Developing a Comprehensive Application for Satellite Anomaly Analysis and Attribution

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ABSTRACT

The number of satellites in near Earth space is growing rapidly to accommodate the needs of our technological society. These satellites are expected to operate continuously while being bombarded by intense particle radiation that can damage electronic components, causing temporary malfunctions, degraded performance, or a complete system/mission loss. Every effort is made to design satellites that can tolerate the harsh environment but on orbit issues still occur. When they do, it is necessary to identify the cause so that appropriate actions can be taken to safeguard the asset and return to normal operations. However, diagnosing space weather related anomalies is challenging because it requires a wide range of environmental information, engineering knowledge, and specialized expertise. Our goal is to enable effective anomaly analysis and attribution by providing tools that bring together all the necessary components and simplify the analysis process for end users. Here we discuss our effort to build a comprehensive satellite anomaly attribution tool. We present a number of ongoing projects including the development of a high-energy electron radiation belt model (SHELLS), the Satellite Charging Assessment tool (SatCAT), and a solar proton access model (SPAM). The SHELLS electron radiation belt model uses a neural network to map real time energetic electron fluxes from low to high altitude filling in the inner magnetosphere. Once the mapping is established, energetic electron fluxes can be specified in the past and into the future using only near real time POES/MetOp data. The SatCAT tool is an online system that allows users to create a timeline of the current and historical internal charging levels of a satellite on orbit for comparison with anomaly times. The tool is configurable and allows users to generate and view internal charging levels for their satellites and design parameters such as shielding thickness and materials. Lastly, the Solar Proton Access Model (SPAM) uses low altitude POES/MetOp measurements to map solar proton fluxes throughout the magnetosphere.

1. INTRODUCTION

Space weather has presented a challenge for satellite operations since the launch of the first satellites more than half a century ago. As discovered by Explorer 1 in 1958, near Earth space is not a benign vacuum, but instead a hostile environment filled with intense particle radiation that can have unexpected consequences for satellite operations [1]. Through numerous types of interactions (see Table 1.0), this radiation can damage or degrade sensitive electronic components ultimately leading to a complete or partial satellite system or mission loss. Today, with increased knowledge of the radiation environment and steady improvements in engineering ability, satellites are designed with the intention of weathering the harsh environment. Nonetheless, on orbit anomalies still occur and require assessment and response [2][3]. Our goal is to deliver tools that will allow operators to routinely monitor the risk of space weather related anomalies on-orbit and quickly diagnose the cause should they occur. Providing real time actionable information will allow a prompt return to normal operations when feasible and enable better understanding of susceptibilities for more robust future designs.

Our effort to develop anomaly monitoring and analysis tools is driven by feedback from satellite industry stakeholders who describe a challenging and time-consuming process for analyzing and resolving on-orbit issues. At the last Space Environment Engineering and Science Applications Workshop (SEESAW) (https://cpaess.ucar.edu/meetings/2017/seesaw-presentations) satellite industry engineers and space weather researchers came together to discuss radiation impacts to satellites and to produce roadmaps for addressing lingering issues. Presentations and discussions highlighted basic difficulties that prevent and prolong routine anomaly attribution such as finding relevant space weather data at the right location in an accessible format. “Knowing what we know now, this process should be automated” is the conclusion from one frustrated engineer and a driving motivation for the work presented here [4]. A direct consequence of the lack of effective anomaly attribution tools is that some anomalies go undiagnosed [5] leaving this infrastructure, which is now critical to our technological society, vulnerable to a possible large space weather event. The threat and the difficulties monitoring and responding to anomalies is only expected to increase as the number of satellites in orbit grows at a rapid pace.

While the need for satellite anomaly attribution tools is clear, the availability of such tools is still limited. Developing effective applications is a considerable challenge. The effort requires a wide breadth of measured or modeled data, scientific understanding, engineering knowledge and software development. There are only 4 effects listed in Table 1 but they are each caused by different particle populations which in turn are controlled by different space weather interactions. Those interactions are part of a magnetohydrodynamic system that starts at the sun and extends beyond the outer planets making an expansive domain to monitor and model. To determine if an anomaly is likely to occur or whether an observed anomaly was caused by space radiation requires a global description of each particle population along with the ability to specify the particle flux along precise satellite orbits and finally transform that flux to its impact on individual satellite components.

Table 1.0 Space Radiation Related Satellite Anomalies

Radiation	Effect	Description	Space Weather Cause
Low energy protons/ electrons (<50 keV)	Surface Charging	Charged particles collect on satellite surfaces producing high voltages, damaging arcs, and electromagnetic interference. Common problem areas- thermal blankets, solar arrays.	Ring current particle fluxes intensify during storms and substorms
High energy electrons (>100 keV)	Internal Charging	Energetic electrons accumulate in interior dielectrics (circuit boards/cable insulators) and on ungrounded metal (spot shields/ connector contacts) leading to electrical breakdown near sensitive electronics.	Electron radiation belts intensify during fast solar wind, Corotating Interaction Regions, Coronal Mass Ejections
Energetic ion/protons (MeV)	Single Event Effect (SEE)	Energetic charged ion passage through microelectronic device node causes instantaneous device failure, latent damage, or uncommanded mode / state changes requiring ground intervention.	Trapped proton belts (L<~3.5) and Solar Energetic Particle Events (SEPs)
Energetic ions/ electrons (MeV)	Total Dose	Energy loss (deposited dose) from proton/ electron passage through microelectronic device active region builds over mission (or step-wise during large events) causing device degradation and reduced performance at circuit/system level.	Electron radiation belts, trapped proton belts, SEPs

Here we describe our ongoing effort to overcome these challenges and develop a comprehensive satellite anomaly attribution tool that addresses all 4 space radiation effects. To do so, we are developing models of the space radiation environment as well as software applications to deliver that information for real time monitoring and assessment. Below we discuss progress toward developing two models in particular: Specifying High altitude Electrons using Low altitude LEO Systems (SHELLS) and the Solar Particle Access Model (SPAM). Finally, we describe the Satellite Charging Assessment Tool (SatCAT). This tool is currently available online for assessing impacts due to internal charging and will provide an architecture for incorporating the other effects as additional models become available.

2. RADIATION ENVIRONMENT MODELING

Comprehensive anomaly attribution and monitoring requires either measured data or models specifying the flux of the four types of particle radiation listed in Table 1. Since most satellites do not carry detectors that give local particle flux at each satellite, we focus our attention on developing models of particle flux. The SHELLS model gives the flux of high energy electrons relevant for understanding internal charging throughout near Earth space. The model uses a neural network to extend the spatial coverage of the limited high energy electron flux measurements that are available in near real time. The neural network is used to define a mapping function between high energy electron flux measured at low and high altitudes. Once the relationship is established, the high altitude electron flux can be projected using only the low altitude data. An initial version of the SHELLS model [6] demonstrated the technique by creating a neural network to map low altitude measurements from a single POES/MetOp satellite to the high-altitude measurements from the Van Allen Probes. The two Van Allen Probes have since been decommissioned after successfully achieving their science goals and consuming on-board fuel resources. The POES/MetOp satellites, however, are expected to operate possibly through the next decade, and follow-on sensors are already on orbit. The initial SHELLS proof of concept showed that the neural network was capable of accurately predicting electron flux at high altitudes using just POES/MetOp data. However, it gave output at a somewhat limited time (daily average) and spatial resolution (near equatorial).

Our expanded version of the SHELLS model provides output at a higher time cadence and covers a greater spatial region. The initial version of the model was developed using daily averages of the POES/MetOp electron fluxes as input which in turn sets the output at a daily cadence. The averaging was necessary to remove the large changes in low-altitude flux measurements caused by the longitudinal variations of Earth's intrinsic magnetic field. Typically, electron fluxes are higher in regions where the magnetic field strength is low. The fluxes measured by polar orbiting satellites such as POES/MetOp then vary as the Earth and its magnetic field rotate beneath the orbiting satellite. We use the Statistical Asynchronous Regression (SAR) [7] technique to remove these orbital variations. After applying this technique, the model can produce high altitude electron fluxes 4 times per each POES/MeOp satellite orbit or every ~20 minutes. In addition, we have expanded the SHELLS model to map particles at off-equatorial regions. We are currently working on defining the model uncertainties to provide users with real time quality indicators. Once completed, the model will be set up to run in real time as new POES/MetOp data are delivered. We will also use the model to generate past data and create historical runs (e.g., a solar cycle) of radiation belt electron fluxes. These extended model runs are valuable for establishing long term correlations between recurring anomalies and the environment which can then be used to forecast and anticipate future anomalies. The long term runs may also potentially be included in design tools such as AE9 [8].

The second model under development, SPAM, is intended to specify the flux of high energy ions for understanding Single Event Effects with a focus on those caused by Solar Energetic Particles (SEPs). SEPs consist of highly energetic ions produced in shock fronts that steepen ahead of Coronal Mass Ejections (CMEs) after being explosively released from the sun. These ions spiral outward across the solar system flooding near Earth space with a steady stream of intense ion fluxes for potentially many days. Earth's magnetic field deflects some of the ions and acts as a shield creating limited radiation free zones. Thus, anomaly attribution and monitoring requires precise knowledge of satellite locations relative to these access regions.

Some models currently exist that define these ion access regions based on statistical compilations of data and simplified physics [9][10], but they are not easily accessible or highly accurate. A recent comparison between measured and modeled ion fluxes suggests that the leading models can predict large scale climatological features but do not capture the highly dynamic variation in the access regions observed throughout an individual SEP event [11]. To better define the access regions, the SPAM model uses real time measurements of SEP fluxes from POES/MetOp satellites at low altitudes and maps those measurements throughout the magnetosphere. The mapping is established by fitting ion flux measurements at high and low altitudes to Weibull functions and analyzing how the fits vary in different regions. As an initial demonstration, the SPAM model was used to predict particle access for a highly elliptical orbit (HEO) satellite [12]. SPAM gave a much better correlation between modeled and measured fluxes than two other often-used models, those of Smart and Shea [9] and Leske[10]. The correlation coefficients r^2 for SPAM, Smart and Shea, and Leske were 0.67, 0.46, and 0.20, respectively. Work is currently underway to improve the SPAM model to determine in more detail how the access regions vary as a function of magnetic local time (MLT) and to expand it to define how the access regions vary with ion species and energy.

3. ANOMALY ATTRIBUTION TOOLS

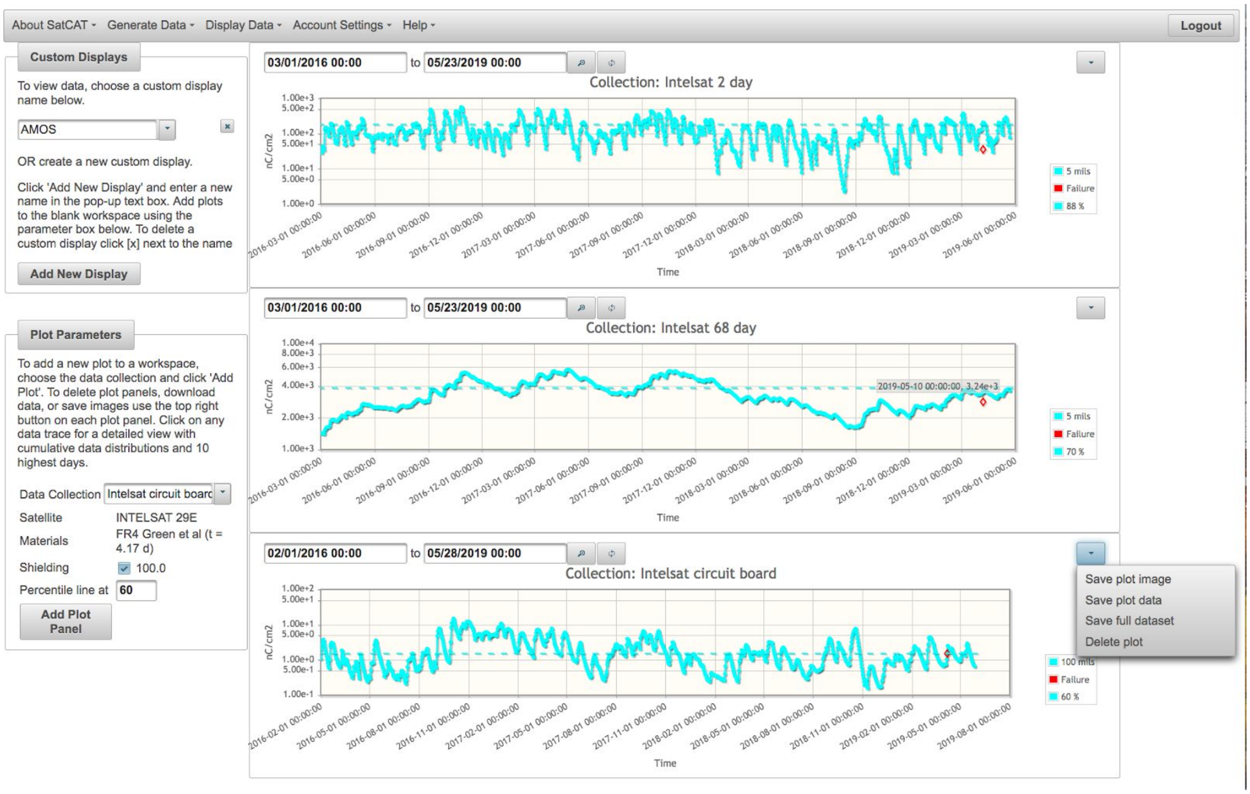
As the models discussed above are completed, they will be incorporated into the framework of the SatCAT application for easy access. SatCAT is an online application that allows users to analyze whether an anomaly is caused by internal charging. It is unique in that it allows users to generate a real time history of the radiation hazard to a specific satellite and system rather than giving a general hazard of the overall environment. It solves the problem faced by the frustrated engineer as described in the introduction by automatically defining the environment at any satellite location without any need to hassle with data and file formats. All that is required from the user are minimal inputs through a GUI interface. We demonstrate how the application works and its utility for anomaly analysis with an example. We walk through the steps one would use to generate the charging history of the Intelsat 29E commercial satellite over its mission and at the time of its final disabling anomaly. In this case, the failure review board concluded that the anomaly was caused by a harness flaw in conjunction with either a space weather related electrostatic discharge or a micrometeoroid impact [13].

Table 2. SatCAT Input Parameters and Charging Likelihood for Intelsat 29E

Component	**Shielding (mils Al)**	**Material and decay constant**	**Charging level at time of anomaly**	**Likely Cause**
Cable	5	Teflon generic (t = 2.2d)	88 percentile	**Possible charging**
Cable	5	Teflon FEP (t = 68.12 d)	70 percentile	No
Circuit Board	100	Fr4 (t = 4.17 d)	60 percentile	No

To generate a history of accumulated charge using SatCAT the user must enter the satellite name, a comma separated list of shielding thicknesses, the material, and the start and stop time in the application's GUI. Without detailed knowledge of the Intelsat 29E design, we consider 3 possibilities: a lightly shielded cable with two types of

Teflon and a deeply embedded circuit board (See Table 2). Once the parameters are selected, the application generates the satellite trajectory based on Two Line Elements (TLE's). The electron flux along the satellite orbit is specified by the Versatile Electron Radiation Belt data assimilation model [14]. The electron flux is passed through the specified shielding and the accumulated charge is found based on a simplified circuit model [15]. If requested by the user, the dataset will continue to update every 5 minutes.



Custom Displays

To view data, choose a custom display name below.

AMOS

OR create a new custom display.

Click 'Add New Display' and enter a new name in the pop-up text box. Add plots to the blank workspace using the parameter box below. To delete a custom display click [x] next to the name

Plot Parameters

To add a new plot to a workspace, choose the data collection and click 'Add Plot'. To delete plot panels, download data, or save images use the top right button on each plot panel. Click on any data trace for a detailed view with cumulative data distributions and 10 highest days.

Data Collection: Intelsat circuit board

Satellite: INTELSAT 29E

Materials: FR4 Green et al (t = 4.17 d)

Shielding: ☑ 100.0

Percentile line at: 60

03/01/2016 00:00 to 05/23/2019 00:00

Collection: Intelsat 2 day

03/01/2016 00:00 to 05/23/2019 00:00

Collection: Intelsat 68 day

02/01/2016 00:00 to 05/28/2019 00:00

Collection: Intelsat circuit board

Fig 1. Demonstration of the SatCAT application showing the expected accumulated charge in three different types of components. The top panel shows the charge expected to accumulate in a lightly shielded generic Teflon cable. The middle panel shows the charge expected to accumulate in a lightly shielded Teflon FEP cable. The bottom panel shows the charge expected to accumulate in a deeply embedded FR4 circuit board. The red diamond marks the approximate time of the Intelsat 29E failure. The dashed lines show the percentile level of the accumulated charge at the time of the anomaly. For example, the 88 percentile line is drawn on the top panel. The accumulated charge was below this level for 88% of the mission and was above this level for only 22% of the mission.

After the data is generated, it can be plotted along with added anomaly times and adjustable percentile levels (Fig 1). The red diamonds mark the time of the anomaly and the dashed lines show the percentile level of the three accumulated charge histories at the time of the anomaly. Percentiles represent the percentage of time the accumulated charge was above or below a given level. For example, the top panel shows that at the time of the anomaly the accumulated charge was at the 88 percentile level meaning that the accumulated charge was below this level for 88% of the satellite mission and above this level for only 22% of the mission. Thus, this quick analysis shows that at the time of the anomaly a lightly shielded generic Teflon cable would have reached moderately high levels (88th percentile) of accumulated charge consistent with the reported findings of the failure review board. At present the SatCAT application is only applicable for reviewing internal charging anomalies. Once the SPAM model is completed it will be added to the application and allow for analysis of Single Event Upsets. The SHELLS electron model output may be assimilated into the VERB model currently used by SatCAT for internal charging analysis to give the most accurate model of the environment.

4. SUMMARY

At present, the sentiment among satellite industry stakeholders is that space weather impacts are manageable with some operational inconveniences to what has proven to be a fairly robust infrastructure [16]. However, as the number of satellites in orbit around Earth steadily grows so will the risk and the need to monitor and quickly resolve any issues to minimize possible large-scale impacts. Experience from the Galaxy-15 satellite anomaly shows that a problem for one satellite can escalate to a problem for many satellites. Galaxy-15, dubbed the ‘zombiesat’ since it stopped responding to commands after an unexplained issue, drifted through geosynchronous orbit for ~7 months threatening to interfere with nearby satellite communications. A similar loss of contact with a satellite in LEO orbit carries an additional risk for possible collisions. During a large space weather event, the issue may be exacerbated by the fact that space radiation induced anomalies and altitude changes from atmospheric heating will most likely coincide. While little can be done to prevent space radiation anomalies once on-orbit, the models and tools presented here will provide real time information for making confident decisions should issues arise and support continued robust satellite operations into the future.

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