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PREFACE

Since the advent of the electrical telegraph about 170 years ago, human technologies have greatly expanded in type and in purpose for civilian, commercial, and national security uses. These include electrical grids, pipelines, radar, wireless signaling, navigation, flying spacecraft, and telephony: technologies that cross continents, oceans, and now space. Regardless of specific application, successful operational use of these technologies has determined that compelling needs exist to take into account Sun and Earth space phenomena and processes in both design and implementation. Increasingly sophisticated technical systems require increasingly detailed understanding of solar and terrestrial space phenomena. Achieving this detailed understanding has been aided by the access to space provided by reliable launch vehicles, and by ever more sophisticated instrumentation deployed to measure Earth's space environment. The data acquired can be incorporated into ever better models to describe and even forecast the environment and its changes. This volume contains nine chapters, written by experts, describing current-day technologies and how solar and terrestrial space processes can affect them. Without these technologies, contemporary life in civil, commercial, and national security realms would be very different, and arguably impossible. One chapter in this volume outlines a number of issues related to human survival in the space radiation environment inside and outside Earth's magnetosphere. An epilogue closes by looking to the future in this broad area of applied geophysics. As the historical record demonstrates, despite specific qualities such as form and function, there is a high likelihood that some electrical technologies yet to be implemented or invented will always require design features whose goals are to ensure successful operations under all levels of solar and terrestrial conditions. The study of these environmental conditions in both basic and applied form will thus remain essential for the future.

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Introduction: Space Weather Underlies Reliable Technologies

Louis J. Lanzerotti[1], Philip J. Erickson[2], and Anthea J. Coster[2]

Descriptions and understandings of the space environment around Earth have grown exponentially over the centuries since William Gilbert described the Earth as a "great magnet" in his classic book *De Magnete* (1600). Gilbert used a model Earth, called a terrella, in his work, and studied several aspects of what can be called "electricity," including static electricity using amber because of its attractive properties. The invention of the telescope concept by Hans Lippershey and the use of the telescope by Galileo Galilei for astronomical (and thus space environment) purposes (including studies of the Moon and Jupiter's four major moons) occurred in the decade following the publication of *De Magnete*.

Initial use of electrical phenomena for practical purposes by humans can perhaps be attributed to the development of the lightning rod in about 1749 by Benjamin Franklin, and of the telegraph system patented in 1837 by Samuel F. B. Morris. The telegraph system revolutionized long-distance communications for personal, commercial, and military purposes. The long grounded wires of the first telegraph systems in the eastern United States and in western and southern Europe formed the detector arrays that first gave evidence of the coupling of Earth's space environment to human technologies. The engineering superintendent of the Midland Railway Company, William Henry Barlow, first documented "spontaneous" currents in the electrical circuits of railway telegraph systems (Barlow, 1849). His data, purposefully taken over a two-week period to study the subject, showed clear diurnal variations in the electrical currents. Barlow also wrote that "in every case which has come under my observation, the telegraph needles have been deflected whenever aurora has been visible."

The large geomagnetic storm that occurred following the discovery by amateur solar astronomer Richard Carrington of the first white light solar flare on 1 September 1859, caused havoc in the telegraph systems of Europe and the U.S. (Prescott, 1866). One example of the havoc of this singular "Carrington event" was that for lengthy intervals the telegraph between Boston and Portland, Maine, could be operated solely on the basis of the "spontaneous" electrical currents flowing in the wires; batteries were not needed at each end of the telegraph line to send messages. Disruptions of telegraphic communications occurred in systems in the U.S. and Europe throughout the extensive geomagnetic storm interval of 1–2 September 1859.

It seemed clear that there was some type of significant coupling between Sun and Earth (including the generation of aurora) and the telegraph systems. But no authorities had any insight of what such couplings might be. Debate waged in the scientific and engineering literatures for several decades in the late 19th century. Indeed, an authority with the eminence of Lord Kelvin (William Thomson), whose analysis work was key in the implementation of the first trans-Atlantic cable, argued in his presidential address to the Royal Society in 1892 that such Sun–Earth coupling was not physically possible (Kelvin, 1892).

Since the days of the advent of the electrical telegraph about 170 years ago, human technologies have greatly expanded in type and in purpose for civilian, commercial, and national security uses. Many of these important contemporary technology developments are illustrated in the figure. These depicted elements, relied on heavily by current society, must by necessity take into account phenomena and processes in Sun and near-Earth space for their design, implementation, and ultimate successful operations. Since the time of the telegraph, several additional

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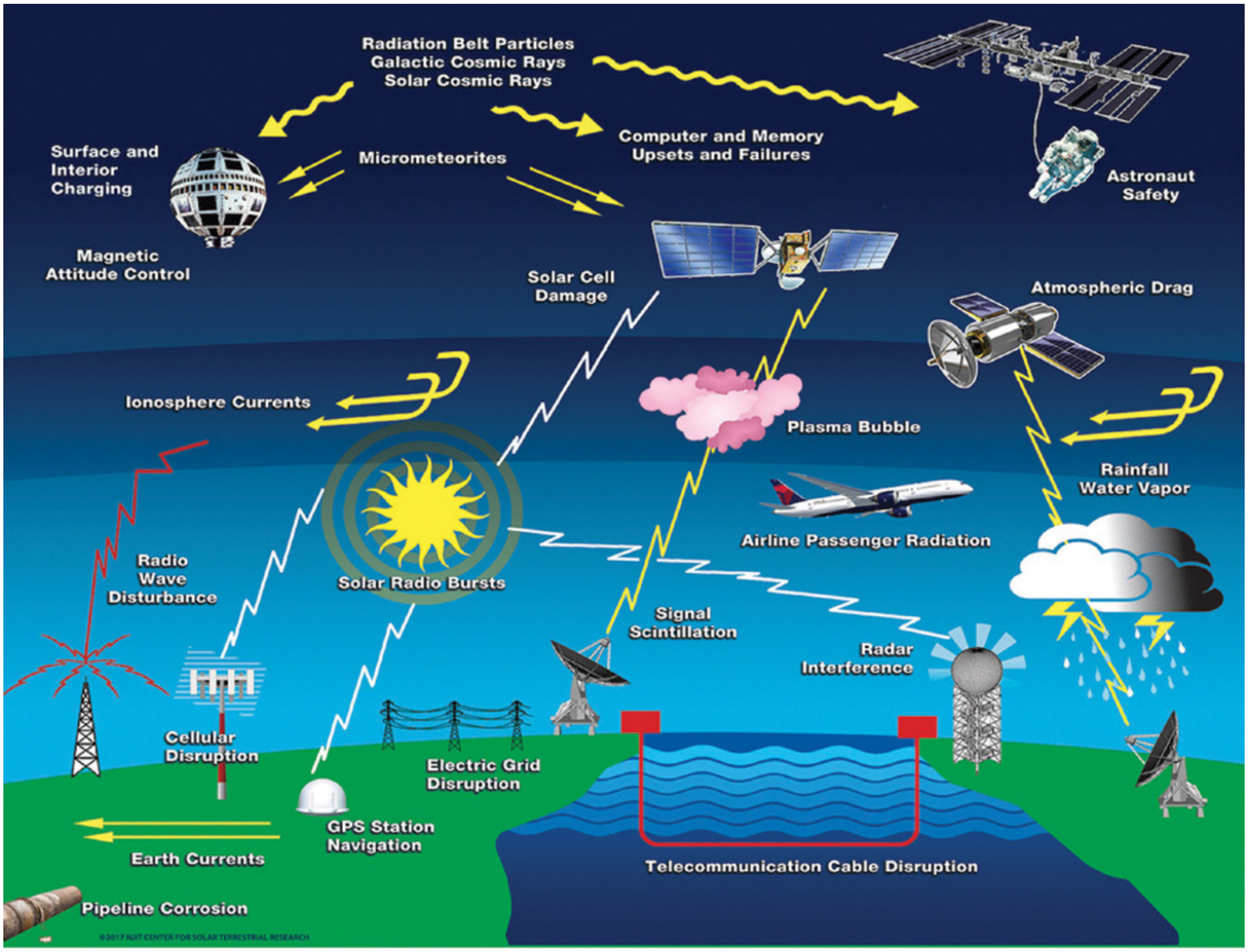

technologies have developed that use long conductors and are therefore susceptible to induced ground currents. These include electrical grids, pipelines, and telephony, both continental and transoceanic.

Successful operations of increasingly sophisticated technical systems require increasingly detailed understanding of solar and terrestrial space phenomena. This has been accomplished by the access to space provided by increasingly reliable launch vehicles since the late 1950s. Ever more sophisticated instrumentation has been deployed to measure Earth's space environment. The data acquired can be incorporated into ever better models to describe and even forecast the environment and its changes. This also has the complementary result of better understanding the effects of the environment on contemporary technologies.

This volume was designed to provide a topical discussion of current day technologies and how they are affected by solar and terrestrial space processes. Without these technologies, contemporary life in civil, commercial, and national security realms would be very different, and indeed impossible. Access to space has also meant that humans can now live, with appropriate support systems, above the sensible atmosphere. Thus, a closely related topic, also covered in this volume, involves the many issues related to human survival in the space radiation environment inside and outside Earth's magnetosphere. These issues deserve serious consideration prior to the planning and execution of projects involving a significant human presence in interplanetary space.

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1

Effects of Space Radiation on Contemporary Space-Based Systems I: Single Event Upsets, Spacecraft Charging, Degradation of Electronics, and Attenuation on Fiber Cabling

Daniel N. Baker[1] and Michael Bodeau[2]

ABSTRACT

Exposure of space systems to solar energetic particles, galactic cosmic rays, and radiation belt fluxes can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers. Moreover, intense solar particle events present a significant radiation hazard for astronauts during the high-latitude segment of the International Space Station orbit as well as for future human exploration of the Moon and Mars. In addition to such direct effects as spacecraft anomalies, a thorough assessment of the impact of space radiation on present-day space operations must include the collateral effects of space-weather-driven technology failures. For example, space radiation can degrade and, during severe events, completely incapacitate various communication and reconnaissance platforms. A complete picture of the impact of space radiation must include both direct as well as collateral effects of incapacitation on susceptible space structures and systems. It is also imperative that we as a technological society develop a truly operational understanding of space radiation in which the benefits of accurate forecasts are clearly established.

1.1. INTRODUCTION

Space systems on which modern society depends mostly operate in the region from altitudes of a few hundred km to ~40,000 km above Earth's surface. This region is filled with various populations of energetic particles. The fact that the Earth is surrounded by belts of very energetic protons and electrons was the first major discovery of the space age in 1958 (see Van Allen et al., 1958, 1959). From the initial realization that the terrestrial magnetic field could "trap" high-energy particles, today there is a much more complete understanding of what are now called the Van Allen radiation belts. There has long been awareness of high-energy solar and galactic cosmic rays as well.

More or less from the beginning of the space age, it was realized that intense populations of penetrating particles could be quite damaging to electronic systems in space (see Gombosi et al., 2017). There also were concerns about spacecraft structural materials and human space travelers (Van Allen, 1966). Thus, from the earliest days, it was realized that the terrestrial space environs were a problem to be reckoned with when it came to flying robotic and human missions in near-Earth regions.

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Today it is recognized that space radiation is one of the most pervasive and concerning threats that constitute what we comprehensively term *space weather* (Baker & Lanzerotti, 2016).

This chapter is intended to provide a brief overview of space radiation sources and their effects. Related impacts are treated in the companion chapter by Bodeau and Baker (chapter 2, this volume). A second goal of this chapter is to describe from an operational perspective the implications of radiation damage to systems in various parts of the geospace domain. In providing such a brief survey, the goal is to characterize in a succinct way the increasing importance of radiation damage on emerging technological systems.

1.2. OVERVIEW OF SPACE RADIATION PROPERTIES

Much of the concern for operational space systems arises from the Earth's radiation belts. A modern view of the radiation belts derived from the Van Allen Probes observations of Baker et al. (Baker, Kanekal, Hoxie, Henderson, et al., 2013) is shown here as Figure 1.1. Closest to the Earth's surface is the inner Van Allen belt. This belt extends from just above the dense atmosphere out to an equatorial altitude of about 10,000 km above the Earth's surface. The inner Van Allen belt is comprised dominantly of very energetic protons (ranging up to multiple GeV energies). Recent results demonstrate that protons with energies from ~10 MeV to ~100 MeV are quite stable in time near the geocentric radial distance of r ~ 1.5R_E (Earth radii = 6372 km), at which the inner zone proton fluxes peak. However, an outer "shoulder" of the radial distribution from $1.7 \leq r \leq 2.5$ R_E shows tremendous temporal variability for protons with $E \leq 60$ MeV. These variable proton fluxes are probably due primarily to evolution of trapped solar energetic protons (Selesnick et al., 2014).

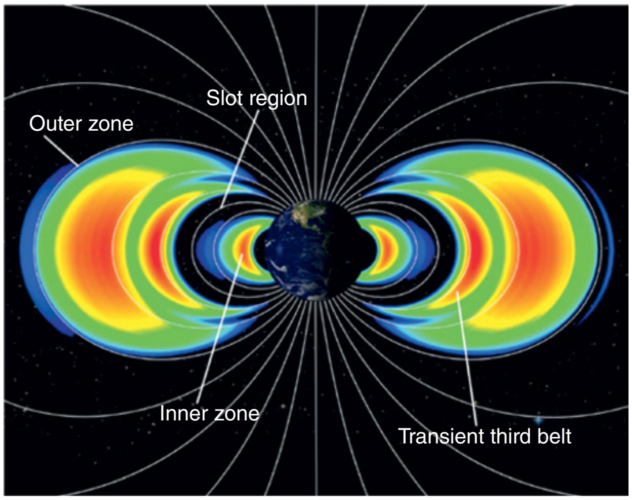

Figure 1.1 A modern-day view of the Earth's radiation belts as observed by the Van Allen Probes mission. (Adapted from Baker, Kanekal, Hoxie, Henderson, et al., 2013.)

The inner Van Allen belt also has copious fluxes of low-and medium-energy electrons (Fennell et al., 2015; Li et al., 2015) as revealed by Van Allen Probes and other spacecraft data sets (Baker, Kanekal, Hoxie, Batiste, et al., 2013). However, the Van Allen Probes era (September 2012–present) has provided many new discoveries about inner magnetospheric ultrarelativistic electrons with energies $E \gtrsim 5$ MeV. In particular, initial results after major storm intervals have shown essentially no detectable prompt ultrarelativistic electron fluxes in the region $r \leq 2.8$ R_E (Baker et al., 2014). The paucity of very energetic electrons in the inner magnetosphere immediately following major magnetic storms is quite striking (Foster, 2016; Baker et al., 2016) with a fascinating dependence on plasmasphere conditions before the storm and perhaps even on in-situ radio signals of terrestrial origin (Foster et al., 2016). The consequences of this energetic electron paucity for space radiation effects will be discussed further in this chapter.

The space weather concerns for the inner radiation zone are several. The intense, high-energy trapped protons are extremely damaging to space systems (Vette et al., 1966) and are quite hard to shield against. There are also more variable, trapped solar energetic ions in the inner zone that can cause dose and single-event effects (see Lorentzen et al., 2002; Baker, 2002). The hazardous proton populations of the inner zone and slot regions have two fundamental sources. In the inner zone, the primary source is the neutron albedo decay process, which has been well defined (Selesnick et al., 2007, and references therein). The outer edges of the inner zone and the lower part of the slot region also host energetic protons and ions that consist of entrained solar particles (Mazur et al., 2005; Selesnick et al., 2007). The inner zone also has trapped galactic cosmic rays (see Klecker et al., 1995; Cummings et al., 1993). Finally, the trapped energetic electrons with $E \leq 1$MeV (Claudepierre et al., 2017; Fennell et al., 2015) also represent a further significant source causing total dose effects.

The so-called "slot region" of the radiation belts extends from roughly L ~ 2.0 to L ~ 3.0 depending on particle energy and species. (L is the geocentric distance in Earth radii at which a dipole magnetic field line crosses the magnetic equatorial plane.) The slot is a region often relatively devoid of energetic electrons. However, during strong geomagnetic storm periods, the gap between the inner and outer zone can be filled to a large degree by moderate (and even high) energy electrons (Fennell et al., 2005). For example, in the intense "Halloween" storm period of late October and November 2003, the slot region was filled with multi-MeV electrons for several weeks (Baker et al., 2004). Thus, the slot region can present several space weather concerns including low- and medium-energy electron enhancements, multi-MeV electrons (on rare occasions), and strong solar energetic particle events (again on relatively rare occasions).

Finally, the outer Van Allen radiation belt represents in many ways the most pervasive space weather risks to operating spacecraft. The outer radiation belt is broad in spatial extent (from $r \sim 3R_E$ to $r \gtrsim 6.5\ R_E$). It is comprised of mildly to highly energetic electrons (~100keV to $\gtrsim$10 MeV) and varies widely in particle intensity. Commercial, military, and scientific satellites operating in medium-Earth orbit and geostationary Earth orbit number in the multiple hundreds worldwide. All of these operating spacecrafts are subject to outer Van Allen belt space radiation impacts.

Obviously, from the above brief description it is clear that the space radiation environment can cause a wide variety of impacts on space systems. Having a deeper understanding of radiation properties including dynamics and temporal trends is crucial for our technological society. This chapter describes the current knowledge of these space radiation aspects.

1.3. SPACE RADIATION EFFECTS

Figure 1.2 shows a schematic diagram of a representative spacecraft presumed to be at some location within the Earth's space environment. At high altitudes, such a spacecraft would be subject to a variety of space effects. Both solar energetic particles and trapped energetic protons can cause significant energy deposition for sensitive electronics on board a given spacecraft. Similarly, galactic cosmic ray nuclei may pass through electrical components and induce radiation degradation effects. As illustrated in Figure 1.2, these ion interactions effects are termed "single event effects." There also can be surface and deep-dielectric (bulk) charging due to energetic electrons.

The record of operating spacecraft over the space age is filled with examples of anomalies and complete satellite

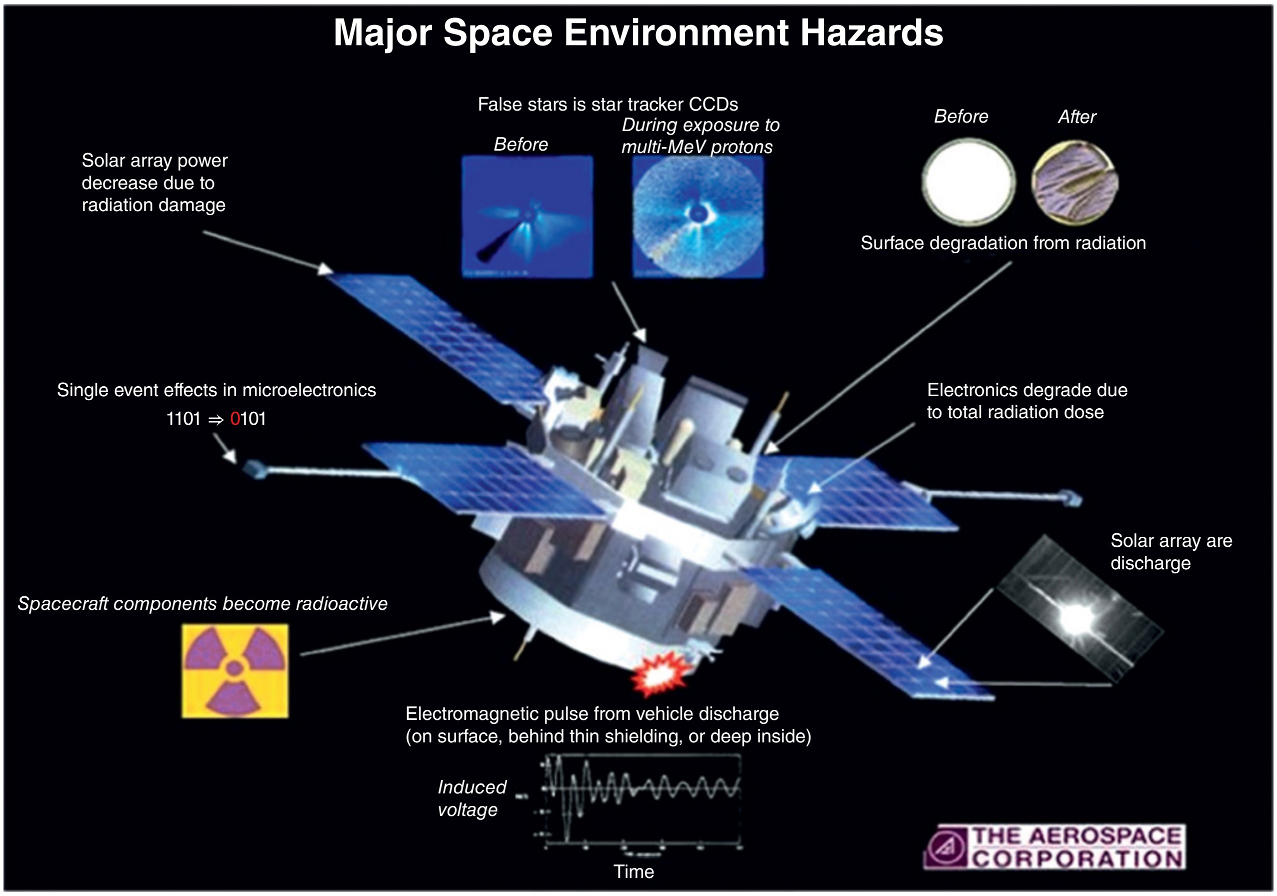

Figure 1.2 A schematic diagram showing spacecraft impacts due to the space environments including single-event ion effects, deep-dielectric charging due to high-energy electrons, and surface charging due to low-to-medium energy electrons. (Source: Aerospace Corporation.)

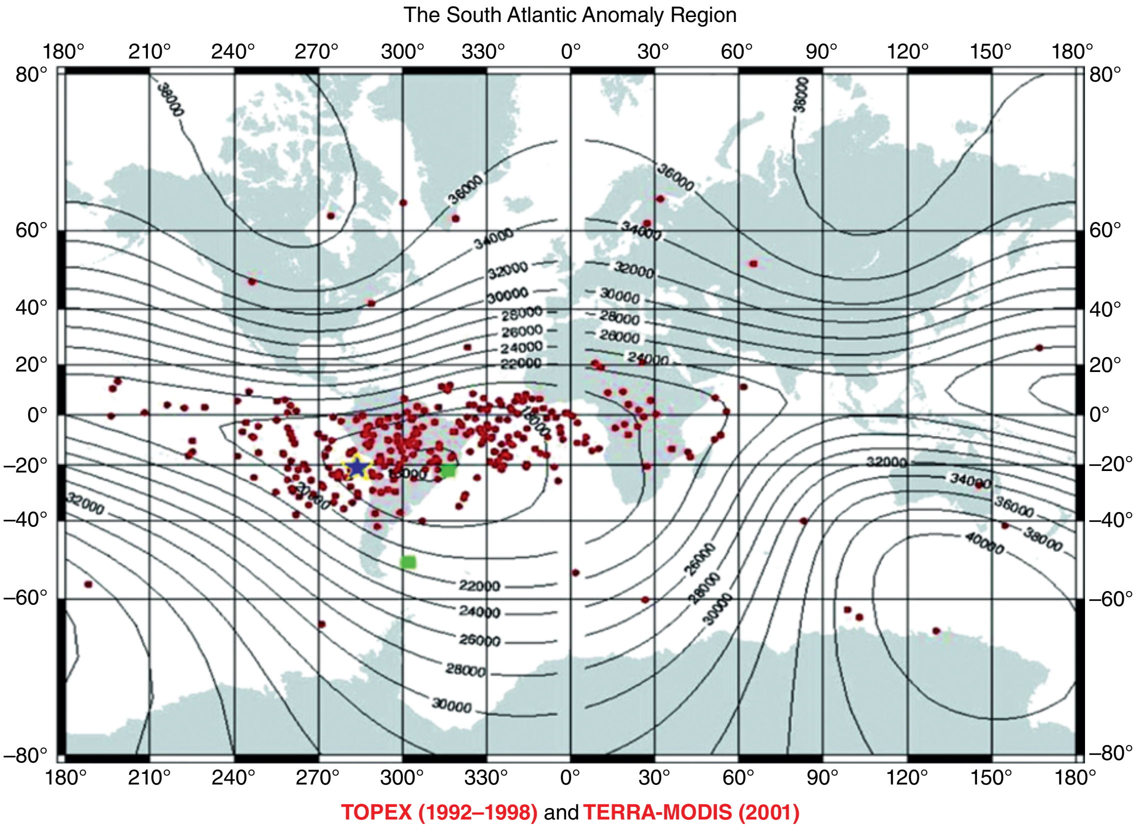

Figure 1.3 A map of the Earth showing contours of constant surface magnetic field strength. The weakest field region over South America is called the South Atlantic Anomaly. The red symbols show where significant operational anomalies occurred for the TOPEX and TERRA spacecraft.

failures due to space weather impacts (Allen, 2002). Many operational issues occur in the South Atlantic Anomaly (SAA) region, as illustrated in Figure 1.3. As shown in the diagram, the Earth's magnetic field is weakest over Brazil and eastward into the South Atlantic Ocean region. This results from the offset, tilted dipole of Earth's intrinsic magnetic field (Cain, 1966). Trapped particles mirroring along terrestrial magnetic field lines, especially high-energy protons in the inner zone, can approach closest to the Earth's surface in the weak SAA field region. Thus, this is the region where low-Earth orbit (LEO) spacecraft encounter the most intense particle radiation. Figure 1.3 demonstrates that the TOPEX (U.S./French Ocean Surface Topography mission) and TERRA (Earth Observing System-1 satellite of NASA at 705 km altitude) spacecraft suffered many electronic anomalies and upsets in the SAA (Allen, 2002), probably due to single-event effects from inner zone protons. The mechanism of single-event upsets is illustrated in Figure 1.4a.

Only the more energetic ions/protons in space are of major concern from a space weather hazard perspective. Very high energy protons and ions can penetrate shielding, depositing their energy in electronic devices. Protons with E > 3 MeV are a primary contributor to solar array degradation, while >15 MeV protons contribute to single-event effects and nonionizing radiation damage to electronic parts within satellites that orbit in or traverse these regions.

Another impact of the space environment is called deep-dielectric charging and is also noted in Figure 1.2. Electrons with energies of hundreds of keV up to multiple MeV energies may penetrate shielding and bury themselves in dielectric materials inside spacecraft. As shown by Figure 1.4b, if the buildup of buried charge is fast enough (and the leakage of charge out of the dielectric material is slow), then a powerful discharge can happen. This can severely damage materials and sensitive electronic components (see Bodeau & Baker, chapter 2, this volume).

Yet another type of space radiation impact within the Earth environment is shown in Figure 1.4c. This is called surface charging. If the space system is subject to hot plasma in its environment and photo-electrons are not able to carry away charge promptly from insulator and dielectric material (as happens in solar eclipse conditions or on the nonilluminated side of a space vehicle), there

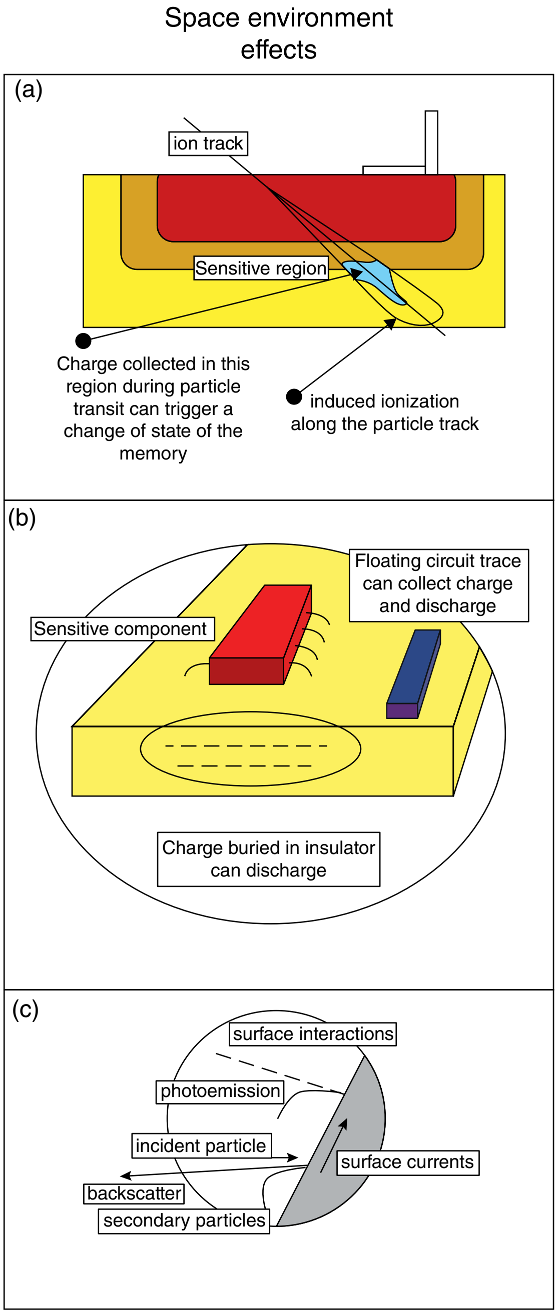

Figure 1.4 Illustration of the (a) single event upset, (b) deep-dielectric discharge, and (c) surface charging mechanisms that can cause severe spacecraft operational anomalies. (Source: Baker, 2005. Reproduced with permission from Springer Nature.)

can be a strong buildup of charge on key areas of the spacecraft surface. When the charge buildup is sufficient, a sudden discharge can result. This may produce material damage and/or a significant electromagnetic discharge around the spacecraft. Such effects cause phantom electromagnetic signals or changes of state in memory

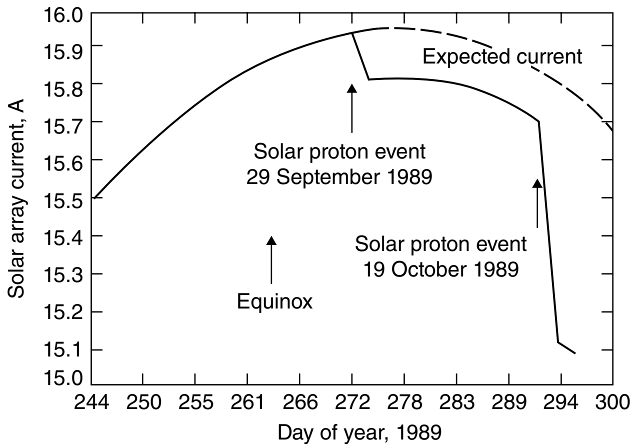

Figure 1.5 Observed solar array current reduction on a high-altitude spacecraft following solar energetic particle events over a three-week period in 1989. (Source: Marvin & Gorney, 1991); reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

systems. There can even be permanent damage to electronics (see Bodeau and Baker, chapter 2, this volume).

In addition to the trapped population, there also are episodic solar energetic particle events, with enhanced energetic solar heavy ions. Those ions that eventually reach the Earth can penetrate deeply into the inner magnetosphere. At such locations, they can cause single-event upsets and enhance the radiation damage to satellite solar arrays and electronic parts, similar to that shown in Figure 1.5 (Marvin & Gorney, 1991). The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) mission (see Baker et al., 1993) at LEO data showed multiple incidences of >15 MeV solar protons penetrating to low L combined with the presence of the protons from cosmic ray albedo neutron decay (CRAND) at very low L, and inherent variability of the proton fluxes in the $2.5 < L < 4$ region in response to magnetic storms (Mazur et al., 2005). This CRAND mechanism was the first idea put forth to explain the existence of trapped energetic particles in the magnetosphere (see Van Allen, 1983).

Solar energetic particle events are the mechanism by which very high-energy protons appear in the outer zone region of the radiation belts. However, these events are very short lived (hours in duration), as the high-energy protons with such large gyro-radii are not able to be stably trapped at these locations. As noted, they can often penetrate to the inner zone, where stronger magnetic fields in a more rigid magnetic topology can entrain these particles for long times. In general, highly energetic protons (multi-MeV energies) are not considered to be a regular feature in the outer zone (see Selesnick et al., 2014).

The characteristics and dynamics of relativistic and ultrarelativistic electron fluxes in Earth's outer radiation

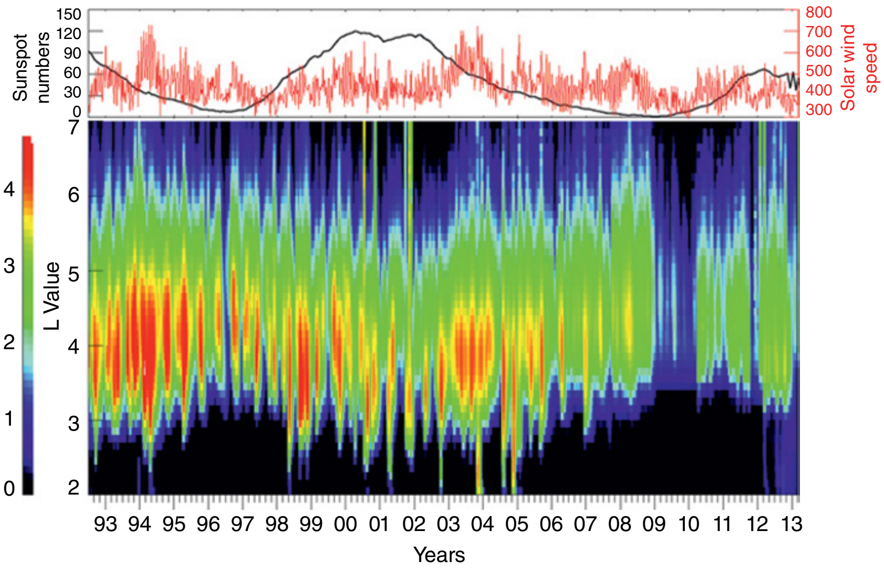

Figure 1.6 Long-term (1992–2013) record of $2 \leq E \leq 6$ MeV electrons measured primarily by the SAMPEX spacecraft at low altitude. The upper panel shows smoothed sunspot number (black) and solar wind speed (km/sec; red trace) for the same period of time (Source: X. Li.)

belt are strongly influenced by geomagnetic storm time processes. These lead both to significant electron loss and local acceleration deep within the inner magnetosphere. The outer Van Allen belt is highly variable on essentially all temporal scales and shows tremendous variability as well as significant variations in the outer belt spatial extent. This is well illustrated by Figure 1.6 adapted from Li et al. (2006). The main (lower) panel of the figure shows integral fluxes of $2 \leq E \leq 6$ MeV electrons measured by sensors on board SAMPEX. The data are color-coded representations of electron flux from L = 2.0 to L = 7.0 (vertical axis) versus time (horizontal axis) from 1992 to 2013. The color bar to the left is the log of electron flux (electrons/cm^2-s-sr). The upper panel of Figure 1.6 shows in black the smoothed sunspot number over the period 1992–2013, while the red trace shows the solar wind speed (km/sec) measured upstream of the Earth's magnetosphere.

As is evident from the figure, the outer Van Allen belt (as monitored from the ~500 km altitude of SAMPEX) typically extends from L ~ 3.0 to roughly L = 6.5. However, the belt's spatial extent was highly variable over the ~20-year SAMPEX lifetime. Also, the peak electron flux levels varied widely as a function of time. For example, in 1994, the peak >2 MeV electron fluxes were over 10^4 electrons/cm^2-s-sr, while in 2008–2009 the electron flux was often barely above background levels (~10^0 electrons/cm^2-s-sr). As is obvious from inspection of the figure, a main controller of the electron fluxes in the outer belt is the solar wind speed impacting Earth's magnetosphere (Baker et al., 1987). Indeed, solar wind speeds with V > 500 km/sec generally are associated with high outer radiation belt electron "content" (Baker, 2004). On the other hand, persistent solar wind speeds of $V \leq 300$ km/sec can lead to virtual disappearance of the outer belt (for electron energies $E \gtrsim 1$MeV). This occurred quite prominently in the profound solar minimum of 2008–2009.

The inner "edge" of the outer zone, as is obvious in Figure 1.6, shows considerable variability in spatial location. During particularly strong solar wind forcing conditions, the inward extent of the outer zone population can appear to reach down to L ~ 2.5. This is typically a rare and brief circumstance. During truly extreme forcing events such as the Halloween Storm events of late 2003 (see Baker et al., 2004), the slot region can be filled with multi-MeV electrons for weeks of time. An event of great strength was also seen in late 2004 (see Figure 1.6).

It has long been clear that large increases in multi-MeV electrons can cause significant spacecraft operational anomalies. For example, Figure 1.7 (taken from Baker, 1987) shows that star-tracker anomalies were observed on an operational geostationary Earth orbit spacecraft whenever the counting rate for E ~ 3 MeV electrons reached or exceeded 7 counts/sec. The vertical arrows show the precise timing relationship between the star tracker problems and the enhanced electron flux episodes during this 1980–1982 period. Many other electron-induced anomalies have been documented over the space age (see Baker, 2005, and references therein).

A final point to note is that newer spacecraft technologies can be quite susceptible to space radiation effects. An example is fiber optic cabling that is increasingly used on

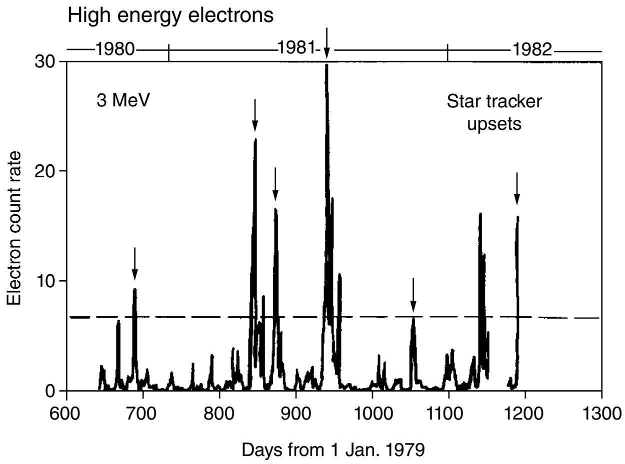

Figure 1.7 Temporal correspondence between star tracker anomalies onboard a geostationary orbit spacecraft (vertical arrows) and enhancements in E ~ 3 MeV electron fluxes measured by sensors on the same spacecraft. (Source: Baker, 1987.)

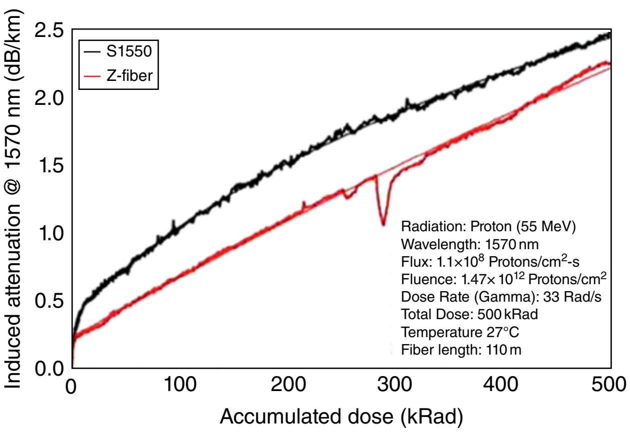

Figure 1.8 Induced attenuation of fiber optic cabling signals due to accumulated proton dose for two different types (S1500 and Z-fiber®) of material (Source: Alam, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10567/105672M/Performance-of-optical-fibers-in-space-radiation-environment/10.1117/12.2308184.full?SSO=1. Licensed under CC BY SA 4.0)

operational spacecraft. Different fiberglass materials and different designs can show substantially different induced attenuations of signals with increasing radiation dose exposure. An example is shown in Figure 1.8 from a study by Alam et al. (2006).

Figure 1.8 shows induced attenuation growth versus accumulated proton dose plots for the two fibers. S1550-HTA fiber with the higher NA (0.16) performs fairly well in comparison to Z-fiber®, which has relatively smaller NA (0.12). For both fibers, attenuation growth data can be represented well by the three-term "saturating exponentials" model (Alam et al., 2006). Solid lines in the figure represent best fit to the data. S1550-HTA shows a trend towards saturation, while Z-fiber® does not indicate any such behavior. Using the data acquired, radiation-induced attenuation of S1550-HTA fiber at room temperature and to a total accumulated dose of 50 kRad was predicted to be 1.33 dB/km and 0.76 dB/km in γ- and proton radiation environments, respectively.

1.4. DISCUSSION AND CONCLUSIONS

This chapter has reviewed evidence that galactic cosmic rays, solar energetic particles, trapped high energy particles, and magnetospheric electrons of moderate energies constitute a significant problem for the operation of spacecraft. These particle populations occur with different frequencies, and the nature of their damage mechanisms are also quite different. Certain types of spacecraft anomalies have been closely linked with environmental factors, while other classes of disruptions may or may not be related to space environmental conditions. More work needs to be done to clarify where the environment is (or is not) implicated. Also, more work is required to understand the physical nature of some disruption mechanisms in spacecraft systems.

There is an increasing physical understanding of the near-Earth space environment. This understanding is sufficient that there is even a significant predictive capability. The first line of defense for space environmental problems is good engineering design. However, systems often degrade over time, and sometimes unexpected sensitivities develop in space components. In such cases, a simple forecast of space environmental conditions may allow operators to change operational procedures, or at least be ready to recover quickly from operational problems should they occur. In yet other circumstances, it may be possible to turn off susceptible subsystems during periods of strong space environmental disturbance. Thus, we assert that accurate and reliable forecasts have great potential benefit to the operational community. In this way, space weather predictions and forecasts are a next logical step in our space environmental research efforts.

We have also shown in this chapter that long-term cumulative effects from space radiation can have a variety of severe effects. Total dose and displacement damage in electronic components and in solar power systems often spell the ultimate demise of space systems. This can be a cost driver over the entire course of a mission. For example, the possibility (or likelihood) of long-term degradation of solar array power output often forces designers to oversize the arrays. Similarly, degradation of thermal control surfaces often forces designers to oversize thermal radiator panels. This is done to be confident of end-of-life heat rejection, but then designers may have to add extra heaters which, in turn, require more solar array power. These compounding design aspects can drive the cost and complexity of space systems to extraordinary levels.

We also note that the degradation of semiconductor part performance often limits the effective operating lifetime of satellite subsystems in space. Having better knowledge of regional radiation environmental conditions would make a huge difference in accurately forecasting mission life and consequent program costs. Presumed knowledge of average space environmental conditions determine the operational regimes for spacecraft. These considerations dictate that certain orbits are not possible or cost effective to fly because of the severity of the radiation environments. We have shown in this chapter that the Van Allen Probes mission has revealed that for present, and recent, solar activity conditions, some parts of the near-Earth environment have been surprisingly benign and nonthreatening. Hence, getting the space system design right requires that we get the space environments right. This ultimately means that designers must be able to forecast with confidence what the expected fluences are for various particle populations over the course of the designed mission. Of course, there needs to be a reasonable sense of margins on these numbers because of the inherent variability of the solar-terrestrial system. This is where design and space weather climatology meet.

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