Monitoring and Managing Space Weather Impacts to Satellite Constellations

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Abstract

Space radiation poses a constant hazard to Earth orbiting satellites that must operate reliably in this extremely harsh and highly variable environment. Much has changed since the first satellite launch, nearly 6 solar cycles ago. Our understanding of the space radiation environment and technology to reduce its impacts have both significantly improved. Despite these advances, space weather still causes satellite anomalies. As the number of satellites in orbit grows and the complexity of coordinating their operation increases, so do the potential consequences of an intense space weather event. Many of the satellites on orbit now were launched during the relatively benign conditions of solar minimum and their ability to withstand future more intense events is uncertain.

To address this hazard, we have developed tools for satellite operators to monitor the space environment so they can anticipate and manage any potential impacts to satellite systems. Here we discuss the Satellite Charging Assessment Tool (SatCAT) and the Solar Particle Access Model (SPAM) and demonstrate how these can be used to identify space weather related hazards. The SatCAT/SPAM tool is an online application that provides information about potential impacts to satellites from different components of the radiation environment including internal charging from high energy electrons and single event effects from energetic ions. It allows users to create a timeline of particle fluxes and impacts at the location of any satellite on orbit with selectable bespoke design parameters such as shielding thickness and component materials. The tool also includes the ability to view and monitor impacts to multiple satellites in a constellation to accommodate the changing satellite infrastructure.

1. Introduction

Space weather poses a hazard for Earth orbiting satellites and is an important aspect to address when considering space sustainability. Contrary to common belief, space is not a vacuum but is instead filled with energetic ions and electrons that can adversely affect satellites causing them to malfunction in unexpected ways. The intensity of these particle populations in space is not constant but varies significantly from low to harmful levels on short time scales (hours to days) much like the more familiar atmospheric weather that tangibly impacts our daily lives. Importantly, space weather induced fluctuations of these harmful particles occurs on large global scales that could potentially impact a significant portion of our satellite infrastructure. Large satellite constellations may be particularly vulnerable because of their identical designs. Thus, to ensure reliable satellite operations, it is important to monitor and anticipate space weather induced changes in the space particle environment. In order to assist in this effort, we have developed the SatCAT/SPAM tool described in detail here.

Our goal with the SatCAT/SPAM tool is to capture the physics that controls the particle environment so that analyzing and monitoring for space weather impacts becomes a simple routine process that does not require specialized knowledge or expertise. However, to appreciate the discussion of how the tool works it is helpful to have a basic understanding of space weather and how it modulates the energetic particle environment near Earth. There are two components to space weather that are important for understanding its impacts on satellites. First is the solar wind which is a steady flow of magnetized plasma that blows outward from the sun and continuously buffets Earth. Energetic particles in the solar wind are not directly connected to the near-Earth space environment because Earth has a magnetic field that intervenes and complicates the interaction. However, some of these solar wind particles ultimately enter and are trapped in Earths magnetosphere. Once trapped, they may subsequently be accelerated to very high energies (MeV) through interactions with phenomenon such as electromagnetic waves. Electrons, in particular, may reach relativistic energies and still remain trapped out to geosynchronous altitudes where many satellites operate. High energy ions, on the other hand, are less likely to remain stably trapped out to large distances. They can more easily escape the magnetosphere because their larger mass increases their gyroradius about magnetic field lines. The trapped population of high energy electrons is always present, but the intensity of this particle flux and therefore the hazard to satellites varies.

The second important piece to space weather in this context is coronal mass ejections or (CMEs). These are very large more intense magnetic structures that are periodically and explosively released from the sun and are sometimes associated with solar flares. They move outward much faster than the solar wind forming a steep shock front. Ions are swept up and accelerated in the shock front and then speed ahead engulfing Earth often for several days. The release of a CME can temporarily lead to a very sudden increase in the charged particle fluxes known as a Solar Energetic Particle (SEP) event. Thus, satellites are constantly bombarded by an ever present but fluctuating environment of energetic particles interspersed with periodic more intense events.

In addition to specifying this changing particle environment, the SatCAT/SPAM application also estimates the unique impact of these particles to specific satellite architectures. The impact will depend on the type of particle (ion versus electron) and its energy as well as individual satellite design parameters such as shielding and materials. The impacts can be grouped into 4 categories: surface charging, internal charging, single event effects and total dose degradation. Detailed descriptions of each are given in Table 1.0. At present, the SatCAT/SPAM application estimates two of these four impacts: internal charging from high energy electrons and SEEs from high energy ions as described in greater detail below.

Table 1.0 Space Particle Impacts

Impact	**Radiation**	**Description**	**Space Weather Cause**
Surface Charging	Low energy protons/ electrons (<50 keV)	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
Internal Charging	High energy electrons (>100 keV)	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
Single Event Effect (SEE)	Energetic ion/protons (MeV)	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)
Total Ionizing Dose (TID)	Energetic ions electrons (MeV)	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

2. Underlying Environment Models and Effects

To provides users with estimates of internal charging and single event effects for their satellite design and orbit the SatCAT/SPAM application uses two different models of the particle populations that are then translated into specific impacts. The two models are the Versatile Electron Radiation Belt (VERB) model [1] and the Solar Particle Access Model (SPAM) [2].

The VERB model is used to provide a real time and retrospective estimate of the high energy electron flux that contributes to internal charging. The model provides differential electron flux (#/cm2-s-str-keV) on a grid of particle energies (.1-193 MeV) and magnetic field parameters (L=1-7 and equatorial pitch angles from 0-90). The model is driven by measured magnetic indices (Kp) and is currently run and made available every two hours with a 30 minute timestep. The model assimilates measured electron fluxes from available real time sources to improve its accuracy. The SatCAT/SPAM application uses this model output data to provide users with the time history of internal charging effects at a particular satellite as follows. First the trajectory for a user selected satellite is created in geographic coordinates at a 5-minute cadence based on Two Line Elements (TLEs) retrieved from https://www.space-track.org/. The geographic coordinates are then translated to magnetic field parameters (L shell and equatorial pitch angle of particles) at each time step. The differential electron flux for these magnetic parameters is determined from the VERB model output at a fixed set of energies. This electron flux spectrum is passed through a user specified shielding layer based on published transmission functions and integrated to get the total charge that passes through that shielding. Finally, the internally accumulated charge (nC/m^2) is calculated assuming a simple circuit model [3]. The method assumes that the charge increases at a rate proportional to the incoming electron flux and decays at a rate dependent on the properties of the user specified component material. Any imbalance in those pieces then leads to a buildup of charge.

The Solar Particle Access Model (SPAM) is used to provide a real time estimate of high energy ion flux in the magnetosphere during Solar Energetic Particle events (SEPs). During an SEP event, the high energy ion flux near Earth is not uniform but will vary with location as the ions interact with Earth's magnetic field. Over the polar cap regions, the SEPs have direct access from the solar wind to low altitudes but near the equator they are deflected by the more dipolar magnetic field lines. SPAM specifies the ion flux during an SEP event at any near Earth location by mapping near real time low altitude (~850 km) proton measurements from the POES/MetOp satellites throughout the magnetosphere. The POES/MetOp data are maintained and archived by the NOAA National Centers for Environmental Information (NCEI) (https://satdat.ngdc.noaa.gov/sem/poes/data/processed/ngdc/uncorrected/full/). The archive is updated as new data is transmitted to the ground, typically once per 90 minute satellite orbit. With 6 operational satellites, the SPAM model output is updated every ~10 minutes. The application provides users with the time history of ion flux or single event effects at a particular satellite in a similar fashion as for the internal charging hazard described above. First the trajectory for a user selected satellite is created in geographic coordinates and translated to magnetic parameters (L shell and Magnetic Local Time (MLT)). The proton flux from the most recent POES/MetOp measurements is mapped to the L, MLT, and altitude of the satellite and to all ion fluxes using a set of empirically derived functions. If requested by the user, the ion flux is translated to the flux as a function of Linear Energy Transfer (LET) and the Single Event Upset (SEU) rate [4].

3. Online Application

Several hurdles currently make it difficult to easily assess and monitor space particle impacts to satellites. Some effective models of the space environment have been developed but the output can be challenging to access and interpret in real life situations without specialized knowledge. In many cases the models are targeted towards researchers with time and resources to invest in extensive studies. More easily accessible information is available through agencies such as the NOAA Space Weather Prediction Center (SWPC) (https://www.swpc.noaa.gov/), but that information is generally distilled down to more simplified sets of alerts and warnings meant to support a broad user community. While still valuable for situational awareness, the generalized information does not indicate unique hazards to specific satellites or address different orbital regions which may have very different environments. In response to these issues, we have developed an online application that allows users to view and assess the internal charging and SEP hazards to their specific satellite assets. Here we review the basic features of the online application to demonstrate its utility for monitoring and assessing space weather hazards.

3.1 Registration and Access

The SatCAT/SPAM application is a suite of web pages that support browser-based access and presentation of ion/electron fluxes and effects data to the end user (https://satcatspam.spacehaz.com/gui-react/frontend). The application provides authentication and authorization levels of security to maintain the integrity of end user data and analyses. Access to the application is available to users upon completion of the online registration process.

3.2 Creating an Internal Charging Dataset

A new user can login to the SatCAT/SPAM application, using the credentials established during registration. In order to assess hazards for any satellite, a user must first create a data collection for a satellite by selecting various input options from the web interface. For example, in order to assess the internal charging hazard the user will be asked to choose a satellite, input the time period of interest, select a component material type, and input a list of shielding thicknesses (See Fig. 1). A list of available satellites is provided from the NORAD catalogue of currently operational satellites. Documentation provided through the Help pages gives users guidance on how to choose materials and shielding thicknesses for some standard designs and components. If a real time dataset is needed for continuous monitoring, users can select the “real-time” option. Doing so, will create a dataset that continues to update at a 5-minute cadence.

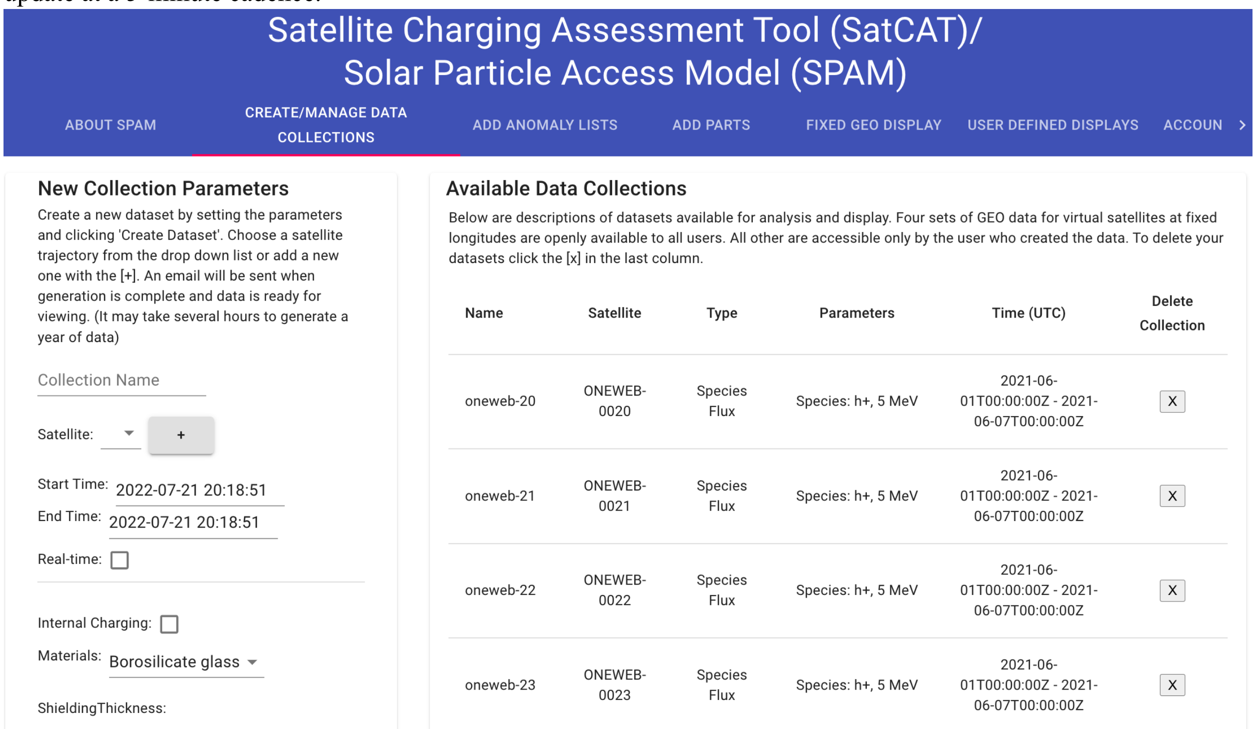

Fig. 1. User input page for generating a data collection of internally accumulated charge

3.3 Creating an SEU dataset

Users may additionally choose to create data collections that estimate hazards from more sporadic SEPs. To create such a dataset users must select various input options similar to the process described for creating internal charging hazards. In this case, 3 different types of SEP data collections are possible as shown in Fig. 2: Species Flux, LET Flux, and SEU Rate. A Species Flux dataset will provide the flux along the chosen satellite trajectory of either Hydrogen or “all species” with atomic numbers from 1-92 at fixed energies input by the user. An LET flux dataset will give the flux for all species as function of Linear Energy Transfer (LET). Lastly, an SEU rate dataset will give the Single Event Upset Rate along the chosen satellite trajectory for different types of components or parts. Pre-defined parts can be chosen from a drop-down menu or individual part parameters can be entered to create custom part definitions. All data collections will update in real time if that option is selected.

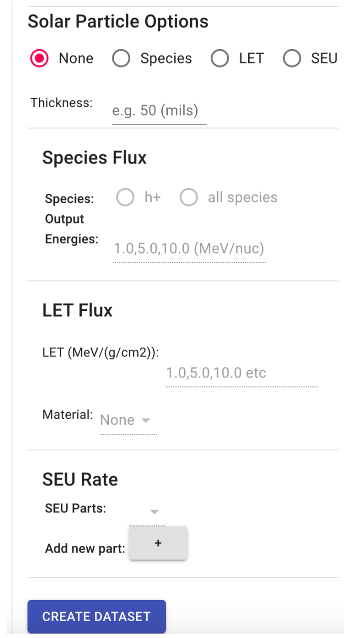

Fig. 2. Input selections for creating an SEP hazard data collection

3.4 Viewing, Analyzing, and Monitoring Hazards

Once data collections have been created, they can be plotted and displayed online for analysis as shown in Fig. 3. Custom displays can be created for viewing hazards from any data collections created by the user. To aid in analysis and identify hazardous time periods, users can choose to plot lines showing hazard percentile levels. For example, Fig. 3 shows a red horizontal dashed line where the accumulated charge is at the 97 percentile over the time period shown. Percentile lines can be used to identify times when the hazard was high relative to other times in the mission. Additionally, users can input anomaly times in order to identify correlations between hazards and unusual satellite behavior. In Fig. 3., an input anomaly is shown at 2022-07-06. Plots and data can be downloaded for further analysis using the top buttons.

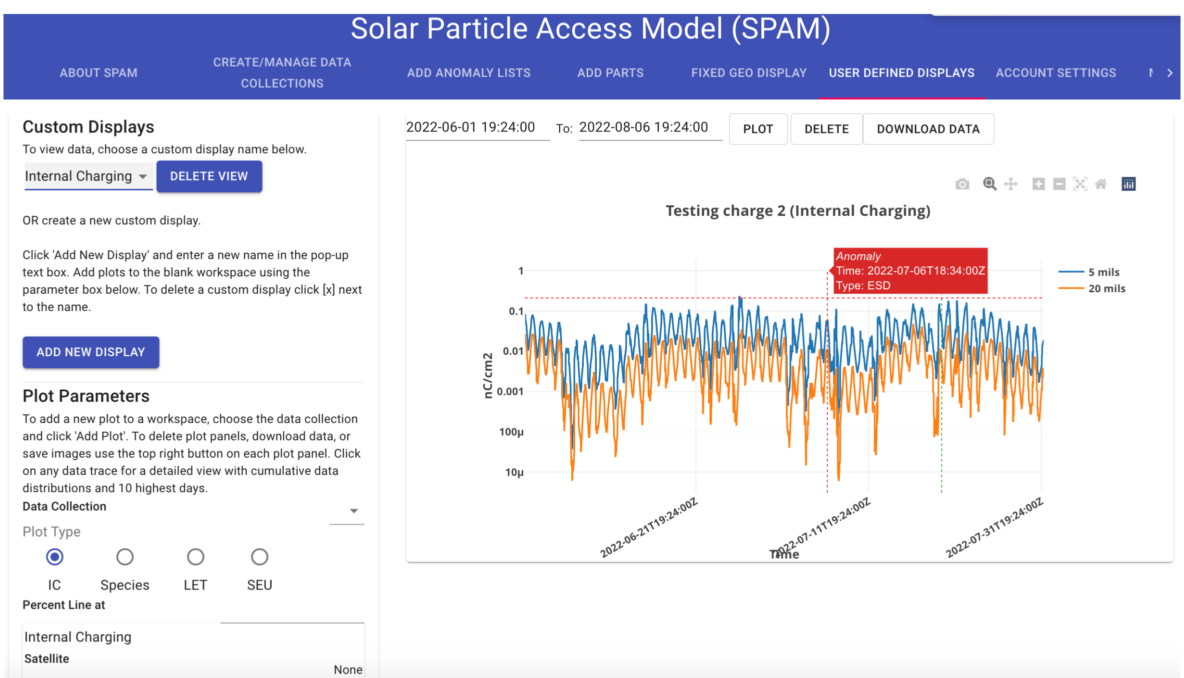

Fig. 3. Example showing how data can be plotted and viewed online within the SatCAT/SPAM application.

4. Summary

Space weather changes in the near Earth particle environment have the potential to impact a large portion of our satellite infrastructure. As the global fleet of satellites grows it will become increasingly important to monitor changes in the environment and its impact on specific satellite systems in order to ensure reliable space operations. Our understanding of the space particle environment and ability to specify changes continues to expand and improve. The SatCAT/SPAM application was developed in order to capture this physical understanding to simplify analysis and allow routine monitoring. It is now available online for analyzing retrospective and real time internal charging and SEEs on satellites near Earth. The application is unique because it allows users to input information about their satellite design to generate bespoke hazards to their satellite system and orbit. The application and underlying models of the environment will continue to improve and evolve through collaboration and input from satellite industry users.

5. REFERENCES

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