

LEO SPACECRAFT CHARGING DESIGN GUIDELINES: A PROPOSED NASA STANDARD

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ABSTRACT

Over the past decade, Low Earth Orbiting (LEO) spacecraft have gradually required ever-increasing power levels. As a rule, this has been accomplished through the use of high voltage systems. Recent failures and anomalies on such spacecraft have been traced to various design practices and materials choices related to the high voltage solar arrays. NASA Glenn has studied these anomalies including plasma chamber testing on arrays similar to those that experienced difficulties on orbit. Many others in the community have been involved in a comprehensive effort to understand the problems and to develop practices to avoid them. The NASA Space Environments and Effects program, recognizing the timeliness of this effort, commissioned and funded a design guidelines document intended to capture the current state of understanding. This document, which was completed in the spring of 2003, has been submitted as a proposed NASA standard. We present here an overview of this document and discuss the effort to develop it as a NASA standard.

INTRODUCTION

Historically, power systems on US space vehicles have operated at the nominal 28 V dc inherited from the aircraft industry. At such low voltages, plasma interactions in LEO are negligible and have not been a consideration in spacecraft design. High-power systems now being deployed for space applications operate at higher voltages in order to reduce power loss and system mass. The emergence of such systems is motivated primarily by a desire to save weight. Since the resistance of the necessary cabling is a strongly de-

creasing function of mass per unit length and cable losses are proportional to current squared, it is desirable to furnish power at higher voltages and lower currents. A further consideration is the reduced effect of magnetic interactions (torque and drag) that will follow from low current operation.

While high voltage systems are clearly desirable to the power system designer, they suffer the drawback of interacting with the ionospheric plasma in several different ways. First, conducting surfaces whose electrical potential is highly negative with respect to the plasma undergo arcing. Such arcing not only damages the material but results in current disruptions, significant EMI, and large discontinuous changes in the array potential.

One of the difficulties in predicting the onset of arcing has been the realization that the threshold potential for arcing depends critically not only on the design of the solar cells, but also in the manner cells are laid down and connected. In the early 1990's traditional wisdom focused on the observation that silicon cells using traditional silver-coated interconnects exhibited a threshold potential for arcing of about -230 volts relative to the plasma. Yet, since that time, catastrophic failures have occurred on operating solar arrays at much lower voltages.

An additional effect that plagues surfaces at high negative potential lies in the fact that inbound ions, accelerated by the high fields, cause sputtering from surfaces with which they impact.

For solar arrays or other surfaces that are biased positively with respect to the plasma, a second effect occurs. Such surfaces collect electrons from the plasma, resulting in a parasitic loss to the power system. Since

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the mass of an electron is much less than an ion, the magnitude of current density is much greater for surfaces with positive bias. At bias potentials greater than about 200 volts, sheath formation and secondary electron emission from the surface causes the entire surrounding surface, normally an insulator, to behave as if it were a conductor. This effect, often referred to as "snapover", results in large current collection from even a very small exposed area.

Besides producing a power loss, currents collected by biased surfaces will significantly affect the potentials at which different parts of the spacecraft will "float." Because of their large mass and low mobility, ions collected by negatively biased surfaces result in a relatively small plasma current density. The lightweight electrons, on the other hand, are readily collected by positively biased surfaces. Ram and wake effects further complicate the picture. Ram energy is considerably higher than ambient thermal energy so ram flow enhances ion collection relative to surfaces that are oblique to plasma flow.

The spacecraft, reacting to these various current sources, must necessarily reach equilibrium at whatever potential results in a net collected current of zero. The worst situations occur when the spacecraft power system uses a negative ground. In such a configuration, large surfaces are negative and must collect slow moving ions to balance the current from electron collection that now occurs only from relatively small areas of positive surface. In the worst case, parts of the spacecraft will be biased with respect to the ionosphere to a level very near the maximum voltage used on the solar arrays.

As experience has accumulated within industry and government, the need to capture the state of understanding has become pressing. Recognizing this, the Space Environments and Effects (SEE) program, managed by the Marshall Spaceflight Center, has commissioned and funded a series of software design tools and guidelines documents to aid the spacecraft community. The latest of these efforts is the document reported here, which focuses on high voltage interactions in Low Earth Orbit (LEO). For a more extensive review of these interactions, see reference 1.

OVERVIEW

The final document is divided into two parts. The first is the design guidelines proper, which will be briefly outlined below. Additionally, it was felt by the authors as well as by the SEE program that it was advantageous at this time to provide a comprehensive

citation of all relevant publications. To this end, the NASA CASI database was extensively searched and a compilation assembled of over 300 relevant publications. These citations, which are provided in the complete CASI format, appear in a separate appendix to the report. Each citation is given a separate page so that header information appears at the top, allowing a quick scan for relevant topics. Additionally, the appendix, like the master guidelines document, was assembled with Microsoft Word as its native format. Conversion to PDF leaves the citations fully searchable.

The guidelines document itself is divided into seven sections, which begin with a brief preface. The remaining six sections are summarized below.

Introduction

The introduction is divided into three subsections. The first introduces the reasons for the current widespread move to high voltage systems, in particular the weight savings to be achieved. A subsection that defines LEO in terms of altitude and latitude follows. While such definitions are somewhat arbitrary, we have made the distinction based on the interactions to be expected. The final subsection introduces the various plasma interactions that are relevant to high voltage systems in LEO.

Environments

The environments section introduces both the ambient and induced environments that spacecraft will experience in LEO. The ambient is further subdivided into the neutral atmosphere and the plasma environment. Basic properties of each are summarized with references to models that may be used to predict environmental properties. The contamination-induced environment is treated with several examples of the changes made to the natural environment by a spacecraft's operations or even by its mere presence.

Plasma Interactions

The fourth section, which reviews the relevant plasma interactions, is the longest in the work. There are two large subsections that deal with current collection and with arcing respectively. The part on current collection begins with an overview of the basic physics with particular attention to the current balance condition and to sheath effects. With this background, we next present the current state of knowledge concerning current collection by structures and the resulting spacecraft charging problem. The next topic treats both ion and electron collection by solar arrays

and introduced the engineering challenges posed by snapover and by parasitic power drain. The current collection subtopic ends with brief discussions of collection at high frequencies and of wake effects.

The second major subsection, which covers arcing, opens with an overview of the current state of knowledge of arcing on solar arrays. Lower level subsections deal with initiation mechanisms, arcing thresholds, typical waveforms, system responses to an arc, and damage potential. The arcing section concludes with subtopics on EMI and on structure arcing, which introduces the highly destructive continuous arc.

Mitigation Techniques

The fifth section, on mitigation techniques, is also divided into current collection and arcing. The emphasis is on controlling spacecraft potential. Techniques for preventing the problem in the first place focus on grounding schemes that are more compatible with the plasma environment. When this is not possible, mitigation techniques such as plasma contactors are described. The subsection ends with topics on the encapsulation of solar arrays and on the use of vented enclosures.

The arcing subsection opens with a subtopic dealing with on-orbit detection of arcs. It is followed with an overview of mitigation techniques and lessons learned that are specific to solar arrays.

Modeling

The sixth section, on modeling, is almost entirely concerned with current collection and resulting shifts in spacecraft potential. A number of modeling tools are available and are briefly surveyed. Guidelines are presented for their selection and use and an example is provided. The section ends with a discussion of arcing, a stochastic process whose onset is very difficult to predict.

Testing

The final section of the document concerns requirements and guidelines for testing. The discussion covers current collection and arcing and concerns solar arrays as well as material samples.

THE LEO GUIDELINES SEARCHABLE BIBLIOGRAPHY

An attempt was made to pull together all published sources of information about designing for the LEO

plasma environment. In order to do this, the CASI database (Center for Aerospace Information) was searched for authors, keywords, and subjects related to LEO spacecraft charging. Over 300 abstracts were obtained, and are listed in chronological order in the LEO Guidelines Searchable Bibliography, located at the end of the same .pdf file as contains the LEO Guidelines. Because of the multiplicity of papers by the same authors in any one year, the CASI Document ID is used as a reference (i.e. Guidice et al, 19980017264 instead of 1998). While every attempt has been made for completeness, we are aware that we may have missed some references and are going to revise the Bibliography, if not the entire LEO Guidelines, every year to try to keep current and correct accidental omissions. To check the searchability of the Bibliography for this paper, we searched within Adobe Acrobat Reader for the name Guidice, and obtained fourteen references in the Bibliography within a few seconds.

Including the Bibliography, the LEO Guidelines comes to over 360 pages. It is recommended that the Guidelines be kept as a computer file reference book, or on CD-ROM, not as a printed reference. This will preserve the searchability feature, save trees, and make the LEO Guidelines completely portable, whereas a 360 page book is cumbersome, not searchable, and wasteful of natural resources. It is not believed that the LEO Guidelines contain any copyrighted, classified or ITAR restricted material, and may therefore be shared with anyone. The authors respectfully request that when material from it is used, we be given the proper credit (Ferguson, D.C. and Hillard, G.B., 2003, "Low Earth Orbit Spacecraft Charging Design Guidelines," NASA/TP-2003-21228, National Aeronautics and Space Administration Marshall Space Flight Center, MSFC, Alabama 35812, February 2003.) The LEO Guidelines has been proposed as a NASA standard. If that status is achieved, it may then be proposed as a world standard under ISO 9001.

AVAILABILITY

The Low Earth Orbit Spacecraft Charging Design Guidelines is available from the NASA MSFC SEE website (<http://see.msfc.nasa.gov>) as part of the Charge Collector CD-ROM (version 2.0) or as a separate CD-ROM, or on CD-ROM directly from the authors at the address given for them in this paper. All authentic versions are in .pdf format. The authors, the SEE program, and NASA are not responsible for incorrect conclusions drawn from it by any party. It is intended solely as an aid for spacecraft designers to prevent harmful effects of LEO plasma interactions. The

authors welcome comments and suggestions for improvements.

NASA STANDARD

Following submission to the SEE program in March of 2003, external review and subsequent revision, the document was made proposed by the SEE program as a NASA standard in June. The Standards office reviewed the proposal and accepted it in October of 2003. The effort will be funded in the FY 2004 budget, still pending at the time of this writing. In addition to rewriting the document to conform to Standards format, the effort will include updating the document reflecting events since its last revision.

These include new European results on sustained arcing thresholds as well as various implications of recent on-orbit failures. In particular, the failure of the Japanese ADEOS-2 mission has drawn attention to the role of the South Atlantic Anomaly, which may have been involved in the event. The Anomaly and its effect on spacecraft during major solar events were not treated in the current version of the document and will be addressed in the next revision. Despite delays following from the budget process, the final document will be delivered to the Standards Program Office at MSFC by the end of FY 2004.

REFERENCE

1. Ferguson, D.C., (1993) "Interactions Between Spacecraft and Their Environments," presented at the AIAA 31st Aerospace Sciences Meeting and Exhibits, Reno NV 11-14 January 1993. AIAA 93-0705