1 Introduction

This book documents engineering guidelines and design practices that can be used by spacecraft designers to minimize the detrimental effects of spacecraft surface and internal charging in certain space environments. Chapter 2 covers space charging/electrostatic discharge background and orientation; Chapter 3, design guidelines; Chapter 4, spacecraft test techniques; Chapter 5, control and monitoring methods; and Chapter 6, materials that should or should not be considered for charging control. The appendixes contain a collection of useful material intended to support the main body of the document. Despite our desire that this be an all-encompassing guideline, this document cannot do that. It is a narrowly focused snapshot of existing technology, not a research report, and does not include certain related technologies or activities as clarified further below.

In-space charging effects are caused by interactions between the in-flight plasma environment and spacecraft materials and electronic subsystems. Possible detrimental effects of spacecraft charging include disruption of or damage to subsystems (such as power, navigation, communications, or instrumentation) because of field buildup and electrostatic discharge as a result of a spacecraft's passage through the space plasma and high-energy particle environments. Charges can also attract contaminants, affecting thermal properties, optical instruments, and solar arrays; and they can change particle trajectories, thus affecting plasma-measuring instruments. NASA RP-1375, *Failures and Anomalies Attributed to Spacecraft Charging* [1], lists and describes some spaceflight failures caused by inadequate designs.

This book applies to Earth-orbiting spacecraft that pass through the hazardous regions identified in Figs. 1-1 and 1-2 [medium Earth orbit (MEO), low Earth orbit (LEO), and geosynchronous Earth orbit (GEO), with less focus on polar Earth orbit (PEO)], as well as spacecraft in other energetic plasma environments, such as those at Jupiter and Saturn, and interplanetary solar wind charging environments. Designs for spacecraft with orbits in these regions should be evaluated for the threat of external (surface) and/or internal charging, as noted. NASA RP-1354, *Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging* [2], describes environmental interaction mitigation design techniques at an introductory level.

Guide to Mitigating Spacecraft Charging Effects, First Edition. Henry B. Garrett, Albert C. Whittlesey.

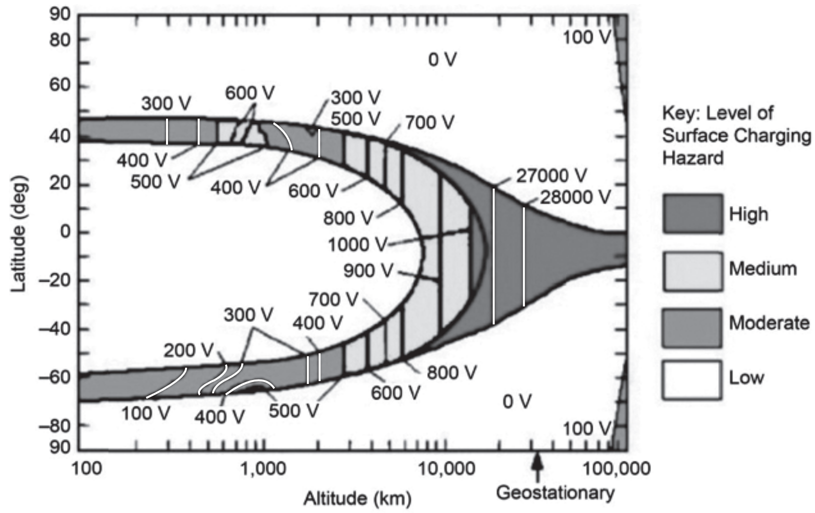

Fig. 1-1. Earth regimes of concern for on-orbit surface charging hazards for spacecraft passing through the latitude and altitude indicated. See Whittlesey et al. [9] for an alternative reference with the "Wishbone" chart. (From [8].) (*See insert for color representation of the figure*.)

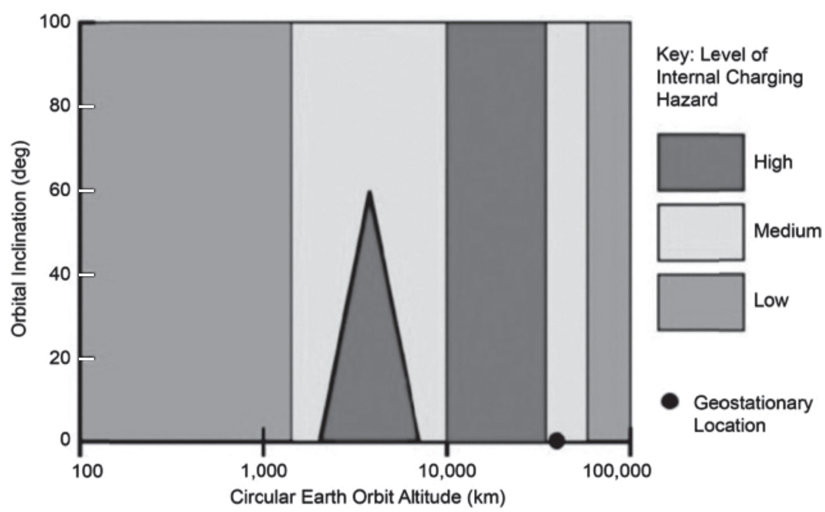

Fig. 1-2. Earth regimes of concern for on-orbit internal charging hazards for spacecraft with circular orbits. (*See insert for color representation of the figure*.)

Specifically, this book does not address LEO spacecraft charging at orbital inclinations such that the auroral zones are seldom encountered. That region is the purview of NASA-STD-4005 [3] and NASA-HDBK-4006 [4]. The book is intended to be complementary to those standards and applies to other regions.

In particular, mitigation techniques for low-inclination LEO orbits may differ from those that apply to regions covered by this book. Spacecraft in orbits, such as GEO transfer orbits that spend time in both regimes, should use mitigation techniques that apply to both regimes. It also does not include such topics as the following:

- Landed assets (e.g., lunar or Martian landers) and their electrostatic dust charging
- Spacecraft sources of charging (such as various types of electric propulsion or plasma sources)
- International Space Station (ISS)–specific design considerations (these encompass substantially different design concerns that are unique to the ISS)
- Solar-array-driven charging (see references [3,4])
- Magnetic field interactions relating to spacecraft charging (refer to tether and ISS sources for information)
- Mars-, Venus-, asteroid-, or Moon-specific charging environments (including surface charging environments)
- Plasma contactors in detail (see ISS references)
- Extravehicular activity needs (see ISS references)
- Specific design advice for pending or future projects
- Highly elliptical (Molniya) orbits

Figures 1-1 and 1-2 illustrate the approximate regions of concern for charging as defined in this book. Figure 1-1 is to be interpreted as the worst-case surface charging that may occur in the near-Earth environment. The north/south latitudinal asymmetry assumes that the magnetic North Pole is tilted as much as possible for this view. Potentials are calculated for an aluminum sphere in shadow. Note that at altitudes above 400 km, spacecraft charging can exceed 400 to 500 V, which has the possibility of generating discharges. Indeed, the Defense Meteorological Satellite Program (DMSP) and other satellites have reported significant charging in the auroral zones many times (as high as -4000 V), and one satellite [Advanced Earth Observation Satellite II (ADEOS-II)] at 800 km experienced total failure due to spacecraft charging [5–7].

Figure 1-2, which illustrates Earth's internal charging threat regions, is estimated assuming averages over several orbits since the internal charging threat usually has a longer time scale and reflects the approximate internal charging threat for satellites with the indicated orbital parameters. It is intended to illustrate the approximate regions of concern for internal electrostatic discharge (IESD).

In this book, the distinction between surface charging and internal charging is that *internal charging* is caused by energetic particles that can penetrate and deposit charge very close to a victim site. *Surface charging* occurs on areas that can be seen and touched on the outside of a spacecraft. Surface discharges occur on or near the outer surface of a spacecraft, and discharges must be coupled to an interior affected site rather than directly to the victim. Energy from surface arcs is attenuated by the coupling factors necessary to get to victims (most often inside the spacecraft) and therefore is less of a threat to electronics. External wiring and antenna feeds, of course, are susceptible to this threat. Internal charging, by contrast, may cause a discharge directly to a victim pin or wire with very little attenuation if caused by electron deposition in circuit boards, wire insulation, or connector potting.

Geosynchronous orbit (a circular orbit in the equatorial plane of Earth at about 35,786 km altitude) is perhaps the most common example of a region where spacecraft are affected by spacecraft charging, but the same problem can occur at lower Earth altitudes, in Earth polar orbits, at Jupiter, and at other places where spacecraft can fly. Internal charging is sometimes called deep dielectric charging or buried charging. Use of the word *dielectric* can be misleading, since ungrounded internal conductors can also present an internal electrostatic discharging threat to spacecraft. This book details the methods necessary to mitigate both in-flight surface and internal charging concerns as the physics and design solutions for both are often similar.

REFERENCES

[1] R. D. Leach and M. B. Alexander, Eds., *Failures and Anomalies Attributed to Spacecraft Charging*, NASA Reference Publication 1375, National Aeronautics and Space Administration, August 1995. This document has a very good list of specific space incidents that have been attributed to electrostatic discharges in space. It does not discriminate between surface charging or internal charging, but that is usually difficult to determine or does not appear in public literature.

[2] J. L. Herr and M. B. McCollum, *Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging*, NASA-RP-1354, National Aeronautics and Space Administration, 1994.

[3] D. C. Ferguson, *Low Earth Orbit Spacecraft Charging Design Standard*, NASA-STD-4005, 16 pages, National Aeronautics and Space Administration, June 3, 2007.

[4] D. C. Ferguson, *Low Earth Orbit Spacecraft Charging Design Handbook*, NASA-HDBK-4006, 63 pages, National Aeronautics and Space Administration, June 3, 2007.

[5] D. L. Cooke, "Simulation of an Auroral Charging Anomaly on the DMSP Satellite," *36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA-98-0385, January 12–15, 1998.

[6] S. Kawakita, H. Kusawake, M. Takahashi, H. Maejima, J. Kim, S. Hosoda, M. Cho, K. Toyoda, and Y. Nozaki, "Sustained Arc Between Primary Power Cables of a Satellite," *2nd International Energy Conversion Engineering Conference*, Providence, Rhode Island, August 16–19, 2004. Contains description of ADEOS-II satellite failure analysis. See also Maejima et al. [7].

[7] H. Maejima, S. Kawakita, H. Kusawake, M. Takahashi, T. Goka, T. Kurosaki, M. Nakamura, K. Toyoda, and M. Cho, "Investigation of Power System Failure of a LEO

Satellite," *2nd International Energy Conversion Engineering Conference*, Providence, Rhode Island, August 16–19, 2004. Contains description of ADEOS-II satellite failure analysis.

[8] R. W. Evans, H. B. Garrett, S. Gabriel, and A. C. Whittlesey, "A Preliminary Spacecraft Charging Map for the Near Earth Environment," *Spacecraft Charging Technology Conference*, Naval Postgraduate School, Monterey, California, November 1989. This original reference paper was omitted from the conference proceedings. See Whittlesey et al. [9] for an alternative reference with the "wishbone" chart.

[9] A. Whittlesey, H. B. Garrett, and P. A. Robinson, Jr., "The Satellite Space Charging Phenomenon, and Design and Test Considerations," *IEEE International EMC Symposium*. Anaheim, California, 1992.