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Impact of space weather on the satellite industry

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Key Points:
- Satellite industry stakeholders believe that most recent space weather impacts to satellites are not severe
- Some satellite anomalies may not be addressed because of the lack of tools for quick root cause attribution
- Satellite industry stakeholders requested guidance to set design specifications and tools to decide if an issue is space weather related

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Abstract This paper describes space weather impacts to the satellite infrastructure as perceived by satellite industry stakeholders. The information was gathered through in-person and remote meetings with both satellite operators and manufacturers. The paper describes current impacts, industry processes for managing and mitigating impacts, costs, and industry needs and requirements. Lastly, we suggest potential improvements and solutions to problem areas based on our observation of the industry processes including (1) improved tools for quick anomaly attribution, (2) training, and (3) coordinated information sharing.

Plain Language Summary The highly variable space radiation environment around Earth can impact the global satellite infrastructure causing temporary malfunctions or permanent loss of satellite functions. International concern regarding this threat is growing as our technological society becomes ever more dependent on satellite capabilities. This paper describes space weather impacts as perceived by satellite industry stakeholders. The information was gathered through in-person and remote meetings with both satellite operators and manufacturers. The paper describes current impacts, industry processes for managing and mitigating impacts, costs, and industry needs and requirements. Lastly, we suggest potential improvements and solutions to problem areas based on our observation of the industry processes including (1) improved tools for quick anomaly attribution, (2) training, and (3) coordinated information sharing.

1. Introduction

This paper describes current space weather impacts to satellite industry manufacturing and operations and the processes for managing these impacts. It suggests areas where additional tools and resources could improve processes leading to reduced cost and a more robust satellite infrastructure. The goal is to provide information that will spur development and guide funding resources where needed. Additionally, the report is intended to give government agencies insights into potential vulnerabilities of the satellite fleet that should be addressed in order to minimize any societal or economic risks. While significant effort has been put into advancing the understanding of the physical processes in support of space weather needs, relatively few efforts have focused on defining the stakeholder's needs and requirements.

This discussion of space weather impacts to the satellite industry is prompted by growing international concern about potential harm from space weather to our technological society. As stated in the recently released U.S. National Space Weather Strategy prepared by the U.S. National Science and Technology Council (NSTC)

"Space weather can disrupt the technology that forms the backbone of this country's economic vitality and national security, including satellite and airline operations, communications networks, navigation systems, and the electric power grid. As the nation becomes ever more dependent on these technologies, space weather poses an increasing risk to infrastructure and the economy."

The concern is further documented in reports such as "Extreme space weather: Impacts on engineered systems and infrastructure" by The Royal Academy of Engineering. Some effort is being made to address these concerns with increased collaboration, development of data sharing plans, and coordinated space weather forecasting through international groups such as the Coordinated Group for Meteorological Satellites (CGMS), the Committee on Space Research (COSPAR), and the United Nations Committee on the Peaceful Use of Outer Space (UN COPUOS).

While the risk to the satellite infrastructure is recognized, the severity is difficult to assess for several reasons. First, there are business and economic reasons for not publicly advertising every on-orbit satellite issue. Failures that are serious enough to be newsworthy are generally infrequent and may not clearly depict the

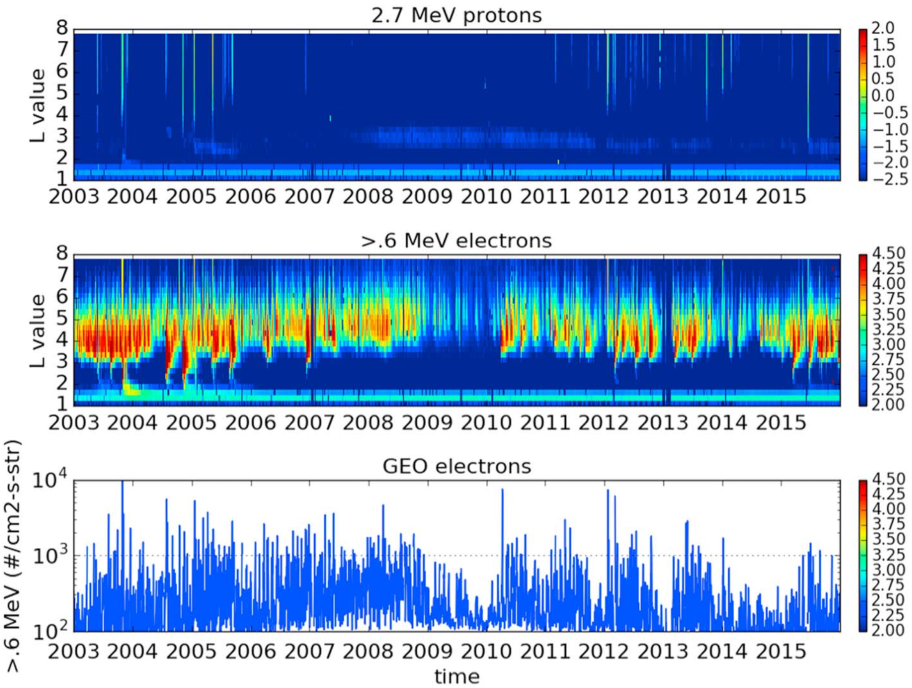

Figure 1. Overview of the radiation environment from the NOAA-15 satellite. (top) The occurrence of solar proton events with relatively few moderate events occurring after 2006. (middle) The high-energy electrons responsible for internal charging that map to radial distance from 1–8 Re with intense fluxes dominating from 2003 to 2006. (bottom) The same energetic electrons that map to geosynchronous orbit with relatively lower intensities after 2009.

current or evolving resilience of the satellite fleet. Second, any seeming decrease in the number of reported failures in recent years may be the result of improved infrastructure or, alternatively, may be due to the relatively mild space environment over the last decade (see Figure 1). For example, in the last 2 years, NOAA reported only three moderate solar proton events that are often associated with satellite anomalies. To put these small events in perspective, the peak intensity of the $>$10 MeV proton flux was approximately 1000 times less than those during the remarkable 29 October 2003 event (25 pfu compared to 29,500 pfu). During this active 2003 storm period, dubbed the “Halloween storms,” a large number of satellite anomalies were reported. Issues included effects on 59% of NASA Space Science missions, lost contact with the ADEOS II satellite, safing of the DRTS satellite and more [*Weaver et al.*, 2004]. Figure 1 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 waning in the following decade.

Lastly, risks to the industry are difficult to predict because the technology continuously evolves and increases in complexity as the industry grows and moves into new service and operating modes and regimes with less space weather heritage. The substantial growth is demonstrated by a factor of 2 increase in total industry revenues over the past 10 years up to $208 billion in 2015 [*Satellite Industry Association*, 2016]. Some of this growth comes from expanding markets such as satellite Earth imaging and internet. These new ventures have increased the demand for larger fleets of small satellites opening up new capabilities and also unknown vulnerabilities. Companies such as O3b/SES are now providing satellite internet services with an operational Medium Earth Orbit (MEO) fleet of 12 satellites with eight more expected to launch by mid-2018 [*Selding*, 2015]. Many groups are soon to follow with even larger proposed constellations. OneWeb will provide internet services from a 700+ satellite fleet [*Selding*, 2016a], LeoSat is expected to begin launching approximately 100 satellites, Boeing is working on a concept with several thousand satellites [*Selding*, 2016b], and SpaceX is planning an eventual constellation of 4425 satellites [*Mosher*, 2016]. Additionally, as the industry expands, so does the overall complexity and potential for cascading risks. Some satellites now use GPS-based navigation or rely on satellite-to-satellite data transfer meaning that a problem on one satellite may impact many. New

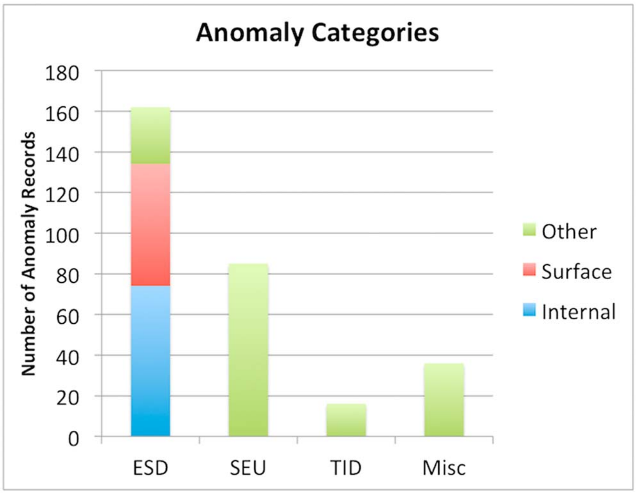

Figure 2. Categorized anomalies from *Koons et al*. [1999].

launch techniques such as electric orbit raising to reach geosynchronous altitude carry uncertain space weather risks. This new technique is attractive because it reduces the need for chemical propellants that increase weight and launch costs, but it places satellites in a much more intense and less well-sampled environment for hundreds of days as they travel through the heart of the radiation belts to their final geosynchronous destination [*Horne and Pitchford*, 2015]. *Odenwald and Green* [2007] estimates that a Carrington-type superstorm would incur $30 billion in losses based purely on the loss of geosynchronous transponders not even considering these new industry ventures, launch techniques, and interdependencies.

Clearly, space weather does affect satellite systems, even if the overall impact on the industry and risk at present is uncertain. Evidence of space weather effects on satellites have been well demonstrated by compilations and analysis of previous anomalies such as those described in *Koons et al*. [1999], *Balcewicz et al*. [1998], and *Iucci et al*. [2005]. Yet up-to-date and routine assessments of the most recent anomalies, their relationship to space weather, and impact to the industry are not readily available. Despite the value of shared anomaly information [*Galvan et al*., 2014], no public centralized reporting system and database exists. Some anomaly information is tracked in private databases kept by manufacturers or insurance companies such as that of the Atrium Science Consortium database. This database includes more than 2300 anomalies on 922 satellites from 1986, 20% of which are attributed to space weather [*Wade*, 2012]. *Koons et al*. [1999] provide one of the most comprehensive assessments of public space weather anomalies and show which types dominate as well as the severity, but it only covers issues that occurred from 1970 to 1999. Of the set of 299 anomaly records considered, the majority were attributed to Electrostatic Discharges (ESD) (see Figure 2). The breakdown according to impacts puts 16% of the issues in a serious category of “System or Part Failure.” The study identified 11 complete failures with the latest being the INSAT 2-D satellite failure due to surface ESD in 1997. While the study is thorough and informative, it cannot be used to predict current or future problems since serious issues are often remedied with improved design strategies and new technologies. Two studies, [*Lohmeyer and Cahoy*, 2013; *Lohmeyer et al*., 2015], provide a more recent example of space weather related issues. These papers suggest that failures of Solid State Power Amplifiers (SSPAs), on one of the Inmarsat satellite fleets could be related to internal charging from high-energy electrons. The SSPAs are critical components needed to amplify and relay information from the satellite. It is worth noting that although the fleet experienced 25 complete SSPA failures between 1996 and 2012, Inmarsat reports no noticeable service interruptions because of the use of redundant systems. A recent example of a more serious satellite issue was the loss of communication with the Galaxy 15 satellite in 2010 which drifted through geosynchronous as a “zombiesat” for several months causing interference issues with nearby satellites until depleting its batteries and finally resetting itself. Several studies on the environment conclude that the anomaly was likely caused by a charging related ESD [*Loto’aniu et al*., 2015; *Ferguson et al*., 2011].

Thus, in order to assess current space weather impacts to the industry, given the lack of publicly available information, we held in-person and remote meetings with 10 organizations. The in-person meetings encouraged input from a broad range of participants including radiation effects engineers and on-orbit support teams. The format encouraged in depth discussions of not only the impacts but also the processes for managing and mitigating those impacts. The organizations can be roughly grouped as either operators or manufacturers with a few in both categories. Here “manufacturers” refer to groups that design and build satellites for delivery to another party. “Operators” refer to groups that purchase and operate satellites for their own business case or lease those services to other customers. One group does not fit well into these two categories and is more aptly described as consultants that assist operators and manufacturers with design choices and anomaly analysis. Of the 10 groups who participated in the discussions, three are categorized as operators, five would be described as manufacturers, one could be described as both, and one would be considered a consultant. It should be noted that two of the operators we contacted that were listed among the Space News 2014 Top 5 Fixed Service operators were not interested in discussing space weather impacts at this time. None of the organizations are explicitly cited in the report in order to provide some confidentiality and enable discussion on possibly sensitive topics.

We present the information learned from our industry discussions below. Section 2 provides a short summary of findings based on the input of stakeholders in four areas. These summaries are each followed by more detailed explanations in subsections 2.1–2.4. Our final goal is to propose solutions for improving the response to space weather issues that ultimately reduces costs and the vulnerability of the global satellite fleet. To get to this point, we first review the current impacts as viewed by stakeholders (section 2.1). We then describe the ways in which stakeholders manage and mitigate space weather impacts in order to highlight areas for improvement (section 2.2). That is followed by a discussion of the costs (section 2.3) and the overall requests from the industry (section 2.4). Lastly, we suggest potential improvements and solutions to problem areas based on our observation of the industry processes (section 3). The study is briefly summarized in section 4.

2. Main Findings

Below are the main findings based on stakeholder's experience that we learned from our industry discussions followed by more detail on each topic.

1. *Space Weather Impacts and Severity*. Stakeholders believe that the majority of recent space weather impacts to satellites are not severe enough to significantly degrade system performance/functionality or limit the system/spacecraft lifetime or reliability and can be fixed with a commandable or autonomous component (box) reset or power cycle. On occasion more severe issues do occur. The most commonly reported type of anomaly is Single Event Effects (SEEs). The occurrence of this type may be overstated due to manufacturer or operator predisposition to categorize unexpected changes of state, spurious shut offs, or other uncommanded actions as SEE due to the statistically uncertain nature of this threat, the fact that it persists in all space weather conditions, and difficulties differentiating from other types of anomalies. (e.g., there is ALWAYS a background event rate).
2. *Managing Space Weather Impacts*. The extent and detail to which space weather issues are considered and managed vary greatly depending on the stakeholder. The level of investigation and mitigation of space weather issues is decided on a case by case basis because processes for anomaly review and response are seldom predefined in Operator/Manufacturer contracts. Some anomalies may go unrecognized and unaddressed because a wide breadth of knowledge is needed to determine root cause, and tools that bring all the necessary information together for quick attribution are lacking. Also hindering the effort is the lack of anomaly information sharing between operators and manufacturers as well as throughout the industry.
3. *Costs*. Operators of communications satellites may pay penalties for satellite downtime on the order of $10 K/min for each outage. Space weather costs to manufacturers are incurred through time spent analyzing anomalies and through derivation, implementation, and testing of appropriate design features.
4. *Needs/Requests*. There were two main requests. One was guidance for operators to prepare appropriate design specifications. The other was for simple, accurate information and tools to diagnose and triage anomalies to definitively say whether a particular issue is caused by space weather.

2.1. Space Weather Impacts and Severity

To define the needs of the industry related to space weather and possible solutions requires first understanding the issues being faced now and their severity. The industry discussions revealed that, overall, stakeholder's perception is that the global fleet of satellites is robust to space weather impacts but not completely immune. Those stakeholders with a long history in the industry noted a significant decline in on-orbit anomalies in the last few decades that they attributed to improved understanding of the environmental impacts and implementation of "best practices." They described a noticeable culture shift as awareness of space weather issues has grown. Space is "just a vacuum" is no longer a common response when space weather related problems are mentioned. Although, with the recent quiet solar activity (see Figure 1), some stakeholders are concerned that the industry may be lulled into a false sense that space weather is no longer an issue and has been completely remedied by engineering solutions. The intense Halloween Storms occurred over 13 years ago. Many are aware of the issues on a theoretical level but have never experienced such an intense and problematic space weather event. Some engineers expressed difficulties convincing upper management that space weather mitigation and preparation was worth possible additional costs. At least one stakeholder expressed specific concern about the performance of Digital Processors during severe Solar Proton Events (SPE), which, as noted, have been rare in recent years (since 2003). Many modern communications spacecraft incorporate Digital Processors that are partially reconfigurable and contain increasingly complex Integrated Circuits and microelectronics (field-programmable gate arrays, application-specific integrated circuits, and memories). Performance verification of these devices is increasingly difficult owing to potential susceptibility to higher-order Single Event Effects and the complexities and costs in characterizing such effects in ground test laboratories. Nonetheless, most issues now are manageable and can be resolved by low risk commandable system or box power cycles to clear the error. More serious problems still occur and may force a system to be retired or operate in a diminished state.

Known space weather impacts to satellites fall into four categories described here for completeness: surface charging, internal charging, Single Event Effects, and total dose effects.

Surface Charging.	Charged particles collect on satellite surfaces producing high voltages, damaging arcs (electrostatic discharges), and electromagnetic interference. Common problem areas are thermal blankets and solar arrays. One past example of a surface charging anomaly was the high-voltage increase in the LICA instrument on the SAMPEX satellite [*Mazur et al*., 2012].
Internal Charging.	Energetic electrons accumulate in interior dielectrics (circuit boards or cable insulators) and on ungrounded metal (spot shields or connector contacts) leading to electrical breakdown in the vicinity of sensitive electronics [e.g., *Fennell et al*., 2001; *Lohmeyer et al*., 2015].
Single Event Effects (*SEE*).	Energetic charged particle (typically ion or proton) passage through microelectronic device node causes instantaneous catastrophic device failure, latent damage, or uncommanded mode/state changes requiring ground intervention [e.g., *Green et al*., 2010; *Likar et al*., 2012; *Sedares et al*., 2016]
Total Ionizing Dose (*TID*) *and Displacement Damage Dose* (*DDD*).	Energy loss (deposited dose) from proton or electron passage through microelectronic device active region accumulates over mission (or stepwise during high dose rate events) causing device degradation and reduced performance at circuit or system level [e.g., *Jenkins et al*., 2009]

Of these four types of issues, SEEs were the most mentioned concern, which differs from past studies that implicated charging as a dominant issue. The responses may indicate a shift as charging concerns have been recognized and remedied. Further discussion made clear that infrequent unattributable upsets were the true concern and that not all these events were clearly attributed as SEEs. Events may be categorized as SEEs because of their infrequent occurrence without a definitive cause. The number of SEEs may be overstated because detailed investigations to clearly distinguish between possible types of anomalies, such as ESDs, are not always performed unless the impact is severe and further analysis is required by the customer or operator. Definitive attribution or rejection of an anomaly as an SEE is difficult because some probability of an impact from an energetic ion always exists. The inherent uncertainty makes SEEs a catch all bucket for difficult to explain issues.

The stakeholders surveyed worked with satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous (GEO) orbit. Of these regimes, anomalies in GEO were considered more frequent and more concerning. The higher occurrence of anomalies at GEO may be due to the larger number of satellites and increased complexity at that orbit. The relative occurrence of anomalies may shift in the near future as constellations of LEO and MEO satellites grow substantially.

2.2. Managing Space Weather Impacts

It is important to understand how space weather impacts are managed in order to identify possible gaps or areas for improvement where additional tools or resources would be beneficial. Stakeholders' process descriptions made clear that space weather impacts are considered and managed in different ways throughout the life cycle of a satellite. The approach used by each group varies greatly depending on factors such as their role (i.e., manufacturing or operations), the breadth of in-house space weather expertise, sensitivity to past or ongoing issues, and budget limitations. The primary management role often passes between or is shared by manufacturers and operators throughout different stages of the satellite life cycle creating a need for coordination that is not always well defined. These life cycle stages include the contract, design, and on-orbit operational phases. In the following subsections, we review each stage and the ways that space weather impacts are handled. We identify various gaps throughout that may leave some lingering space weather related issues unresolved. These shortcomings include minimal tools for quick, accurate, and specific anomaly attribution and the lack of defined processes for exchanging anomaly information. Here we only highlight these difficulties and suggest ideas for improvements in section 3.

2.2.1. Contract Phase

During the contract phase operators seeking to procure a satellite provide one or more manufacturers with a list of specifications they would like their satellite to meet. Understanding these specifications and how they are defined is important for being able to gauge the overall robustness of the fleet to nominal, moderate, and potential extreme space weather. With regards to space weather, the specifications provide details such as the radiation models and engineering tools to be used for design, radiation qualification levels of parts (e.g., EEE parts) to be used, and allowable material properties. Well-written specifications are the first line of defense for preventing space weather problems, but the level of detail and extent of the specifications in each contract varies. Some operators may have in-house expertise to guide detailed specifications, while others may rely more heavily on a manufacturer's experience and demonstrated on-orbit performance and knowledge. The tolerance or conservatism of the specifications is always balanced by the need to work within a budget and schedule while still achieving the mission goal with acceptable risk. Some projects with a critical mission may have a very low tolerance for risk that will be evident with stricter specifications. More strict specifications call for more extensive verification activities on the part of the manufacturer including analyses, tests, and detailed reviews that will increase costs and potentially delay schedules. Also considered during the contract phase are anomalies on other satellites made by the manufacturer. These past anomalies must be addressed and shown to be nonapplicable to the new satellite because of design differences or improvements, often supported by engineering tests to back up the claims.

Ideally, the specifications contain requirements related to each of the anomaly categories. For example, to minimize the threat of SEEs the specifications typically define the maximum upset rate requiring ground intervention, the model environmental flux to be used when determining that rate, and the minimum Linear Energy Transfer (LET) that will produce an upset (LET is the rate of energy transferred as an ion passes through matter). To mitigate impacts of TID/DDD, the specifications define the Radiation Hardness Assurance (RHA) requirements for components and the model environmental fluxes, with margins, to be used to calculate the total expected radiation dose. Spacecraft charging related requirements are more difficult to quantify and are often less consistent with respect to each company's design and verification methods. The specifications may give the maximum external flux and duration, or the allowable internal flux as a means to reduce internal charging hazards. Or they may give the maximum resistivity of materials to be used in order to reduce the chance of charge build up in dielectric materials. While these are sensible guidelines, they do not guarantee that a system will be impervious to charging, or how it will respond should a discharge occur.

Defining the right specification may be difficult or challenging owing to user unfamiliarity with state-of-the-art radiation environmental models and application against heritage models. There is a knowledge gap between scientific model developers and engineers responsible for their application regarding the differences between various models and the levels and cause of uncertainty in different orbital regions. Some models may give very different representations of the environment. For example, the new AP9 model suggests more intense inner zone proton fluxes than the older AP8 model that it is intended to replace.

Some are uncertain about using the new more intense fluxes as the specification since previous satellites performed well when designed to the less severe environment. Likewise, some manufacturers may be reluctant to change a design when a new model gives a less severe environment because the risk of a possible failure and changes to routine manufacturing are more costly than the advantages gained from reduced shielding or cheaper parts. Others may have difficulty transitioning to using new models because of the time involved to understand the more specific and detailed inputs needed. Additionally, some engineers may not be fully aware of how the accuracy of the models varies in regions where the measured data used to build the models are sparse and validation is challenging. As an example, the TACSAT-4 satellite experimentally demonstrated an underestimation of proton fluxes in the AP9 model that was improved upon in later versions [*Jenkins et al*., 2014]. Not all regions have equally thorough validation. In this area, the operators surveyed, would welcome more guidance on how to choose the right environment, keep up with best practices, understand impacts of requirement trades, and define appropriate and meaningful specifications for the best performance of their mission.

While specifications establish a robust design and verification process intended to yield acceptably reliable performance, stakeholders were clear that they should not be interpreted as a threshold beyond which space weather anomalies are inevitable. Satellites may repeatedly withstand environments well beyond the specifications because of additional margins and other design features that, combined, increase robustness against failures. The design of some satellites may exceed their specifications because it is often cheaper to build a single, enveloping, design architecture than it is to make small changes to suit each unique mission or customer. LEO satellites often exceed their specifications because they are built with features and components required to withstand the GEO environment which has harsher TID and charging standards. Finally, the specifications do not cover all the design strategies used to reduce problems as discussed in the next section.

2.2.2. Design Phase

During the design phase, the manufacturers have responsibility for minimizing space weather effects within set budgets while meeting the defined specifications. At this stage, the level of analysis, verification, mitigation strategies, and testing varies greatly on the particular manufacturer, the satellite orbit being considered, the type of issue being addressed (i.e., charging, SEE, and TID), and budgets. The goal is to meet the specifications, but the full set of mitigation strategies often goes beyond that especially in instances where full verification cannot be performed. Two satellites designed to the same specifications may experience different problems even within the same environment because of small design differences. These variations may be intentional design changes or may result from physical variability and uncertainty in part performance or manufacturing processes. The present era predates large-scale high volume spacecraft manufacturing (ushered in by OneWeb and others) where “clone” spacecraft are, in fact, not identical because of this inherent variability. The design stage is the point in the product life cycle when previous anomalies and “lessons learned” can be considered and changes made to fix potential and perceived problem areas. However, some issues may not be recognized because of obstacles that inhibit anomaly root cause attribution, and therefore, they do not get properly addressed. These obstacles will be discussed in more detail in a later subsection 2.2.3.

Those surveyed considered the effects of TID/DDD on the system by using an environmental flux model such as AP9/AE9 or AP8/AE8 along with transport models such as NOVICE [*Jordan*, 1990] or FASTRAD [*Pourrouquet et al*., 2011] to predict mission TID/DDD. Most will also use tools such as CREME [*Tylka et al*., 1997] or CREME-MC [*Weller et al*., 2010; *Mendenhall and Weller*, 2012] to ensure that SEU rates due to GCR and trapped protons as well as peak solar proton event fluxes are within the expected and accepted limits.

Approaches to charging issues, on the other hand, are much more variable. This is an area where manufacturers have specific approaches tailored and validated against their own products, architectures, and spacecraft. Here some groups simply adhere to qualitative guidelines such as described in NASA-HDBK-4002A section 5.2.1. (Other such guidelines can be found in the ECSS (European Cooperation on Spacecraft Standardization) documentation in the standard ECSS-E-ST-10-12C and the JAXA (Japan Aerospace Exploration Agency) Spacecraft Charging and Discharging Design Standard JERG-2-211A). These guidelines are described in the handbook as qualitative but give extensive and detailed suggestions about proper grounding, material selection, wire separation, filtering, and more, all dedicated to eliminating potential ESDs or reducing their intensity and ability to propagate and couple to other systems. Some groups also do detailed numerical modeling of components and structures [*Wong and Kim*, 2016] that are likely to charge using codes such as NUMIT [*Kim et al*., 2016] or DICTAT [*Rodgers*, 1999]. These numerical codes calculate electric fields as a function of time and depth for specific configurations of material given an external electron flux spectrum. They can be used to analytically test whether material breakdown will occur for different worst-case flux intensities. However, the accuracy of the analytical solution is dependent on the electrical properties of the materials involved, which is not always well known. Other important strategies are to ensure that any potential problems such as floating conductors and dielectrics have either appropriate bleed paths to reduce charge build up or filters to minimize the size and passage of any resultant ESD pulses. Finally, lab testing is sometimes carried out to investigate the susceptibility of hardware to ESD, and the impact should occur [*Likar et al*., 2009; *Wright et al*., 2012; *Hoang et al*., 2012; *Wong et al*., 2013, *Likar et al*., 2013].

2.2.3. On-Orbit Operation Phase

Stakeholders described how space weather anomalies during on-orbit operations are managed by both the operators and manufacturers. In this phase, as in others, the level of analysis varies significantly between groups depending on resources, expertise, and budgets. Definitively identifying the root cause of anomalies is certainly beneficial and helps to guide meaningful fixes. Best efforts are made to do so but attribution is difficult because analysis time and budgets are limited and not allotted for in contracts. Interpretation of space weather data and information currently requires large time investments to locate available measurements, understand its accuracies and appropriate uses, and extrapolate to the right location, to the actual hazard, and to place the information into a climatological and statistical context with other similar anomalies. Additionally, there are not well-defined processes for sharing information needed to build statistical correlations between anomalies and the environment. The communication gap exists between operators and manufacturers as well as within the industry. Information about repeat anomalies may not be passed from operators to manufacturers once a response is defined. Information about concurrent anomalies is not shared between industry groups. In this case, operators hold a wealth of information about how products from different manufacturers respond and compare because they often operate fleets composed of satellites with different architectures. The end result of this communication gap is that issues may go unrecognized and unresolved. Some anomalies may seem minor, but they indicate a problem that could be exacerbated in the future by seemingly small design changes or a more intense environment.

Operators have the primary responsibility for real-time monitoring of telemetry and are the first to recognize problems. However, they may not have detailed knowledge of the satellite design or possible vulnerabilities that could explain the observed changes. Thus, when an anomaly does occur, the operator will often defer back to the manufacturer rather than investigate the probable cause. Some manufacturers maintain an on-orbit support group that gives customers guidance on how to respond to an anomaly. This support group will do the first assessment of any possible space weather associations, but the immediate goal is to protect the satellite and return to operations as quickly as possible. Resources rather than science and technology may drive the depth and complexity of this initial assessment. Manufacturers may be motivated to respond quickly and minimalistically; Operators may, similarly, be inclined to accept such responses in order to expedite return to nominal operations and minimize investigation times. Most stakeholders in this initial assessment phase reported using the 3 day GOES proton or electron flux plots from the NOAA Space Weather Prediction Center as general space weather indicators. Some were unaware of measurements available at different locations or other formats. For example, the GOES satellites also measure the flux of >4 MeV electrons that indicate a hardening of the particle spectrum relevant for more heavily shielded components. These data are not shown in the standard 3 day plots but are available in text outputs or at the NOAA National Centers for Environmental Information. If the anomaly is resolved, and the system is brought back to normal operations, analysis may stop here without any specific root cause attribution.

A more thorough analysis may be done, only if the problem is severe and could affect system lifetime or future builds. In this case, a full anomaly review board will be convened that brings in a wider range of expertise. A fishbone diagram is developed with lines that identify each possible cause (the bones of the fish). These are evaluated and eliminated until a probable cause is found. Sometimes more detailed modeling or lab testing is done to recreate the anomaly. Even with a detailed analysis, attribution is difficult because the problems are not necessarily a design issue but an unintended mistake or manufacturing flaw. Space weather is sometimes left as an unresolved hole in the fishbone diagram because local environmental data are lacking.

2.3. Costs

Costs due to space weather are important to consider because high costs will drive requirements and desire for improvements. The costs from space weather anomalies are inflicted in different ways upon operators and manufacturers. Operators incur the most direct and obvious costs. In some cases, operators may pay penalties for satellite downtime to customers if continuous coverage is expected. The full impact is difficult to quantify here because of lack of information received about this topic. Suggested, anecdotal, costs are on the order of \$10 K/min. Additional costs may be accrued in the time spent recovering an asset after an anomaly that typically requires the efforts of two to three people for six or more hours.

Costs to manufacturers are less direct. For this group, cost is incurred through lengthy analysis of problems and design changes that may prove to be ineffective at solving anomaly issues. Estimates for the cost of a thorough analysis with an anomaly review board are on the order of one million dollars. The investigation is not focused entirely on space weather and includes laboratory testing, software review, and other thorough subsystem investigations. Information that could target the investigation or eliminate possible causes prior to lengthy testing would reduce costs. Likewise, more definitive anomaly attribution will minimize unnecessary design changes. Additional costs are incurred whenever design changes are required in order to requalify the new design and verify the problem has been addressed.

2.4. Needs/Requests

There were two main requests for help with space weather related issues. One was from operators for additional guidance to develop satellite specifications defined in contracts with manufacturers. The other, from both manufacturers and operators, was the means to reduce the uncertainty about whether an anomaly is related to space weather.

To expand on the first request, choosing the right specifications is the first line of defense for reducing space weather related anomalies, so defining appropriate specifications is important for a robust fleet. Difficulties surround understanding and choosing appropriate environmental models. As mentioned previously, comparisons between environments show differences that are not well explained or inline with on-orbit experience. Additionally, space weather science and satellite technologies are continuously evolving. Updates, training, and guidelines often target manufacturers, but information dissemination to operators is more limited.

The second request was universal. Root cause attribution of anomalies even under the best conditions is a challenge due to their relatively infrequent nature and lack of onboard sensors for monitoring the environment at the satellite and its effect. While such sensor packages are available, they are not commonly flown because of a perceived sizeable investment that includes integration, data collection, processing, and analysis. Some stakeholders suggested that insurance incentives might be used to encourage investment in such instrumentation, but insurers are unlikely to support this request given current low rates. Without local information, attribution must be inferred from other data sources, only available at limited locations. Most stakeholders rely on data from the NOAA GOES instruments that provide data at geosynchronous orbit at just two longitudes. These data provide proton and electron flux suitable for inferring internal charging and SEE issues only. Most stakeholders also referred to 3 day plots that do not provide climatological context. More sophisticated plots from the Space Environmental Anomalies Expert System Real Time (SEAESRT) [*O'Brien*, 2009] also available at the Space Weather Prediction Center (SWPC) were generally not used because of a lack of descriptions and understanding about how to use the information. With a large list of hurdles and no defined budgets to perform anomaly analysis, much uncertainty and confusion cloud any space weather attribution.

The features requested for an anomaly attribution tool include the particle flux or hazard at locations other than GOES. If a model is used to infer the local flux, clear error estimates were requested to give users confidence in the validity of the modeled data. The full mission environment history is needed in order to put the current environment in context with past levels and anomalies. In some cases, stakeholders found real-time information and future predictions useful for knowing when the environment is no longer extreme, and it is safe to take intervening actions to restore function after an anomaly. In most other situations, timely information for quick attribution is valuable but real time is not critical. The actual hazard, not just the fluxes, also provides useful information for attribution. Some requested further details about charging hazards than is currently available from tools such as NASCAP-2 K [*Davis et al.*, 2003; *Mandell et al.*, 2005] and NUMIT. These give information about when a satellite will charge and potentially discharge but stop short of predicting ESD pulse sizes and shapes. This pulse information was requested in order to understand which components will be affected once a discharge does occur. Such details are difficult to predict because they depend on the material and area of the discharge location, but general bounds may be possible with additional material lab testing and knowledge of the specific satellite structure.

3. Solutions

The last section described the requests directly from stakeholders. Here we give suggested solutions and ideas for improvement based on our own observations of the industry and its processes for managing space weather. To address the problems elaborated in the previous section, we suggest three main solutions (1) improved tools for quick anomaly attribution, (2) training, and (3) coordinated information sharing.

3.1. Anomaly Attribution Tools

To address the requests and concerns of the industry requires tools that can quickly and accurately determine whether an anomaly is the result of space weather. These tools would not replace other investigations. Instead, they would provide as much certainty about space weather anomaly attribution as is possible from environmental and hazard information in order to guide further investigation into design and manufacturing processes. (*Bodeau* [2007] describes some of the problems attributing anomalies based on space weather data only). Such a tool would have to be simple to understand and interpret and be readily available so that anomaly attributions could be catalogued routinely in a timely and cost effective manner. Here we suggest how this attribution could be done and the feasibility for building such a resource with current data and models. Clear attribution would require global specification of the ion and electron flux environment to address all orbits, the past history of the environment to put the anomaly time into context with the mission experience and other anomalies, translation of the flux into the actual specific satellite hazards, and uncertainty estimates. To be complete, it should include information about the hazard for SEEs, internal charging, surface charging, and TID/DDD.

Methods for calculating specific hazards that induce anomalies (such as those discussed in section 2.2) have been developed and are used for design and testing that designs meet specifications. Our recommendation is to build attribution tools that adopt these same methods but uses actual time-varying measured or modeled flux environments as input in place of the climatological ones appropriate for design predictions. With a record of the time-varying hazard, anomaly attribution can be done by comparing the hazard at anomaly times to that of the whole mission. In most cases, the challenge to building such attribution tools is the limited flux measurements and lack of models for filling in spatial gaps.

As an example of such a product, we developed the Satellite Charging Assessment Tool (SatCAT) for attribution of internal charging. Figure 3 shows the internal charging hazard from the interactive web display that was presented to stakeholders as a test demonstration. The web-based tool calculates expected accumulated charge as a function of time for any chosen shielding thicknesses and material time constants using the method described by *Bodeau* [2010] and *Frederickson* [1979]. In this example, the plot shows the charge accumulated (# of charges/cm^2) through 50 mils of shielding for material with a 1 day decay time constant for 2016 (For units in nC/cm^2 multiply charges/cm^2 by 1.6×10^{-10}). These accumulated charge values can be compared to breakdown thresholds for the material. The accumulated charge calculation is done here using fluxes from the VERB-3D [*Shprits et al.*, 2009] data assimilation model for a satellite at the location of GOES 13. The assimilative version of VERB-3D [*Shprits et al.*, 2013; *Kellerman et al.*, 2014] currently uses real-time data from the Van Allen probes and GOES satellites. Using Kalman filtering, the code blends data and observations according to the data and model errors. It allows data to be included from different sources accounting for the fact that each instrument has different observational errors. For this example, the chosen shielding is minimal and below the 110 mils recommended by NASA-HDBK-4002A. The output shows high internal charging hazards in late September and October compared to the rest of 2016. *Bodeau* [2010] gives typical charge limits of 6–20 nC/cm^2 ($3.75–12.5 \times 10^{10}$ charges/cm^2) above which breakdown is expected. For this level of shielding, the accumulated charge hovered near or below the threshold for most of the early part of 2016 just barely reaching the 6 nC/cm^2 in early January and late February. The environment and hazard became more intense in recent months reaching the highest levels for the year well exceeding the 6 nC/cm^2 several times

Recent Data

Statistics

Histogram

Highest Days

#	Date	Q
0	2016 Oct 4	5.75e+10
1	2016 Oct 31	5.79e+10
2	2016 Oct 27	6.39e+10
3	2016 Oct 29	7.04e+10
4	2016 Oct 1	7.05e+10
5	2016 Oct 28	7.14e+10
6	2016 Sep 30	7.19e+10
7	2016 Oct 3	7.62e+10
8	2016 Oct 2	8.05e+10

Figure 3. Demonstration of the SatCAT tool web display. (top) The accumulated charge for 2016 for a satellite at the geosynchronous longitude of GOES 13. (middle) The last week of data. (bottom left) The full distribution of values and the cumulative distribution. (bottom right) The days of highest charging.

since late September (maximum charge 12.8 nC/cm^2 or 8 × 10^{10} charges/cm^2). A satellite with less shielding or materials with larger decay constants would experience higher charging levels.

Similar tools could be developed for surface charging and SEE hazards by adapting methods used in design codes such as NASCAP-2K and CREME96 to work with actual time varying environmental inputs. However, for these hazards the global environmental inputs are not well specified. Improved near-real-time availability of measured fluxes and data assimilation models are both needed. For the surface charging hazard, particle fluxes are currently available from satellites such as the Van Allen probes and the Los Alamos National Laboratory (LANL) geosynchronous satellites but there is no guarantee that these measurements will continue or be made publicly available in near-real time. The NOAA POES satellites provide some flux measurements, but at the critical energies for surface charging the data are sparsely sampled in time and energy. In the future, the next generation of GOES satellites will provide the appropriate low-energy particle measurements, but models are needed to fill in other spatial regions. Several codes exist that can fill these spatial gaps such as the VERB-4D [*Shprits et al.*, 2015], IMPTAM [*Ganushkina et al.*, 2015], CIMI [*Fok et al.*, 2014], RAM [*Jordanova et al.*, 2010], and HEIDI [*Fok et al.*, 1993, 1995; *Jordanova et al.*, 1994, 1996], but they do not currently include data assimilation and may lack needed accuracy. Current codes do not provide information on the dynamics of the background plasma density that is also needed to estimate surface charging. Modeling of these surface charging particles is one area with a mismatch between the science goals to understand basic physics and engineering need for accurate determination of fluxes and uncertainties [*O'Brien et al.*, 2013]. To describe SEEs the environmental information is even sparser. The particles that cause SEEs include the high-energy protons in the belt that surrounds Earth, the ever present galactic cosmic rays (GCRs), and solar energetic particles (SEPs) events that sporadically intercept Earth. The recently launched GOES-R satellite will provide heavy ion and energetic proton measurements making a limited geosynchronous tool possible. Potentially, the GOES and POES data could be combined to approximate the global ion flux environment, but no physics-based models are available for filling in these measurement gaps. While some attribution tools such as SatCAT are feasible now, more development is needed to manipulate available data into accurate global environments and adapt existing hazard determination methods into a complete tool that includes attribution for all space weather-induced anomalies.

3.2. Training

The purpose here is to provide those that do both the quick anomaly attribution and more extensive analysis with training and information about the available resources and how to use them. Ongoing training is essential because the physical understanding of the complex processes that cause space weather, the measurements of the environment, the knowledge of the engineering effects, and tools for interpreting measurements and the information is constantly improving and evolving. This high-level detailed knowledge needs to be distilled into a manageable and understandable form for those that are not immersed in each of the various physics and engineering fields that span space weather. To do the training, we suggest regular webinars that review each type of anomaly and explain how tools available now can be used for attribution. Providing information in a webinar-type format would eliminate large time and travel investments and allow more participants to join from each company than the few that are able to attend large meetings and workshops. The webinar format also allows those participating to ask questions and provide feedback about the functionality of tools and needed improvements encouraging better tools and continued industry engagement. The webinars may also be archived for users to watch at their own convenience, allowing for participation from those who may wish to remain anonymous.

To address the request from operators for guidance with preparing appropriate specifications, we suggest further documentation directed specifically to this process. A document with a menu of possible specifications for each type of anomaly and a description of how variations and trades affect the final product would be extremely useful. This is an area where consultation services from experts who understand satellite design would also be beneficial, since each operator may not have a full time need for such space weather expertise.

3.3. Information Sharing

The final solution we suggest is to improve anomaly information sharing throughout the industry. More specifically, a mechanism is needed to ensure that anomaly occurrences are shared between operators who monitor problems and manufacturers who can feed that information back into better design. While exchanges may take place after significant failures, the information sharing should be extended to include smaller nuisance problems so that all problems are recognized allowing better statistical correlations with space weather. To make this information sharing work may require a formal agreement within contracts. At the very least, recognition of the mutual benefit of sharing the information should encourage collaboration.

Sharing of anomaly information between operators and manufacturers will improve statistics and the ability to correlate problems with the environment. Sharing of anomaly information throughout the industry would serve to further bolster those statistics and inferences. Such information would be of great benefit to government agencies interested in routinely assessing the state of the industry and providing resources for addressing any needs. During an extreme event, a predefined process for providing anomaly information would be critical for quickly assessing impacts. The minimum set of information needed to make the anomaly data useful is described in *O'Brien et al*. [2011].

While the benefits of information sharing are clear, there are obstacles to the creation of such a centralized anomaly database. There are understandable concerns that sharing specifics might negatively impact business. Some companies may view their processes and procedures for mitigating anomalies as a discriminatory selling point for customers and sharing information may level that playing field. Some of these qualms may be addressed by keeping information anonymous. A recent report by the RAND Corporation describes methods for incorporating proprietary data into a database [*Galvan et al*., 2014]. Regardless of these objections, the development of such a database has been recommended as part of the U.S. National Space

Weather Action Plan. There are also successful examples from other areas where sharing information has benefited those that participate. As an example, the Satellite Data Association has brought operators together to share location information to avoid collisions and radio frequency interference. This type of solution may work for the commercial side, but it could be difficult for government satellite groups to work with a nongovernment entity. Likewise, commercial groups may be less inclined to give their anomaly information to a central government run database. To accommodate the interests of both groups, separate commercial and government databases may be required. With the U.S. national interest in such a database and successful examples, it may be feasible now to build systems that meet the anonymity requirements and the government/commercial needs.

4. Summary

While concerns about space weather impacts to our technological infrastructure are growing, the overall perception from satellite industry stakeholders is that effects on satellites are diminishing as research has matured, awareness has increased, and mitigation strategies have been improved and implemented. Some stakeholders expressed concern that the apparent decrease in anomalies may be more directly related to the mild environmental conditions in the last decade and that the industry may be ill prepared and lack experience to mitigate problems should the environment intensify. Even during these mild conditions, a low level baseline of issues still linger and will likely persist as technologies evolve and the growing industry expands to meet service demands from new and emerging markets. Although space weather impacts are tolerable at present, our stakeholder discussions revealed areas that could be improved in order to ensure and promote continued success. More specifically, operators need more guidance to keep updated on changing technology, define appropriate specifications, and ensure their satellites meet their mission goals. Additionally, we noted that manufacturers face challenges getting the right space weather information and interpreting that data to quickly and accurately determine whether an anomaly is caused by space weather. They also may not receive notice of all anomaly occurrences limiting statistics that highlight space weather correlations. Better tools, regular training on how to use them, and defined mechanisms for sharing anomaly occurrences would overcome these obstacles. Ultimately, these solutions would lead to improved anomaly attribution, identification of problems, and the implementation of fixes. Fixing the bottlenecks in this design feedback cycle now will ensure safe and reliable operations into the future.

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