Characterising Space Weather Risks for LEO SmallSats Using the ESA Space Weather Service Network

Lenka Zychová
Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Uccle, Belgium
lenka.zychova@aeronomie.be

Norma Crosby[a], Erwin De Donder[a], Mark Dierckxsens[a], Siemen Burssens[a], Jennifer O'Hara[b], Alexi Glover[c], Hannah Laurens[d], Michalis Karavolos[e], Sandro Krauss[f], Sylvie Beck[g], Olga Malandraki[e], Mike Marsh[h], Manuela Temmer[j]

a Royal Belgian Institute for Space Aeronomy, Uccle, Belgium
b Royal Observatory of Belgium, Uccle, Belgium
c ESA Space Weather Office, Darmstadt, Germany
d Starion Deutschland GmbH, Darmstadt, Germany,
e National Observatory of Athens, IAASARS, Athens, Greece
f Graz University of Technology, Institute for Geodesy (IfG), Graz, Austria
g Université catholique de Louvain, Center for Space Radiations (CSR), Louvain-la-Neuve, Belgium
h Met Office, Exeter, UK
i University of Graz, Institute of Physics, Graz, Austria

Abstract — *SmallSat missions in Low Earth Orbit (LEO) operate in an environment that can change rapidly in response to space weather. Limited design margins, growing levels of autonomy, and the increasing number of satellites in orbit make it essential for operators to understand and anticipate space weather-driven risks. This paper focuses on three operationally significant categories: atmospheric drag, spacecraft charging, and particle radiation-induced effects. Through the ESA Space Weather Service Network and its online portal, a suite of monitoring, nowcasting, forecasting, and post-event analysis products is available to support SmallSat operators. Selected use cases demonstrate how these capabilities support characterisation of the space environment and pre-operational risk assessments, enhancing space situational awareness for LEO missions.*

Keywords — Space Weather, LEO, SmallSat, Atmospheric Drag, Spacecraft Charging, Single Event Effects, ESA Space Weather Service Network

1. Introduction

SmallSats and Cubesats represent a growing fraction of active spacecraft in the increasingly congested Low Earth Orbit (LEO) region. Unlike heritage large-satellite programmes, SmallSat missions are often developed with tighter design margins, limited radiation shielding, reduced power budgets, and shorter development timelines. These constraints make them inherently more vulnerable to the impact of space weather and less able to tolerate the anomalies that space weather can trigger.

Space weather is mostly driven by a broad range of solar eruptive phenomena: solar flares, coronal mass ejections (CMEs), solar energetic particle (SEP) events, geomagnetic storms, and enhanced fluxes of trapped radiation belt particles. For LEO-based spacecraft, three operationally significant effects stand out: (1) enhanced atmospheric drag caused by thermospheric heating during geomagnetically active periods; (2) surface and internal electrostatic charging driven by plasma and energetic electron environments; and (3) single event effects (SEEs) and cumulative radiation damage caused by particle radiation.

Understanding and anticipating these effects require access to timely, reliable, and operationally relevant space weather information. The ESA Space Weather Service Network, developed under the Space Situational

Awareness (SSA) and Space Safety Programmes, provides exactly this kind of information at a European level on a pre-operational basis. Through the ESA Space Weather Portal (https://swe.ssa.esa.int), operators can access products and tools spanning monitoring, nowcasting, forecasting, and post-event analysis gaining increased understanding of space weather phenomena and their potential impact on mission hardware and operations [1].

This paper provides a structured overview of the space weather effects most relevant to LEO SmallSat operators, the ESA SWE Service Network and its pre-operational spacecraft operations services, and the specific data products available for each of the aforementioned effects. Selected use case scenarios illustrate how space weather information can be integrated into operational practice to reduce risk and support informed decision-making.

2. Space Weather Effects Relevant to LEO SmallSats

2.1 Atmospheric Drag and Orbital Decay

The upper thermosphere, in which LEO spacecraft orbit, is not a static medium. During periods of enhanced solar extreme ultraviolet (EUV) radiation and geomagnetic activity, the thermosphere absorbs additional energy, causing it to heat, expand, and increase in density. For a spacecraft at a given altitude, even modest increases in density translate directly into increased atmospheric drag, which accelerates orbital decay.

This effect is particularly consequential for small spacecraft with high area-to-mass ratios, such as SmallSats and particularly CubeSats. During major geomagnetic storms — such as the one of May 2024 — dramatic thermospheric density enhancements have been observed, leading to sudden and significant orbit drops for low-altitude constellations [2]. Operators must be able to anticipate these changes to plan corrective manoeuvres, manage propellant budgets, and avoid conjunction risks with other objects.

2.2 Surface and Internal Spacecraft Charging

Spacecraft surfaces and internal dielectric materials can accumulate electrostatic charge due to interactions with the ambient plasma and energetic particle populations. In LEO, surface charging is most pronounced at high geomagnetic latitudes, due to enhanced fluxes of high energy (~keV) electrons during space weather induced disturbances in the magnetosphere. Substorms are transient magnetospheric disturbances that release stored magnetic energy from the magnetotail, driving intense bursts of energetic electron precipitation towards Earth. This precipitation is concentrated in the auroral zone — the high-latitude belt surrounding the magnetic poles — making polar and high-inclination orbits particularly susceptible. Charge accumulation can result in electrostatic discharges (ESD) that damage surface coatings, disrupt sensitive electronic components, or generate electromagnetic noise that corrupts data.

Internal charging, driven by higher-energy electrons (>100 keV) penetrating deep into dielectric materials, poses a somewhat different but equally serious risk. Deep dielectric charging can lead to slow build-up and sudden, potentially mission-ending, discharges within the spacecraft structure. Even for relatively well-shielded LEO spacecraft at mid-to-low inclinations, enhanced radiation belt electron fluxes — particularly after geomagnetic storm-time injections, when geomagnetic storms energise and push electrons deeper into the inner magnetosphere — can increase internal charging risks.

2.3 Particle Radiation: Single Event Effects and Dose

The radiation environment in LEO is a superposition of trapped protons and electrons in the Van Allen belts, SEPs during active solar periods, and a continuous background of galactic cosmic rays (GCRs). These sources impact spacecraft electronics in two ways: cumulative dose effects and SEEs.

Long-term radiation exposure leads to cumulative total ionising dose (TID) and total non-ionising dose (TNID). These effects degrade semiconductors, reduce solar cell efficiency, increase noise in detectors, and can eventually result in permanent failure. By contrast, SEEs are stochastic events triggered by individual particle interactions. They include single event upsets (SEUs, or bit flips), single event latch-ups (SELs), and single event burnouts (SEBs), each with a different risk profile and mitigation approach.

For LEO spacecraft, the South Atlantic Anomaly (SAA) — a region where the inner radiation belt dips to low altitudes due to the offset between the Earth's geographic and magnetic axes — is a particularly intense source of particle radiation. Every orbit pass through or near the SAA increases the cumulative dose and SEE rate. During SEP events following large solar eruptions, polar-orbiting spacecraft are additionally exposed to high-energy proton fluxes that penetrate even well-shielded electronics.

3. The ESA Space Weather Service Network

The ESA Space Weather Service Network is a pre-operational European infrastructure dedicated to monitoring, nowcasting, forecasting, and analysing the space environment and its effects on technology and human systems [1]. Established under the ESA SSA programme and continuing under the Space Safety Programme, the network integrates assets and expertise from over 40 European institutes, industry and academic organisations into a suite of preliminary services, providing a platform to demonstrate and test a wide range of state-of-the-art space weather capabilities with end users in the loop.

The network is organised around five Expert Service Centres (ESCs), each responsible for a specific phenomenological domain: Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather, and Geomagnetic Conditions. A central Space Weather Coordination Centre (SSCC), located at the Space Pole in Brussels, Belgium, provides coordination, a user help desk, and the operational link between ESCs and end users. The user help desk offers support and space weather domain expertise to users during normal working hours. Overall service availability targets for the pre-operational services are on average >95%.

All 29 user-tailored services targeting specific groups of end users are accessible through the ESA Space Weather Portal, which combines more than 350 individual products and tools within the 29 user-tailored services [1]. A dedicated Spacecraft Operations Dashboard provides operators with a curated entry point to products directly relevant to spacecraft mission planning and operations. Services are grouped into five categories: In-orbit Environment and Effects Monitoring; In-orbit Environment and Effects Forecast; Mission Risk Analysis; Post-Event Analysis; and Space Weather in the Solar System. Additionally, a Space Surveillance and Tracking dashboard is available presenting an overview of the current atmospheric, geomagnetic and solar conditions for drag calculation.

The network follows a pre-operational service provision model — products are developed, tested, and validated in collaboration with end users in order to demonstrate their maturity and applicability to real service user needs. This model allows for systematic quality control while maintaining a research-to-operations pipeline that continuously incorporates advances from the scientific community.

For SmallSat operators, the portal represents a significant resource and feedback on the service performance and relevance to this community along with further insight into service needs is welcome and strongly encouraged. Products can be accessed directly via the web interface, and an Application Programming Interface (API) supports programmatic data retrieval. Notification and alert functionalities allow operators to receive automated warnings when predefined thresholds are exceeded.

4. Space Weather Products Relevant to LEO SmallSat Operations

The following sections describe the key ESA SWE Service Network products most directly applicable to the three principal space weather effect categories relevant to LEO SmallSats. Table 1 provides a summary overview. Some of the products are listed as Demonstration Products (Demo), 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.

4.1 Atmospheric Drag and Orbital Decay

Two complementary products directly address the atmospheric density and orbit decay challenges facing LEO SmallSat operators.

ATMDEN (Atmospheric Density) Products, provided by the UK Met Office (UKMO), deliver forecast and prior-estimate fields of thermospheric neutral density using the DTM2013 model developed and maintained by CNES [7]. Products are available in three forms: a high-cadence 3-day forecast updated every 3 hours; a 27-day forecast issued daily; and a 12-month historical prior estimate. Coverage spans 120–1500 km altitude, encompassing the full LEO regime. These products enable mission operators to anticipate periods of enhanced drag, plan propulsion manoeuvres proactively, and maintain altitude control during geomagnetic storms.

SODA (Satellite Orbit DecAy) Product, jointly developed with the Graz University of Technology and provided by the University of Graz (UNIGRAZ/IGAM), delivers 15-hour forecasts of satellite qualitative orbit decay induced primarily by interplanetary CMEs with strong southward magnetic field (negative Bz) [8]. Results are normalised for spacecraft at approximately 490 km altitude. SODA complements ATMDEN by providing event-specific, short-term orbit decay alerts tied directly to observed or forecast solar wind conditions, giving operators the earliest possible warning of impending altitude loss driven by geomagnetic storm-time thermospheric expansion.

FORIND, provided by Institute of Space Science Romania (ISS Romania), is a tool that provides nowcasts and forecasts of solar and geomagnetic indices needed for atmospheric modelling in support of atmospheric drag calculation. These indices can be retrieved, in a custom tailored and homogenous form, via the dedicated web page or a REST interface, allowing users to be able to integrate the data into their own pipelines.

4.2 Surface and Internal Charging

Spacecraft charging risks in LEO, while somewhat less severe than in GEO, are operationally significant — especially for high-inclination and polar orbits.

RB-FAN (Radiation Belt Forecast and Alert Now-cast) Products, developed by ONERA/ERS, address charging risks by providing nowcasts and three-day forecasts of radiation belt dynamics relevant to surface and internal charging at LEO altitudes. The Deep Charging Risk Alert component estimates internal electric potential build-up, while the broader product suite tracks electron flux environments that drive surface charging, particularly during substorm-associated injections. Operating as a demonstration product, RB-FAN integrates solar wind predictions and magnetospheric models to anticipate periods of elevated particle flux across multiple orbit regimes including LEO [6].

SREM (Standard Radiation Environment Monitor) Products contribute to charging risk assessment by providing high-energy electron flux measurements in LEO. Elevated fluxes of electrons with energies above a few hundred keV are associated with increased risk of internal charging in poorly shielded dielectrics. SREM data help identify periods when these flux levels are elevated, enabling informed operational decisions.

4.3 Single Event Effects, Ionising and Non-Ionising Dose

Several complementary products address the radiation environment driving SEEs and dose accumulation in LEO.

PROBA-V/EPT Electron and Proton Flux Maps, derived from measurements by the Energetic Particle Telescope (EPT) aboard the PROBA-V satellite, provide high-resolution geographic distribution of particle fluxes in the LEO environment. These maps are particularly valuable for visualising electron flux variations in the polar horns and SAA region, and for tracking the penetration of solar protons during SEP events into lower latitudes. While not available in real time, they are highly effective tools for post-event analysis of anomalies or increased dose accumulation episodes [4]. In addition, PROBA-V/EPT provides, among others, near real-time survey of the high-latitude polar proton flux (>10, 50, 100 MeV), daily TID and TNID estimation in Silicon behind 2 mm Aluminium shielding on a polar orbit at 820 km altitude.

HESPERIA REleASE (Relativistic Electron Alert System for Exploration), provided by NOA/IAASARS, uses relativistic electron data from SOHO/EPHIN and near-relativistic electron data from ACE/EPAM to issue deterministic forecasts of SEP proton flux at energies of 15.8–39.8 MeV and 28.2–50.1 MeV [5]. Alerts are triggered when forecast flux exceeds predefined thresholds. This early-warning capability is essential for polar-orbit SmallSat operators: it allows protective actions such as switching off sensitive instruments or entering safe mode before the radiation environment deteriorates.

RB-FAN Products also support radiation risk assessment, providing nowcasts and three-day forecasts of radiation belt dynamics including risk alerts for solar cell degradation and radiation dose.

SREM Products additionally provide daily reports on high-energy electron and proton measurements, supporting LEO operators in monitoring particle flux variations and radiation conditions. SREM data are valuable both for operational monitoring and for calibrating radiation environment models against in-situ observations.

Coming Soon: SEPForecast provided by BIRA-IASB, will deliver real-time risk alerts for SEP events for energies greater than 10 MeV and 60 MeV in the form of a risk level. It combines the probability and expected impact intensity for every observed Earth directed solar flare with a magnitude of at least M1, providing early warning essential for LEO operators of polar-orbiting spacecraft that have direct exposure to solar proton precipitation. SEPForecast is a reimplementation of the COMESEP SEPForecast module [3] as a stand-alone tool.

4.4 Summary of Space Weather Products Relevant to LEO SmallSat Operations

Table 1: Summary of key ESA SWE Service Network products for LEO SmallSat operations.

Product	Expert Group	Space Weather Effect	Usage	Demo
SEPForecast (coming soon)	BIRA-IASB (BE)	SEEs, SEPs	Nowcast/Alert	No
PROBA-V/EPT Proton Flux Maps	UCLouvain/CSR (BE)	Radiation Dose, SEEs	Post-event analysis	No
PROBA-V/EPT Electron Flux Maps	UCLouvain/CSR (BE)	Charging	Post-event analysis	No
HESPERIA REleASE	NOA/IAASARS (GR)	SEEs, SEPs	Forecast/Alert	No
RB-FAN Products	ONERA/ERS (FR)	Radiation, Charging, SEEs	Nowcast/3-day Forecast	Yes
SREM Products	BIRA-IASB (BE)	Radiation, SEEs, Charging	Monitoring	No
ATMDEN Products	UKMO (GB)	Atmospheric Drag	3-day/27-day Forecast	No
SODA Products	UNIGRAZ/IGAM (AT)	Orbit Decay / Drag	15-hr Forecast	No
FORIND	ISS Romania (RO)	Atmospheric Drag	Forecast	No

5. Discussion and Outlook

The ESA Space Weather Service Network represents a growing research-to-operations (R2O) infrastructure geared towards translating space weather observations and models into user-focussed products and information.

For SmallSat operators — who often lack the dedicated space weather support teams available to larger institutional programmes — the portal provides a centralised, accessible, and free resource that can meaningfully improve understanding of the potential impact of space weather on mission operations and help characterise the information most needed.

Several aspects are particularly aligned with the needs of the SmallSat community. First, the increasing provision of demonstration products — products that are available for early testing and validation — allows operators to evaluate capabilities before they are integrated into the relevant service. By engagement with these products in an early phase, operators provide valuable insights that help the space weather service developer community to further improve their services.

Second, the combination of LEO-specific products — like SODA for orbit decay, ATMDEN for drag, HESPERIA REleASE for SEP warnings, and PROBA-V/EPT products for post-event analysis — gives SmallSat operators an overview of the type of products which may address the full cycle of space weather risk management, from pre-event alert to post-event diagnosis.

Ongoing development priorities for the network include enhanced portal usability for non-specialist users, improved product validation and uncertainty quantification and broader API functionality.

6. Conclusions

SmallSat missions in LEO face three principal space weather-driven operational risks: enhanced atmospheric drag, spacecraft charging, and particle radiation effects including SEEs and cumulative radiation dose. These risks are manageable with timely, reliable, and operationally relevant space environment information.

The ESA Space Weather Service Network, accessible through the ESA Space Weather Portal, provides a comprehensive suite of pre-operational data products and tools that directly address each of these risk categories. From real-time SEP alerts via HESPERIA REleASE and SEPForecast, to three-day atmospheric density forecasts by ATMDEN, storm-induced orbit decay predictions from SODA, and retrospective event analysis through PROBA-V/EPT related products, the network offers a coherent and increasingly integrated capability demonstrating the potential for LEO SmallSat operators to mitigate space weather impacts.

We encourage SmallSat operators and mission planners to engage with the ESA SWE Service Network — to explore available products, participate in targeted test user campaigns, where users can provide feedback on the products that will drive further service improvements. Space weather risk characterisation is not a niche concern for large government missions; it is an operational necessity for every spacecraft in LEO.

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