the latest data products and tools designed to help spacecraft operators anticipate and mitigate space weather effects.

2. Overview of the ESA Space Weather Service Network

The ESA Space Weather Service Network is a robust initiative dedicated to demonstrating and testing European space weather capabilities with end users in the loop [1]. Through a robust and well tested pre-operational service provision model the network supports monitoring and forecasting space weather as well as the potential impact on technologies and biological systems. Implemented through five Expert Service Centres (ESCs) and the SSA Space Weather Coordination Centre (SSCC), the network is a collaboration of over 40 participating institutes and organizations across Europe. Each ESC brings together a set of Expert Groups focussing on a specific phenomenological domain within the space weather field, providing detailed scientific and technical expertise, as well as the necessary technical assets for data processing and service provision. The SSCC, located at the Space Pole in Brussels, Belgium, also hosts a Space Weather Helpdesk, offering support and responding to queries related to space weather services and conditions during normal working hours.

The ESCs monitor and forecast various aspects of space weather, including solar activity, heliospheric conditions, space particle radiation, ionospheric and upper atmospheric conditions, and geomagnetic conditions.

The ESA Space Safety Programme addresses the needs of space weather service users in various domains through targeted service developments. These service domains include:

- Spacecraft Designers
- Spacecraft Operators
- Human Spaceflight Mission Operators
- Space and ground-based service users affected by the ionosphere including GNSS System Users and communication System Users and Operators
- Space Traffic Coordination
- Power System Operators
- Pipeline Operators
- Airlines and Aerospace Sector including Regulatory Authorities
- Resource Exploration
- Aurora Observation and Forecast

The ESA Space Weather Portal (https://swe.ssa.esa.int) is the online component of the space weather services, offering access to 29 user-tailored services built on more than 335 individual products and tools [2]. The portal features a variety of data products, tools and reports along with graphs, graphics, maps, and observations of the Sun, interplanetary medium, solar wind, Earth's atmosphere, and geomagnetic environment. User-friendly features such as tiles, widgets, and dashboards enhance the experience and help users navigate through the wealth of information provided.

3. Services For Spacecraft Operations

The ESA's Space Weather Service Network offers a range of products and tools tailored to support spacecraft operations. These resources are designed to help operators anticipate and mitigate space weather effects. On the portal, a dedicated Spacecraft Operations Dashboard (see Figure 1) is available, from which users can explore specific spacecraft operation services in more detail. This dashboard also highlights selected key products, helping users quickly identify relevant data for their operational needs. The services for spacecraft operations include:

- <u>In-orbit Environment and Effects Monitoring:</u> This service provides real-time monitoring of the space environment and its effects on spacecraft systems. Operators can access data on ionizing radiation, plasma, microparticles, atmosphere, and ultraviolet radiation, along with information on resulting effects such as dose, single event upsets, sensor background, accumulated charge, and spacecraft anomalies. This information is crucial for assessing the current state of the spacecraft and making informed operational decisions.
- <u>In-orbit Environment and Effects Forecast:</u> This service offers forecasts of the space environment and its potential effects on spacecraft systems. By providing predictions of ionizing radiation levels, plasma conditions, and other relevant parameters, operators can proactively implement mitigation strategies to protect spacecraft systems from anticipated space weather impacts.
- <u>Mission Risk Analysis:</u> Aimed at personnel involved in spacecraft operations planning, this service provides information necessary for performing mission risk analysis and assessing susceptibility due to expected space environment conditions. It utilizes statistical models and historical data to inform operators about potential risks and guide the development of mitigation strategies.

- Post Event Analysis: This service helps spacecraft operators correlate spacecraft anomalies with space environment data. The network provides an archive of space weather events like solar storms, Coronal Mass Ejections (CMEs), and radiation enhancements that could impact spacecraft. This service supports understanding the causes of issues such as malfunctioning of avionics or orbit changes, allowing operators to take precautions and inform future spacecraft designs.
- Space Weather in the Solar System: This service offers forecasts, nowcasts, and alerts on space weather in the heliosphere, focusing on solar wind and its propagation. It supports solar system mission operators with decision-making based on solar observations and historical data. Future developments will enhance predictions for solar energetic particle events and extend solar wind models beyond Mars.

Figure 1: Snapshot of the Spacecraft Operation Dashboard: https://swe.ssa.esa.int/sco_dashboard

4. Space Weather Effects on Spacecraft Operations

Space weather encompasses various phenomena, including solar flares, coronal mass ejections (CMEs), geomagnetic storms, and energetic particle events, all of which can significantly impact spacecraft operations. These effects pose challenges to satellite performance, reliability, and longevity, necessitating continuous monitoring and developing mitigation strategies.

4.1 Ionizing and Non-ionizing Dose Effects

Energetic particles, such as protons and electrons from the Sun and cosmic rays, can cause gradual and cumulative damage to spacecraft electronics and materials. Ionizing radiation can degrade semiconductors, reducing the efficiency of solar panels and increasing noise in onboard sensors. Non-ionizing radiation, primarily from high-energy protons, leads to displacement damage in electronic components, affecting their long-term functionality.

4.2 Single Event Effects (SEEs)

High-energy particles penetrating spacecraft electronics can trigger single event effects, including:

- Single Event Upsets (SEUs): Bit flips in memory, potentially leading to incorrect data storage or software malfunctions.
- Single Event Latch-ups (SELs): Unintended current pathways in microchips, which can cause permanent failures if not mitigated.
- Single Event Burnouts (SEBs): Permanent damage to power transistors due to high current surges induced by particle interactions.

4.3 Surface and Internal Charging

Energetic electrons accumulating on spacecraft surfaces or within insulating materials can lead to electrostatic discharge (ESD), which may cause damage to electronics or even mission-ending failures. Surface charging typically occurs in low-energy plasma environments, while internal charging arises from higher-energy electrons penetrating deep into spacecraft structures.

4.4 Drag and Orbital Decay

Variations in atmospheric density, particularly during geomagnetic storms, alter spacecraft drag, affecting orbiting satellites in low Earth orbit (LEO). Increased drag can lead to premature orbital decay, necessitating corrective manoeuvres to maintain operational altitudes and avoid collisions with other space objects.

5. New Data Products and Tools for Spacecraft Operations Support

As space weather effects on spacecraft operations become more widely recognized, the need for advanced tools that enhance forecasting capabilities and post-event analysis is increasingly critical. To address these challenges, the ESA Space Weather Service Network continues to expand its portfolio with new data products and tools designed to support spacecraft operators in assessing environmental conditions and mitigating potential risks. These new offerings provide improved situational awareness by delivering detailed post-event analysis capabilities and enhanced forecasting tools, enabling operators to better understand past anomalies and anticipate future disruptions. The following section presents some of the latest additions (within the last two years) to the network's services, highlighting their role in supporting mission planning, anomaly resolution, and operational decision-making. For clarity on the new products and tools, we provide descriptions of their connections to the space weather effects on spacecraft, summarized in Table 1. Some of the products are listed as Demonstration Products, meaning that they are provided for the purposes of demonstration and testing, but not yet sufficiently validated against the criteria for use in the intended operational context and/or not yet sufficiently being demonstrated to meet operational use.

5.1 PROBA-V/EPT Total Ionizing and Non-Ionizing Dose Estimation (UCL/CSR)

The new PROBA-V/EPT products provide daily estimates of the total ionizing and total non-ionizing doses for a sun-synchronous orbit at 820 km altitude, along with corresponding particle contributions (electrons, protons, and helium), based on measurements from the Energetic Particle Telescope (EPT) aboard PROBA-V, see Figure 2, [3]. These measurements, collected over one calendar day, are compiled into monthly time series. The dose accumulation is compared against long-term averages, with significant increases (approximately 10 or 100 times higher) triggering color-coded alerts (yellow for x10 and orange for x100).

The new PROBA-V/EPT products help in monitoring accumulated radiation doses, enabling operators to anticipate degradation trends and implement mitigation strategies.

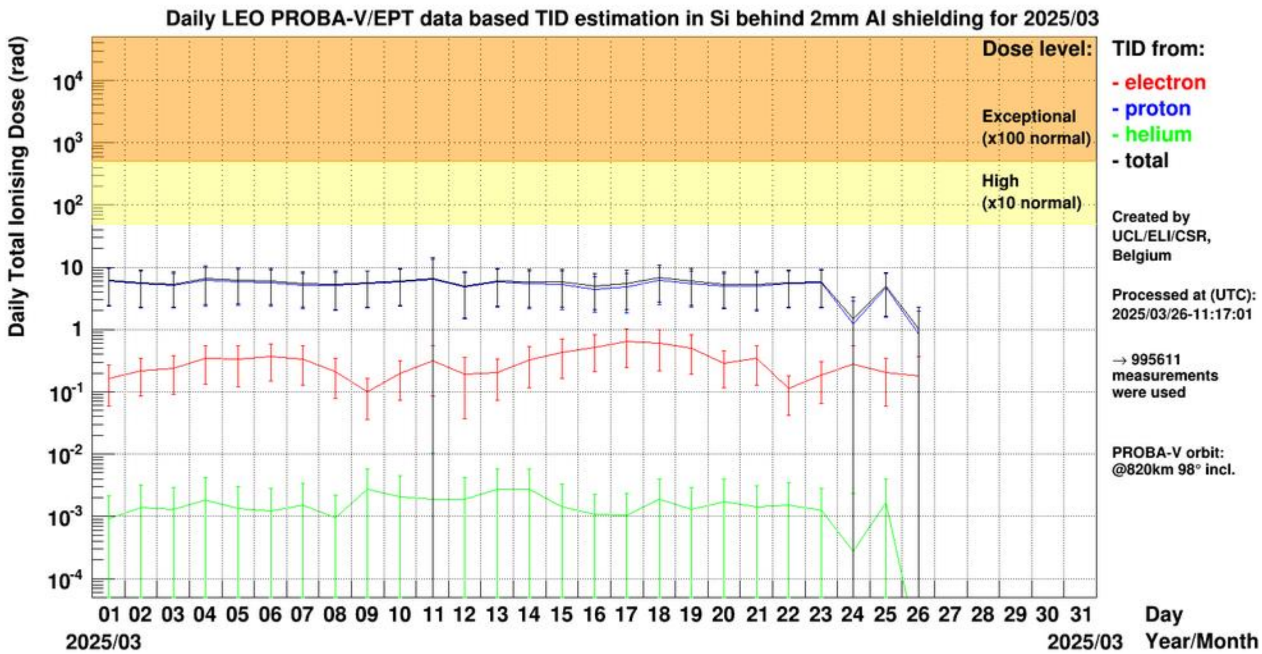

Figure 2: Example of PROBA-V/EPT Total Ionizing Dose Estimation as captured on 2025-03-26

5.2 GEO/NGRM Products (SPARC)

The ESA Next Generation Radiation Monitor (NGRM) is designed to measure energetic protons (starting from a few MeV up to 200 MeV) and electrons (from a few hundred keV and above) using a sophisticated detection system in GEO orbit [4]. The products help assess ionizing dose, SEE risks, internal charging and support post-event analysis, see Figure 3. The product suite includes several datasets:

- EDRS-C/NGRM L2 Electron Differential Fluxes and Proton Differential Fluxes, which offer interactive plots and cross-calibrated flux data for electrons and protons.
- GEO Electron Integral Flux Alerts and Proton Flux Alerts, providing real-time monitoring of radiation conditions at GEO with alerts based on deviations from historical measurements, with the possibility of subscribing to email alerts.
- EDRS-C/NGRM Electron Daily Fluences, offering daily averaged integral fluxes for electron energies exceeding 0.20, 0.60, and 1 MeV.
- GEO Multiple Electron Fluxes, integrating near real-time electron flux measurements from EDRS-C, Himawari-8, and GOES-16 satellites, enabling a comprehensive assessment of the electron environment at GEO.

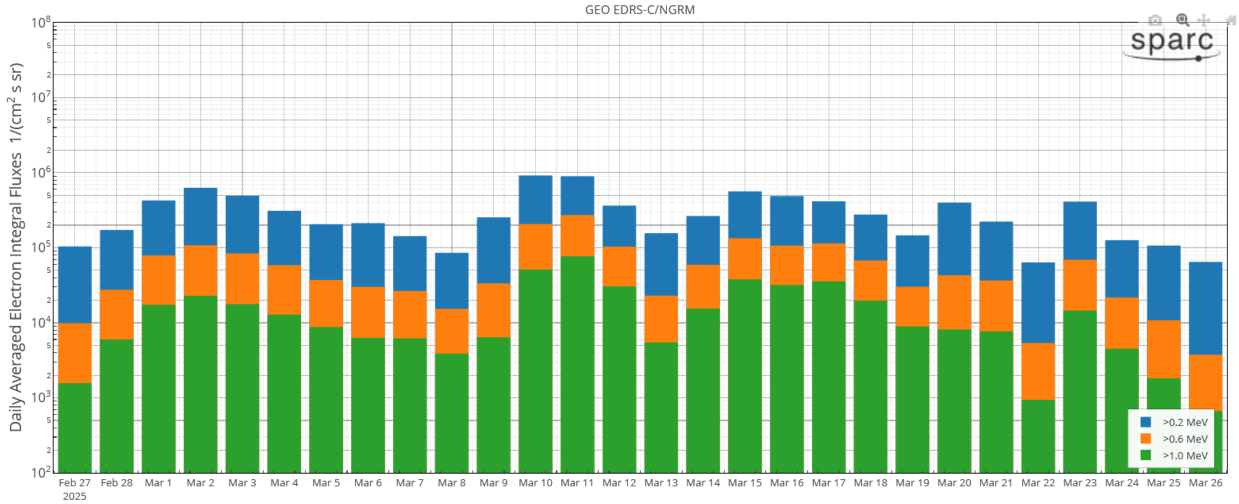

Figure 3: Example of EDRS-C/NGRM Electron Daily Fluences

5.3 ICEA Products (BIRA-IASB)

The Internal Charging Environment Analysis (ICEA) demonstration product suite evaluates the electrostatic discharge (ESD) risk at Geostationary Orbit (GEO) using the Dielectric Internal Charging Threat Assessment Tool (DICTAT). As a demonstration product, ICEA allows users to evaluate its potential benefits, validate its performance, and provide feedback for further development. By analyzing electron flux data from GOES-16 and forecasting electron environments using the Sheffield NARMAX Radiation Belt models [5], ICEA predicts potential ESD hazards for spacecraft. Key products include, see Figure 4:

- Internal Charging Environment and Analysis Report, which compiles daily updated reports on ESD risks.
- Internal Charging Environment Nowcast, providing real-time warnings for internal charging effects.
- Internal Charging Environment Forecast, offering predictions on when electron fluxes may reach hazardous levels.

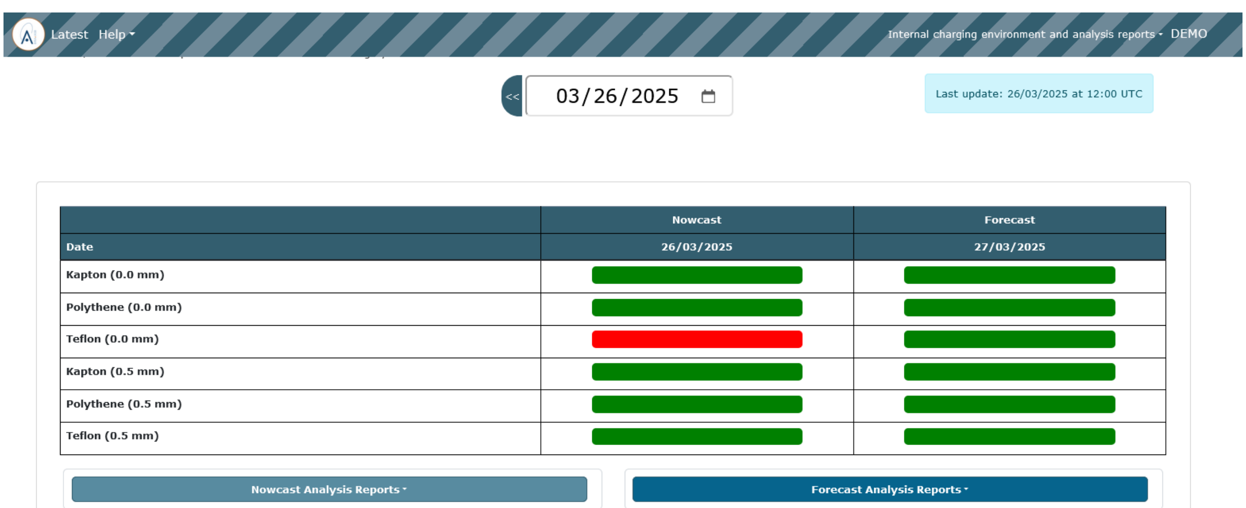

Figure 4: Example of ESD ICEA risk nowcast and forecast

5.4 RB-FAN Products (ONERA/ERS)

The RB-FAN demonstration products deliver nowcasts and three-day forecasts of radiation belt dynamics, offering actionable insights for spacecraft operators [6]. The system integrates models for predicting solar wind parameters, magnetospheric perturbations, and radiation belt variations. RB-FAN provides forecasts of radiation belt dynamics to anticipate potential hazards, see Figure 5.

The product suite includes:

- Radiation Belts Orbits Dedicated Risk Alert, summarizing daily radiation risk levels across different orbits (LEO, GNSS-MEO, GEO, and customizable orbits) using a color-coded system (green, orange, red).
- Deep Charging Risk Alert, estimating the spacecraft's internal electric potential to assess deep charging threats.
- Solar Cell Risk Alert, providing daily assessments of solar cell degradation risks.
- Expert Pages, which offer advanced analysis tools, including Kp index time series, omnidirectional differential proton flux forecasts, and solar cell degradation trends. RB-FAN simplifies space weather risk assessment by combining predictive models with real-time monitoring, ensuring effective decision-making for space missions.

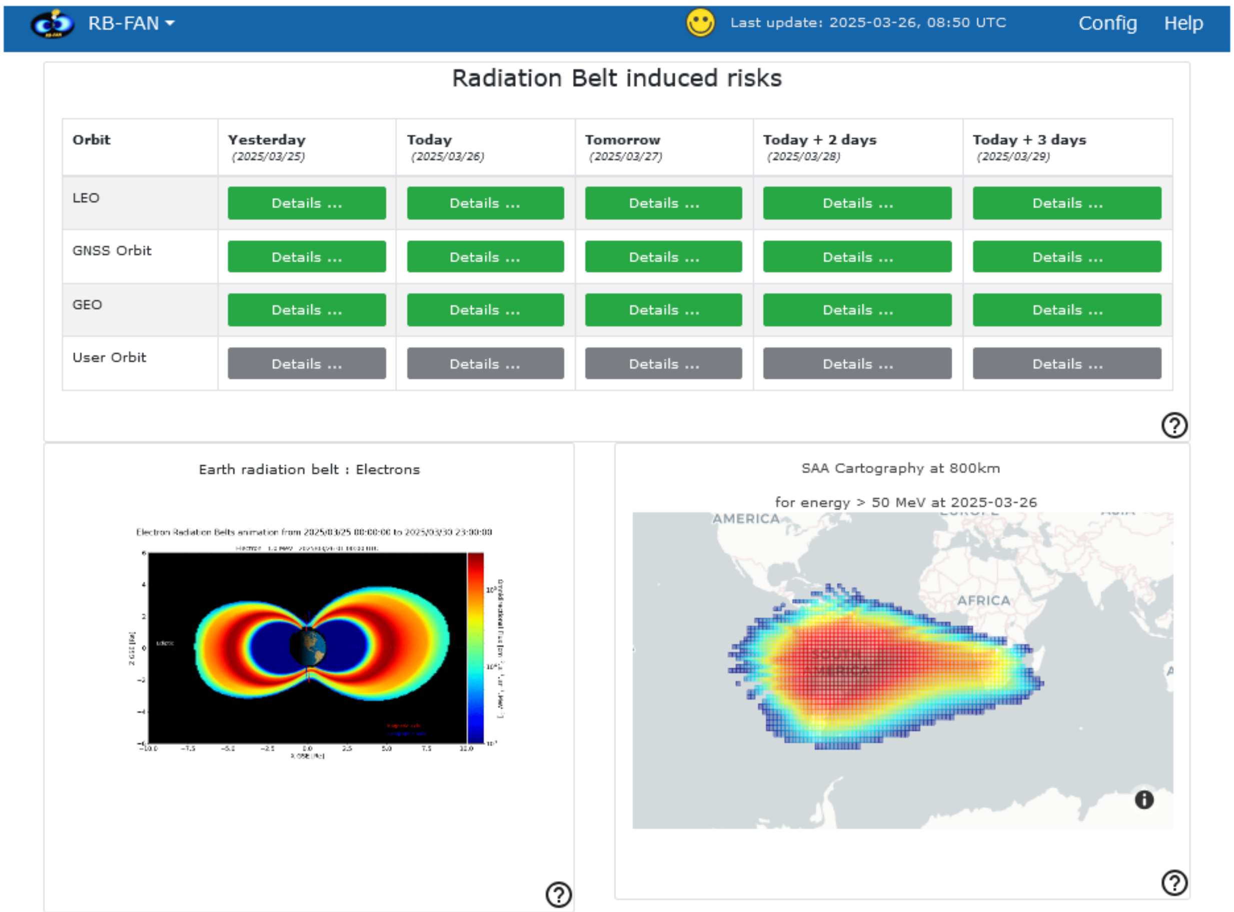

Figure 5: Example of RB-FAN Products Homepage

5.5 ATMDEN Products (UKMO)

The atmospheric density products provided by the UK Met Office include forecast and prior-estimate fields of thermospheric neutral density, from output of the DTM2013 model (developed and maintained by CNES), in the altitude range 120–1500 km to support users concerned with the calculation of spacecraft drag [7]. These forecasts, see Figure 6, help operators plan propulsion manoeuvres to counteract unexpected altitude changes, reducing the risk of premature re-entry or loss of control. The three neutral density products consist of:

- A higher cadence 3-day forecast issued every 3 hours,
- A 27-day forecast produced daily, and

- A historic prior estimate intended to provide the density estimate from the previous 12 months.

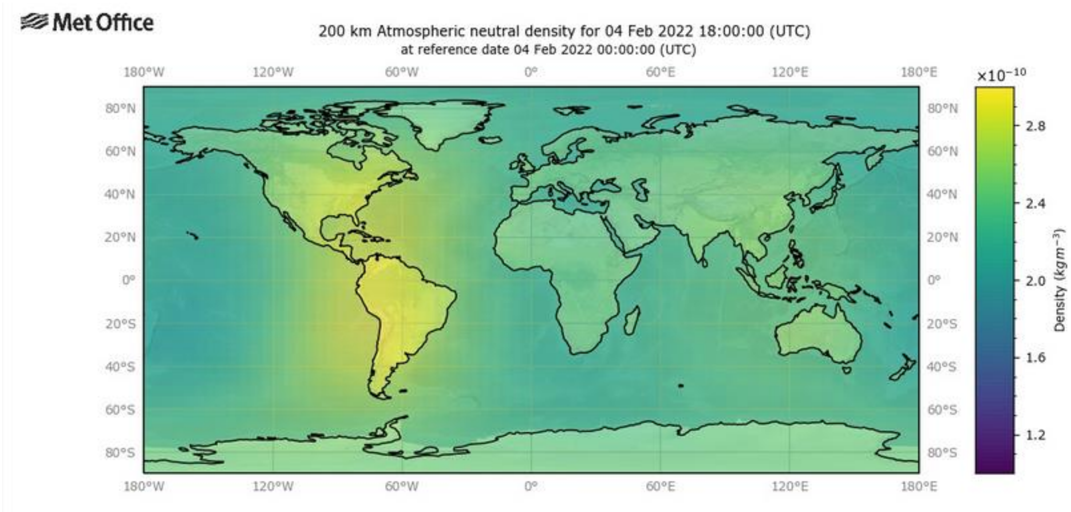

Figure 6: Example of ATMDEN atmospheric density map

5.6 SODA Product (UNIGRAZ/IGAM)

SODA (Satellite Orbit DecAy) provides a 15-hour forecast for satellite orbit decays induced mostly by interplanetary coronal mass ejections (ICMEs), having strong negative Bz. The calculated orbit drop (OD) results are normalized for satellites at orbit heights of about 490 km [8]. The SODA product, see Figure 7, helps predict these effects, allowing operators to prepare for altitude corrections, ensuring mission longevity.

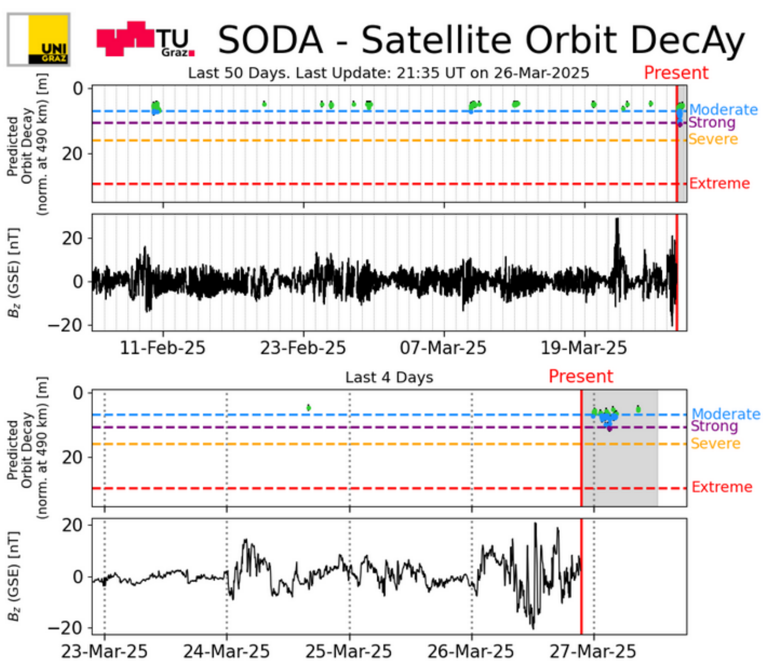

Figure 7: Example of SODA plots

5.7 HESPERIA REleASE Alert (NOA/IAASARS)

The HESPERIA Relativistic Electron Alert System for Exploration (HESPERIA REleASE) utilizes relativistic electron data from the Electron Proton Helium Instrument (EPHIN) on Solar and Heliospheric Observatory (SOHO) and near-relativistic electron measurements from the Electron Proton Alpha Monitor (EPAM) aboard the Advanced Composition Explorer (ACE) to provide deterministic forecasts of SEPs; proton flux at two energy ranges: 15.8–39.8 MeV and 28.2–50.1 MeV [9]. The system triggers an alarm, see Figure 8, when the forecasted proton flux reaches a specified threshold and when a short-term forecasted flux surpasses a lower predefined level. An event is confirmed if the actual measured proton flux exceeds the designated threshold. The system delivers alerts when proton fluxes exceed specific thresholds, allowing operators to implement protective measures such as shutting down sensitive electronics, reorienting spacecraft, or enhancing shielding. This early warning capability is essential for space missions operating beyond Earth's protective magnetosphere, ensuring the safety and longevity of onboard systems and instrumentation.

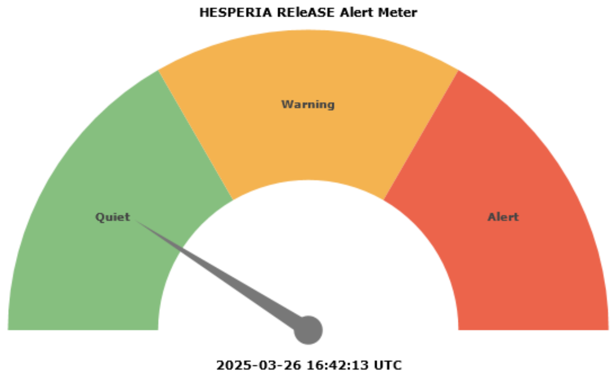

Table 1. HESPERIA REleASE Alert Gauge Meter's States and Flux / Conditions.

State	Flux/Condition
Quiet	flux is < 10^{-3} (cm^2 sec sr MeV)$^{-1}$
Warning	$10^{-3} \leq$ flux < 10^{-1} (cm^2 sec sr MeV)$^{-1}$
Alert	flux ≥ 10^{-1} (cm^2 sec sr MeV)$^{-1}$

The HESPERIA REleASE Alert System can generate alerts which are distributed to registered users. You can register here.

Figure 8: Example of HESPERIA REleASE Alert

5.8 SIDC Latest Moderated Solar Weather Event List (ROB/SIDC)

This product provides a list of solar weather events (sunspot groups, solar flares, and coronal holes, see Figure 9) compiled daily by the forecaster on duty at the SIDC (RWC Belgium), useful for post-event analyses [10]. Tracking these events supports forecasting of space weather disturbances that may impact spacecraft.

Help Similar products Related products Latest Query

SIDC Latest Moderated Solar Weather Event list

This service provides a list of solar weather events (sunspot groups, solar flares, and coronal holes) compiled daily by the forecaster on duty at the SIDC (RWC Belgium) starting from existing reference event lists.

SIDC Flares

Flare	Start Time [UTC]	Peak Time [UTC]	End Time [UTC]	GOES X-ray class	Location	SIDC Sunspot Group
3901	2025-03-24 23:09	2025-03-24 23:18	2025-03-24 23:33	C2.5	S07W65	0450
3902	2025-03-25 01:48	2025-03-25 01:54	2025-03-25 02:01	C1.7	NA	0450
3903	2025-03-25 00:36	2025-03-25 00:40	2025-03-25 00:46	C3.4	S07W65	0450
3904	2025-03-25 03:50	2025-03-25 03:55	2025-03-25 04:06	C1.6	NA	NA
3905	2025-03-25 08:11	2025-03-25 08:19	2025-03-25 08:29	C2.6	N18W70	0405
3906	2025-03-25 17:57	2025-03-25 18:04	2025-03-25 18:09	C2.5	NA	0442
3907	2025-03-25 20:39	2025-03-25 20:47	2025-03-25 20:53	C2.5	NA	0455
3908	2025-03-26 04:39	2025-03-26 04:44	2025-03-26 04:49	C1.9	S13E52	0450
3909	2025-03-26 07:12	2025-03-26 07:24	2025-03-26 07:30	C2.3	S13E51	0455
3910	2025-03-26 07:44	2025-03-26 08:09	2025-03-26 08:21	M1.0	S13E51	0455
3911	2025-03-26 09:07	2025-03-26 09:12	2025-03-26 09:20	C6.5	S13E50	0442

SIDC Coronal holes

Coronal Hole	First Time [UTC]	Last Time [UTC]	Polarity
0082	2024-12-02 11:06	2025-03-25 10:40	Positive

v

Evaluation Time [UTC]	Location	Crossing central meridian
2024-12-02 11:06	S09E60	False
2024-12-03 05:54	S07E51	False
2024-12-04 10:15	S06E34	False
2024-12-05 08:55	S08E19	False
2024-12-06 09:50	S06E05	True
2024-12-07 11:01	S11W06	True
2024-12-08 00:00	S11W13	False
2024-12-09 00:00	S11W26	True
2024-12-11 00:00	S11W53	False

Figure 9: Sample (crop) of the SIDC Latest Moderated Solar Weather Event List

5.9 Product Assessment Report (STFC/RAL Space)

Product Assessment report, see Figure 10, provides an interactive retrospective analysis of CME events and other heliospheric phenomena [11]. By integrating in-situ data, when available, the product assesses the accuracy of original CME forecasts and adds valuable post-event insights, though some data may only become available long after the event.

The system highlights significant events and allows users to analyse CME propagation using Drag-Based Ensemble Model (DBEM) geometry visualizations, indicating potential solar system target intercepts. Product Assessment Report serves as a crucial tool for validating space weather forecasts and improving the understanding of CME propagation, supporting spacecraft operators and mission planners in assessing historical space weather conditions and refining predictive models.

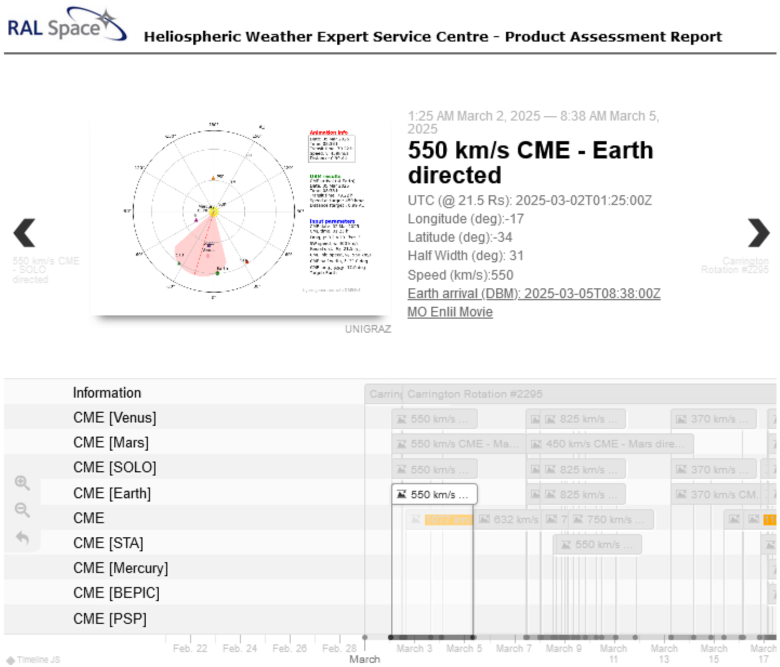

Figure 10: Example of CME - Earth directed - analysis through Product Assessment Report

Table 1: List of highlighted new Products, including the Expert Group, Space Weather Effect, Type of Data, and additional Note.

Product(s)	Expert Group (country)	Space Weather Effect	Usage	Demonstration Product(s)
PROBA-V/EPT Total Ionizing and Non-Ionizing Dose Estimation	UCL/CSR (UK)	Radiation Dose Effects	Nowcast Forecast	No
GEO/NGMR Products	SPARC (GR)	Single Event Effects Radiation Dose Effects Internal Charging	Nowcast	No
ICEA Products	BIRA-IASB (BE)	Internal Charging	Nowcast Forecast	Yes
RB-FAN Products	ONERA/ERS (FR)	Radiation Dose Effects Internal Charging Surface Charging	Nowcast Forecast	Yes
ATMDEN Products	UKMO (GB)	Spacecraft Drag	Forecast	No
SODA Products	UNIGRAZ/IGAM (AT)	Spacecraft Drag	Forecst	No
HESPERIA REleASE Alert	NOA/IAASARS (GR)	Single Event Effects	Forecast	No
SIDC Latest Moderated Solar Weather Event List	ROB/SIDC (BE)		Post Event Analysis	No
Product Assessment Report	STFC/RAL Space (GB)		Post Event Analysis	No

6. Use Case Scenarios

Use cases are structured scenarios that illustrate how a particular system, product, or service can be utilized in real-world applications. In the context of spacecraft operations, use cases demonstrate how space weather data and tools can support decision-making, enhance mission safety, and mitigate risks associated with the space environment. By defining clear use cases, mission operators and engineers can integrate space weather products into operational workflows, allowing for proactive responses to potential hazards such as elevated radiation exposure causing, electric charging and single-event effects (SEE). Two use cases are presented as examples.

6.1 Spacecraft Operations at LEO
Satellites in Low Earth Orbit (LEO) operate within a highly dynamic environment influenced by atmospheric density variations, plasma interactions, and radiation exposure. During periods of high solar activity, increased atmospheric heating causes the thermosphere to expand, leading to greater atmospheric drag on satellites. This results in orbit degradation, requiring more frequent orbital manoeuvres to maintain altitude and avoid premature re-entry.

Surface charging is another key challenge in LEO operation (especially in the auroral regions), as spacecraft interact with the surrounding space plasma, leading to charge accumulation on their surfaces. This can cause arcing, power disruptions, or even damage to coatings and critical systems. Additionally, solar radiation and energetic particles contribute to long-term degradation of spacecraft components, affecting solar panel efficiency, communication systems, and overall mission longevity. As the number of LEO satellites increases, particularly with the rise of mega-constellations, understanding and mitigating space weather effects is essential for ensuring mission success and satellite sustainability.

<u>Selection of products (including newly added products and demo products) in relevance for specific space weather impacts:</u>

Single Event Effects (SEEs), Ionizing and Non-ionizing Dose Effects

- COMESEP (COronal Mass Ejections and Solar Energetic Particles) provided by BIRA-IASB delivers real-time risk alerts for SEP events following solar eruptions.
- PROBA-V/EPT proton maps, showing the flux variation in the SAA region during the main and recovery phase of a geomagnetic storm. They also show the penetration zones of solar protons during SEP events. The maps are not available in real-time but very helpful for post-event analysis
- RB-FAN Products – Includes risk alerts for solar cell degradation for multiple orbits, including LEO; providing nowcasts and three-day forecasts.
- SREM (Standard Radiation Environment Monitor) measures high-energy electrons and protons, providing daily reports to help LEO operators monitor radiation conditions and particle flux variations.
- HESPERIA RELeASE: Provides deterministic forecasts of proton flux during SEP events, helping operators protect spacecraft systems from radiation exposure.

Surface and Internal Charging

- RB-FAN Products – Includes risk alerts for radiation belt dynamics and deep charging, for multiple orbits, including LEO, providing nowcasts and three-day forecasts.
- SREM, provided by Paul Buehler, measures high-energy electrons and protons, providing daily reports to help LEO operators monitor radiation conditions and particle flux variations.

Drag and Orbital Decay

- ATMDEN Products – Atmospheric density forecasts to support spacecraft drag calculations, crucial for LEO operations. These forecasts help mission planners adjust orbital manoeuvres to counteract altitude variations caused by space weather, preventing premature re-entry or loss of control.
- SODA Products – Forecasts satellite orbit decay due to space weather, particularly relevant for LEO satellites. By predicting altitude drops caused by interplanetary coronal mass ejections (ICMEs), SODA enables operators to prepare corrective actions to extend mission lifetimes.

6.2 Spacecraft Operations at GEO
Satellites in Geostationary Orbit (GEO) are exposed to a harsh space environment dominated by high-energy radiation, which can significantly impact spacecraft electronics and overall mission performance. A major concern in GEO is internal charging, where energetic electrons penetrate spacecraft shielding and accumulate within insulating materials. If the charge buildup reaches a critical level, it can lead to electrostatic discharges (ESD), potentially damaging onboard systems and causing unexpected anomalies.

Another critical risk is Single Event Effects (SEE), where highly energetic particles, such as solar energetic protons or galactic cosmic rays, directly impact spacecraft electronics. These interactions can induce bit flips in memory (Single Event Upsets), disrupt processor operations, or even cause permanent damage to critical components (Single Event Latchups or Burnouts). To mitigate these risks, operators rely on space weather forecasts and real-time monitoring to implement protective measures, such as system reconfigurations and error correction protocols.

Additionally, continuous exposure to high-energy particles in GEO leads to radiation-induced degradation, particularly affecting solar panels and electronic components over time. Prolonged radiation exposure reduces power generation capacity, accelerates material wear, and can shorten mission lifetimes. By leveraging predictive tools and radiation environment monitoring, operators can optimize spacecraft design, anticipate potential failures, and take proactive steps to safeguard mission operations.

<u>Selection of products (including newly added products and demo products) in relevance for specific space weather impacts:</u>

Single Event Effects (SEEs), Ionizing and Non-ionizing Dose Effects

- GEO/NGRM products provide proton differential flux measurements to help assess SEE risks and support post-event analysis.
- RB-FAN Products forecast radiation belt dynamics and solar cell risk alerts for radiation-driven power system adjustments for several orbits, including GEO.
- COMESEP delivers real-time alerts for solar energetic particle (SEP) events.
- GOES Proton Flux, provided by UKMO, provides continuous monitoring of energetic proton levels, helping to assess the radiation environment in near-Earth space.
- HESPERIA RELeASE provides deterministic forecasts of proton flux during SEP events, helping operators protect spacecraft systems from radiation exposure.
- SARIF Products, provided by UKMO, provide risk indicators for electronic component degradation due to total ionizing dose. Environment panels offer radiation belt data, solar wind conditions, and geomagnetic activity to aid forecasting.

Surface and Internal Charging

- GEO/NGRM products provide real-time flux alerts to detect elevated electron environments that may increase charging risks.
- ICEA Products deliver daily ESD risk reports, real-time warnings for increased internal charging risk, and high-energy electron flux predictions specifically at GEO to help satellite operators prevent operational anomalies.
- RB-FAN Products forecast radiation belt dynamics, offering Deep Charging Risk Alerts for tracking charge build-up in several orbits, including GEO.
- SARIF Products provide risk indicators for internal satellite charging due to high-energy electrons. Environment panels offer radiation belt data, solar wind conditions, and geomagnetic activity to aid forecasting.

By using these products and data, spacecraft operators can determine whether an observed anomaly is related to charging effects or single event effects (SEE) caused by space weather events. This insight enables them to take preventive actions such as altering spacecraft orientation, modifying operational schedules, implementing enhanced grounding techniques, improving spacecraft design, and applying software error-correction methods to mitigate the impact of high-radiation periods.

7. End User Engagement

The ESA Space Weather Service Network prioritises end user engagement to ensure its products and services remain relevant, effective, and tailored to specific operational needs. This engagement is facilitated through a variety of mechanisms, including targeted test campaigns, dedicated training courses, webinars, and user feedback mechanisms such as surveys and help-desk interactions.

By maintaining an open dialogue with users across different domains—such as spacecraft operations, aviation, and GNSS downstream service users—the network continually refines its offerings, ensuring they align well with real-world operational requirements. This continuous improvement cycle is driven by direct user consultations, structured test campaigns, and interactive training initiatives.

7.1 Targeted User Test Campaigns

One of the most effective ways the ESA SWE Service Network engages with users is through targeted test campaigns. These campaigns are tailored to specific operational needs and involve customised space weather bulletins, dashboards, and training sessions, all developed collaboratively with end users. By working directly with operators, the ESA SWE Service Network ensures that space weather information is presented in a format and on a schedule that aligns with their mission-critical activities.

Key aspects of these targeted campaigns include:

- Customized Data Products – Users receive tailored space weather reports relevant to their operational needs. This includes selecting specific indicators, defining thresholds, structuring bulletins, and planning delivery schedules.
- Pre-Agreed Delivery Schedules – Campaigns provide timely and actionable information at intervals that match mission planning cycles.
- Real-Time and Historical Data Integration – Information is drawn from real-time monitoring tools and historical databases, allowing users to assess both immediate risks and long-term trends.

The value of these test campaigns extends beyond immediate operational support and the SWE Service Network is designed to provide an important opportunity for development and testing with end users in the loop rather than operational service provision. The campaigns also serve as an essential feedback loop for ESA SWE developers. User feedback is continuously collected and integrated into future product updates and ESA SWE Portal improvements. This iterative approach ensures that space weather services evolve in response to real-world operational demands. The operation of the campaigns in terms of delivering tailored space weather bulletins is currently performed during office hours only. See the list of spacecraft operation relevant test user campaigns in Table 1 and an example of a customised dashboard developed together with a mission operator in Figure 11.

Table 1: Relevant Spacecraft Operation Test User Campaigns

User Test Campaign	Time Span	Content
EUMETSAT Spacecraft Operations	Ongoing since 06/2024	• Tailored dashboard • Weekly bulletin
Solar Orbiter and Bepi Colombo Missions	Ongoing since 12/2024	• Tailored dashboard • Event triggered bulletin
Commercial GEO/MEO Fleet Operations	02/2023-02/2025	• Tailored dashboard
ESA Mission Spacecraft Operations	Ongoing since 02/2024	• Tailored dashboard

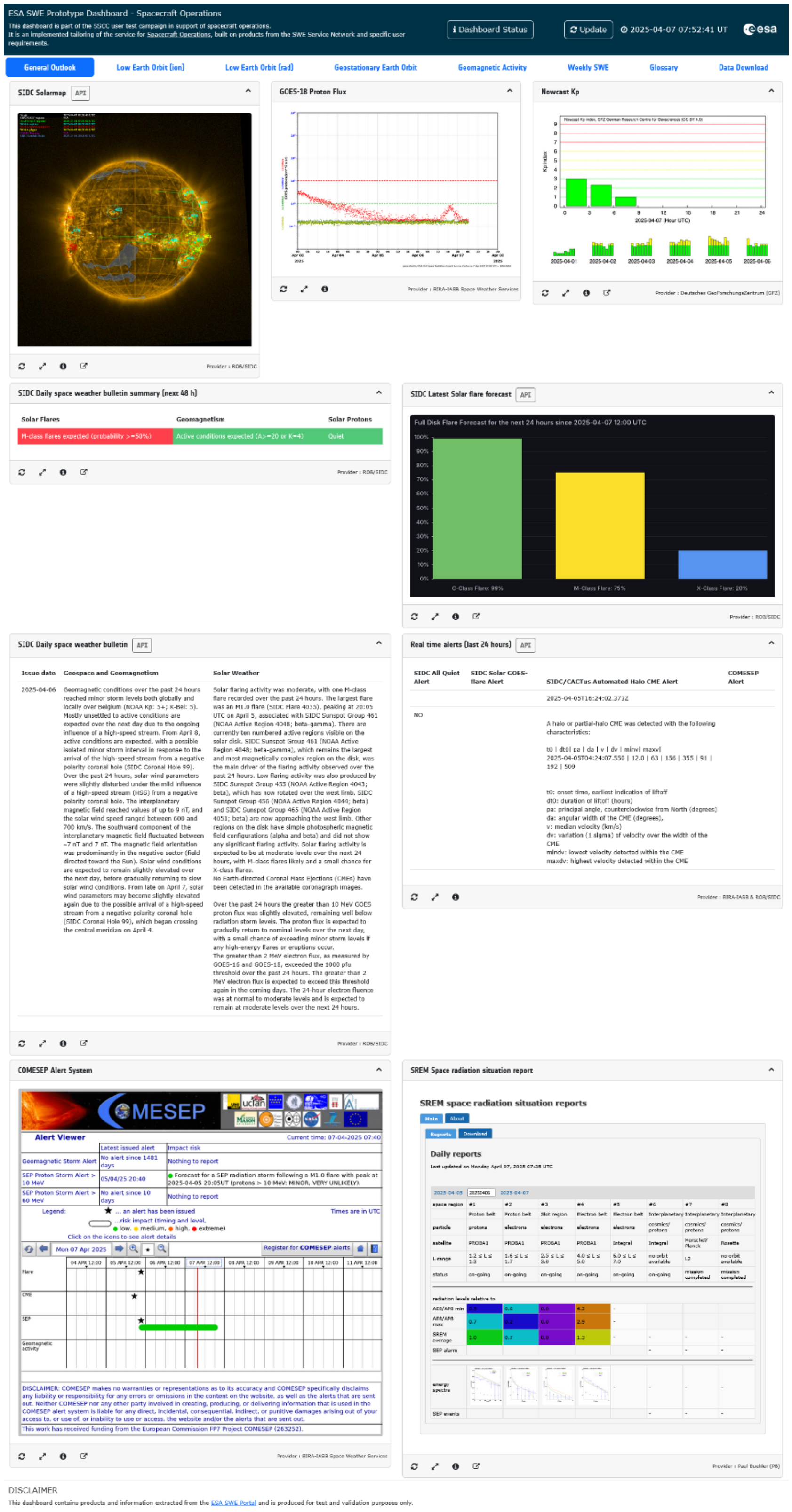

Figure 11: Example of a test user campaign dashboard, showing the general conditions and agreed product selection.

8. Key Recommendations for service Enhancement

ESA's Space Weather Service Network has identified several key recommendations for the next development steps aimed at improving service accessibility, data reliability, and operational usability for spacecraft operations. One of the primary areas of focus is the enhancement of service availability and accessibility, particularly through improved service portal design. Improved navigation, a high-level summary of space weather conditions, and a more intuitive search function are essential to ensure that end users can quickly find the information they need. Additionally, making the portal fully mobile-friendly and ensuring compatibility across all major browsers will enhance usability, particularly for operators who require real-time updates in dynamic operational environments.

Another significant recommendation pertains to strengthening research-to-operations processes by improving product validation, inter-comparison studies, and performance assessments. It is crucial to provide clear metrics on data accuracy and uncertainty as they feed into space weather models used in spacecraft operations.

As space missions diversify, particularly with the emergence of NewSpace initiatives and human spaceflight beyond Low Earth Orbit (BLEO), the Space Weather Service Network must anticipate evolving user requirements.

In other affected domains, this also includes addressing cross-sectoral hazards, such as radiation effects on power systems and the need for improved forecasting tools for launch operations. Developing more integrated, cross-domain solutions will ensure that space weather services remain relevant to a broad range of applications, from low Earth orbit (LEO) satellites to deep-space missions.

Further recommendations highlight the need for improved service integration and decision-support tools. A unified API allowing seamless data access and fallback mechanisms in case of provider outages would enhance operational resilience. Additionally, the introduction of interactive concept maps illustrating space weather causes and effects, as well as clearer guidance on product selection, would assist users in navigating complex datasets. A standardized event classification system would also improve the consistency of risk assessments across different space weather centres.

9. Conclusion

The ESA Space Weather Service Network provides a world class framework for demonstrating and testing space weather capabilities with end users in the loop through its robust and well tested approach to pre-operational service provision. This paper has presented an overview of the network's capabilities, highlighting recent additions to its portfolio of data products and tools. These new offerings, including advancements in radiation dose estimation, energetic particle monitoring, internal charging analysis, radiation belt forecasting, and atmospheric density modelling, demonstrate the network's commitment to providing cutting-edge support for mission planning, anomaly resolution, and real-time operational decision-making. By addressing specific space weather effects such as surface and internal charging, single event effects, and atmospheric drag, these tools demonstrate how operators may utilise this information to proactively mitigate risks and ensure the continued success of their missions. Furthermore, the emphasis on end-user engagement through targeted test campaigns, training, and feedback mechanisms ensures that the services provide relevant and tailored information to the evolving needs of the space community. The recommendations outlined for enhancing the network's accessibility, data reliability, and integration capabilities, including improvements to the service portal and research-to-operations processes underscore the network's dedication to continuous improvement. Implementing these recommendations will further strengthen the network's ability to support diverse space missions, from LEO satellites to future deep-space endeavours, ultimately contributing to the long-term resilience and sustainability of space-based infrastructure.

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.

References

[1] Resolution on ESA Programmes: Addressing the Challenges Ahead, ESA/C-M/CCLXXXVI/Res.3, 28 November 2019. https://esamultimedia.esa.int/docs/corporate/Resolution_3_Space19+Final-28Nov-12h30.pdf

[2] ESA Space Weather Network Service Product Catalogue Summary, SSA-SWE-SSCC-TN-0011, version 22.0, October 10, 2024, https://swe.ssa.esa.int/documents/d/guest/product_catalogue_summary

[3] S. Benck, et al., The Proba-V/EPT data products within the ESA Space Weather Service Network, 44th COSPAR Scientific Assembly, 16-24 July 2022. https://ui.adsabs.harvard.edu/abs/2022cosp...44.3234B

[4] I., Sandberg et al., First Results and Analysis from ESA Next Generation Radiation Monitor Unit Onboard EDRS-C, in IEEE Transactions on Nuclear Science, vol. 69, no. 7, pp. 1549-1556, July 2022, doi: 10.1109/TNS.2022.3160108

[5] R. J. Boynton, M. A. Balikhin, and S. A. Billings, Online NARMAX model for electron fluxes at GEO, Ann. Geophys., 33, 405–411, https://doi.org/10.5194/angeo-33-405-2015/, 2015

[6] V. Maget, et al., An ESA-SSA and S2P activity to forecast the dynamics of the Earth radiation belts: the RB-FAN service, AGU Fall Meeting Abstracts, 2023. https://ui.adsabs.harvard.edu/abs/2023AGUFMSH21E29.2M

[7] M. Marsh, et al., The Met Office Atmospheric Density Forecast Service, AMOS Conference, 2019. https://cdn.eventsforce.net/files/ef-q5vmtsq56tk6/website/1528/1310_-_marsh.pdf

[8] S. Krauss, et al., SODA – A tool to predict storm-induced orbit decays for low Earth orbiting satellites, Advances in Space Research, 2023. https://graz.elsevierpure.com/en/publications/soda-a-tool-to-predict-storm-induced-orbit-decays

[9] A. Papaioannou, et al., HESPERIA Forecasting Tools: Real-Time and Post-Event, Solar Particle Radiation Storms Forecasting and Analysis, 2017. https://link.springer.com/chapter/10.1007/978-3-319-60051-2_7

[10] S.600z SIDC Moderated Solar Weather Event list (contribution to ESC Solar Weather), SWE Portal 3.12, https://swe.ssa.esa.int/sidc-S600z-federated

[11] H.112a Product Assessment Report (contribution to ESC Heliospheric Weather), SWE Portal 3.12, https://swe.ssa.esa.int/ral-hparc-par-federated