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Establishing a Spacecraft Anomaly Database for Correlation with Space Weather Effects

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Abstract

This paper outlines the efforts of the CGMS - the Coordination Group for Meteorological Satellites - to establish a database of satellite anomalies from which the relationship with space weather effects can be determined. The objective is that space weather services may utilise this relationship to provide spacecraft operators with improved alerts on space weather events with the potential to cause spacecraft mission disruption. Improved understanding of the likely impact of space weather events on spacecraft subsystems can also be critical in promptly determining whether other causes of a spacecraft malfunction may need to be considered, including malicious intervention by a third party. Satellite manufacturers may also be able to improve radiation tolerance of components in a more targeted manner, based on the output of this database analysis. The paper describes the rationale for the database, the foreseen analytical processes to obtain the results, as well as the mechanisms used to collect anomaly reports from the global spacecraft operational agencies making up the membership of the CGMS. In particular, the paper highlights the difficulties encountered in accessing data due to security and confidentiality concerns, the measures being taken in response and their impact in increasing participation. An alternative method of accessing publically available anomaly information to perform space weather analyses was undertaken in the National Institute of Information and Communications Technology (NICT). This study is described in the paper, together with results which demonstrate the potential for obtaining useful alert thresholds from analysed correlations between anomalies and space weather events. The next steps to achieve the goal of a consistently updated anomaly database are described and spacecraft operators in the commercial field are encouraged to participate in the activity for the mutual benefit of achieving a more statistically significant dataset and their own access to the outputs, which can in turn guide design and operations decisions of those commercial entities.

Acronyms/Abbreviations

CGMS - Coordination Group for Meteorological Satellites
EUMETSAT - European Organisation for the Exploitation of Meteorological Satellites
GCR - Galactic Cosmic Ray
GEO - Geostationary Orbit
LEO - Low Earth Orbit
MET - Meteosat
NCEI - National Centers for Environmental Information (NOAA)
NGDC - National Geophysical Data Center (NOAA)
NICT - National Institute of Information and Communications Technology (Japan)
SEDA - Space Environment Data Acquisition monitor
SEE - Single Event Effect
SEP - Solar Energetic Particle
SWCG - Space Weather Coordination Group
SWPC - Space Weather Prediction Center
WMO - World Meteorological Organization

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1. Space Weather Activities within the Coordination Group for Meteorological Satellites

CGMS - the Coordination Group for Meteorological Satellites - is the group for global coordination of meteorological satellite systems, consisting of 16 governmental organisations from around the globe (Figure1.)

Figure 1. CGMS Members

The main goals of the Coordination Group for Meteorological Satellites are to support operational weather monitoring and forecasting as well as climate monitoring, in response to requirements formulated by the World Meteorological Organization (WMO), its programmes and other programmes jointly supported by WMO and other international agencies. Analogous support to Space Weather aspects was introduced in 2018 in response to the growing realisation of CGMS member states of the potential societal and economic impact posed by space weather activity. WMO have also introduced space weather within their mandate to ensure the effective coordination of both space and ground-based measurements of space weather phenomena in their Vision for the WMO Integrated Global Observing System in 2040 Vision [1]. An overview of the value to the spacecraft operations community coming from all activities of the CGMS SWCG was published for SpaceOps2021 [2].

As part of this effort, the CGMS Space Weather Coordination Group (SWCG) coordinates satellite systems of its members with an end-to-end perspective, including protection of in-orbit assets and support to users, in order to facilitate and develop shared access to and use of satellite data and products. In this context, users include space weather services and the satellite operations community (who are represented within the CGMS agencies and the SWCG).

2. Need for Space Weather Awareness on Space Missions

Space Weather impacts the environment within which spacecraft missions operate in a number of ways:

- The local drag environment may change substantially as a result of geomagnetic disturbances leading to significant orbital perturbations, which will may lead to the need to perform additional corrective manoeuvres and impact debris conjunction analyses with potential for rapid responses in collision threats emerging at late notice.
- Significant charged particle flux may be encountered in the following ways:
    - Solar Energetic Protons (SEP) triggered by a Solar flare, striking the spacecraft may cause Single Event Effects (SEE) on the software and hardware components. These generally lead to temporary mission outages, but may cause permanent damage with associated mission degradation. Note that these are similar effects to those encountered from Galactic Cosmic Rays (GCR) which generally have higher energy than SEPs. GCRs are emanating from sources outside of our solar system. The flux level of GCRs shows an anti-correlation with the solar-cycle variation, because the long-term solar activity modulates GCRs penetration within the solar system.
    - Increased electron flux due to geomagnetic disturbances may lead to a build-up of electrical charge on the spacecraft surface or internal components, leading to a sudden discharge which has the potential to cause damage to components or disruption of internal communications protocols and recoverable outages.
- Total dose radiation cumulative effects will degrade solar array efficiency over the lifetime

With the exception of reacting to the local drag environment, ensuring resilience against space weather effects has typically been left to satellite developers, such that satellite operations teams have not needed to pay specific attention to the solar environment. Indeed, anomaly statistics do show that solar activity has not caused significant issues on the EUMETSAT satellites to date, with most outages being attributable to either GCRs or LEO satellite regular passes through the South Atlantic Anomaly [3]. A look at solar activity since the dawn of the space age indicates that we have been fortunate to operate in a relatively benign environment, but this was not the case in the past and there is a significant probability of a solar storm which would severely challenge the design resilience of all space and ground assets [4,5].

Furthermore, it is increasingly important to be able to attribute anomalies swiftly and reliably from various perspectives [6]:

- For space system design, feedback on parts selection and system qualification is of increasing importance with the shift in emphasis to fleet operations using satellites designs with lower engineering margins than was typically the case in the past.
- For spacecraft operators, who need to ensure mission availability, understand vulnerabilities and potential failures and develop operational workarounds or patches to regain system capabilities (a good example is the Metop-A anomaly, investigation and workaround [7]).
- For space weather analysts, where the correlations of anomalies may help validate space environmental models.
- For defence analysts, where understanding the cause of a disruption of space system operations might prevent unnecessary and escalatory actions.
- For insurers, where unambiguous identification of the cause for anomalies and failures can provide valuable input for insurance processing.

In summary, an improved understanding of the correlation of spacecraft anomalies against the specific radiation environment will raise awareness of operators and other space actors to specific threats and eventually aid satellite design authorities, space weather service providers and space operators to enhance the global satellite fleet resilience.

3. Correlating Spacecraft Anomaly Data with Space Weather Events

Although the basic mechanism about how space weather events cause satellite anomalies is well known, knowledge about the quantity of such spacecraft anomalies is quite limited. This is because detailed information about individual spacecraft anomalies is not disclosed in general. This is one of the motivations for encouraging the reporting of such information into a spacecraft anomaly database.

As opposed to the active reporting of anomaly information, a passive mechanism to collect information on spacecraft anomalies has been used to provide an indication of the value of spacecraft anomaly information. The NICT have examined the correlation between spacecraft anomaly information and space weather events using event logs of Himawari-8 and Meteosat (MET-7 and MET-8) in 2015–2017 [8]. Since the meteorological observations are a global public service, CGMS recommends that the meteorological satellite operating organisations disclose the observation data obtained from the meteorological satellites to the public, and record and publish the event log for comparison and calibration of the data between the satellites [9]. In the event log, various events that affect the observation data, such as planned events (data outage due to eclipse period, manoeuvres, etc.) and sporadic data outage (data missing, quality degradation, etc.), are recorded.

Figure 6 shows 1-MeV electron 24-hour fluence observed by Himawari-8/Space Environment Data Acquisition monitor (SEDA) from 2015 to 2017. Circles indicate the 84 spacecraft anomalies that occurred in MET-7 (red) and MET-8 (magenta). Blue circles indicate the 11 spacecraft anomalies of Himawari-8. The vertical position of each symbol corresponds to the electron fluence when the anomaly occurred. From Figure 2, it is found that the spacecraft anomaly tended to occur when the electron fluence increased. However, there were no simultaneous occurrences of anomalies on Himawari-8 and Meteosat, and anomalies did not always occur when the fluence increased. This suggests that enhanced electron fluence increases the likelihood of an anomaly, but is not a sufficient condition for spacecraft anomalies to occur. Also, it is apparent that the frequency of spacecraft anomalies is different depending on the satellite. It is suggested that spacecraft anomalies are closely related to the individual structure and properties of the spacecraft system.

Our results suggest that the non-negligible number of spacecraft anomalies occurred during severe space weather events. However, it must be noted that the current information on the individual spacecraft anomalies obtained from the event logs of meteorological satellite is quite limited and therefore may include anomalies which are due to other root causes. Furthermore, the number of spacecraft for which public information can be extracted is rather small. A spacecraft anomaly database based on active reporting from many operators should therefore be established including detailed information of specific the spacecraft anomaly such that the likelihood of it being due to the space radiative environment can be taken into account.

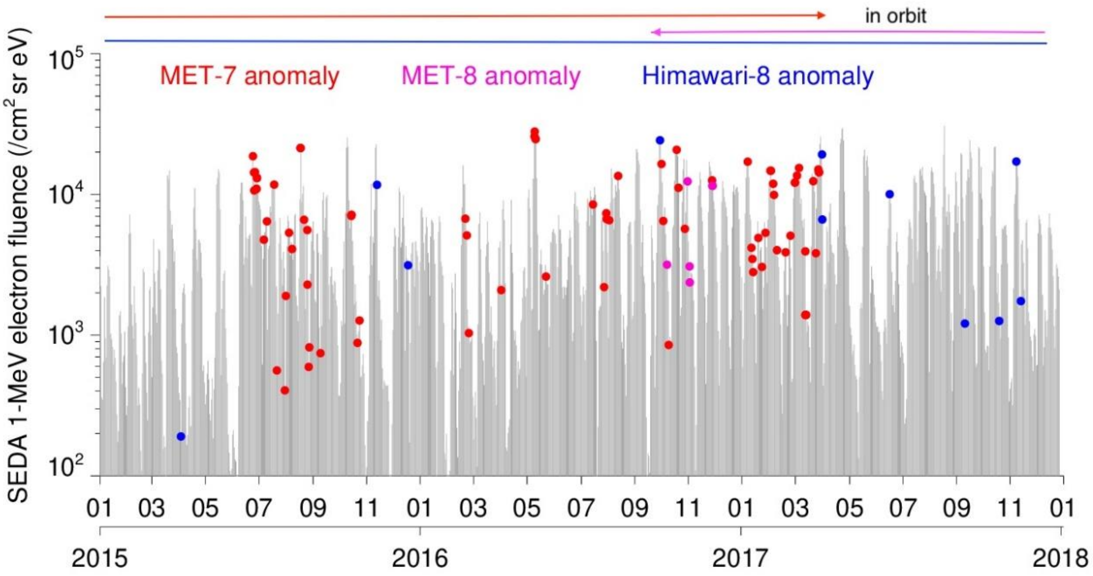

Figure 2: Himawari-8/SEDA-e observation of 1-MeV electron fluence and its relation to spacecraft anomalies. Red and magenta circles indicate spacecraft anomalies of MET-7 and MET-8, respectively, and blue circles indicate spacecraft anomalies of Himawari-8. The vertical height of each symbol indicates the electron fluence when the anomaly occurred. [Sakaguchi and Nagatsuma, 2022]

4. Space Weather Spacecraft Anomaly Database

The Vision

The spacecraft anomaly database is envisaged to contain details of a statistically significant number of spacecraft anomalies from global operators, where space weather effects are a potential root cause, allowing space weather experts to analyse the correlation with historical space weather activity.

Figure 3, illustrates a cycle of space weather resilience improvement with the output of this database correlation forming a central hub to the benefit all space actors, who then in turn can use this knowledge to interact with each other more effectively. The spokes emanating from this hub show how the various actors take advantage of the correlation output:

- Space Weather Services benefit from:
  - Improved understanding of space weather events likely to cause space mission disruptions
- Spacecraft operators, who benefit from
  - Improved space weather service capability to identify space weather events with the potential to cause spacecraft mission disruption.
  - Improved ability to determine whether other causes of for a spacecraft malfunction may need to be considered, including malicious intervention by a third party.
- Spacecraft designers, who benefit from
  - feedback on specific component and design susceptibilities enabling improved engineering of radiation tolerance of components and system design in a more targeted manner.
- Standardisation bodies, who benefit from
  - overall tracked susceptibilities allowing an independent identification of best practices and evaluation of their effectiveness.
- Space Insurance industry, that benefits from
  - Improved understanding of the background risk and application of best practices to the insured assets.

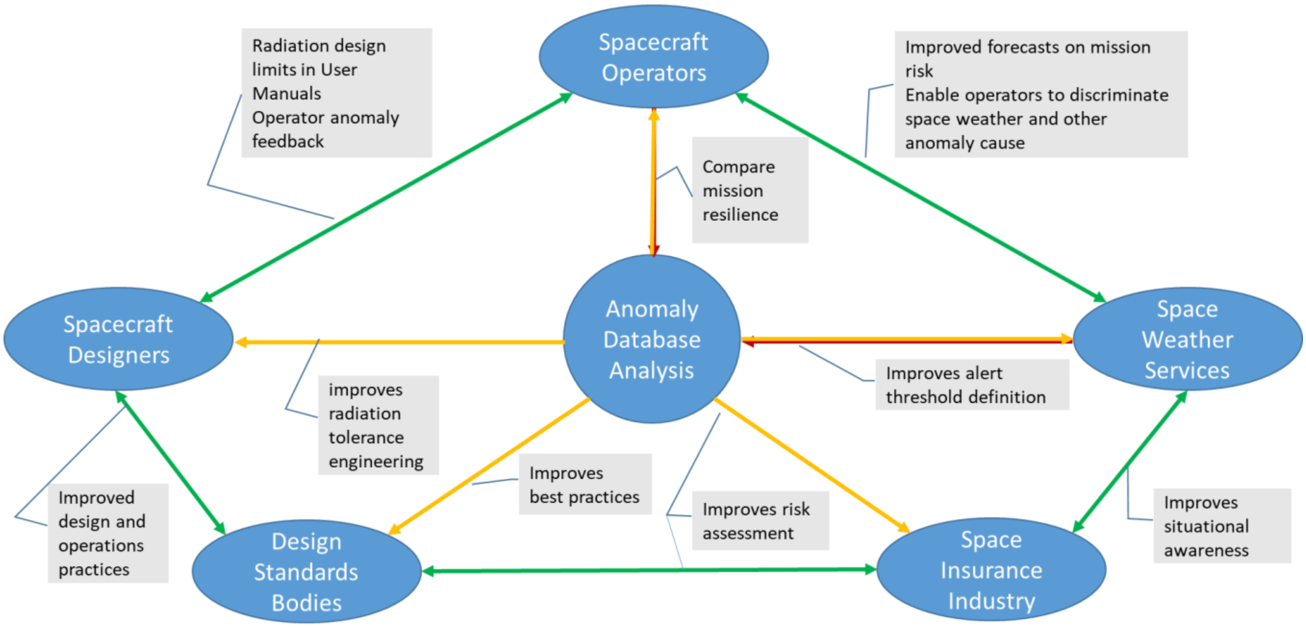

Figure 3. Space weather correlation with spacecraft anomalies benefits all actors

The outer ring illustrates the interactions between the various space actors, which magnify the benefits from the improved understanding of effect of space weather on spacecraft subsystems afforded by the database at its hub. Looking at each actor in turn:

- Spacecraft Operators:
  - As customer to the Space weather forecast service, the improved alerts and warnings threshold definition will provide a stronger foundation for decision on the appropriate operational mitigations. This can be complemented by specific tailoring of these thresholds based on inputs from the manufacturer's user manual and known sensitivities experienced in-orbit.
  - For post-anomaly analysis, the improved understanding of the likelihood of a given space weather event contributing to an outage can be crucial in discriminating between natural events and those from man-made interventions.
- Space Weather Services:
  - Based on the correlations analysed in the database and the subsequent improvement in alerts threshold definitions, service quality to spacecraft operators, insurers and other actors will benefit.
- Space Insurers:
  - Can better correlate insurance claims against specific events reported by the space weather services.
- Standardisation bodies:
  - Benefit primarily from the close interaction with spacecraft designers' and operators' feedback on new outlier events which have the potential to change underlying assumptions within the standards and guidelines.
- Spacecraft Designers:
  - Benefit from feedback from the operators on specific radiation sensitivities detected during operations, allowing improved designs and definition of workarounds on these and similar space assets.

Spacecraft Anomaly Data Collection

The process relies on the collection of well-structured anomaly reports from numerous space operators and covering a diverse set of spacecraft designs operating in various orbits and covering a substantial number of years, thereby ensuring:

- A statistically significant set of data points
- Detection of the impact of the phase of a ~11-year solar cycle and differences between solar cycles
- Differentiation of space weather effects based on orbital regime and position.
- Detection of differences between the susceptibility of different spacecraft designs to space weather.

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The CGMS has requested those members responsible for their own spacecraft operations to report on spacecraft anomalies for which a link to the space weather environment is suspected, or cannot be ruled out. If in doubt, the spacecraft operator is encouraged to supply all anomaly information.

The anomaly reports themselves are requested using the form reproduced in Figure 4. with an example entry taken from a typical CGMS member LEO satellite.

CGMS-49 XXX-WP-XX
V1, DATE

3 IMPACT ON <NAME OF SATELLITE SERIES A> SATELLITES DUE TO SPACE WEATHER *(LEO EXAMPLE ENTRY PROVIDED)*

Source: Recommendations for Contents of Anomaly Database for Correlation with Space Weather Phenomena, P. O'Brien, J.E. Mazur, T. Guild, November 2011, AEROSPACE Report No.TOR-2011(3903)-5.

1. Date and Universal Time of the anomaly	**2. Fully specified location of the anomaly** (spacecraft location)	**3. Velocity or orbital elements at time of the anomaly**	4. Eclipse state of the vehicle (full, penumbra, partial, none)	5. Vector to Sun in spacecraft coordinates	6. Velocity vector of spacecraft in spacecraft coordinates	7. Initial guess at type of anomaly (See taxonomy below)	8. Estimated confidence of that guess	9. Anomaly category (e.g., affected system or kind of disruption)	10. Vehicle identity	11. Notes (e.g. unusual operational states or recent changes to operations (recent commands, attitude scheme, etc.)
2018-12-19 13:18:50	*LON[deg] = 57.511W LAT[deg] = 1.056S (SAA)*	*a[km] = 7204.569 e[-] = 0.00143 i[deg] = 98.808 RAAN[deg] = 50.199 PSO[deg] = 180.996 PSO[rad] = 3.15897*	*none*		*VY [km/s] = -7.425 VZ [km/s] = 0.197*	*Geomagnetically trapped protons/ electrons*	*high*	*Payload software processor*	*Agency LEO satellite*	*Power cycle restored functionality*

Taxonomy of Satellite Anomalies Caused by In Situ Charged Particle Environment (to be used for column 7):

1. Electrostatic discharge (charging)
    1.1 Surface charging
        1.1.1 Plasma sheet (subauroral)
        1.1.2 Auroral
    1.2 Internal charging
        1.2.1 Subsurface charging (e.g., beneath blanket)
        1.2.2 Deep charging (e.g., inside a box)
2. Single-Event Effects
    2.1 Protons
        2.1.1 Solar proton event
        2.1.2 Geomagnetically trapped protons
    2.2 Heavy ions
        2.2.1 Galactic Cosmic Rays
        2.2.2 Solar energetic particles
        2.2.3 Geomagnetically trapped heavy ions
3. Total Dose
    3.1 Long-term dose accumulation (multiple causes combined)
    3.2 Short-term (days or less) dose accumulation
        3.2.1 Solar protons
        3.2.2 Geomagnetically trapped protons

3.1.3 Geomagnetically trapped electrons

Figure 4. Space weather spacecraft anomaly report template

As stated on the form itself, the form was devised from work performed in 2011 and further elaborated in Section 5 of this Paper [10]. The template document available on the CGMS website explains the meaning of each required field.

Not only new anomalies, but also reoccurrences of anomalies should be reported, even if the cause has been understood and mitigating operational actions put in place, otherwise the information to Space Weather experts is being artificially shortened and less useful.

5. Generation of Warning/Alert Thresholds for Spacecraft Operators

The role of the Anomaly Form envisaged by the above referenced report is to populate a database of space weather related anomalies. In 2011, this was maintained by NOAA's National Geophysical Data Center (NGDC), in partnership with the Space Weather Prediction Center (SWPC). However, this database is no longer active. This Paper [11] describes a statistical model (for GEO satellites only) based on the anomaly data, relating observable (and forecastable) environmental parameters to an anomaly probability, a so-called "Hazard Quotient", that satellite operators can take into account in their operational planning. Hazard Quotient models relate environmental parameters to the elevated risk of an anomaly. When the vehicle's average anomaly rate is known and it has a Hazard Quotient model for the anomaly, then one can use environment forecasts to predict the expected anomaly rate. This assists operators in deciding what type of mitigation is appropriate: none, staffing adjustments, or rescheduling risky operations, or even switching subsystems to a safe configuration.

A critical element in developing Hazard Quotient models is anomaly lists for recurring anomalies on a single vehicle or series of vehicles of similar design. With as few as ~10 cases, a reasonable fit can be obtained relating the environmental parameter to the anomaly risk. This fit then becomes the tailored Hazard Quotient model specific to a vehicle, versus the generic ones provided in [11]. A common example is the relationship between >2 MeV electrons at geostationary orbit and the risk of internal charging. If the 24-hour trailing average electron flux is x, then with only a few anomalies it is possible to estimate an internal charging Hazard Quotient of the form $x^\gamma/<x^\gamma>$, where γ is a free parameter and $<>$ indicates a simple arithmetic average. If the long-term average rate of internal charging anomalies is λ, then the instantaneous anomaly rate is $\lambda x^\gamma/<x^\gamma>$. This simple formula can then be used with a forecast of the electron flux to determine whether an anomaly is likely in any given time within the forecast horizon. We have found that while λ varies from vehicle to vehicle, γ tends to be fairly similar across vehicles of the same design. If λ is unknown, a reasonable initial guess, e.g., for a new vehicle, is λ=1/year.

The tailored Hazard Quotient model may be used in operations as follows: with a 3-day electron flux forecast, the integral of $\lambda x^\gamma/<x^\gamma>$ over each day in the future gives the number of expected anomalies on those days. Such anomaly rate forecasts can naturally be used as the basis of alerts and warnings, whether for a specific vehicle, or for a generic vehicle (when multiple anomaly lists are combined in the fitting procedure). In summary, with only a few recurring anomalies, it is possible to estimate two parameters (γ,λ) that can then be used to predict the expected number of anomalies during a forecast window, which can then be used to issue alerts and warnings. The fitting procedure is described in [11]. It is believed that these kinds of tailored forecasts, expressed as anomaly risk, are far more actionable in satellite operations than the underlying forecasts of environmental parameters.

6. The CGMS SWCG Task Group

To progress, the CGMS SWCG has established a dedicated Task Group for a Space Weather Spacecraft Anomaly Database, consisting of CGMS Member Agency nominated participants from the relevant Working Groups, as well as experts representing the other potential database users:

- spacecraft operations experts
- spacecraft design experts in space weather resilience / standards committees
- space weather service providers

The main issues to be addressed by the Task Group are to ensure that there are:

- recognised recipients of the anomaly forms
- use cases to validate that the anomaly information in the forms is fit for purpose
- sufficient guidelines to the spacecraft operators on data collection which can be incorporated into the regular reporting mechanisms
- resources assigned to build and maintain a database of anomalies
- defined processes in place to make use of the collected data
- clear objectives supporting user groups, whether they be space weather researchers, spacecraft design engineering authorities and standardisation bodies, space weather service providers or spacecraft owner/operators.
- mechanisms in place to overcome confidentiality and security concerns.

7. Issues concerning the supply of anomaly data

Concerning the last point of the list above, experience has shown that even within CGMS itself, many satellite operators are not able to provide satellite anomaly information due to security and confidentiality issues surrounding their satellite missions.

One approach to overcome this is allowing reports without identifying the specific spacecraft, but providing all other data. Although the location information in the reports would allow the identification of the specific vehicle, this approach is nevertheless sufficient for some operators. Of course, without the location, the analysis against space environment hazards is nearly impossible. Also, one of the potential benefits of the data analysis, namely the detection of differences between the susceptibility of different spacecraft designs to space weather becomes more difficult, as direct feedback to the manufacturer will not be possible. Although reducing the clarity of correlation results, the relative susceptibility to radiation events between different spacecraft would nevertheless be visible from anonymised data, allowing better understanding of thresholds and feedback to all operators and manufacturers who may then determine independently and confidentially whether their own assets have been impacted by such events.

Alternatively, non-disclosure agreements would allow the database itself to contain the full identities of the spacecraft, but bind the recipients not to divulge the details – only the statistical results could be shared, and even then, only with the space vehicles' identities anonymised. While this provides the best case for the database analysts, enforcement and therefore acceptability may be problematic.

The identification of a "Trusted Agent" has therefore been widely discussed in Space Weather fora. The Trusted Agent would be able to hold all this proprietary and sensitive data, and establish a legal framework for sharing it with a strong non-disclosure agreement. While this may work in a controlled, national context, achieving a similar setup with a centralised database to work in an international context can be foreseen to be problematic.

In the international context, it is proposed to consider targeting a dispersed anomaly database with trusted agents specific to a group of regional operators. As long as procedures and processing methods are coordinated internationally and considered reliable, anonymised results from each regional database could be shared and integrated. Support of regional government agencies in helping to facilitate the communication between owner/operators with the respective space weather experts managing their part of the database would be beneficial. This concept requires validation in close liaison with global CGMS member agencies.

Furthermore, anomaly collection and translation to the required inputs can be labour intensive, which is an additional barrier to data provision. Development of machine readable data collection formats and interfaces with anomaly reporting tools used within operational environments can help, although the tools used by operators are not well standardised.

Beyond the provision of data by CGMS members with a relatively limited number of in-orbit assets, access to a more statistically significant set of data is required to extract maximum value to all actors involved. Commercial operators are also being approached to assess their willingness and ability to share such anomaly data, such that the knowledge base can leverage the experience of large fleet operations in various orbital domains. In this respect, engagement with the commercial operators to jointly find solutions for overcoming barriers to providing perceived commercially sensitive data is in progress.

It should be however noted that following the principle of scientific open data access, analysis results regarding the relationship between the space environment and spacecraft anomalies must be disclosed in published scientific papers. Furthermore, in order to ensure the reproducibility and traceability of such papers, it is necessary to allow the provision of source anomaly data to third-party experts by accepting non-disclosure agreements.

With the potential benefit of feedback from space weather experts being made available in return for the effort put into providing the data, it can be expected that a virtuous cycle of improvements in mitigating environmental risk and increasing our understanding of the environment itself can result.

Spacecraft operators already able to volunteer participation in such a scheme should contact the authors.

8. Conclusions

A spacecraft anomaly database for correlation with space weather events promises to yield many benefits for all actors involved in supporting space missions, yet the establishment of a sufficiently populated database has so far remained elusive, primarily due to concerns on data confidentiality. Overcoming these concerns to enable the supply of a statistically significant and well described set of anomaly reports remains the challenge. Through outreach and discussion with individual actors in the field, the value which can be returned to those actors based on their collaboration is becoming better understood and there are increasing indications that more data may be made available, at least at regional level. In addition, opportunities exist to leverage the scale of commercial operations and operators representing both government and commercial entities are encouraged to engage with the CGMS to identify the potential scope of collaboration in this endeavour.

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