2.11

SPACE WEATHER EFFECTS ON SPACECRAFT SYSTEMS

Janet L. Barth*
NASA/Goddard Space Flight Center, Greenbelt, Maryland

ABSTRACT

Space-based systems are developing into critical infrastructure required to support the quality of life on Earth. Hence, spacecraft reliability is a serious issue that is complicated by exposure to the space environment. Complex mission designs along with rapidly evolving technologies have outpaced efforts to accommodate detrimental space environment impacts on systems. Hazardous space environments, the effects on systems, and the accommodation of the effects are described with a focus on the need to predict space environments.

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.

Revolutionary changes have occurred in space-based systems since the first exploratory missions of the "space age". 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 which often require the use of rapidly evolving, miniaturized 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 orbits (MEOs) and geostationary/geosynchronous orbits (GEOs) results in a significant increase in radiation exposure. 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. Reliability cannot be increased without careful management of the effects of the space environment on systems. Mitigation must include both design accommodations and operational counter-measures. Mitigating space environment effects requires simulations of the effects with accurate models of the environment and environment interactions. The goal of simulations is to accurately predict the level of hazard. As shown in Fig. 1, uncertainties in the simulation process translate directly into design margins that add overhead and can preclude the use of some technologies.

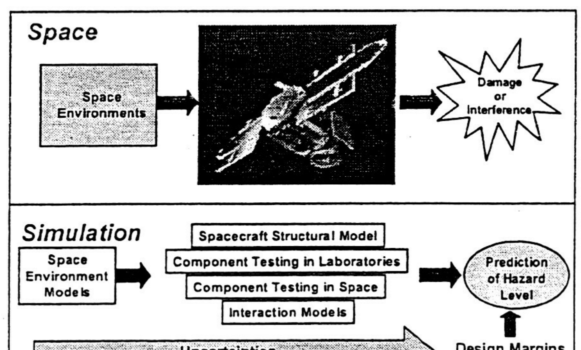

Fig. 1: Accommodation of space environment effects on spacecraft requires ground simulations that include models of environments and effects.

* *Corresponding author address:* Janet L. Barth, NASA/Goddard Space Flight Center, Code 561.4, Greenbelt, MD 20771,
email: Janet.L.Barth@nasa.gov.

Before discussing environment effects and effects accommodation, a review of space environments that are hazardous to spacecraft will be given. More detailed discussions of the hazardous environments can be found in Barth (1997), Dyer (1998), and Mazur (2002).

2. THE SPACE ENVIRONMENT

Spacecraft are exposed to a multitude of environments that are not present at the surface of the Earth, including micrometeoroids and orbital debris, ultraviolet irradiation, neutral particles, cold and hot plasma, and particle radiation. The interaction of these environments with spacecraft systems cause degradation of materials, thermal changes, contamination, excitation, spacecraft glow, charging, radiation damage, and induced background interference. There are large spatial and temporal variations in the constituency and density of the environments; therefore, exposure to the environment is highly dependent on the location of the spacecraft. For the purpose of discussion of environmental definitions, missions can be roughly categorized into LEOs, MEOs, GEO, geosynchronous transfer orbits (GTOs), and interplanetary.

2.1 *Meteoroids and Orbital Debris*

Meteoroids are primarily remnants of comet orbits. Several times a year Earth system encounters increased meteoroid exposure as it intersects a comet orbit. Also, sporadic particles are released on a daily basis from the asteroid belt. Orbital debris consists of operational payloads, spent rockets stages, fragments of rockets and satellites, and other hardware and ejecta. The United States Air Force Space Command's North American Aerospace Defence Command (NORAD) tracks over 7,000 objects in LEO that are greater than 10 cm in size, and there are tens of thousands smaller objects.

2.2 *Ultraviolet Irradiation*

The sun is the natural source of ultraviolet (UV) irradiation, which has wavelengths of about 100 to 400 nanometers. UV irradiance can penetrate the atmosphere to reach the surface of the Earth. UV radiation diffuses with distance from the sun at a rate of $1/R^2$ where R is the radial distance from the Sun.

2.3 *The Solar Wind*

The sun's outer atmosphere, the corona, extends several solar diameters into interplanetary space. The corona continuously emits a stream of protons, electrons, doubly charged helium ions, and small amounts of other heavy ions, collectively called the solar wind. The high temperature of the corona inputs sufficient energy to allow electrons to escape the gravitational pull of the sun. The result of the electron ejections is a charge imbalance resulting in the ejection of protons and heavier ions from the corona. The ejected gas is so hot that the particles are homogenized into a dilute plasma*. The energy density of the plasma exceeds that of its magnetic field so the solar magnetic field is "frozen" into the plasma. The electrically neutral plasma streams radially outward from the sun at a velocity of approximately 300 to 900 kilometers per second with a temperature on the order of 104 to 106 K. The energies of the particles range from approximately 0.5 to 2.0 keV/n. The average density of the solar wind is 1 to 30 particles/cm^3.

2.4 *High-energy Interplanetary Particles*

In addition to the solar wind plasma, interplanetary space contains high-energy charged particles called galactic cosmic rays (GCRs) that are present at all times. Solar events that occur sporadically (coronal mass ejections and flares) can also be a source of high-energy particles.

GCR intensities rise and fall slowly with the solar cycle variations such that GCRs are at their peak level during solar inactive times and at their lowest level during solar active times. The difference between the extremes of the GCR fluence levels is approximately a factor of 2 to 10 depending on the ion energy. Fig. 2 shows the slow, long-term cyclic variation of the cosmic ray (C, N, O) fluences for a 20-year period as measured by the IMP-8 spacecraft.

During active phases of the solar cycle, the numbers and intensity of coronal mass ejections and solar flares increases. These events can cause periodic increases in the levels of interplanetary particles that are orders of magnitude higher than the GCR environment. The sharp spikes superimposed on the cosmic ray background seen in Fig. 2 are caused by solar events. The particles consist of ions of all elements, but protons usually dominate the abundances. Solar particles diffuse as they move through the interplanetary medium. Therefore, the solar particles abundances are a function of radial distance from the Sun.

The Earth's magnetic field provides some protection to Earth-orbiting spacecraft from interplanetary particles by deflecting the particles

* Plasma is ionized gas in which electron and ion densities are approximately equal. Plasma is distinguished from the energetic particle population in that it does not cause radiation effects and has energies < 100 keV.

as they impinge upon the magnetosphere. The exposure of a spacecraft primarily depends on the inclination and, secondarily, the altitude of the trajectory. For example, interplanetary particles have free access over the polar regions where field lines are open to interplanetary space. The penetration power of these particles is also a function of the particle's energy and ionization state and of solar wind and magnetospheric conditions. Analysis of the exposure of spacecraft orbiting the Earth as a function of the geomagnetic disturbances that are often associated with solar events is especially critical. For example, Gussenhoven *et al.* (1996) showed with data from the CRRES that solar protons reached L shell values as low as 2.

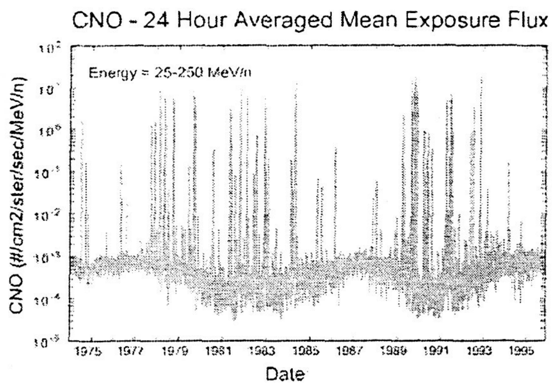

Fig. 2: IMP-8 measurements of interplanetary ions from the C-N-O group. Note the solar particle event spikes superimposed on the lower level, slowly varying galactic cosmic rays.

2.5 *The Earth's Magnetosphere*

The Earth's magnetosphere is a cavity formed by the interaction of the Earth's magnetic field and the solar wind. In the absence of the solar wind, the Earth's magnetic field would be shaped like the field of a bar magnet; non-varying, nearly symmetric about the magnetic axis, extending outward to long distances, and open at the poles. The bar magnet representation is accurate up to altitude of 4 to 5 Earth radii. The solar wind plasma, with its embedded solar magnetic field, compresses the geomagnetic field until there is balance between the magnetic pressure from the Earth and the momentum pressure from the solar wind forming a "bow shock". On the dayside, during moderate solar wind conditions, the magnetosphere terminates at the magnetopause at ~10 Earth radii altitude. At the location of this "collisionless" shock, the solar wind plasma cannot penetrate deeply into the geomagnetic field because of its charged particle composition. In fact, 99.9% of the solar wind particles pass around the Earth's magnetosphere. The flow of the solar wind around the flanks of the magnetopause stretches the geomagnetic field in the anti-solar direction into a long tail of up to ~300 Earth radii altitude. Some tail field lines are not closed and are connected to the solar magnetic field embedded in the solar wind.

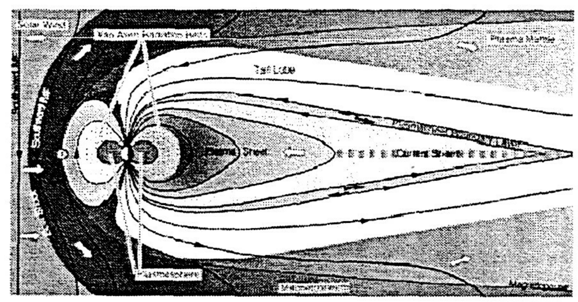

Fig. 3: The Earth's magnetosphere, diagram adapted from T. W. Hill by P.H. Reiff

The magnetosphere is filled with plasma that originates from the ionosphere and the solar wind. The plasmasphere is at low and mid latitudes in the inner magnetosphere, and the plasma sheet resides in the magnetotail. Overlapping the plasmasphere and the plasma sheet are the high-energy radiation belts or Van Allen belts (named for their discoverer, James Van Allen). Charged particles become trapped because the Earth's magnetic field constrains their motion. They spiral around the field lines in a helicoidal path while bouncing back and forth between the magnetic poles. Superimposed on these spiral and bounce motions is a longitudinal drift of the particles.

The Van Allen belts consist of protons, electrons and heavier ions. The trapped electrons have energies up to 10s of MeV, and the trapped protons and heavier ions have energies up to 100s of MeV. These particles have complex spatial distributions that vary by several orders of magnitude depending on orbit inclination and altitude. The sun is a driver for long and short-term variations in the locations and levels of trapped particles. A feature of the Van Allen belts is the South Atlantic Anomaly (SAA). The 11° angle between the magnetic and geographic axes and the offset of the geographic and geomagnetic centers of the Earth cause a depression in the magnetic field in the South Atlantic. This magnetic field sink causes charged particles to be trapped at low altitudes (<1000 km) in that region thereby forming the SAA.

2.6 *Earth's Thermosphere*

The Earth's atmosphere is composed of complex layers of matter that are loosely defined by their dominant constituents. Starting from the surface of the Earth, the layers are the troposphere, stratosphere, mesosphere, the neutral thermosphere, and the charged thermosphere (ionosphere). The layers overlap and form a connected system. Low altitude spacecraft (< 800 km) are exposed to the environments of thermosphere.

The neutral thermosphere, the neutral portion of the Earth's atmosphere at 90 to 600 km altitude above the surface of the Earth, is primarily composed of neutral gases. In the lower thermosphere, the neutral population is dominated by atomic oxygen and by hydrogen and helium in the higher thermosphere. The distribution of the thermosphere neutral gases varies with solar activity because of heating caused by absorption of solar extreme ultraviolet radiation (EUV). A proxy commonly used for EUV is the 10.7-cm radio flux (F10.7).

The Earth's charged thermosphere (ionosphere) is the electrically charged portion of the upper atmosphere from 100 to 800 km altitude. The ionosphere is characterized by a low energy (eV), high-density plasma. The ionosphere plasma varies with changes in altitude, latitude, magnetic field strength, and solar activity.

3. EFFECTS ON SPACECRAFT

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 due to 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 (Barth *et al.*, 2003)) and the ensuing problem of shortened spacecraft lifetimes emphasized the degradation problems associated with the trapped particle environment.

Dramatic advancements in technology have enabled the exploration and utilization of space. However, to meet mission requirements, spacecraft are increasingly complex and the technologies that meet requirements are increasingly sensitive to environment effects and/or have responses that are difficult to quantify. For example, the demand for commercial microelectronics reduces the availability of components hardened for space environments. Also, the need to design lighter and more complex spacecraft structures pushes the development of exotic materials for space use.

Table 1 gives some of the common environment induced effects on spacecraft and the environments that cause them. These effects are described in more detail below.

Table 1: Spacecraft Effects

Effect	Consequence	Space Environment
Total Ionizing Dose	Performance degradation, Loss of function, Loss of mission	Trapped and solar protons, Trapped electrons
Non-ionizing Dose	Degradation of optical components and solar cells	Trapped and solar protons, Trapped electrons, Neutrons
Surface Erosion	Changes in thermal, electrical, and optical properties	Ultraviolet, Atomic oxygen, Particle radiation, Micrometeoroids, Contamination
Single Event Effects	Data corruption, Noise on images, Interruption of service, Loss of spacecraft	GCR ions and solar particles, including protons, Neutrons
Surface Charging	Biasing of instrument readings, Power drains, Physical damage	Dense, cold plasma, Hot plasma
Deep-dielectric Charging	Electrical discharges causing physical damage	High-energy electrons
Impacts	Structural damage and decompression	Micrometeoroids, Orbital debris
Drag	Torques, Orbital decay	Neutral thermosphere

3.1 *Total Ionizing Dose*

Total ionizing dose (TID) is a cumulative effect which causes degradation of microelectronics and materials. As TID accumulates, parametric degradation occurs, degrading performance, and components can eventually fail to function. TID is caused by exposure to electrons and protons. Some technologies are hardened to TID effects through specialized processing. However, shielding is often used to mitigate the effects of TID on unhardened components. Fig. 4 is a plot of total ionizing dose in krads of silicon as a function of aluminum shield thickness for various orbits around the Earth. The two curves in the lower half of the graph are for LEOs that pass through the SAA. The curves that are higher on the graph are orbits that pass through more intense regions of radiation that are at higher altitudes in the belts. At > 300 mils (7.6 mm) of shielding, highly energetic trapped protons dominate the dose levels.

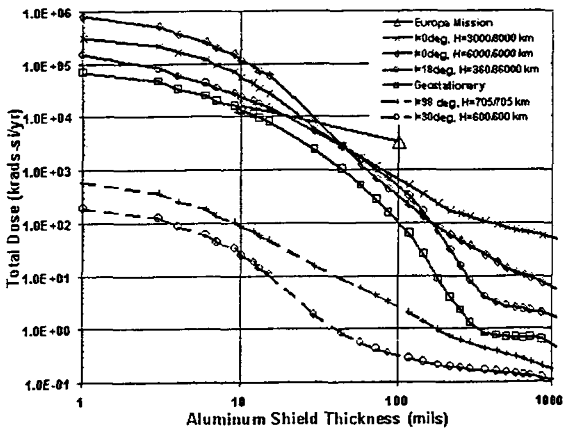

Fig. 4: Total ionizing dose-depth curves for various orbits around the Earth

Low-energy ionizing particles also degrade surface materials. This will be discussed in more detail in Section 3.3.

3.2 *Non-ionizing Dose*

Non-ionizing dose (also known as displacement damage or bulk damage) is another cumulative degradation effect. As particles slow down in material and come to rest, they knock atoms out of their lattice location creating defects which increase the resistance of the device changing its electrical properties. Electrons, protons, and neutrons cause non-ionizing dose, and the energy spectra of the particles are used to evaluate the level of the hazard.

Non-ionizing dose degrades the performance of solar cells, detectors in focal plane arrays (e.g., charge coupled devices), optocouplers, and optical lenses. It is difficult to harden against non-ionizing dose with processing techniques, therefore, the use of shielding and planning for "graceful" degradation is used to mitigate its effects. Systems sometimes employ shutters to close during times of exposure to high levels of particles while on orbit. As with TID, particles in a broad energy range must be considered when evaluating non-ionizing dose. 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.

3.3 *Surface Erosion*

The degradation of spacecraft materials is a complex problem because all space environments impinge upon surfaces and act synergistically. Surface material degradation is severe problem in very low earth orbits due to the presence high levels of atomic oxygen at 200 to 400 km. The erosion of surface materials causes changes in thermal, mechanical, and optical properties. Micrometeoroid impacts, sputtering, UV exposure, contamination, and ionizing radiation can aggravate these effects. In MEO environments, where the levels of low-energy trapped particles are extremely high, material degradation is difficult to assess because the accuracy of the trapped particle models is unknown.

Optical emissions generated by excitation of metastable molecules can also cause spacecraft glow. The surface acts as catalyst, therefore, the effect is material dependent.

3.4 *Single Event Effects*

Modern microelectronic systems are plagued by the effects of single particle strikes on sensitive regions of devices, namely single event effects (SEEs). The consequences of SEEs in systems range from loss of data to the loss of a spacecraft. SEEs are caused by GCR ions, particles from solar events, trapped protons, and neutrons that are generated in the atmosphere and in shielding materials.

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, and detectors. 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.

Fig. 5 shows the geographic location of single event upsets (SEUs) or "bit-flips" on the SEASTAR satellite (98° inclination, 705 km altitude) flight data recorder (FDR) on a world map of latitude versus longitude. Trapped protons in the SAA cause the concentration of SEUs near South America. In fact, the location of the SAA protons is clearly mapped out by the upsets. The SEUs that occur in the polar regions are due to galactic cosmic rays and solar particles which, at high latitudes, have access to low altitudes due to the open magnetic field at the poles. Fig. 6 plots the daily average SEU rates on the SEASTAR FDR. The rates are normally dominated by passes through the SAA. However, particles accessing polar regions during solar events are responsible for sudden increases in SEU rates. Less noticeable is the slow decrease in average daily rates. This is due to depletion of SAA protons from increased heating of the atmosphere during solar maximum.

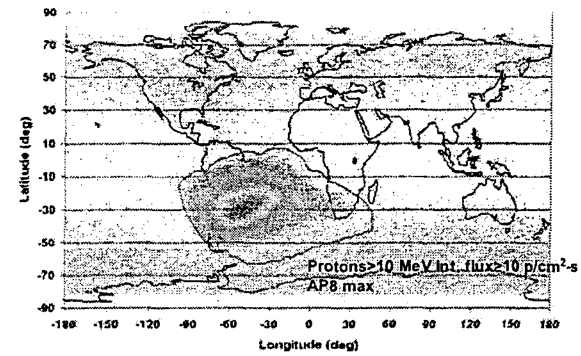

Fig. 5: SEUs on the SEASTAR flight data recorder at 705 km altitude clearly show the location of trapped protons in the South Atlantic Anomaly

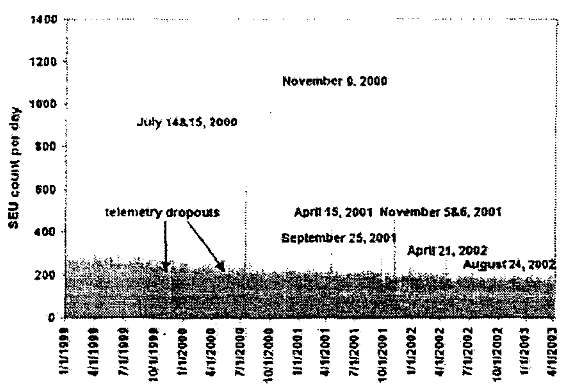

Fig. 6: Large increases in daily SEU rates are observed during solar particle events. The gradual decrease in rates is due to the depletion of SAA protons during solar maximum.

SEU 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 (SETs), single event functional interrupts (SEFIs), and multiple bit upsets (MBUs). 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.

While shielding is commonly used to partially reduce dose effects, it is not effective for mitigating SEEs because it is not practical to shield out the very high-energy particles that cause SEEs.

3.5 Spacecraft Surface Charging & Deep-dielectric 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. Geomagnetic substorms in the magnetotail plasma sheet can create "hot plasmas" which are injected into near-Earth regions of the magnetosphere.

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 Baker (2001).

Missions strongly affected by storm injections are those in GEOs, GTOs, and MEOs. Conditions for the charging effects are large differentials, large fraction of total flux, darkness, and large spacecraft. Satellites at GEO have also measured strong local time effects on the rates of spacecraft charging with most occurring as the satellite passes into the dawn sector.

Spacecraft in LEOs that have high orbital inclinations can experience charging in auroral regions during solar storms. Also, supersonic spacecraft motion through background ions in the ionospheric plasma regions can cause solar array coupling to the plasma causing current drain on solar arrays.

3.6 *Impacts*

Meteoroids and orbital debris are a threat to spacecraft by causing structural damage and decompression, hypervelocity impacts from larger particles, surface erosion from collisions with smaller objects, and surface effects that cause changes in thermal, electrical, and optical properties. Mission risk factors include increased duration, increased vehicle size, vehicle design, solar cycle, orbit altitude, and inclination, and the threat is highly directional. Koontz *et al.* (2002) give examples of micrometeoroid and orbital debris impacts on the International Space Station (ISS).

3.7 *Spacecraft Drag*

Atmospheric drag affects spacecraft in LEOs where they pass through the relatively dense neutral particles in the thermosphere. Drag results in altitude decay and torques. It causes spacecraft to slow, lose altitude, and finally reenter the atmosphere. Drag is a function of the density of the neutral gas, hence is strongly affected by solar activity induced changes in the neutral densities. The impact of solar storms on the Earth's atmospheric density often causes sudden changes in the location of tracked objects. Fig. 7 is a plot of the number of objects that were lost after a large magnetic storm in March of 1989.

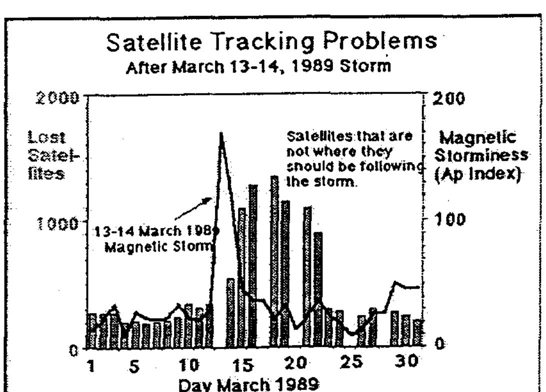

Fig. 7: A plot of the number of tracked objects lost after a large magnetic storm

4. MITIGATION OF EFFECTS

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.

Table 2 reviews the approaches commonly used to mitigate space environment effects. The challenge is to maintain the balance between meeting mission requirements, cost, and reliability.

Table 2: Spacecraft Effects and Mitigation

Effect	Mitigation
Total Ionizing Dose	Selection of hardened components, Shielding
Non-ionizing Dose	Selection of hardened components, Shielding, Plans for degradation, Close shutters
Surface Erosion	Selection of materials
Single Event Effects	Selection of components, Error correction, Watch-dog timers, Current limiters, Operational "workarounds"
Surface Charging	Grounding, Material selection, Operational "workarounds"
Deep-dielectric Charging	Shielding, Grounding, Material selection, Circuit protection
Impacts	Shields, Material selection, On-orbit maneuvers
Drag	Fuel consumption estimates, re-boosts, Relocation

4.1 *Risk Assessment*

Spacecraft reliability assured without using preventative measures throughout the mission life cycle, i.e., in concept, planning, design, launch, operations, and anomaly resolution phases. Note that in Table 2 all effects require mitigation measures that start in early mission phases. The pre-launch phases are the most effective time to prevent anomalies because technology selection and system design techniques can be used to minimize risk. However, 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 countermeasures for spacecraft operators and instructing the operators on how to use them effectively.

Space environment definition needs change dramatically as the mission passes from risk minimization to risk management modes, i.e., from pre-launch to launch and operations. Fig. 8 clearly shows the important role that space climate and space weather models play in increasing reliability.

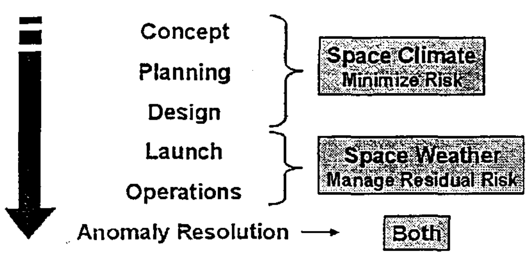

Fig. 8: Phases of mission development which require space environment models. Different models are required for each mission phase.

4.2 *Space Environment Definition - Pre-launch*

Space environment models that are used in pre-launch phases of mission development need to specify the environment, i.e., they describe the space climate in which the spacecraft must operate over its lifetime. Below is a description of the factors that are taken into account during pre-launch and the space environment information that is required to develop design accommodations.

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. Mission planning and design phases require similar environment information. 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).

4.3 *Space Environment Definition - Launch and Operations*

Good engineering practice is not a guarantee of a spacecraft that is 100% free from vulnerabilities from the space environment. As mentioned 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 during space storms. Therefore, launch and operation phases require models that can forecast changes in levels of the space environment due to 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 the energy range.

4.4 *Space Environment Definition - Anomaly Resolution*

If an anomaly occurs, it is critical to be able to restore a space-based system to normal operations quickly regardless of the service provided by the system. 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.

4.5 *Model Requirements Summary*

Table 3 summarizes the characteristics that models need to have to be useful for space environment mitigation.

Table 3: Summary of Models

Mission Phase	Characteristics of Models
Pre-launch "Climate" Models	Levels throughout the solar cycle, Spatial resolution, Worst-case environments Time distributions of changes in levels due to solar activity, Confidence levels, Broad energy range
Launch & Operations "Weather" Models	Forecasts specific to the region, Forecasts specific to particle population, Energy range information, Quiet-time forecasts
Anomaly Resolution "Climate" and "Weather" Models	Time specific, Location specific, Environment component relevant to the effect, Energy spectrum of environment component

5. SUMMARY

Space environment models play a crucial role in developing reliable spacecraft throughout the mission life cycle. Model requirements change dramatically when a mission moves from pre-launch phases to launch and operations. 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 minimizing risk in pre-launch phases of missions.

Unknowns in space environments and effects translate directly into large design margins because of the need to reduce risk. Design margins increase overhead on systems, reducing capability, and can preclude the use of newer technologies in spacecraft systems.

In spite of the central role that models play in spacecraft design and operations, development of both space climate and space weather models lags behind the increase in the complexity of space systems and our dependence on space-based assets.

REFERENCES

Baker, D.N., Space Storms and Space Weather Hazards, Chapter 11, Satellite anomalies due to space storms, Kluwer Academic Publishers, 2001.

Barth, J.L., 1997 IEEE NSREC Short Course, "Applying computer simulation tools to radiation effects problems, Section II: Modeling space radiation environments," 21 July 1997, Snowmass Village, Colorado.

Barth, J.L., C.S. Dyer, and E.G. Stassinopoulos, Space, Atmospheric, and Terrestrial Radiation Environments, IEEE Trans. on Nucl. Sci., June 2003.

Dyer, C.S., 1998 IEEE NSREC Short Course, "Radiation effects in the new millennium – Old realities and new issues, Section II: Space radiation environment dosimetry," July 20, 1998, Newport Beach, California.

Gussenhoven, M.S., E. G. Mullen, and D. H. Brautigam, "Improved Understanding of the Earth's Radiation Belts from the CRRES Satellite," IEEE Trans. on Nucl. Science, Vol. 43, No. 2, April 1996.

Koontz, S.L., M. Pedley, R. R. Mikatarian, J. Golden, P. Boeder, J. Kern, H. Barsamian, J. I. Minow, R. L. Altstatt, M. J. Lorenz, B. Mayeaux, J. Alred, C. Soares, E. Christiansen, T. Schneider, and D. Edwards," Materials Interactions with the Space Environment: International Space Station - May 2000 to May 2002," Proc. from the 6th International Conference on Materials and Structures in Space Environments, June 2002.

Mazur, J., 2002 IEEE NSREC Short Course, "Radiation effects - from particles to payloads, Section II: The radiation environment outside and inside a spacecraft," July 15, 2002, Phoenix, Arizona.