Chapter ??

Prevention of Spacecraft Anomalies – The Role of Space Climate and Space Weather Models

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Abstract Space-based systems are developing into critical infrastructure to support the quality of life on Earth. Mission requirements along with rapidly evolving technologies have outpaced efforts to accommodate detrimental space environment impacts on systems. This chapter describes approaches to accommodate space climate and space weather impacts on systems and notes areas where gaps in model development limit our ability to prevent spacecraft anomalies.

Keywords NASA, ESA, space weather, space climate, anomaly prevention

1. INTRODUCTION

The Sun emits time-varying magnetic fields, plasmas, and energetic particles. This solar variability drives changes in the interplanetary environment which then interacts with the Earth's magnetic field and outermost atmosphere to produce changes in the near Earth space environment. The space environment and its solar induced changes interact with spacecraft and instrument components and can cause anomalies resulting in loss of data, degradation of capability, service outages, and, in extreme cases, the loss of spacecraft. The most effective time to prevent spacecraft anomalies is during the pre-launch phases when risk can be minimized through technology selection and system design. For most missions, some level of "residual risk" must be assumed due to cost constraints, increasing complexity of space systems, unknowns in the space environment, and/or unknowns in space environment effects mechanisms. Possible consequences of the residual risk on spacecraft health and safety and on degradation of service must be evaluated and mitigated by writing operational guidelines for spacecraft operators and instructing the operators on how to use them effectively. The need for space weather models to manage residual risk during launch and operational phases is clear. However, space "climate"* models are equally important because of their crucial role in reducing risk in pre-launch phases of missions. In the case of both space climate and space weather models, model development lags the increase in the complexity of space systems and our dependence on space based assets.

Even during the early 1960s, when space systems were very simple, spacecraft electronics were found to be unreliable in space environments. Problems from differential charging from the solar wind and from noisy data transmission to the Earth from soft fails were noted. These problems were largely dealt with by building redundancy into systems. However, the production of enhanced radiation levels from the explosion of nuclear devices at altitudes above 200 kilometers (Starfish and others) and the ensuing problem of shortened spacecraft lifetimes emphasized the need for a uniform, quantitative description of the trapped particle environment. Later, as other effects induced by space environments were better understood, efforts to model the space environment resulted in models of all components of the environment (Barth et al., 2003, Daglis, 2001).

Revolutionary changes have occurred in space based systems since the development of the commonly used models of the space environment. First, humanity is increasingly reliant on space-based assets. In addition to the research functions that are performed in space in the areas of space science, earth science, human exploration of space, and aeronautics and transportation; critical services are also space-based, including navigation, telecommunications, defense, space environment monitoring, and terrestrial weather monitoring. Second, the performance demands of reconfigurable systems, constellations of small spacecraft, large deployable structures, imagers, and on-board computing increase the complexity of spacecraft and payloads and may require the use of rapidly evolving, complex technologies. Finally, space agencies and industry are developing missions that must operate in challenging space environments. For example, earth science missions that seek to understand complex global change processes require global coverage that cannot be achieved in Low Earth Orbits (LEOs). However, placing spacecraft in the higher altitude regions of Medium Earth

* Dave Schwartz (htpp//www.Weather.com) defines weather as "the historical record and description of average daily and seasonal weather events that help describe a region. Statistics are usually drawn over several decades". This definition is easily adapted to space climate used by inserting "space" before weather.

Orbits (MEOs) and geostationary orbits (GEO), exposes them to much higher radiation. Europe's global positioning satellite system and NASA's Living With A Star (LWS) Program also plan multiple spacecraft in high radiation regions of the magnetosphere.

Our increasing dependence on space based systems demands that we increase their reliability, ideally achieving "all weather" space systems. This requires that we address the effects of space environment through design accommodations and operational countermeasures. However, most of the current space environment models are inadequate to effectively prevent anomalies, especially on technically complex systems in challenging environments.

2. THE CAUSES OF SPACECRAFT ANOMALIES

To understand where best to focus efforts to improve our ability to prevent spacecraft anomalies, it is useful to examine compilations of spacecraft anomalies and to understand the space environment effects that cause them. The components of the space environment that can pose hazards to normal spacecraft operations include micrometeoroid and orbital debris which cause impact damage and increased contamination; the neutral thermosphere which causes surface erosion due to atomic oxygen, satellite drag, and spacecraft glow; hot plasmas which induce charge on surface of spacecraft; relativistic electrons which cause deep dielectric charging; and particle radiation environments which cause surface material degradation (in synergy with atomic oxygen and ultraviolet radiation), microelectronics and sensor degradation, and single event effects. (A review of the radiation environments can be seen in Daglis (Daglis, 2001).

Mazur (Mazur, 2002) presented the results of an Aerospace Corporation study (Koons, 1999) that analyzed the causes of spacecraft anomalies. Figure 1, from that study, shows the number of anomalies as a function of the space environment effects that caused them. "ESD" is damage from electrostatic discharges (spacecraft surface charging and deep-dielectric charging), "SEU" is single event upsets or bit-flips, "Radiation Damage" is total ionizing dose and non-ionizing dose, and "Other" represents other and unknown causes. Below is a description of these common causes of anomalies.

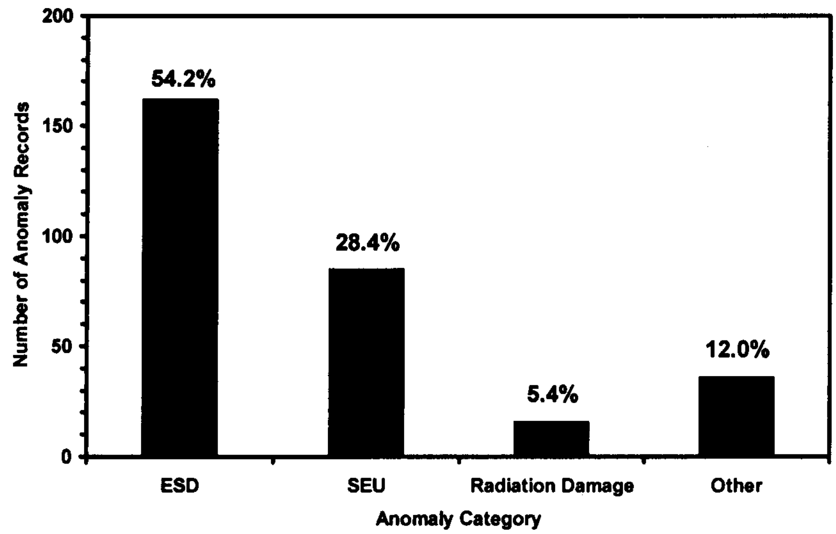

Figure 1. Spacecraft anomalies as a function of the space environment effect, where ESD is electrostatic discharge, SEU is single event upsets, Radiation Damage is total ionizing or non-ionizing dose, and Other represents other causes or unknown sources, from Koons et al., Aerospace Technical Report, 1999

2.1 Spacecraft Charging

Spacecraft surface charging and deep dielectric charging result in discharges that can cause background interference on instruments and detectors, biasing of instrument readings, physical damage to materials, upsets and physical damage to electronics, increased current collection, reattraction of contaminants, and ion sputtering which leads to acceleration of erosion of materials. Plasmas are responsible for surface charging; particularly in planetary radiation belts where storm induced fluctuations occur. Deep dielectric charging results from higher energy electrons penetrating and collecting in non-conducting materials until the material's dielectric breakdown is reached and a discharge occurs. As with plasmas, storm induced increases in high energy electron levels are known to increase the risk of deep dielectric charging problems. For an overview of spacecraft charging and induced anomalies, the reader is referred to Daglis (Daglis 2001).

2.2 Single Event Upsets and Single Event Effects

Single event effects (SEEs) occur as a result of charge being generated along the path of a primary or secondary ionizing particle, collected on circuit nodes, and disrupting normal circuit operation. Both the total collected charge and the rate of charge collection can be important in triggering the effect. SEEs affect memories, power devices, control logic devices, etc. Although increased levels of protons and heavy ions from solar particle events can increase the level of SEEs on systems, daily exposure to background levels of protons and ions in interplanetary space and in planetary radiation belts is a significant source of SEEs.

Single event upsets (SEUs) in memories is the most common and best known SEE, however, other effects on newer technologies can be more disruptive to spacecraft operations. Less known non-destructive effects are single event transients (SET), single event functional interrupts (SEFI), and multiple bit upsets (MBU). MBUs can result in uncorrectable errors in data systems. SEFIs occur in high density memories when control regions of a device are hit by a particle possibly resulting in system lockup or reset. SETs are a well known problem in some detector technologies generally limiting their use to low radiation regions, however, SETs also cause voltage dropouts in logic devices which can result in system resets. For example, the increase in the heavy ion population during the November 2001 solar particle event caused an SET on a linear bipolar device on NASA's Microwave Anisotropy Probe (MAP). As a result, MAP's processor was reset and the spacecraft went into a safehold condition.

SEEs can also be destructive resulting in permanent loss of the functionality of a component. Single event latchup (SEL), single event gate rupture (SEGR), and single event burnout (SEB) are examples of permanent failures from single particle strikes and can cause the loss of a system or a spacecraft.

SEEs must be mitigated through component selection or system design to avoid temporary or permanent loss of spacecraft service. The SEE vulnerability of newer technologies used in spacecraft and instrument systems is increasing because it is difficult to use processing techniques to make devices immune to SEEs. "Hardness by design" is gaining in use to mitigate SEEs, however, the penalty in required overhead is severe. Regardless of the technique used to mitigate SEEs in designs, the overhead required in the system is increased by inaccuracy in space climate models, and operational countermeasures are compromised by inaccurate space weather forecasts.

2.3 Radiation Damage

Cumulative radiation damage is caused by two mechanisms, total ionizing dose (TID) and total non-ionizing dose, otherwise known as displacement damage dose (DDD). TID degrades the performance of surface materials, such as, lens coatings and thermal control materials, and of electronics. It is possible to avoid TID effects through the selection of radiation-hardened components. Unfortunately, these components are increasingly unavailable because the space market share for microelectronics is less than 0.5% of the total market share (down from 40%). Also, many radiation hardened components do not meet mission requirements because they are based on older generation technologies. It has become common practice to use commercial off the shelf (COTS) devices; however, their radiation response can be difficult to characterize due to large variation of radiation response within a device lot and the difficulty of testing imposed by packaging and hybridization. Large safety margins are used to accommodate the uncertainty, which when combined with inaccurate space climate models, often results in "overdesigning" systems. Electrons and protons in interplanetary space and trapped in planetary radiation belts cause TID. Because TID affects components from the surface to deep inside a spacecraft or instrument, particles across broad energy range (eVs through MeVs) are a concern.

DDD degrades the performance of solar cells, detectors (e.g., charge coupled devices), optocouplers, and optical lenses. It is more difficult to harden against DDD, therefore, the use of shielding and planning for "graceful" degradation is used to mitigate its effects. As with TID, particles in a broad energy range affect systems. When using heavy shielding to protect detectors, inaccuracies in the estimates of the levels of high energy particles (>100 MeV) result in large error bars on damage estimates.

2.4 Other

Other causes of anomalies could include damage from micrometeoroid and orbital debris or degradation of materials from combined surface effects or operator error. Often the causes of anomalies cannot be determined due to the lack of information on either the space environment at the time and location of the anomaly or the specific effect or the system in which it occurred.

3. PREVENTION OF ANOMALIES

Reports of spacecraft anomalies in the space weather community focus on the space weather phenomena that cause them but they rarely discuss the mechanism of failures or the "lessons learned" that can be applied to design methodologies or to operational countermeasures to prevent anomalies in future systems. The causes of spacecraft anomalies given in Figure 1 are effects that can be minimized in pre-launch phases of missions by defining the expected space environment over the lifetime of the mission, understanding the effects that it has on the components used on the spacecraft, and defining specific environment accommodations.

The accommodation of space environment effects is a complex process that involves both physics and engineering disciplines. To ensure mission success, engineers, scientists, and program mangers rely on engineering judgment as guided by analysis of component response to the space environments. The success of such analysis depends on several factors. Accurate climate models of the space environment that represent variations for all conditions of the solar cycle are crucial for evaluating the extent to which environment threats may compromise mission goals. Measurements of component responses to laboratory simulations of the space environment provide critical data for bounding on-orbit device performance. Equally important, however, is a detailed model of the interaction and transport of environment sources through observatory models and device structures. Such models not only serve as a bridge for understanding laboratory data to prediction of on-orbit performance, they also provide guidance as to the test methods and laboratory measurements needed for such predictions. Of necessity, these models make simplifying assumptions that must be reexamined as mature technologies evolve, as new technologies are introduced, and as advances in desktop computing make more powerful and realistic analyses feasible.

Figure 2 shows the sources of uncertainties in simulating the space environment and effects on spacecraft and instrument components. The uncertainties translate directly into design margins that must be applied to estimates of space environment hazards to minimize the risk of mission failure. While the focus of this chapter is on requirements for space environment models, it is important to point out that it is not the only source of uncertainty in simulation of space environment and effects. Concurrent efforts are underway to develop tools such as GEANT4 (Apostolakis, 2000, Truscott et al., 2000), MCNPX (Walters, 2003), workbenches, and integrated mission design centers.

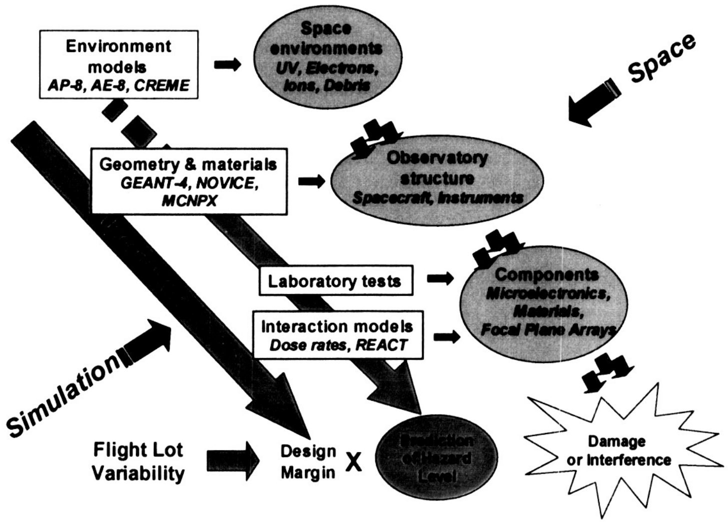

Figure 2: Sources of uncertainties in simulation of the space radiation environment. Simulation is required to predict performance in space. Errors in simulations result in under and over predictions of the hazard level.

The most effective way to assure spacecraft reliability is to use preventative measures throughout the mission life cycle. The challenge is to maintain the balance between meeting mission requirements, cost, and reliability. Residual risk for a mission is assumed when it is recognized that 100% reliability is not possible due to cost constraints and mission requirements drivers. The level of this residual risk must be assessed <u>before</u> launch and operations so that a risk management plan can be implemented early in the program. Where possible, spacecraft vulnerabilities should be identified so that operators can be trained on effective use of space weather forecast models.

The phases of mission development that must take into account space environment effects can be divided into concept, planning, design, launch, operations, and anomaly resolution. Figure 3 clearly shows the important role that space climate and space weather models play in minimizing risk for space-based systems.

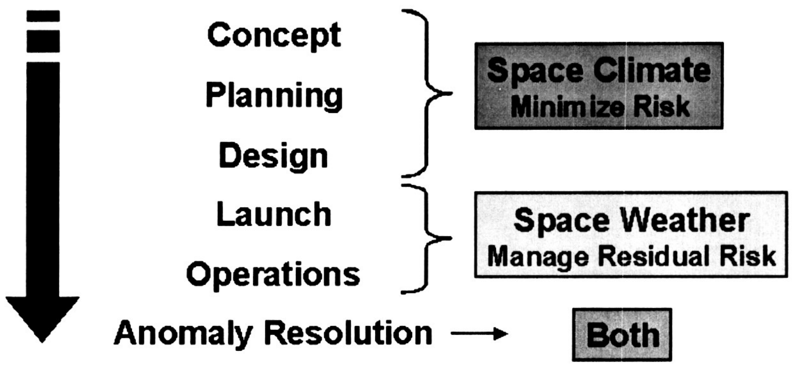

Figure 3. Phases of mission development which require space environment models. Space climate models are critical for minimizing risk of mission failure.

3.1 Space Environment Information for Pre-launch Phases

Issues that are addressed during the mission concept phase include observation requirements, observation vantage points, and development and validation of primary technologies. Required capabilities at this stage are integrated mission design tools, which include space climate models that can simulate the space environment throughout the solar cycle. Spatial resolution is also required so that trades between vantage points can be considered. Worst-case space environments are also needed to assess the survivability and function of the primary technologies.

Issues that are addressed during the mission planning phase are observation requirements, mission success criteria, architecture trade studies, and risk acceptance criteria. Most accommodations for space environment effects are implemented during mission design including component selection and testing, subsystem design, shielding requirements, grounding, error detection and correction, and estimates of observation loss. Time distributions of levels of activity are needed to estimate lost observation time from instrument interference and data corruption. Worst-case levels of the space environment are also required for determining the survivability of components and the level of required error mitigation. To guide decisions on the acceptable level of risk, confidence levels for the space climate models are required and the capability of forecasting models for specific environments of concern should be assessed. One of the most critical features of the space climate models is that they cover an energy range that is adequate for addressing degradation or interference from the surface (e.g., thermal control materials) to heavily shielded systems (e.g., detectors).

3.2 Launch and Operations

Good engineering practice is not a guarantee of a spacecraft that is 100% free from vulnerabilities from the space environment. As discussed above, this is due to cost constraints, increasing complexity of space systems and technologies, unknowns in the space environment, and unknowns in space environment effects mechanisms. As a result, spacecraft are often vulnerable to increases in space environment levels, i.e., space storms. Therefore, launch and operation phases require models that can forecast space storms to protect the space-based asset by shutting down systems or avoiding risky operations, such as, maneuvers, system reconfiguration, data download, or re-entry. The need to forecast quiet times is as important as forecasting storms to give operators "windows" during which these risky operations can be performed. Spacecraft operation facilities find it useful to be able to schedule extra personnel when space storms are expected. Forecasts must be specific to the region, the particle population, and even the energy range.

3.3 Anomaly Resolution

Regardless of the service provided by a space-based system, it is critical to be able to restore the system to normal operations quickly after an anomaly. Often this is accomplished before resolution of the anomaly. However, as soon as possible, the anomaly must be resolved in order to prevent possible permanent damage to the system. Once the anomaly is resolved, the risk is reevaluated, and operational countermeasures AND design guidelines are updated. It is not unusual for anomalies to be unresolved. Health and safety monitoring on the spacecraft may be inadequate to pinpoint the system component that was sensitive to the in the space environment hazard. Frequently the space environment hazard is inadequately defined in terms of spatial resolution or energy and particle resolution. Science spacecraft often have data that are valuable for anomaly resolution; however, timely access to that data is generally an impediment.

The third type of model for "nowcasting" the environment is used to resolve anomalies so risk can be reassessed for both the operating systems and for other systems that are in development. As with forecasts, nowcasts must be specific to the region, the particle population, and the energy range. If anomaly resolution is critical to the mission and must be performed in near real-time, monitors that are in close proximity to the system may be required.

4. MODEL DEVELOPMENT ACTIVITIES

Before discussing the status of model development, a review of organizations supporting model development is useful. The discussion is not intended to be inclusive of all researchers, but instead focuses on major agency support.

The European Space Agency (ESA) recognized the need to define priorities for new space climate models in the early 1990s and initiated a series of studies to improve the models of the radiation belts. The goals of the Trapped Radiation ENvironment Development (TREND) studies were to first analyze existing models for shortfalls and to later develop new models of the radiation belts (Heynderickx, 2003). Using data from SAMPEX, UARS, and CRRES, the TREND studies have resulted in some improvements in the radiation belt models which will be listed in the next section. Later, the United States (U.S.) National Aeronautics and Space Agency (NASA) started the Space Environment and Effects (SEE) Program (Kauffman, 2003) to develop space climate models, environment interaction models, and databases to be used for spacecraft design. The SEE program has sponsored space climate modeling development efforts for solar protons and heavy ions and trapped protons.

The need for space weather forecasting capability was outlined in the U.S. National Space Weather Program for a broad user base (NSWP, 2000). The original study identified the need for space weather forecasting for spacecraft operations, and in 2003, it was recognized that improved space climate models are also required to reduce the risk of on-orbit failures through design accommodations. Since 1965 the U.S. National Oceanic and Atmospheric Administration's (NOAA) Space Environment center (SEC) has been the official U. S. course of space weather alerts, warnings, and forecasts. Activities include monitoring, data management, providing space environment information, research and research transition to operations, including models, and education. The origin of the international component can be traced to the early 1910s. Currently, the International Space Environment Service (ISES) includes several world wide regional warning centers with NOAA acting as a hub ("World Warning Agency"). An overview of NOAA's role and activities is given in Daglis (Daglis, 2000).

Recently, the European Space Agency conducted two parallel space weather feasibility studies to assess the requirements for space weather service in Europe. ESA has now begun a space weather applications pilot project to expand the results of the studies and to develop the European space weather community (Daglis, 2000, Daly, 2003).

In 2001 NASA's Living With a Star (LWS) Program (LWS, 2003) was initiated with the goal to develop the scientific understanding to address the aspects of the connected Sun-Earth system that affect life and society. One target area is to improve knowledge of space environments for spacecraft applications. Space missions are being developed which will help to fill the need for environment measurements, and a Targeted Research and Technology Program has been defined to address the need for improved modeling capability for both space climate and space weather.

In 2002 the international science community established the International Living With a Star Program (ILWS). The mission of the program is to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. The objectives are to stimulate and facilitate 1) study of the Sun-Earth connected system and the effects which influence life and society, 2) collaboration among potential partners in solar-terrestrial space missions, 3) synergistic coordination of international research in solar-terrestrial studies, including all relevant data sources as well as theory and modeling, and 4) effective and user driven access to all data, results, and value-added products (Sibeck, 2003).

5. SPACE CLIMATE PREDICTION

This section will describe the current capabilities of the space climate models commonly used in the pre-launch phases of mission development. Areas where models improvements are required will be highlighted.

5.1 Galactic Cosmic Rays

The need for understanding the galactic cosmic ray (GCR) environment for astronaut protection was identified early in space programs resulting in a program to measure (IMP-8 spacecraft) and model the variations in GCR levels. Later when GCRs were identified as the cause of SEEs on spacecraft, the microelectronics community benefited from this work. The model most commonly used for mission planning and spacecraft design is embedded in the CREME96* (Tylka et al., 1997) workbench tool that calculates SEU rates in devices. This GCR model predicts energy-flux spectra for all of the ions from Hydrogen through Uranium for energies from 1 to 10,000 MeV/n. The energy-flux spectra are converted to linear energy transfer (LET) spectra

* Funded by the U.S. Naval Research Laboratory and by the NASA Space Environments and Effects Program

which is a crucial metric to understand the level of the space environment hazard to microelectronics. The current GCR models, including the CREME96, are acceptable because they are estimated to predict the GCR levels over the solar cycle to within ±15-25%.

5.2 Solar Heavy Ions

The CREME96 tool also contains a model of the solar heavy ion environment based on analysis Dietrich's analysis of the solar heavy ion data from the University of Chicago instrument on the IMP-8 satellite (Tylka et al., 1997). The dataset was especially important for modeling the energy-flux spectra at higher energies. The analysis of 100 solar heavy ion events in Dietrich's database showed that the October 1989 solar particle event could be used to represent an upper bound on the maximum solar heavy ion environment. The CREME96 model gives a "worst-case" flux-energy spectra for H through U ions based on that event. Later Dyer et al. (Dyer et al., 2000, Dyer et al., 2002) presented data on the LET spectra of solar particle events occurring between 1998 and 2001. While there are very low enhancements of high LET fluxes for many of the events, three events approach or equal the CREME96 worst day model. At low LET, where protons dominate and usually lead to single event effects by nuclear interactions, two events slightly exceed the model.

The CREME96 solar heavy ion model represents a large improvement over previous models but, unlike the GCR models, fails to meet the requirements of pre-launch phases of missions. It is not always practical or possible to design microelectronics systems that are 100% free from destructive and non-destructive SEEs in worst-case solar heavy ion environments. Increasingly, mission planners require space climate models that are based on confidence levels which guide risk acceptance decisions.

In recognition of the need to understand the statistical variation of the solar heavy ion event intensities, the NASA Space Environments and Effects program funded Xapsos et al. (Kauffman, 2003) to study solar heavy ion data sets and to develop a statistical model. The Xapsos model of the solar heavy ion environment will provide a statistically based upper limit on the event fluxes for systems that must operate through events and will allow assessment of the levels of risk for other systems by providing a distribution of the flux levels as a function of confidence levels. The major obstacle to modeling solar heavy ions is the lack of measurements. The infrequency of the events requires several solar cycles of data to get a database large enough to do statistical analysis.

5.3 Solar Protons

King (King, 1974) published the first statistical model for solar proton events using Poisson distributions. He concluded from his analysis of proton data from the 20th solar cycle that solar proton events could be classified into "ordinary" and "anomalously large". This was based on the fact that only one anomalously large event occurred in the 20th solar cycle - the August 1972 event. That event alone accounted for 84% of the total proton fluence in the solar cycle at energies E > 30 MeV. However, when Feynman et al. (Feynman et al., 1993) added cycle 19 and 21 data to the solar proton event database, they were able to conclude that individual solar proton events actually form a continuum of event severity from the smallest to the largest, blurring the distinction between ordinary and anomalously large events. Their work resulted the JPL model for solar proton events (Feynman et al., 1993).

Many large events similar to the August 1972 event occurred in cycle 22 increasing concern about the validity of the solar proton models. With the goal of improving the ability to address practical aspects of spacecraft reliability, a team led by Xapsos began compiling solar proton data for solar cycles 20, 21 and 22 and using statistical techniques to derive probability distributions of cumulative solar proton fluences. Xapsos et al. (Xapsos et al., 1999) applied extreme value theory to determine probability of encountering a single large event over the course of a mission. They also used compound Poisson process theory to describe the probability of encountering various fluence levels during a mission. The work of the Xapsos team confirmed the Feynman conclusion that a "typical event" cannot be defined.

The Xapsos team have also worked on models that define the peaks of solar proton events for E > 10 MeV. To accomplish this, they applied Maximum Entropy Principle (MEP) to select the least biased event probability distribution. The MEP, used for earthquake predictions, is valuable for analyzing incomplete datasets. They validated the results with Lunar Rock Records dating back to ancient times. The Xapsos team continued their work by establishing worst-case solar proton spectra for solar events (Xapsos, 1999). When comparing their model with the CREME96 (Tylka et al., 1997) solar proton model, which was based on the October 1989 solar particle event, they found that, statistically, the CREME96 model is closer to a 90% worst-case event model. Xapsos et al. have combined the model elements into the Emission of Solar Protons (ESP) model (Xapsos et al., 2003).

The JPL and ESP models are commonly used to predict solar proton levels for total ionizing dose, displacement damage, and single event effects.

Both models would benefit from a larger database of solar proton event measurements and from measurements of protons at energies > 100 MeV. Large uncertainties in the solar proton environment at high energies translate into large design margins for heavily shielded applications, especially, instrument detectors operating outside of the radiation belts where solar proton induced damage dominates.

5.4 Trapped Particles

The trapped particle models that are most often used at this time are the AP-8 (Sawyer and Vette, 1976) for protons and the AE-8 (Vette, 1991) for electrons. The AP-8 model, released in 1976, was the culmination of a long-term effort to include all of the previous models under one common approach and to include all of the data after 1970. After 1977, the modeling budget was significantly reduced so a similar effort to consolidate the electron models into the AE-8 model was not completed until 1983. The formal documentation of that model was released in 1991. The AP-8 and AE-8 models include data from 43 satellites, 55 sets of data from principal investigator instruments, and 1,630 channel-months of data.

By the 1970s, scientific interest had shifted from trapped particles to the plasma regime to determine the physical mechanisms of particle energization and transport. As a result, the number of new data sets available for trapped radiation environment modeling was drastically reduced. It was not until the measurement of storm belts by the CRRES mission in 1991 that concerns were renewed about the ability to model the trapped radiation belts to sufficient accuracy for using modern microelectronics in space. Analysis of the CRRES instrument and experiment data showed that not only is the environment extremely dynamic but also that electronic parts respond to the short-term changes. The AP-8 and AE-8 radiation belt models, with their 4-6 year averages, are not adequate for application to design mitigation problems related to effects on shorter time scales. Also, the frequency of occurrence of the atypical events that could form storm belts is unknown, therefore, applying AP-8 and AE-8 or like models to setting design and operational rad-hard requirements creates uncertainties that are impossible to quantify.

The U.S. Air Force Research Laboratory (AFRL) CRRES Program, the ESA TREND Program, and the NASA SEE Program have sponsored efforts to improve in the radiation belt models including:

- ESA TREND Program - an alternate interpolation method for AP-8 and an additional L increment at the low L values to give better resolution at steep gradients (Daly et al., 1996)

- AFRL - the CRRESPRO model (Gussenhoven et al., 1993) to give estimates of the trapped proton levels before and after the March 1991, simulating quiet and active conditions in the magnetosphere
- AFRL – the CRRESELE model (Brautigam et al., 1992) to give estimates for eight conditions of magnetic activity, six ranges of activity as determined by the AP15 magnetic index and for the average and worst case conditions that CRRES measured
- AFRL – the CRRESRAD model (Gussenhoven et al., 1992) to give estimates of dose based on the CRRES 4-domed dosimeter for quiet and active conditions
- AFRL – the APEXRAD model (Gussenhoven et al., 1997) from a CRRES-like dosimeter on the APEX spacecraft to extend the CRRESRAD model to low altitudes and high latitudes.
- NASA SEE Program – the LOWTRAP model (Huston and Pfitzer, 1998) to predict proton fluxes below 850 km as a function of the solar radio flux proxy for atmospheric heating
- ESA TREND Program – the SAMPEX/PET model (Heynderickx et al., 1999) to predict proton flux levels as a function of solar activity effects
- ESA TREND Program – Ap15 dependent models of the outer electron belt to understand storm-time behavior of trapped electrons in the outer part of the radiation belts using Salammbô (Bourdaire et al., 1995) and data from Meteosat-3/SEM-2, CRRES/MEA, and STRV-1b/REM (Heynderickx, 2003)
- ESA TREND Program – proton flux anisotropy in the altitude range of the MIR and ISS stations including secular, solar-cycle, and seasonal variations (Heynderickx, 2003)

6. SPACE WEATHER FORCASTING AND NOWCASTING

Regardless of the space environment in question, most space weather forecasting models do not provide adequate information or are accurate enough to be of practical use for operators of space systems. Operational actions cannot be taken every time a forecast of increased solar activity is issued. To be effective tools, warnings need to have spatial and spectral resolution and provide information about the level of severity. They also need to be specific about the ion composition of particle events. For space assets operating in the Earth's magnetosphere, current forecasting is particularly ineffective. Forecasting capability focuses on storms, however, it is equally important to know when the space environment will be "quiet" so that critical operations, such as, reprogramming, maneuvers, or reentry, can be performed.

Anomaly resolution and subsequent modifications to design guidelines and operational countermeasures are not effective without identifying the specific cause of the anomaly. This requires local knowledge of all relevant environments and information on the expected technology response. In some cases, the current monitoring capability provided by the NOAA GOES and TIROS spacecraft have been very useful to resolve anomalies, particularly for spacecraft outside of the magnetosphere, in geostationary, or in orbits similar to TIROS. Comments on capabilities for specific environment components are given in the sections below.

6.1 Galactic Cosmic Rays

The variations in the GCR levels occur slowly in comparison with the other space environment populations, and CREME96 model predicts the levels adequately for spacecraft design and operations needs. Therefore, there is no need for a GCR forecasting capability.

6.2 Solar Heavy Ions

Solar heavy ions pose a significant threat to spacecraft systems through their ability to cause SEEs on spacecraft microelectronics which can result in loss of spacecraft service. At this time there is little capability to monitor or forecast solar heavy ions. Science instruments on ACE and WIND make heavy ion measurements, however, because the data are not available within a reasonable time, this does not comprise a monitoring capability that can be used for forecasting or nowcasting (anomaly resolution). For warnings or anomaly resolution for microelectronics, direct measurement of the linear energy transfer (LET) profile of the event is crucial for understanding if systems are vulnerable to the event. The MAP anomaly caused by an SET on a linear bipolar device was resolved because the spacecraft is outside of the magnetosphere at L2, and LET data were available from the CREDO environment monitor (Dyer et al., 2002) on a U.S. Naval Research Laboratory space environment testbed, the Microelectronics and Photonics Testbed (MPTB).

6.3 Solar Protons

The NOAA series of GOES spacecraft carry proton monitors that have been very useful for nowcasting solar proton levels. It has been shown that, for levels of nominal spacecraft shielding, increases in SEUs are correlated to

> 100 MeV solar protons (Poivey et al., 2003). Therefore, the addition of the > 100 MeV channel to the NOAA Space Environment Center space environment nowcasts has been particularly useful for analysis of solar proton effects on spacecraft microelectronics.

Forecasts of increases of solar proton levels are still not accurate enough to be of practical use for spacecraft operations. Although it is generally, useful to know when a problem might arise, the forecasts of non-specific storms are too frequent to allow preventative shutdowns. For solar protons, forecasts of the expected maximum energy would help to reduce false alarms.

6.4 Trapped Particles

As with the space climate models, trapped particle forecasting capabilities are poor. The "geoeffectiveness" of solar events can't be forecast and existing monitoring is not adequate to cover geospace regions inside of geostationary and below high-latitude inclinations. Since the CRRES mission, there have been some improvements in "post-diction" of events. In 1993 Li et al. (Li, 1993) used a simplified model of the Storm Sudden Commencement (SSC) compression of the magnetosphere to show that electron belts like those measured by CRRES can be created in tens of seconds when the interplanetary shock wave from the storm interacts with the magnetosphere. Later Hudson et al. (Hudson, 1996) showed that this shock acceleration theory could also be used to explain the sudden formation of proton storm belts. Bourdaire et al. (Bourdaire et al., 1995) are developing a 4-D diffusion code to calculate the transport of particles throughout the inner magnetosphere. Case studies have been validated using CRRES and STRV-1b measurements.

7. CAPABLITY GAPS

In spite of recent developments in space climate and space weather models and forecast capabilities, serious shortcomings remain, including:

- Climate Models
  - Solar heavy ions: larger database required for statistical analysis
  - Solar protons: larger database required for statistical analysis and higher energies needed
  - Trapped particles: no statistical information to predict extreme climates or climate distribution as a function of confidence level; inaccurate predictions at extremes of energy spectra; unknown

accuracy in many regions, particularly at GEO and MEOs; lack of long term (yearly) and short term (hourly) time resolution; lack of understanding of variations in "slot region"; lack of understanding of duration of slot region storm populations

- Weather Models
  - Solar heavy ions: no forecast or nowcast capability
  - Solar protons: inaccurate forecast capability, forecasts do not have energy resolution
  - Trapped particles: little forecast capability, nowcasts not available for all regions

The Living With a Star Program was established to address research aspects of science. The Targeted Research and Technology Element of LWS has funded grants to support improvements in the models (LWS, 2003). Examples of current efforts on the radiation belt models climate models are:

- Understand the fundamental plasma interactions and particle transport processes responsible for the extreme conditions that pose the most serious threat to space systems
- Address the deficiencies in the AE-8 models by understanding variance from long-term average models and worst case levels
- Develop time-dependent maps of energetic particles fluxes in inner magnetosphere
- Establish Center for Space Radiation Modeling (CIRM), data acquisition and management, construction, validation, dissemination
- Develop quantitative of the geomagnetic field that is valid in the entire geospace region
- Understand long-term dynamics of the trapped radiation slot region
- Understand variability in the Low Earth Orbit plasma environment
- Determine the conditions in the solar wind and within the magnetosphere that are responsible for the variability of relativistic electrons
- Understand the dynamics of energetic electron fluxes in the inner magnetosphere, produce electron models coupled to the solar wind variables

LWS is also supporting numerous efforts to improve space weather modeling capability by funding research that addresses physical processes from the interior of the sun to the ionosphere. The reader is referred to the LWS website for a list of those efforts (LWS, 2003). ISES members also support numerous research projects to understand space weather processes.

In spite of the infusion of opportunity provided recently by space agencies, major roadblocks to developing effective space climate and space weather models remain:

1. Other than the GCRs, long term baseline measurements throughout Sun-Earth space do not exist for understanding trends and for model validation. In particular, the radiation belt missions in the LWS program are inadequate to provide the required solar cycle and regional coverage.
2. Transition of research models to validated space climate and space weather models is not adequately addressed. Space programs are reluctant to increase the risk of mission failures by endorsing the use of new, unproven environment models to guide mission designs and operations.
3. The length of time required to "authorize" space environment models is too long. More support for these activities from agencies is required, and there needs to be better international communication.
4. The assessment of user requirements needs to be more formal and coordinated between agencies.
5. There needs to be more opportunities for researchers and users to interact effectively. NOAA Space Weather Week and the NATO Advanced Research Workshops should continue to bring together researchers and users for open discussions of requirements. ILWS and LWS need to include users on their panels and task groups.

8. SUMMARY

The protection of space assets requires attention to the effects of space environments through all phases of mission design, development, and operation. Space weather models only address post-launch phases when it is difficult to effectively prevent anomalies. Reducing the risk of anomalies in pre-launch phases requires space climate models which have not received as much attention by the international community. Neither space climate nor space weather models meet current or future needs of spacecraft designers or operators. The lack of resources is not the only obstacle to the development and implementation of effective space environment models. Serious thought needs to be given to requirements definition, model transition from research to applications, and model standardization. The most important need is for increased communication between research, application, and user communities.

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