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

SpaceOps-2023, ID # 695

Integrating Space Weather into Satellite Operations: Necessity or Dead End?

Dominique Montero[a]*, Sebastien Bourdarie[b], Robert Ecoffet[c], Edmund Trollope[d]

[a] *Flight Operation Division, EUMETSAT, Eumetsat Allée, D64295, dominique.montero@eumetsat.int*

[b] *Département physique, instrumentation, space environment, ONERA – The French Aerospace Lab, 2 Avenue Edouard Belin, F31400, Toulouse, Sebastien.Bourdarie@onera.fr*

[c] *Department space environment and new components, CNES, 18 Avenue Edouard Belin, F31400, Toulouse, Robert.ecoffet@cnes.fr*

[d] *Flight Operation Division, EUMETSAT, Eumetsat Allée, D64295, Ed.Trollope@eumetsat.int*

* Corresponding Author

Abstract

Spacecraft operations' main driver is often the mission lifetime and availability. Whereas the mission lifetime can be achieved by operational asset safing measures whenever a threat can be identified, the mission availability resides in the satellite's resilience to the space radiative environment and more particularly to high-energy particles. It has been apparent for a long time that the constraints of the space environment must be embedded into the space domain from early design phases to the operations implementation.

The need for Space Situational Awareness (SSA) services has been emerging for more than a decade to operate space infrastructures securely, sustainably and safely. One of these services – a Space Weather (SWE) service - is of particular interest to space operations, but is still in its infancy and in need of user requirement clarification.

The main results of this study are to clarify the potential benefits of such a space environment service for satellite operations in Low Earth Orbit (LEO) to Geostationary (GEO) missions, outlining the need to distinguish between «space weather» and Space Climate service». End-to-end satellite operations needs, i.e., from alarm detection to the implementation of the mitigation action and associated problematics to be overcome are discussed, encompassing the following aspects:

- Service applicability conditions for real time service to prevent against destructive effect but also offline service to improve mission availability;
- The need of customisable alarms distinguishing level/types of radiation, threshold, operated orbit;
- The necessity to estimate time of impact with appropriate notification notice;
- The practicality for an unambiguous decision chain from the satellite probability risk assessment to the implementation of the mitigation action to be applied;
- The practicality for anomalies support providing probability of time/space correlation between satellite anomaly and space radiation event.

Retrospective interest from simulation of the selected services requirements against track record of anomalies observed on EUMETSAT/CNES fleet of satellite over the last 15 years is assessed, and a set of user requirements established.

Finally, the potential benefits for future mission and mega-constellation including automation of alert propagation and safing of new technology is presented.

The interest for space weather prediction service appears to be low w.r.t. the practicality/complexity of the decision chain to be implemented but also w.r.t. retrospective applicability to past anomaly track records and projection into future technology. However, the interest of the restitution aspect of both space weather and climate service seems to be very promising assuming accuracy of data can be demonstrated.

Keywords: space, environment, radiation, weather, climate, satellite, operations.

Nomenclature

L — The L parameter in the table ("Mc Illwain parameter") is the number of Earth radii at which a magnetic field line crosses the magnetic equator.

A geostationary satellite remains located at L=~6.6. A polar LEO satellite crosses almost all L values

Acronyms/Abbreviations

CIR:	Co-rotating Inertial regions
CME:	Coronal Mass Ejection
COSPAR	Committee on Space Research
DDD	Displacement Damage Dose
EOR	Electric Orbit Raising
ESD:	Electro-Static Discharge
FDIR	Fault Detection, Isolation and Recovery
GCR:	Galactic Cosmic Rays
GEO:	Geostationary Orbit
IMF:	Interplanetary Magnetic Field
LEO:	Low Earth Orbit
NRT:	Near Real Time
RAMS	Reliability, Availability, Maintainability and Safety
SAA:	South Atlantic Anomaly
SCL:	Space Climate
SEL	Single event Latch-up
SEB	Single Event Burn-out
SEE	Single Events Effects
SEGR	Single Event Gate Rupture
SEP:	Solar Energetic Particles
SILSO	Sunspot Index and Long-term Solar Observations
SSA:	Space Situational Awareness
SWE:	Space Weather
TID	Total Ionizing Dose
WMO	World Meteorological Organisation

1 Introduction

Spacecraft operations' main driver is often the mission lifetime and availability. Whereas the mission lifetime can be achieved by operational asset safing measures when natural or unnatural threat can be identified, the mission availability resides in the satellite resilience to space radiative environment and more particularly to high-energy particles. The main contribution of interruptions to satellite missions comes from Electro-Static Discharge (ESD) and Single Event Effects (SEE) triggered by high-energy particle radiation due to:

- Galactic cosmic rays (GCR) (heavy ions from outside the solar system);
- Solar particles (ions, protons from solar particles events, electrons from coronal mass ejection);
- Trapped particles (high-energy electrons in the radiation belts and protons in particular in the South Atlantic Anomaly (SAA).

The only two relatively constant sources, modulated by variations in the Interplanetary Magnetic Field (IMF) such as the 11-year solar cycle, are galactic cosmic rays and the high energy proton belt (> 30 MeV), which is a by-product of cosmic rays. Solar particle fluxes can be highly variable, and consequently the electron radiation belt and the low energy proton belt, which are driven by solar events.

Spacecraft operators' need for a Space Situational Awareness (SSA) Space Weather (SWE) service is closely linked to a desire to predict and potentially mitigate these interruptions. Unfortunately, space environment scientists and spacecraft operators do not always speak the same language, whereas they need to define a service jointly. Furthermore, the statistical aspect of the environment modelling, the difficulty to define proper observables with appropriate mitigations actions constrains the development of an SSA SWE service.

The purpose of this paper is to establish a bridge between these two worlds in order to have a mutual understanding of both sides' possibility and expectation, and subsequently derive the service's specification. The scope of the study is limited to a fleet of GEO to LEO satellites.

Outcomes of a survey involving the satellite operators from CNES, EUMETSAT and the scientific experts from ONERA put into evidence that the applicability of the SSA SWE service for the LEO/MEO/GEO satellite operations should be focused on three aspects, each of those presenting different needs in terms of observables and timeliness:

- ***The conceptual or design phase***, where the long term prediction of environment model can be consolidated by the monitoring of the space weather and retrofitted into the future satellite design; The observables are mainly linked to **solar activities** and have a timeframe over **years**;
- ***The operations phase***, aiming to ensure the safety and integrity of the space assets; The observables are source of **high energy particle radiation** and the timeframe is in **real time**;
- ***The support to operations***, aiming to improve the satellite availability by directly supporting the investigation e.g., by providing a snapshot of the spatial environment at a time of anomaly in order to clear up branching of the anomaly identification tree, or to indirectly support the implementation of an on board solution to prevent reoccurrence of similar anomalies. The observable is **high-energy particle radiation** and the timeframe can be from **hours to days**.

In the first part of the paper, the needs of SSA services are clarified w.r.t. physical impact of the space environment on the satellite, and the potential benefits of SSA services for Satellite Operations are established for each of the presented aspects.

Then, all SSA SWE services are discussed and traded off against user interest, and a final set of requirements established; encompassing service applicability conditions, the alarm definition and the end-to-end decision process to be put in place within all actors.

The second part quantifies the interest of the selected services requirements from retrospective simulation against track record of anomalies observed on EUM/CNES fleet of satellite over the last 15 years, and a set of final user specifications are established.

Finally, potential benefits for future mission and mega-constellation including automation of alert propagation and safing of new technology are presented.

2 Space Situational Awareness

2.1 Effects of the space environment on spacecraft

As the space environment has now been characterised, the next step is to identify its effects on the spacecraft. Depending on the local or diffuse nature of energy deposition, but also on the orders of magnitude of the energies involved, three (3) main classes of effects can be derived (Ecoffet, 2013):

- The first class is a degradation of system lifetime through the accumulation of Total Ionizing Dose (TID)* and Displacement Damage Dose (DDD)† over time. These effects induce a gradual modification of the electrical properties of the component, finally leading to component failure;
- The second class is composed of single event effects (SEE) in response of the passage of a single ionising particle (typically ion or proton) through semi-conductor devices, inducing functional flaws, latent damage, or permanent failure (destructive effects); these effects are related to system dependability and performance, and are treated as a probabilistic and risk estimation problem;
- The third class is Electro Static Discharge (ESD) resulting from the surface charging producing high voltages, damaging arcs, and internal charging from energetic electrons in dielectrics component leading to electrical breakdown.

2.2 «Space weather » and «Space Climate»

The effects of the Earth's space radiation environment are design drivers for space systems. The nature of the environment varies greatly between low earth orbits, medium earth orbits and geostationary orbits. It is now well established that this space environment is affected by the Sun's activity. It is therefore judicious to look at the dynamics of the Earth Radiation Belts (ERB), the Solar Energetic Particles (SEP) and the Galactic Cosmic Rays (GCR) at different time scales as a function of the effect (of the degradation) to be studied:

- The short term variations (less than a week or so) will be related to **space weather** events, i.e. it refers to the day-to-day environmental conditions in Earth's magnetosphere due to the Sun and the solar wind that can influence the functioning and reliability of space borne systems. This will encompass *prediction* and *restitution* of the space environment variation, in particular for the monitoring of the solar particle events (protons, ion) and the radiation belt (proton, e-);
- The long-term variations (on the order of a solar cycle) will be related to **space climatology**, i.e. it refers to the average space weather conditions that prevail over a given region for a long period that can influence ageing of space borne systems, in particular for the radiation belt (proton, e-) and cosmic rays (protons and ions).

Figure 1 summarizes those effects along an energy scale and indicates the source of origin of the particles, the associated timeframe and the affected orbits as introduced in the previous sections that will serve as a skeleton for the remainder of the paper.

---

* TID can be induced by the energetic charged particles in two ways:

- Interaction with the electrons of the target atoms, pulling them out of their orbits around the nucleus, and releasing them in the surrounding medium.
- Sudden loss of velocity when particles enter dense matter so called "Bremstrahlung" effect, releasing high-energy photons, which can in their turn induce ionization along their paths.

† DDD are induced by interaction with the nucleus of the target atom, either through electromagnetic or nuclear interaction. They have a much lower probability

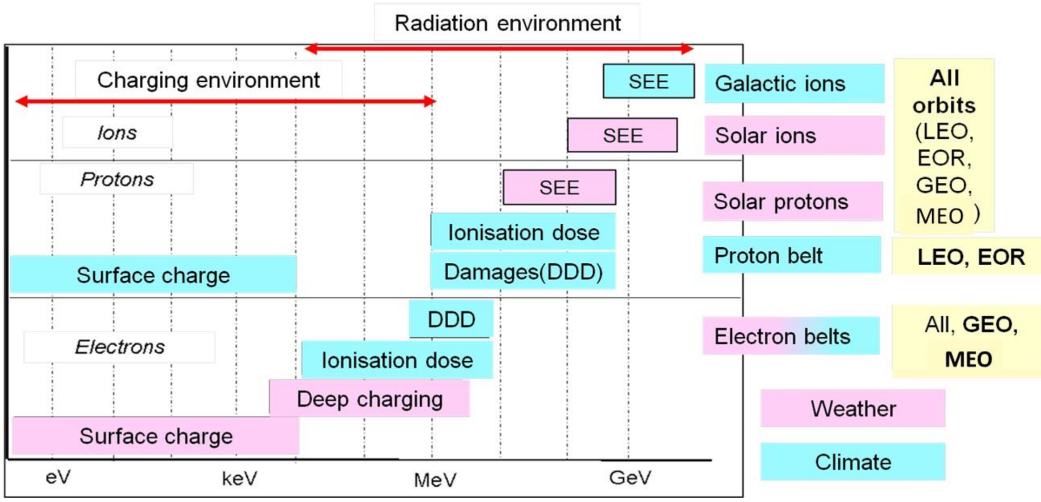


Figure 1: Space weather and climate monitoring services

2.3 High-energy particle radiation

The high-energy radiation found in outer space is responsible for space system degradation. Figure 2 illustrates the correspondence between radiation sources and effects on space systems. In more details, heavy ions and energetic protons induce single events; protons, electrons induce displacement damage and ionizing dose; and electrons lead to electrostatic discharges.

These energetic particles have different origins, heavy ions come from cosmic rays and solar particle events, protons are found in solar particle events and are trapped in the radiation belts, and electrons are trapped in the radiation belts. Each of these radiation sources are described in the following sub-sections.

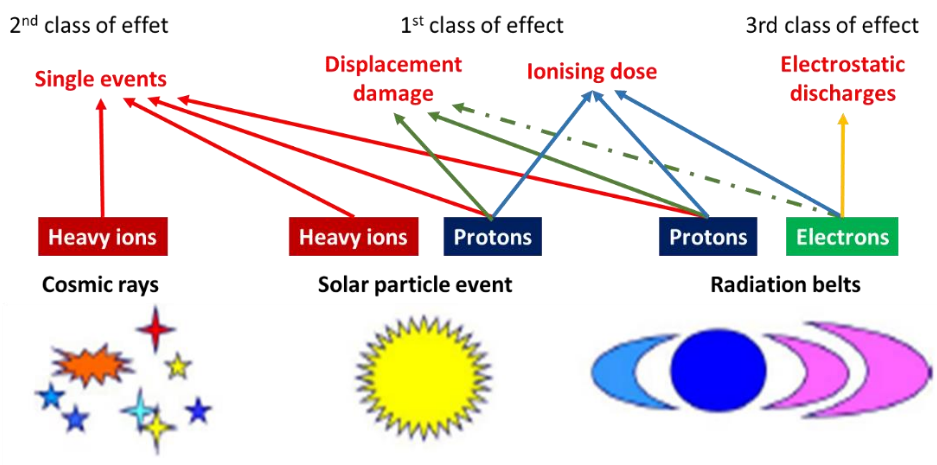


Figure 2: Correspondence between radiation sources and effect on components

2.3.1 Earth Radiation Belts

The magnetic field in the vicinity of the Earth becomes such that relativistic charged particles are trapped. These special conditions are thus favourable to the accumulation of high-energy charged particles near the Earth which creates the radiation belts. The energy ranges commonly encountered extend from some keV up to some tens or even hundreds of MeV. Table 1 summarizes the properties of the Earth's radiation belts.

Table 1: Characteristics of the Earth's Radiation Belts

	Particle	**Energy**	**Extension (Earth radii)**
ERB	e-	1 keV-7 MeV	L: 1-10
	p+	1 keV-500 MeV	L: 1-7 LEO: SAA

<u>Space climatology of the radiation belts:</u>

The proton radiation belt (high-energy component > 30 MeV) varies slowly as a function of the solar cycle [1, 2],. The flux levels are roughly at their highest when the solar cycle is at its lowest and vice versa.

The variations in the electron belt are dependent on altitude, and are essentially located where MEO and GEO spacecraft are orbiting. In geostationary orbit, the fluxes of electrons are at their lowest when the solar cycle is at its highest and are at their highest three or four years after the top of the cycle (just before the solar cycle is at its lowest) [3]. This modulation as a function of the solar cycle shows that the amplitude increases with the energy (MeV and above) whereas, at low energy levels (some hundreds of keV) no significant long-term variations are observed.

<u>Space weather of the radiation belts:</u>

Radiation belts are affected by two main perturbations from the Sun: The Coronal Mass Ejections (CME) and the Co-rotating Inertial Regions (CIR) from high-speed solar wind streams. CMEs are explosive events where large quantities of plasma are ejected from Sun’s corona while CIRs result from the interaction of high-speed solar streams escaping from Sun’s coronal holes with the ambient solar wind. Both types of event can induce major magnetic storms at Earth.

The populations of low-energy protons (some tens to some hundreds of keV) are very sensitive to magnetic storms [4]. The fluxes of particles therefore follow the Earth's magnetic activity in a region going from L=2 to L=6 with time scales extending from a minute to several hours.

At higher energy levels (several tens of MeV) the belt is generally very stable but major events can dramatically change the flux levels in intermediate regions of the radiation belts, i.e. in a region between L=2 and 2.5. The example of the event in March 1991 storm is striking. Particle populations in orbits like the O3b satellite constellation (8000 km, equatorial) might be affected in such a case while those in LEO orbits would not. Because the energetic proton belt is not very much extended, MEO and GEO orbits are not affected at all by such events.

It is clear that there are many magnetic storms affecting the Earth’s electron radiation belts (middle panel of Figure 4) [5]. According to the observations made in geostationary orbit the low-energy electrons (which induce surface charging) appear right from the first instants of the disturbance whereas the higher-energy electrons (which induce the internal charging) are detected some days after the beginning of the event.

2.3.2 Solar Energetic Particles

The most harmful particles produced by Solar Energetic Particle (SEP) events are protons and sometimes heavy ions (He, O, C, Fe ...). If among the ions, protons are always in the majority, some eruptions are accompanied by emission of heavy ions whose spectra, charge states and relative abundances vary from one event to another, and are therefore difficult to model. It takes about an hour for those particles to reach the Earth space environment. These eruptions last from several hours to several days (top panel of Figure 4). The spectra vary considerably from one eruption to another, and during the event, may extend up to energies of several hundred MeV. The solar particle events are not equally distributed over the solar cycle: solar proton and ion events are very likely to occur during solar maxima (top panel of Figure 3).

Table 2: Characteristics of the Solar Energetic Particles

	Particle	Energy	Extension
SEP	ions	1 to several 10 MeV	LEO: High latitudes MEO-GEO: all orbit
	p+	1 keV-500 MeV	LEO: SAA MEO-GEO: all orbit

Space climatology of solar particle events:

The long-term average of solar particle events is nicely correlated with the solar cycle. Solar particle flux exhibits a maximum at solar maximum phase and a minimum at solar minimum phase. The more intense the solar cycle is, the higher will be the maximum of the solar particle flux recorded at the Earth.

Space weather of solar particle events

Solar particle events are likely to reach the Earth's space environment during solar maximum phase. Nevertheless, single but very intense eruptions sometimes appear during the late solar declining phase (e.g. August 1972) [6].

Prediction of solar particle events is at present extremely difficult. In the short term, when an event is triggered it can be observed in the electromagnetic field (X-ray emission), an evaluation of proton flux becomes possible with a lead of several hours on the maximum of the eruption. A statistical analysis nevertheless demonstrates that this technique can give good predictions in only 50% of cases.

2.3.3 Galactic Cosmic Rays

The origin of Galactic Cosmic Rays (GCR) lies outside the solar system. It comes from very distant galactic and extragalactic point sources. It is propagated throughout space that is not occupied by dense matter. The cosmic rays represent a continuous background of ions whose energy levels can be very high. They can reach several thousands of GeV (significantly higher than those observed in most solar particle events). The spectra tend to peak around 1 GeV per nucleon. It consists approximately of 83% protons, 13% helium (4He ion), 3% electrons and 1% heavy ions [7].

Table 3: Characteristics of the Galactic Cosmic Rays

	Particle	Energy	Extension
GCR	ions	Max flux about 300 MeV/nucleon	LEO: Polar regions MEO-GEO: Everywhere
	protons		

Space climatology of cosmic rays

The cosmic rays, in the energy range of interest for space missions, (10 MeV/n – few hundred MeV/n) are maximum during solar minimum phase while they are minimum during solar maximum phase but lags behind the solar cycle by ~1 year (middle panel of Figure 3:) [8]. They are only slowly varying along the solar cycle.

Space weather of cosmic rays

The day-to-day variations of cosmic rays are negligible so that space weather is not relevant in this case.

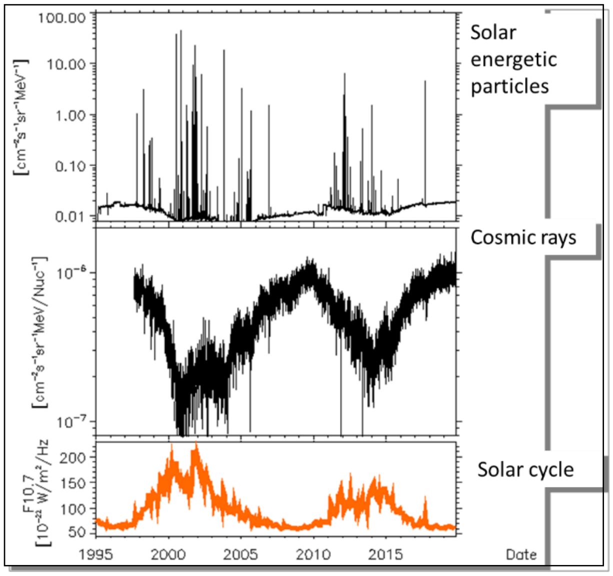


Figure 3: Space Climatology - solar cycle variations of solar energetic particles and cosmic rays (from ONERA IPODE Data Base)

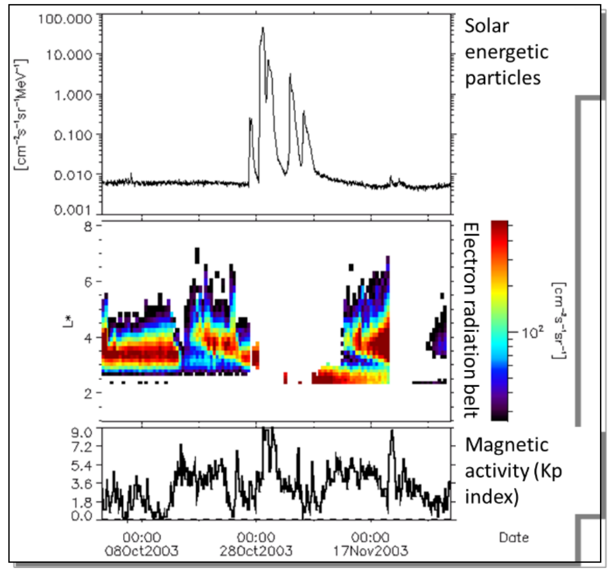


Figure 4: Space weather - Solar energetic particle event recorded at GEO and the energetic electron belt dynamics induced by a major magnetic storm (from ONERA IPODE Data Base

3 SSA Services for Satellite Operations

3.1 Main Operational Drivers

It might be worth recalling the main drivers during the operations phase for any space system actor, i.e.:

- To ensure the safety and integrity of the space assets, i.e., protecting against potential loss or degradation of the mission;
- To optimize the in-flight mission availability without endangering asset integrity, eventually improving satellite resilience to space environment.

However, these drivers might not be as a simple fact of operations implementation, but involve the full chain of satellite lifecycle. Therefore, the first step to be conducted was to identify where are the area of SSA service interest throughout the full mission life cycle of a space system.

Outcomes of a survey involving CNES, ONERA and EUMETSAT put into evidence that the applicability of the SSA SWE service for LEO/GEO satellite operations should be focused on three aspects as defined in the introduction, each of those presenting different needs in term of observables and timeliness throughout the space system lifecycle.

As introduced in the previous section, short-term and long-term variations for each of the three sources of radiation in the space environment can be handled by two different types of services, applied specifically for the design, operations and in-flight support phases.

3.2 In flight Anomalies Inventory

Rather than starting from a more theoretical view, we choose the approach to analyse the potential benefits of the SSA SWE services w.r.t. the current in flight anomalies situation. Fortunately, European space industry has been very prolific over the last decades and allowed us to start from a very clear basis for quantifying the effects of the radiations rather than assessing only their theoretical impacts to derive clear statements.

From the anomaly track records over the last decades, we can divide the reported anomalies into two classes:

- The “true anomalies”, unexpected behaviours generally triggered by design weakness or susceptibility of components to exceptional space environment conditions;

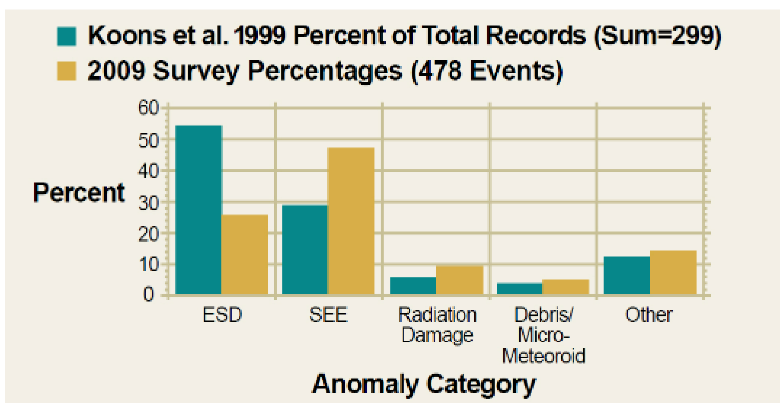
- The "expected anomalies", where the designers knew that the behaviour could occur, but the availability figure remains within the availability specification (they are generally considered in the Reliability, Availability, Maintainability and Safety (RAMS) analysis, but not included the availability figures), in other words those are "anomalies" for the ground control, but not for the designers.

"True anomalies" are by essence not planned (no one is intentionally launching satellite with bug or failure), and their intrinsic characteristics renders their prediction almost impossible. However short-term restitution of their space environment correlated in time and space with an observed anomaly offers potentiality for supporting their investigation but also consolidate the worst dimensioning case assumption into the model during the design phase.

"Expected Anomalies" are a measure of the satellite resilience to space environment. The designers from the early phase of the lifecycle build up satellite resilience to space environment by implementing such device than EDAC, current latch up devices or Fault Detection, Isolation and Recovery (FDIR) to get the maximum mission availability out the spacecraft design. These anomalies allow to consolidate the design assumption and extrapolate for the future missions. They are generally recovered by a processor restart or a power cycling of the unit.

Table 4 provides a snapshot of the relative importance of different causes of anomalies from two databases of satellite anomalies at 10 years interval in all types of missions environments. There are differences in the most frequent attributions [ESD] or [SEEs] in the two surveys, but it is difficult to quantify the allocation due to the evolution of technology and the ambiguity in the mapping, as fast SEE transients can be interpreted as ESD signals in some electronics systems [9, 10]. Furthermore, the figure may be biased by corrections applied within one satellite production cycle.

Table 4: Categorized anomalies [9]



Ionizing dose and displacement damages are a cause for long-term degradation of components and materials and therefore could affect the mission lifetime. Very few cases of mission degradation have been observed over the last decades [1], and the vast majority of our satellites exceed their nominal mission lifetimes.

Spacecraft charging with the resulting discharge are root cause of problems, such as phantom commands response, damage to electronics, loss of control, and even satellite failure. Logical circuits and computer chips are becoming smaller and less power consuming but are more delicate, therefore become more susceptible to charging, anomalies, damage, or catastrophes.

Single event effects are probabilistic effects, which have the most of impact on the availability of on-board systems as they do represent 85% of the anomalies encountered. This is the return from CNES over 10 LEO CNES, ESA, or EUMETSAT satellites or payloads operated by CNES. The figure may be biased by the use of recurring platforms: if one subsystem has a problem, it is likely to occur on all missions using this subsystem. Depending on the electronic component's vulnerabilities, the operating mode of the component, the incident and the timing of the particle energy, SEEs can results into range from recoverable effects (SET, SEU, MEUs) to permanent damage (bit stuck, or destructive SEL, SEB or SEGR).

Therefore, it seems logical to put emphasis on the mitigation of this effect on the spacecraft through the following services components as follows: In Low Earth Orbit the two hazard zones are the South Atlantic Anomaly (protons from the radiation belts) and the polar zones (entry of galactic cosmic rays and occasionally solar event particles). A mapping of spacecraft anomalies encountered in space was performed, and an inventory of more than 1000 "anomaly" cases over the period 2004 – 2020, including LEO CNES, ESA and EUMETSAT satellites, where 20 different equipment or instrument types were broken down to their root cause as per the graph presented in Figure 5. This is particularly interesting when addressing the trade-off discussion, where priorities have to be made.

None of these anomalies were related with solar events, and it turns out that the **radiation belt protons** and the **galactic cosmic rays** are the main contributors.

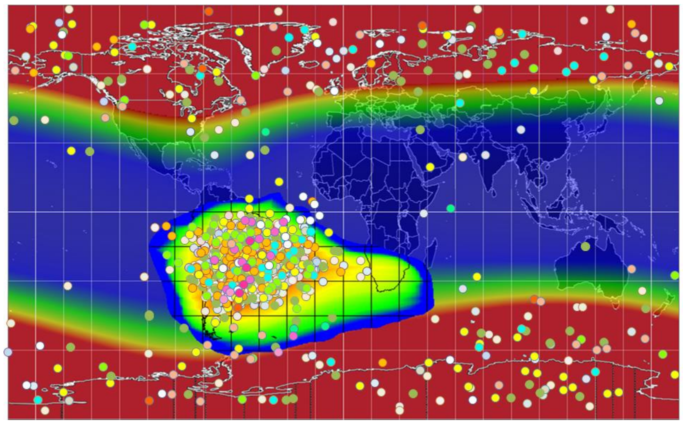


Figure 5: LEO Anomalies Distribution

Similarly, for GEO satellites, the mapping of spacecraft anomaly shows a very clear pattern of highlighting ESD and cosmic rays contribution. The level of energy of the electrons in the radiation belt (inducing transient ESDs) and GCRs protons/heavy ions (following the solar cycle and dependency to the magnetic storm) are the main factor to anomalies.

Figure 6 gives an overview of the radiation environment during the last solar cycle and shows intense solar proton events and energetic electron fluxes (responsible for satellite charging) dominating from 2003 to 2006 and then fading in the following decade [1].

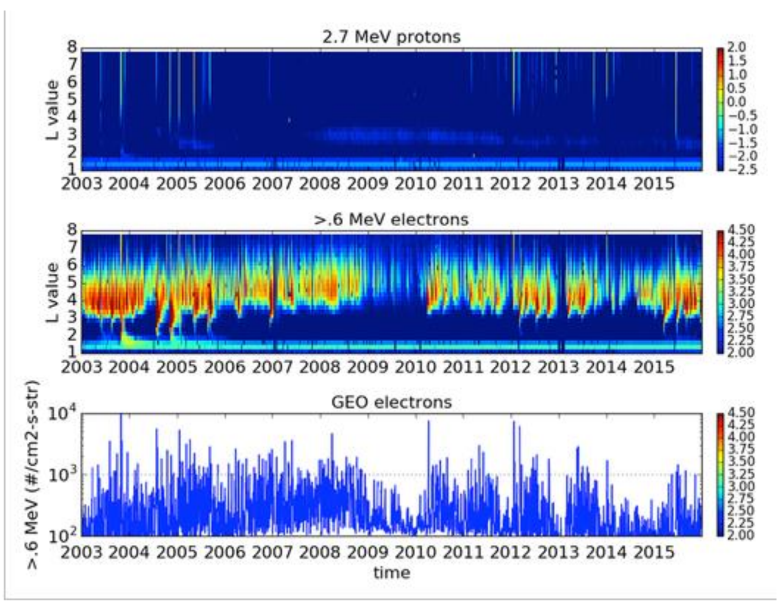


Figure 6: Radiation environment (2003-2016)

3.3 Potential Benefit of SSA Services

As introduced in the section 2.2, the SSA services should consider two timeframes to cover Space Weather and Space Climate services. The benefits should be palpable for all stake holders throughout the space system lifecycle i.e. for:

- Design and conceptual phase, aiming to increase satellite resilience to space environment;
- Operations phase (real-time), aiming to protect space assets integrity;
- In-orbit support phase (offline), aiming to optimize space asset lifetime and support anomalies investigation and characterisation.

The two dimensions, namely the prediction and restitution of events are applied as described here after:

Space weather: Near Real Time (NRT) prediction

The near real time prediction of exceptional space environment condition (e.g., Carrington event, centennial event), represent level of energy exceeding the qualification threshold. These events might trigger cautious safing actions from the operator in respect of satellite industry recommendations.

Space weather: Short-term Restitution

Component weaknesses are generally identified in flight and result in operation zone exclusion, or implementation of new procedure, fast recovery procedure, handled on board or by the ground. The space weather restitution allows the satellite operator to react faster by clearing up some branches in the anomalies decision tree. However, the information is generally not conclusive due to the predictability of the environment SEEs as explained in the section 4.1 but can still be correlated with the anomaly signature.

Space climate: Long-term Restitution

Even if the centennial episode in 2003 demonstrated the robustness of satellite design (47 satellite anomalies were reported, but no avoidable[‡] loss), this will probably be more a concern for the future mission with high level of integration. Space environment long-term restitution, will permit the scientist to improve their environment modelling and therefore reinforce during the design phase the satellite resilience to space radiation.

These potential benefits are summarized din the following table:

Users	**Space Weather**		**Space Climate**
Timeliness	**Prediction** **(NRT, 3 days)**	**Short term restitution** **(Offline, ca. 1-2 days)**	**Long term restitution** **(Offline- 1 month)**
Design and conceptual	N/A		Space environment long-term restitution, to support design phase and reinforce satellite resilience to space radiation. Future mission
Operations phase (Real time)	Space environment prediction, to protect space asset and trigger safing actions		N/A
In-orbit Support phase (Offline)	Space environment short-term restitution, to support anomaly investigation and reinforce satellite resilience to space radiation by appropriate on-board and on ground operations		Space environment long-term restitution, to optimize/assess space asset lifetime.

Table 5: Potential SSA service benefits

4 Associated Problematics

In this section, we will only address the problematic of the short term prediction of space environment events, as the restitution aspects of the SSA is an offline service that can be expressed as user requirements in section 5. The two retained predictive aspects of the SSA service will be for the SEEs and ESDs class effects. Furthermore, they represent the large majority of the encountered satellite anomalies (refer to Table **1**).

[‡] A dramatic example on the loss of ADEOS (JAXA) satellite in LEO, where a space weather service would not have saved the mission

The real time end-to-end decision process from alarm detection to implementation of mitigation action can be assimilated to a debris/collision warning service (to be served as reference) but presents rather different problematics that can be summarised in the following questions:

- Can we predict SEEs/ESDs? What are their intrinsic variability/latency?
- What is the alarm suitability? the confidence in the alarm detection is crucial, as any false alarm would result in an additional unnecessary mission unavailability and at contrary, no mitigation of a strong event could result in a permanent mission degradation;
- Which type of mitigation action? an un-ambiguous reaction associated to a specific alarm is primordial, as it could lead to a confusion and operation error in the other case.

4.1 Environment Predictability

The use of space weather products in an operational context suggests that services are mature enough, reliable and alarm are timely provided so as to implement counter measures (when possible). To investigate how far our current knowledge helps in this direction, the confidence in predicting SEP, GCR and ERB is evaluated as well as the latency prediction may offer. Note that the latency is the time interval between the event detection and the time of impact; Operators require additional time to prepare any mitigation (from few hours to one day). The characteristics of the alarm detection are summarised in the table hereafter:

Table 6: Environment predictability – Index of confidence

Event	Observable	Dependency	Confidence	Latency	Comments
SEP	Flux of ions/Protons >10 MeV/nucleon	Solar activity (Sun spots)	50%	1h	Notification notice too short Risk of false events Missed events
GCR	Flux of ions >10 MeV/nucleon	Solar Cycle	90%	Years	Background levels used for worst case dimensioning
ERB	High energy fluxes protons/e- Magnetic Storms	CMEs	50-60%	2-4 days	Propagation direction/speed difficult to assess, IMF not predictable yet. Risk of false events Missed events
		CIRs	70-80%	27/28 days	Recurrent pattern according to solar rotation Highly Predictable

Predicting SEP events as well as Coronal Mass Ejection (CME) geo-effectiveness is still very challenging. A better scientific understanding is necessary before any prediction reach an acceptable level of accuracy (low risk of false event as well as very low missed events). The system performance does not actually fit into the operations scheme, as the decision mechanism is not reliable enough for the short term predictability.

4.2 SEE Intrinsic Variability

An important point to take into account is the probabilistic nature of single event effects. Let us illustrate this through real examples.

One case of true anomaly was "crash" of the IASI (atmospheric infrared sounder) developed by CNES on EUMETSAT's METOP satellite. Unexpected upsets were observed on Honeywell's HX6828 radiation hardened 1Mbit SRAMs of the on board computer, which uses approximately 130 of those devices. Upsets were found either in the SAA or in high latitude zones in about equal numbers. In this case, two independent external causes (SAA protons and GCR heavy ions) contribute to the upset count.

The mean occurrence over the series was one event every 90 days, but in practice, we had also 480 days without any event and two events separated by 5 days only. In fact, this falls into the "natural" statistical variation. The intrinsic variability is larger than the environment variability.

Note the depth of penetration of these charged particles depends on its incident angle and the shielding nature of the component. In other words, the particles could be stopped, or could go completely through a spacecraft, resulting into different effect.

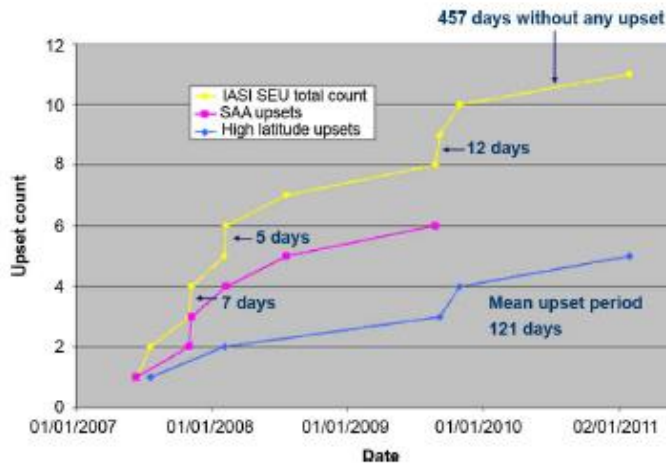


Figure 7: IASI HX 6628 memory Upset account

Many similar cases have been observed on other mission, e.g., for GOME on MetOp satellite where a ghost equipment switch off line was triggered randomly and the prediction of such events would have been simple gambling.

Another interesting case of a more recent satellite true anomaly is the PDHU packet store dump anomalies observed on two Sentinel-3 spacecraft, understood to be caused by radiation upsets during dumps over the north pole. In this case, the external cause is expected to be GCR heavy ions. The mean rate of occurrence across the two satellites is once per 101 days (or 94 and 115 individually), but in practice, we also had 555 days without any event on one satellite and two events separated by just over 1 day on the same satellite. Although it can be seen that the general trend in **Figure 8** is correlated to the flux of GCRs as expected (Figure 3), the intrinsic variability is larger than the environmental variability.

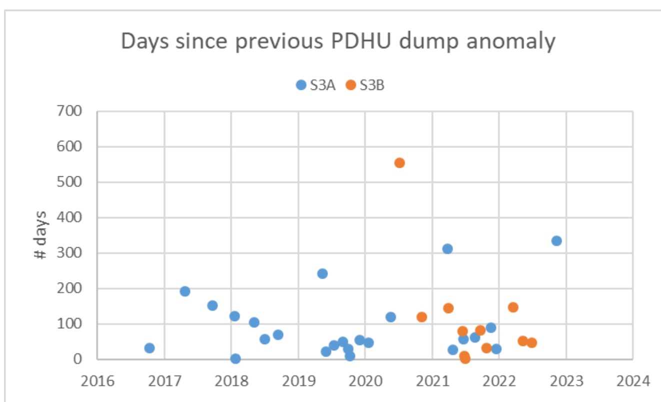


Figure 8: Copernicus Sentinel-3 Time Between Consecutive Packet store dump anomalies

As a consequence, the intrinsic variability of SEEs is larger than the environment predictability, and would result in unacceptable number of false alarms. As a consequence, SSA prediction service would not be suitable to satellite operations.

4.3 ESD Dependencies

The problematic on the ESDs is paradoxal: whereas the root cause, mainly flux of electrons from radiation belt environment are modelled with better accuracy (ref. to SafeSpace project part of H2020 research and innovation initiative for the safety of space assets), the knowledge of the different system satellite variables render the quantification of the impact very tricky to trigger alarms. One can mention:

- For the surface charging: the design of the satellite unit, the Sun illumination ratio, the level of e- flux low energy, the radiation induced conductivity and the ageing impact (material properties drift such as conductivity);
- For the internal charging: the design of the satellite unit, the 3D shielding around the unit and the level of e- flux high energy and the ageing impact (material properties drift such as conductivity).

The prediction of a specific event can only be defined in exceptional circumstance for identified design weakness (SADM connector susceptibility), or during the in flight operations (protection of redundant unit where prime unit has been permanently dammaged).

4.4 Alarm Suitability

Bouncing back on the analogy with the space debris service, where the alarm is a bulletin containing the probability of collision and the predicted time of impact, the space weather/prediction service would need to generate a bi-daily high energetic particle event warning to the satellite operator, including the probability and evolution of the high energetic particle event, with a predicted time of occurrence for a satellite in time to allow implementation of a mitigation action.

The difficulty for establishing real time alarms for the space radiation resides in space environment variability, the event detection timeliness but also the ability to define satellite maximum sustained radiation threshold. After the warning processing, the alarm suitability from an operational point of view can be described by its:

- Event threshold exceeding confidence, (traffic light);
- Alarms confidence: A high % of alarms frequency will disturb the operations and is deemed not appropriate. A value of 2% is acceptable;
- Alarm pertinence: as discussed in sections 4.2 and 4.3, the knowledge of the different system satellite variables imped the proper definition of threshold to trigger alarms;
- Readability/Applicability: Interpretation of the alarm pointing a direct and unambiguous directive in the Flight Operations Manual;
- Qualification threshold for satellite/unit/instrument (fluxes) – building database from past experience.

Consequently, the service performance does not actually fit into the operations schema of today as the alarm detection would likely result in either an unacceptably high number of false alarms or missed events, and potentially both.

4.5 Mitigation Action Suitability

The RAMS analysis generally provided by the space industry contains valuable indications about potential satellite FDIR actions but not provide any indication about the worst case conditions used in the modelling. Providing such information over even defining a list of component threshold and associated conditions would help implementing an alarm system and may even reduce the development cost for the future constellation mission.

From an operational point of view, the applicability of such cases shall be restricted to true anomalies only (refer to section 3.2) whereas the expected anomalies shall be handled by the satellite resilience.

Indeed, another aspect of the trade-off for improving the mission availability is to increase the satellite resilience to the space radiation. Although resilience is often thought of in terms of preventing upsets via radiation hardening, it can also be achieved through automation i.e. minimising the recovery duration by implementing more on board autonomy – an approach typically reserved for platform units, but can be extended to the payload. This is motivated by current high performance of the satellite, and the potential high cost required for each gain of one tenth of mission unavailability by increasing the satellite robustness, where a large majority of the anomaly are transient and can be recovered very quickly.

In other words, a new approach for designing the next generation of fleet of satellite shall consider a better resilience to the “real” space radiation environment inheriting from the new technology and active payload FDIR, i.e., restart or power cycling of instrument without affecting thermal environment e.g. with cryogenic subsystem.

The implementation of the mitigation actions relies on the confidence on the triggered alarm which is far from being mature. Assuming an acceptable alarm is triggered, the second problem will be to identify the appropriate action. The variability of the potential impact renders the definition of the action extremely complex and could lead to unnecessary mission outage.

So far, the preferred way should be to improve the satellite resilience with the support of the SSA restitution service rather to predict events.

5 SSA Space Weather/Climate Services User Specifications

As introduced in the paper, the 2 time frames restitution aspects of the SSA services can be of high interest for the handling of anomalies as follows:

- For the true anomalies:
    - SWE-Restitution: Short term restitution used for anomalies investigation/branching;
    - SCL-Restitution: Long term restitution of space radiation environment to improve satellite design state of the art.
- For the expected anomalies:
    - SWE-Restitution: Short term restitution used for anomalies investigation.

Following User service specifications have been established for all stake holders for each of the 3 services.

5.1 Space Weather-Prediction

Nowadays, SWE *are not yet* mature enough to be operationally use by satellite operators *on a day-to-day basis.* For such a service to be operational, the prediction should be reliable and accurate but the operators themselves should also put into place a suitable process for responding to a notification. Such processes should observe the basic principle that any mitigation actions taken do not introduce greater mission outages overall than would result from doing nothing, but still ensuring the asset integrity. Inappropriate and frequent (too cautious) safeing recovery would cause much more inconvenient for the satellite operations teams and generate unnecessary mission outage. *For an End to End SWE service to be operationally utilized, it would need to meet the following criteria:*

- *Reliability service:* The service should offer regular updates of the prediction over the next 3-5 days, focusing on the region of interest.
- *Prediction confidence:* The prediction should be sufficiently accurate in terms of timing and magnitude to avoid excessive false alarms or excessively long safing durations - < 1%.
- *Warning notification (and timeliness):* The notification should be received by the operator with sufficient time for the operator to process the information and put into place any necessary mitigation actions. It should be noted in this context that many satellites missions do not have commanding passes available on an orbital basis.
- Impact Risk assessment: The operator should be able to assess the potential impact on satellite (specific to each design, attitude) unambiguously against the qualification thresholds for their respective satellites units, and to assess the likelihood risk of an anomaly occurring to within a reasonable degree of certainty.

  Satellite operators do not always have a space weather expert available 24/7 (if at all) to support each operations team, and workforce trends across the domain are towards reducing team sizes. Consequently, the information must be presented in a clear and “translated” format for easy comparison against predefined thresholds, without need for the operator to perform any analysis that would be either time-consuming and/or require SWE domain specific knowledge.
- Mitigation/Safing action: The operator should be able to timely execute pre-defined contingency/safing procedure w.r.t. level of identified risk.

The notification must be clearly linked to the potential for triggering an anomaly onboard or causing permanent damage to the satellite, to facilitate identifiable consequences in terms of mission data loss. E.g. a spurious switch-off of a unit or mode change to some variant of a REFUSE mode has a known consequence in terms of mean time to recovery.

5.2 Space Weather-Restitution

For quick anomaly analysis, the classical approach consists in cutting branches in order to not investigate in details all potential causes. In this context, the radiation situation (electron and proton) must be known at all times especially along popular orbits, i.e. mainly GEO, Navigation, EOR and eventually LEO. A two level service would fulfil most requirements:

- A first one, simple like a traffic light, indicating “quiet”, “moderate” or “extreme” situation where “quiet” would allow to cut the space environment branch very shortly even by non-expert;
- A second one with full details of the radiation level where particle fluxes would be made available along user’s orbit to allow performing detailed analysis by experts.

Such a service provision could be derived according to SEE (energetic protons), surface charging (low energy electrons) and internal charging (energetic electrons) and should be made available with a timeliness of 1 or 2 days relative to real time. Historical data should be accessible to users on time range of payloads lifetime to perform statistical analysis of anomalies with space environment conditions, i.e. at least 15-20 years but longer time would be even better.

5.3 Space Climate – Restitution

The middle and long term restitution of environment conditions (space climate) is essential for improving space environment engineering models used in satellite design and better understanding and optimizing design margins. The space plasma and radiation environment is driven by solar activity. Since the beginning of the space era, we only have a sample of about 6 solar cycles of varying intensity (as illustrated in

Figure 9). Whatever solar events, radiation belts or cosmic rays are concerned, the accumulation of data with time allows to better define worst cases, mean cases, confidence level percentage cases, over time scales from months to decades and one day centuries, exactly like is done in Earth surface meteorology and climatology.

In terms of satellite post-event anomaly analysis, the service provision timeline is roughly one month before the anomaly, especially in the case of ESD where the charge may have built up days before, then passes a threshold and triggers the anomaly.

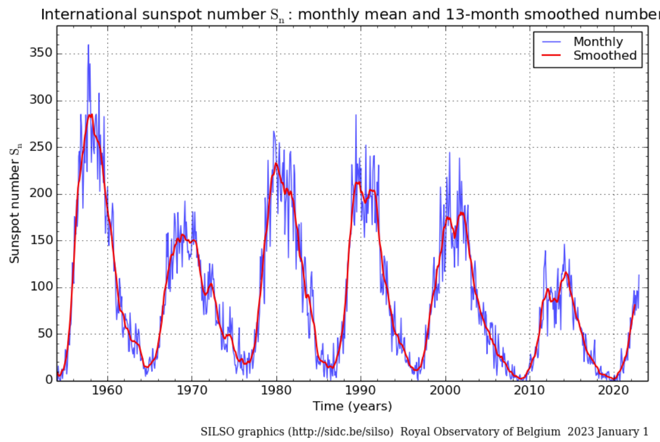
The accessibility to long term data sets also permits statistical analysis when compared to anomaly series. Trying to figure out if the anomalies are always correlated to given environment conditions necessitates comparing series, not looking at individual events which could be due to mere bad luck or coincidence. For example, one has to ask the questions:

- Why the anomaly did not occur, whereas environment conditions where worse?
- Why does the anomaly occur again but environment conditions are benign?

This helps in finding the root cause (mainly between ESD and SET) and give information on possible ageing effects leading to an increased – or decreased susceptibility.

It is very important to maintain and secure archive space environment databases in a sustainable way. Today, institutes like NASA, NOAA, USAF, ESA, ONERA and others, archive data, and provide excellent access service, but those archives need government or agency support in the long run, possibly subject to financing ups and downs. It would be an interesting subject of reflection, possibly within the COSPAR, to come as close as possible to a world system equivalent to WMO for meteorology.

Figure 9: Sunspot number series (SILSO)



6 Conclusion

Whereas the analogy between the space radiation environment monitoring and the classical monitoring Earth weather (prediction) and climate (restitution) service is obvious, the handling of the radiation effects into two temporal series shall be considered to approach the stakeholders' needs.

The predictive aspect of the meteorological weather service has drastically gained in accuracy the last decades, the SWE is still in its infancy phase and do not yet offer reliable event prediction. The service performance does not actually fit into the operations schema of today as the low environment predictability confidence and the intrinsic variability of SEEs/ESDs would likely result in either an unacceptably high number of false alarms or missed events, and potentially both. Furthermore, there is no suitable decision mechanism in place that can be considered to be reliable enough to mitigate an alarm raised by a SW service, and might even result in un-necessary turning off of the instruments or otherwise interrupting the mission. Nevertheless, potential interest in high energy flux prediction for specific critical true anomaly leading to a risk of permanent damage subsists and could be traded off on ad-hoc circumstance. As a consequence, the SWE prediction service is not yet appropriate for an operational service and the recommendation would be to increase the satellite resilience through rapid/autonomous recovery rather than reliance on predicting the space radiation environment conditions.

SWE short term restitution (1-2 days) can be of operational use for the satellite operator to support the in-flight anomaly investigation, in particular for the isolation of the anomaly root cause. Direct access to a space radiation environment monitoring database with spatial (LEO/MEO/GEO) and temporal correlation with user specified levels of energy fluxes, e.g., exceeding the worst dimensioning case used during the design, or defined in flight operation phase (which could potentially lead to a destructive effect on a satellite component resulting in a loss or permanent degradation of the mission), would be seen as beneficial for the satellite operator.

SCL or long term restitution is definitively key for the future design of spacecraft to best adapt the satellite resilience to the space environment. Indeed, access to data record for 15 years or more, would allow to optimize the satellite dimensioning thanks to an empirical approach based on historical data, and consequently be able to reduce margins and associated cost for production and validation. Another interesting aspect is the support to mission lifetime assessment in particular for the solar array ageing or degradation of rotating mechanism.

Bearing in mind the track anomaly records over the last decades, where no (avoidable) loss of satellite or unit has been reported, the satellite designers proved their expertise in designing satellite to space environment. However, high concerns are also raised for future mega constellation missions, which might be more sensitive due to electronic circuit miniaturisation, usage of off-the shelf components. Because of their business model, the knowledge of the space radiation environment is vital to minimize the repercussion on other stake holders.

What next?

- **Resilience rather than prediction:** A new approach for designing the next generation of fleet of satellite shall consider a better resilience to the real space radiation environment inheriting from the new technology and implementing active payload FDIR with a similar concept as exists already for the platform. Indeed, whereas the platform anomalies are covered by a hot redundancy concept and generally do not impact the mission, the payload is often switched to a safe status, i.e., either in standby or even off losing the thermal conditions (thus requires long recovery in case of with cryogenic subsystem and can impact the products due to the detector thermal sensitivity).

Assuming a proper design where no failure can be propagated, an autonomous restart or power cycling of instrument would save considerable mission time and operations effort. An evolving on board FDIR is preferable to also adapt to true anomalies in order to automatically recover the satellite payload in case of repeated on board conditions.

- **Restitution service - Consolidation via S2P ESA program:** Several initiatives to offer space environment nowcast (and forecast) do exist, the SafeSpace and PAGER EU-H2020 projects and RB-FAN and SaRiF ESA-S2P projects. Whereas EU projects are three years long and focused on science, the research to operation activity is conducted by ESA via the long term SSA-SWE / S2P-SWE program. It is then recommended to improve and perpetuate a radiation space environment restitution service part of the ESA-S2P program. Following the approach proven to be efficient in meteorology, an operational implementation of a radiation belt restitution should be improved by:
    - Combining in-situ data with physical dynamical models of the radiation belts. This approach is well known under data assimilation techniques including Kalman, ensemble Kalman, variational or ensemble variational filters. The most up-to-date data assimilation approach widely used in meteorology/oceanography should then be adopted and transposed to the space environment;
    - Defining regions where in-situ data are necessary (and how much), nice to have and useless such as to optimize the data assimilation tools performances while minimizing the cost. Note that good system performances are required at least along LEO/Navigation/GEO and EOR orbits. Today some regions are much better sampled than others, which leads to biased data assimilation tools rather than improving its performances;
    - Converting the environment situation into an effect according to the design of the satellite to obtain a nowcast as close as possible to the observables. This would greatly help non-space environment expert to perform the analysis themselves;
    - Offering the possibility to customize the service to any given satellite design to account for their different susceptibility to the space environment;
    - Offering historical data to perform statistical analysis with observed anomalies;
    - Setting-up a forum with all stake holders which gather space agencies, space industries and scientists to find out the best practices (access to design, access to space environment, effect calculation, correlation to observations).
- **Space climate:** the recommendations are very similar to the one of restitution services but with longer timeframe (several solar cycles)/ Specific recommendations are listed next:
    - Built a long term re-analysis (full reconstruction of the space environment) of the proton and electron radiation belt (several solar cycle long) to account for various conditions and increase the statistics of large (extreme) events;
    - Retrofit the improvements into specification models to be used by industry/Space Agency. Note that any new model should account for short-term mission phase like EOR;
    - Normalise new specification in ECSS standard.

7 References

[1] A. Vacaresse, D. Boscher, S. Bourdarie, M. Blanc, J.A. Sauvaud, "Modeling the high energy proton belt," *J. Geophys. Res., 104, 28601*, 1999.

[2] D.N. Baker, J.B. Blake, R.W. Klebesadel, P.R. Higbie, "Highly relativistic electrons in the Earth's outer magnetosphere. 1. Lifetimes and temporal history 1979-1984," *J. Geophys. Res., 91, 4265,* 1986.

[3] Sicard-Piet, A., et al. , *A new international geostationary electron model: IGE-2006, from 1 keV to 5.2 MeV." Space Weather 6.7* , 2008.

[4] R.H.W. Friedel, A. Korth, "Long term observations of keV ion and electron variability in the outer radiation belt from CRRES," *Geophys. Res. Lett., 22, 1853-1856,* 1995.

[5] G. Reeves, "Relativistic electrons and magnetic storms: 1992-1995," *ophys. Res. Lett., 25,* Vols. 1817-1820, 1998.

[6] M. A. Xapsos, J. L. Barth, E. G. Stassinopoulos, E. A. Burke, G. B. Gee, *Space Environment Effects: Model for Emission of Solar Protons (ESP)—Cumulative and Worst Case Event Fluences,* 1999.

[7] R.A. Nymmik, M.I. Panasyuk and A.A. Suslov, " "Galactic Cosmic Ray Flux Simulation and Prediction",," *Adv. Space Res., Vol. 17, No. 2, (2)19-(2)30,* 1996.

[8] J. G. G. L. E. R. a. J. Z. Yuming Wang, "Variation in Cosmic-Ray Intensity Lags Sunspot Number: Implications of Late Opening of Solar Magnetic Field," *The Astrophysical Journal,* vol. 928, no. 2, p. 157, 2022.

[9] Koons et al, "The space radiation environment and its effects on electronics," [Online]. Available: https://nap.nationalacademies.org/read/24993/chapter/4. [Accessed 2018].

[10] H.C. Koons, J.E. Mazur, R.S. Selesnick, J.B. Blake, J.L. Roeder, P.C. Anderson, "The impact of space environment on space systems," *6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578,* 1 September 2000.

[11] R. Ecoffet, "Overview of In-Orbit Radiation Induced Spacecraft Anomalies," *IEEE Transactions on Nuclear Science, Volume: 60, Issue: 3,* 2013.

[12] S.L. Huston and K.A. Pfitzer, "A New Model for the Low Altitude Trapped Proton Environment," *IEEE Trans. Nucl. Sci., Vol. 45, 2972-2978,* Dec. 1998.

[13] J. C. Green, J. Likar, Yuri Shprits, "Impact of space weather on the satellite industry," 2017. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017SW001646#swe20471-bib-0025..