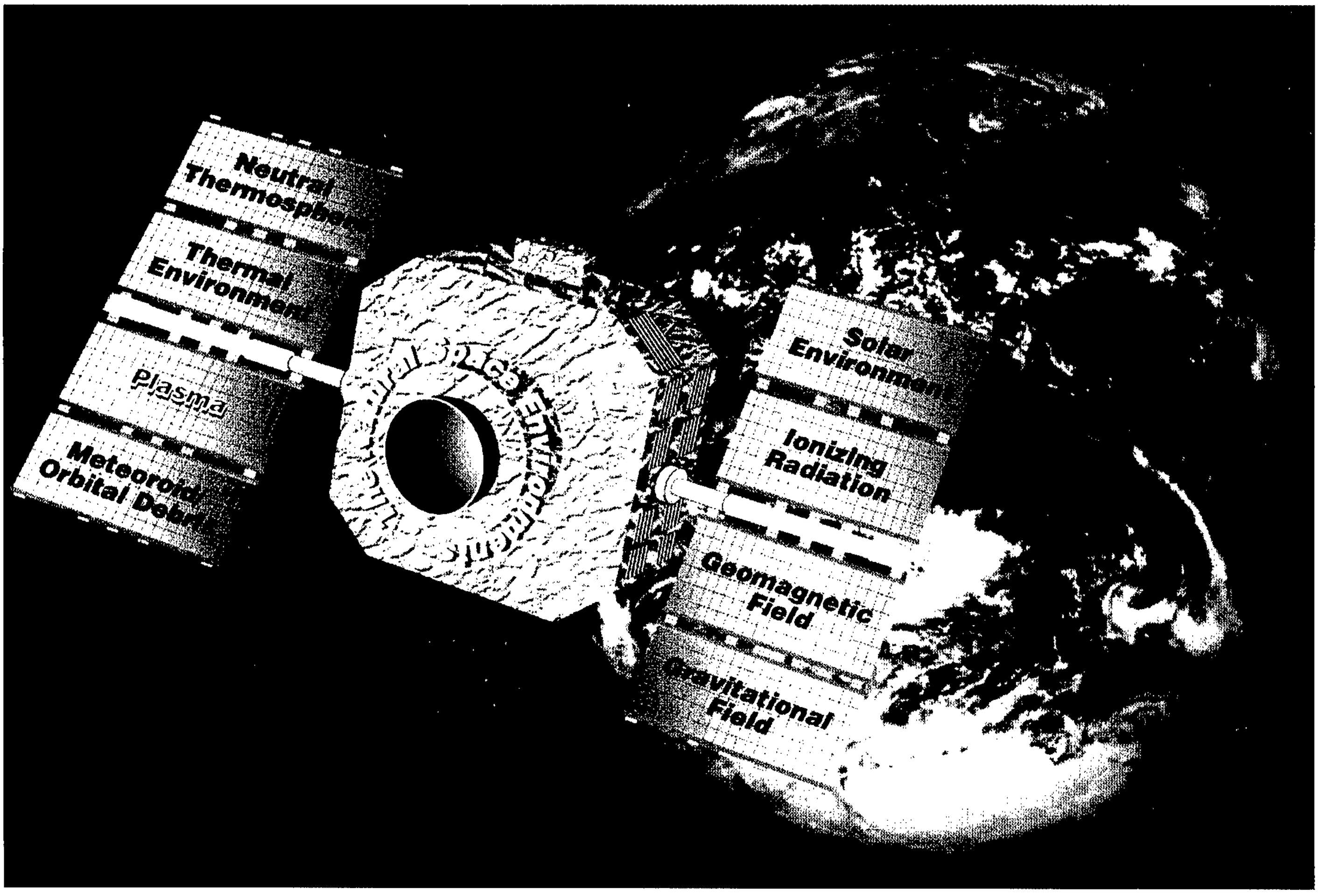
NASA Reference Publication 1354

Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging

J.L. Herr and M.B. McCollum



November 1994

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Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging

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PREFACE

The effects of the natural space environments on spacecraft design, development, and operation are the topic of a series of NASA Reference Publications currently being developed by the Electromagnetics and Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center. This primer, second in the series, describes the interactions between a spacecraft and the natural space plasma. Under certain environmental/spacecraft conditions, these interactions result in the phenomenon known as spacecraft charging. It is the focus of this publication to describe the phenomenon of spacecraft charging and its possible adverse effects on spacecraft, and to present the key elements of a spacecraft charging effects protection plan.

An overview of the natural space environments and their effects on spacecraft is found in the NASA Reference Publication 1350 entitled "The Natural Space Environment: Effects on Spacecraft." Figure A-1 through A-3 in the appendix of this document are taken from the aforementioned publication. These figures are a listing of the natural space environments and their major areas of interaction with spacecraft systems.

The objective of this series of Reference Publications is to increase the understanding of the natural space environments and their effects on spacecraft, thereby enabling program management to more effectively minimize program risks and costs, optimize design quality, and successfully achieve overall mission objectives.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ACRONYMS

cm	centimeter
eV	electron volt
GEO	geosynchronous orbit
hr	hour
keV	kiloelectron volt
km	kilometer
kV	kilovolt
LEO	low-Earth orbit
LT	local time
mm	millimeter
NASA	National Aeronautics and Space Administration
NASCAP	NASA Charging Analyzer Program (computer code)
ng	nanogram
Polar	high inclination, low-Earth orbit
POLAR	Potential of Large spacecraft in Auroral Regions (computer code)
P78-2	Spacecraft Charging at High Altitudes Program satellite
V	volt
V_f	equilibrium charging level or floating potential of a spacecraft

REFERENCE PUBLICATION

SPACECRAFT ENVIRONMENTS INTERACTIONS: PROTECTING AGAINST THE EFFECTS OF SPACECRAFT CHARGING

INTRODUCTION

The following sections introduce the phenomenon of spacecraft charging and its effects, and present the key elements of a Spacecraft Charging Effects Protection Plan that would be implemented to evaluate the impact of spacecraft-charging-related effects on a spacecraft.

Spacecraft charging is the process by which all orbiting spacecraft accumulate electric charge from the natural space plasma. An understanding of spacecraft charging is needed because the effects attributed to spacecraft charging have proven to be of serious engineering concern. These effects include:

- Operational anomalies (i.e., telemetry glitches, logic upsets, component failure) caused by the coupling of arc-discharge induced transients into spacecraft electronics

- Physical spacecraft surface damage as a result of arc-discharging

- Degradation of spacecraft surface material thermal and electrical properties due to increased surface contamination and sputtering.

Just recently, for example, the electronics controlling the gyroscopic stabilizing wheels on Telesat's Anik E-2 telecommunications satellite were permanently damaged by effects believed to be due to spacecraft charging.

A Spacecraft Charging Effects Protection Plan is implemented to evaluate the impact of spacecraft-charging-related effects on a spacecraft. The plan involves defining the properties of the natural space plasma to which the spacecraft will be exposed, developing design guidelines with the purpose of reducing or eliminating the effects attributed to spacecraft charging, and performing computer analyses to model the charging level of the spacecraft and determine how spacecraft-charging-related effects may interfere with mission goals and objectives. On the basis of the analysis, design recommendations are made to address spacecraft charging issues that arise.

The properties of the natural space plasma are discussed followed by an overview of the causes and characteristics of spacecraft charging. Documented effects attributed to spacecraft charging are described. Key elements of a Spacecraft Charging Effects Protection Plan are outlined, and the use of computer analysis to study the interaction between the natural space plasma and a spacecraft is described.

NATURAL SPACE PLASMA

Above an altitude of 90 km, a portion of the molecules comprising the Earth's atmosphere is ionized by solar radiation producing positively charged ions and free electrons. This collection of electrically charged particles, known as the natural space plasma, exists in all spacecraft orbits.

Definition of the natural space plasma depends on several factors. The most dramatic variations in its properties are due to changes in altitude and latitude (fig. 1). The properties of the natural space plasma are described by specifying particle density and particle energy. The particle density and energy are approximately the same for the electrons and positively charged ions in the different spacecraft orbits. Low inclinations, low altitude Earth orbit (LEO) plasma is relatively dense, as compared with other plasma around the Earth, and has low energy. At high inclination, LEO (Polar), high energy electrons are precipitated during auroral events. These high energy electrons are best known for the aurora they produce. At geosynchronous (GEO) altitudes, spacecraft frequently encounter high-energy low-density plasma associated with geomagnetic substorms.

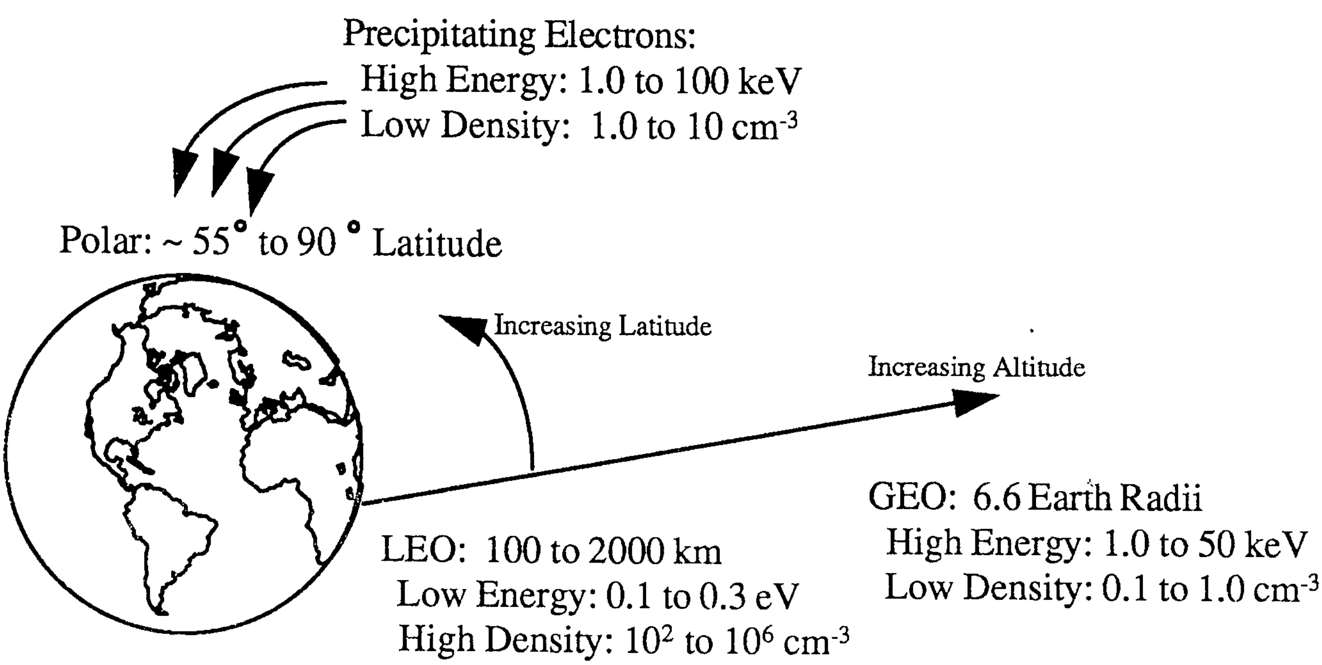


Figure 1. Properties of the natural space plasma.

The energy of the charged particles comprising the natural space plasma causes them to continuously move. Moving charged particles create electrical current. Moving electrons are negative current, and moving positively charged ions are positive current. When a spacecraft orbits the Earth, some of the electrical current will flow to the spacecraft resulting in charge accumulating on its exposed surfaces. This phenomenon is known as spacecraft charging.

SPACECRAFT CHARGING OVERVIEW

Spacecraft charging is the accumulation of charge on exposed surfaces of a spacecraft and is caused by unequal negative and positive currents to spacecraft surfaces (fig. 2). As one type of charge (positive or negative) accumulates, it generates an electric force field that decelerates like-charged particles, decreasing their current (positive or negative), and accelerates oppositely-charged particles, increasing their current (negative or positive). The charging process continues until the accelerated particles can be collected rapidly enough to balance the currents. At this point the spacecraft has reached its equilibrium charging level or "floating potential," V_f, and no more charge accumulates.

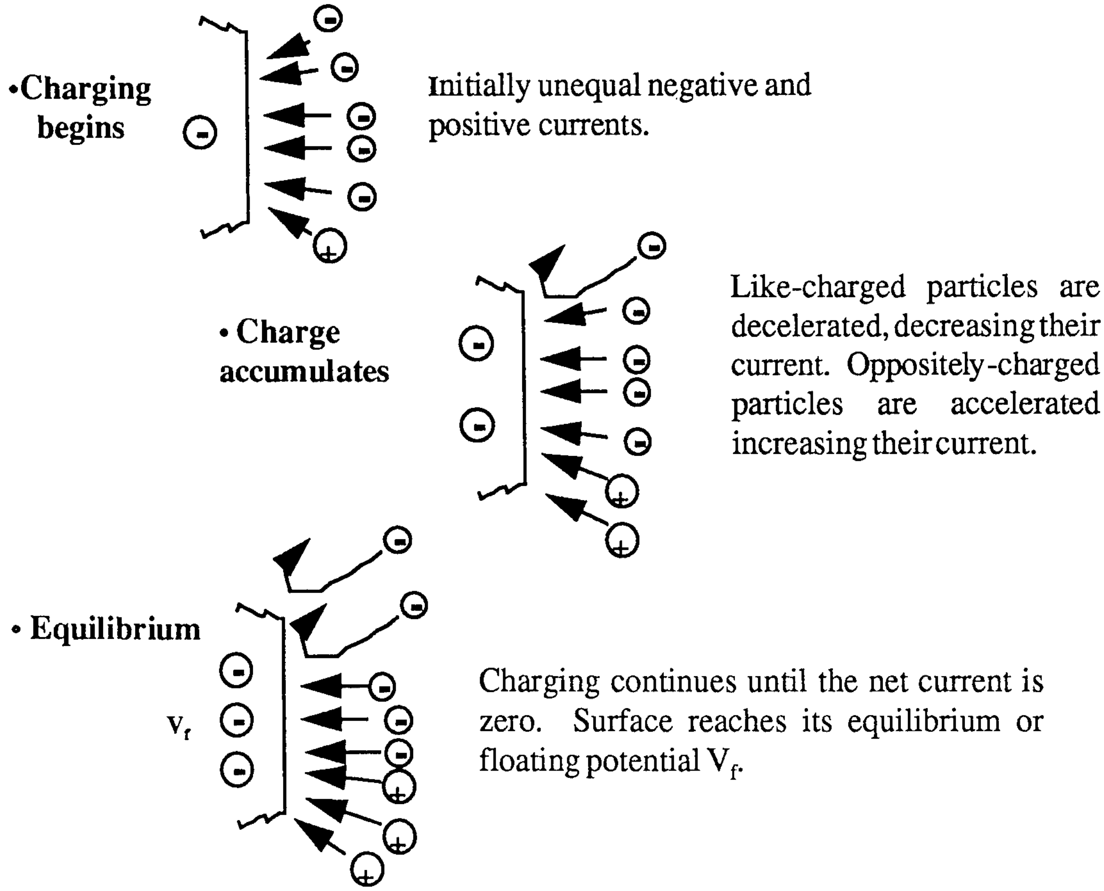


Figure 2. Cause of spacecraft charging.

In the preceding section it was mentioned that the density and energy of the electrons and positively charged ions composing the natural space plasma are approximately equal. The mass of the positively charged ions, on the other hand, is orders of magnitude greater than the mass of the electrons at all spacecraft orbits. Since their energies are equal, this means that the negative electron current will be greater than the positive ion current to spacecraft surfaces because lighter particles move faster. Therefore, spacecraft charging will occur at all spacecraft orbits.

The natural space plasma is not the only source of electric current to spacecraft surfaces. Another important source is the photoelectron current which, in some cases, can be greater than the natural space plasma current to spacecraft surfaces. The photoelectron current is a flow of electrons moving away from spacecraft surfaces, and is composed of electrons liberated from spacecraft surface materials when given sufficient energy by solar radiation. The photoelectron current acts as a positive current, since the electrons are leaving the spacecraft surfaces. Because the photoelectron current can be relatively large, it is necessary to account for variations in the solar radiation caused by eclipse periods, temporal and seasonal changes in the Sun's angle, and orbital changes in the spacecraft orientation to the Sun (fig. 3).

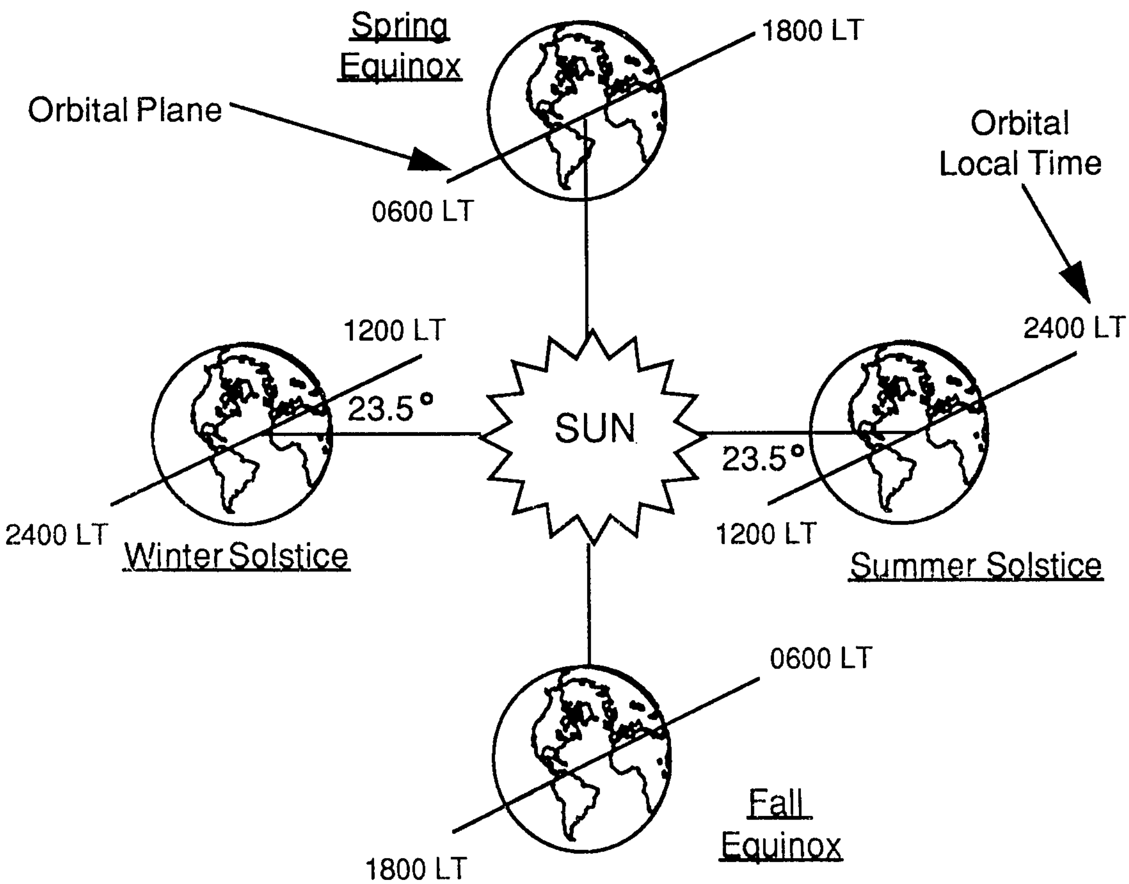
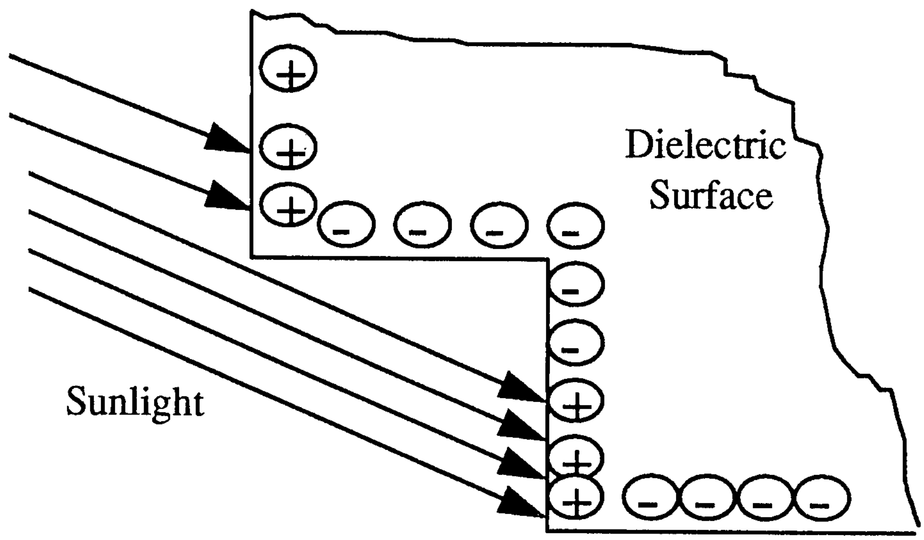


Figure 3. Seasonal, temporal, and orbital variations in the Sun angle.

In the case of the three-axis stabilized spacecraft, for example, the solar arrays maintain a constant orientation relative to the Sun while other instruments remain fixed on an object in space such as the Earth. As a result, different sides of the spacecraft body are illuminated by the Sun at different points in an orbit. Each variation in the Sun's angle causes changes in the photoelectron current which must be accounted for when determining the equilibrium or floating potential of a spacecraft.

In summary, charging is caused by unequal positive and negative electric current to spacecraft surfaces. Equilibrium is reached when the sum of the current to and from spacecraft surfaces is zero. If the spacecraft is all metal (i.e., conductive), the entire spacecraft will be charged to the same potential. However, if dielectric surface materials are used on a spacecraft, and the current from surface to surface varies, surface may charge to different floating potentials, a process called differential charging (fig. 4).

Dielectrics (e.g., Kapton and Teflon™) are poor distributors of accumulated charge, maintaining a portion of the charge deposited on them. A variation in the charged particle flux causes surfaces to reach different floating potentials. The largest levels of differential charging will typically develop between sunlit and shaded surfaces because the photoelectron current (which in some cases can be the largest source of positive current to a surface) maintains the floating potential of sunlit surfaces positive relative to shaded surfaces. A difference in floating potentials causes an electric force field to develop between the two surfaces. Electric force fields can produce stress in spacecraft surface materials and can lead to some of the effects discussed in the next section.



Differential charging is caused by a variation in the charged particle flux from surface to surface and the use of dielectric external surfaces which are poor distributors of accumulated charge. The largest differential potentials will be between sunlit and shaded surfaces.

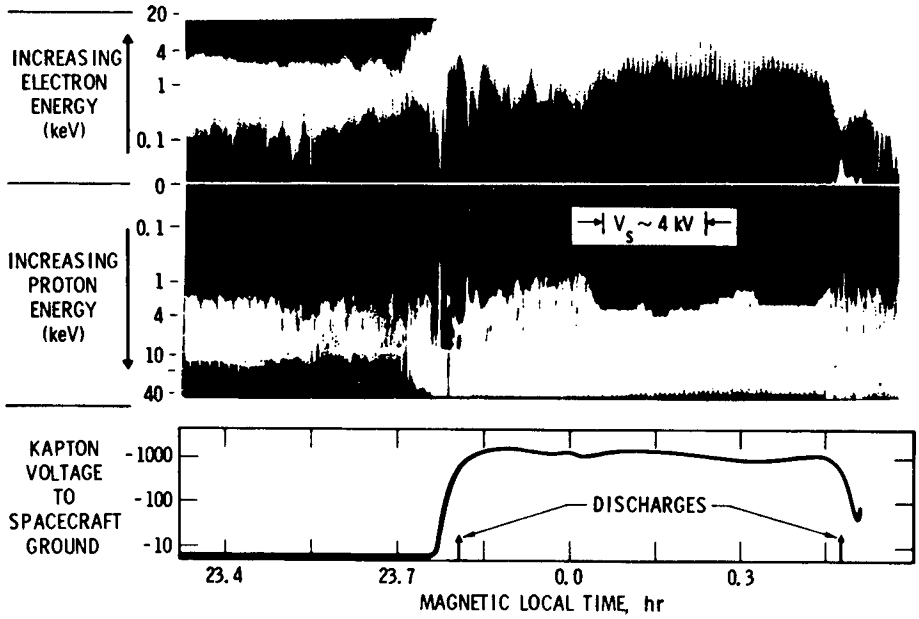
Figure 4. Differential charging.

EFFECTS ATTRIBUTED TO SPACECRAFT CHARGING

The primary mechanism by which spacecraft charging disturbs mission activities is through arc-discharging (fig. 5). Arc-discharging occurs when generated electric fields from differential charging exceed breakdown thresholds. The arc-discharge process rapidly releases large amounts of electric charge which gives rise to currents flowing in the spacecraft structural elements. The arcing produces a broadband electromagnetic field which can couple into spacecraft electronics and cause operational anomalies ranging from minor irritations to the fatally catastrophic.

Two types of arc-discharges are punch-through and flashover arc-discharges. Any area of dielectric material is a possible site for a punch-through arc-discharge. In this case, the dielectric surface material is differentially charged relative to the underlying spacecraft structure, and the resulting arc-discharge transfers charge from the surface to the spacecraft structure. An arc-discharge between differentially charged neighboring surfaces, called flashover, results in negative charge being redistributed to the more positively charged surface.

Besides generating electromagnetic interference that can couple with spacecraft electronics, arc-discharging leads to physical damage of affected surfaces (fig. 6). Arc-discharging produces localized heating and ejection of surface material from the arc-discharge site. The loss of material degrades spacecraft structural integrity and alters the properties of spacecraft surface materials. The ejected material is also a source of contamination for other spacecraft surfaces.



The upper panels are spectrograms of electron and ion (i.e., proton) fluxes. The lowest panel shows the differential charging level between a dielectric Kapton sample and the spacecraft ground (i.e., spacecraft structure). Two arc-discharge detected by the Pulse Analyzer are shown (Vampola, 1980).

Figure 5. Natural spacecraft charging event on P78-2 spacecraft in eclipse.

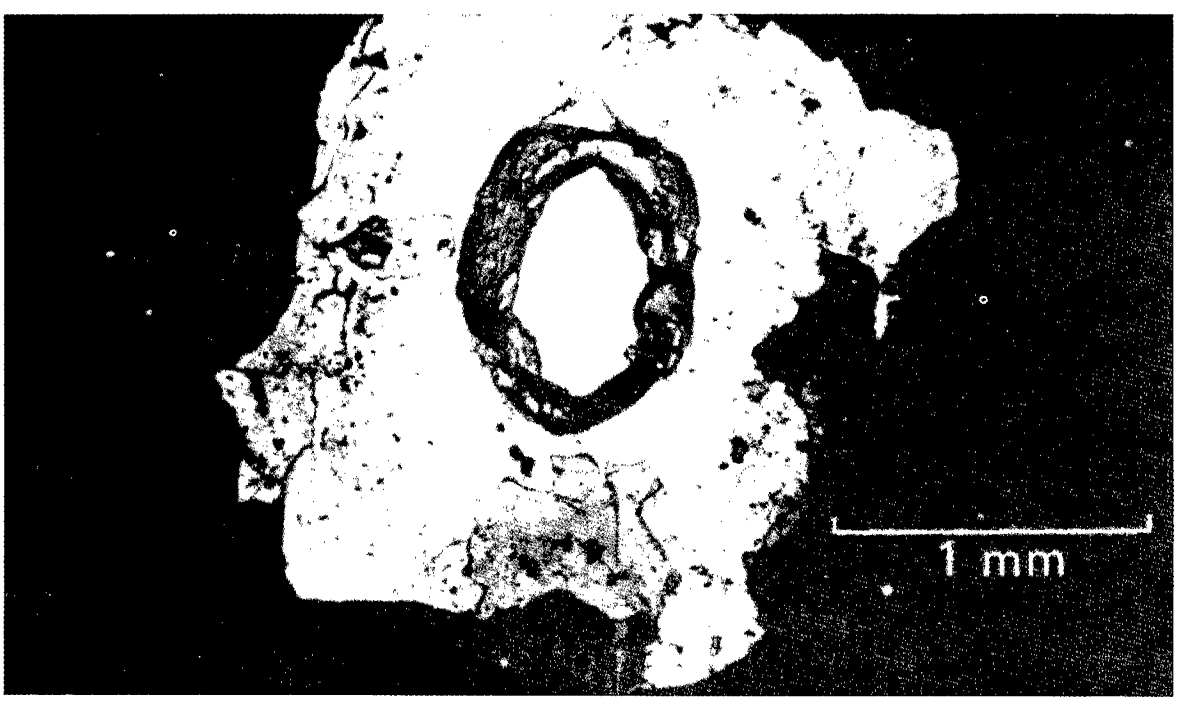


Figure 6. Evaporation of polymer and metal due to discharge in electron-irradiated aluminized Kapton. Magnification ×12 (Verdin, 1980).

Other spacecraft-charging-related effects of concern include degradation of spacecraft surface material properties due to increased surface contamination and ion sputtering. In the case of sputtering, large negative floating potentials of spacecraft surfaces accelerate positively charged ions to high energies leading to the physical removal of surface atoms (i.e., sputtering) by the impacting ions (fig. 7, top).

Organic molecules outgassed from spacecraft surfaces can be ionized while still near the spacecraft by solar radiation and can be attracted to negatively charged surfaces. The more negative the floating potential of a surface is, the greater the probability of its contamination (fig. 7, bottom).

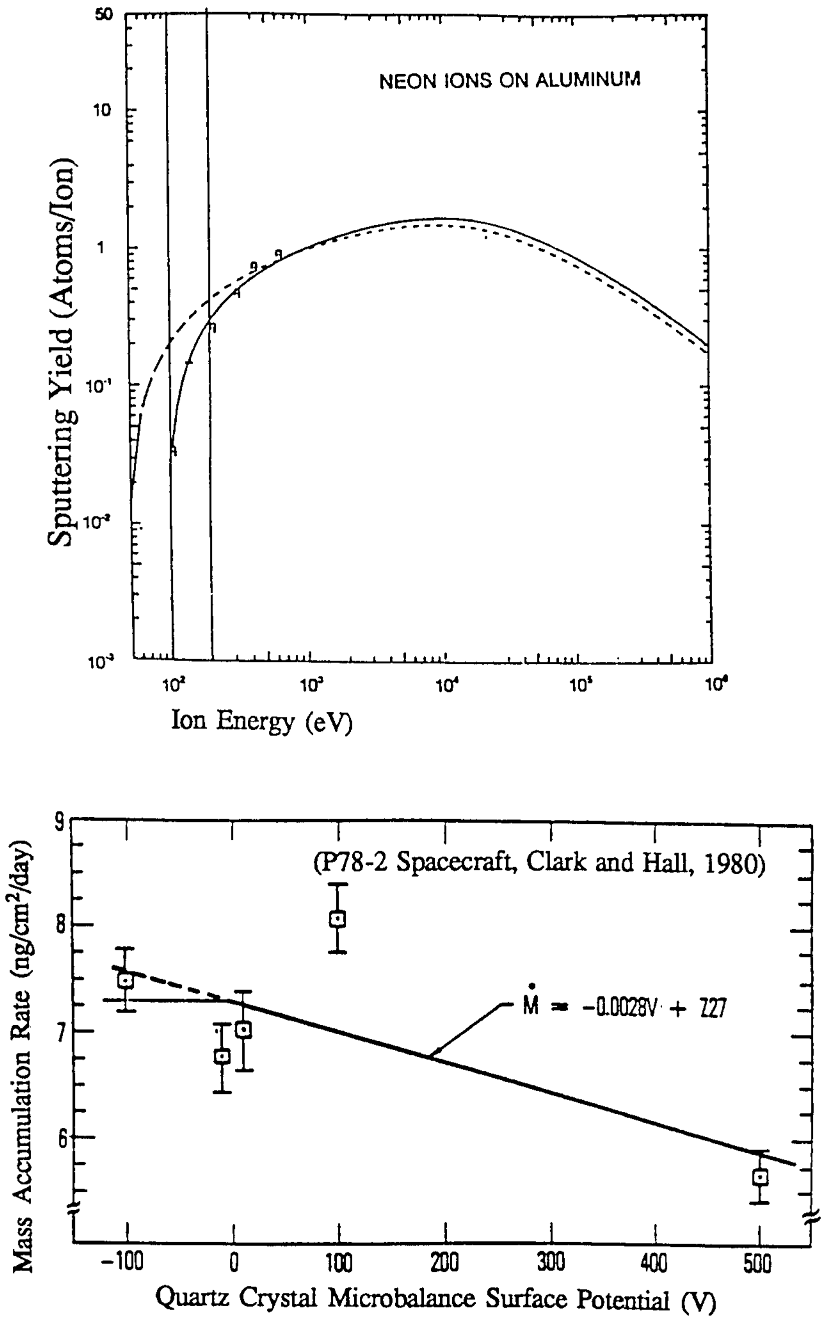


Figure 7. Other spacecraft-charging-related effects.

SPACECRAFT CHARGING EFFECTS PROTECTION PLAN

A method to protect against the detrimental effects attributed to spacecraft charging is to implement a Spacecraft Charging Effects Protection Plan. A protection plan involves defining the natural space plasma to which the spacecraft will be exposed, developing design guidelines with the purpose of reducing or eliminating the detrimental effects attributed to spacecraft charging, and performing computer analyses to model the charging level of the spacecraft and determine how spacecraft-charging-related effects might interfere with mission goals and objectives (fig. 8). Computer analysis is particularly important if some design guidelines are excluded in favor of other design considerations. As a result of the computer analyses, design recommendations are made to address spacecraft charging issues that arise.

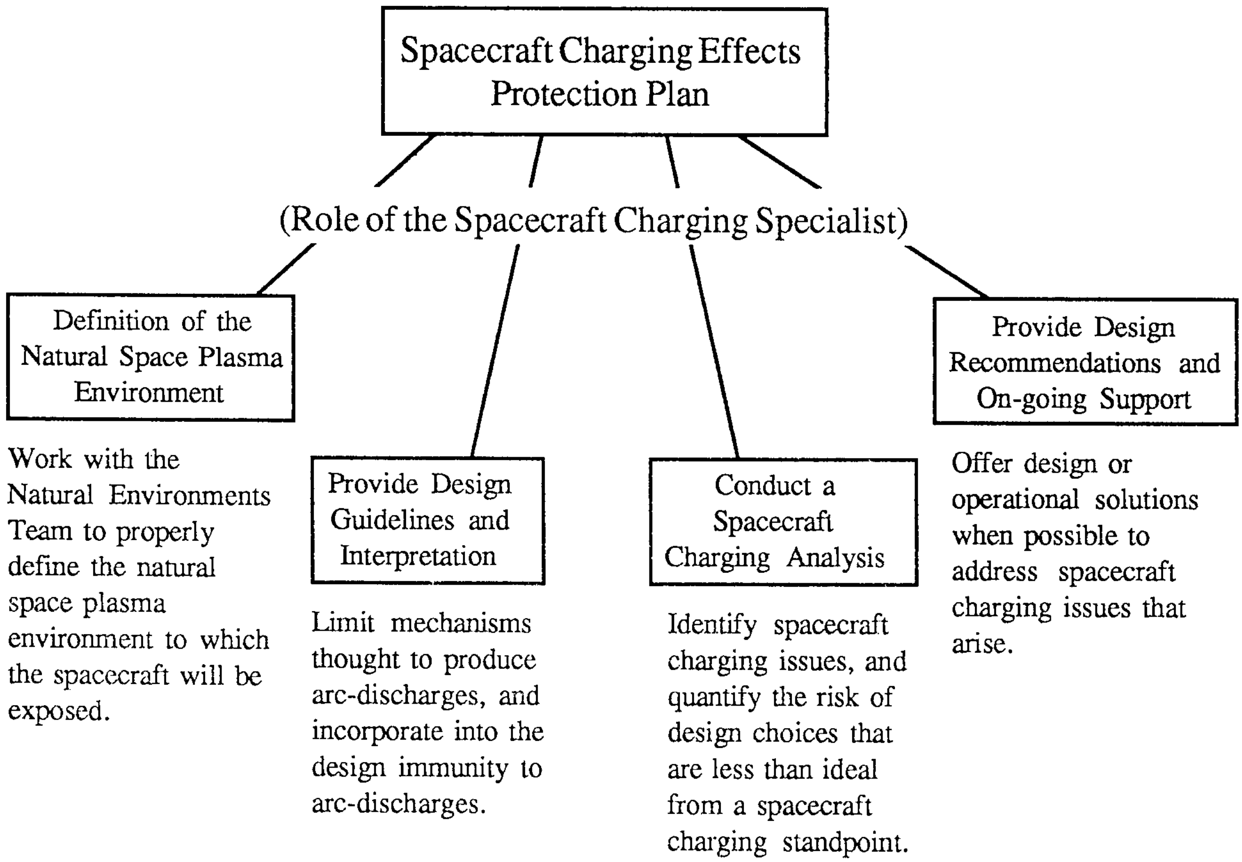


Figure 8. Spacecraft Charging Effects Protection Plan.

A complete set of design guidelines and recommendations tailored for the particular mission is provided in a Spacecraft Charging Effects Protection Plan document. Included in the document is a summary of the spacecraft charging analysis conducted on the spacecraft, and a description of the associated spacecraft-charging-related effects.

An important step in implementing a Spacecraft Charging Effects Protection Plan is the application of computer modeling to estimate the extent and likelihood of electric charge buildup on spacecraft surfaces. Three-dimensional computer programs specifically designed for this purpose are: NASA Charging Analyzer Program for Low-Earth Orbit (NASCAP/LEO) used to simulate spacecraft charging of low inclination, low altitude Earth orbit spacecraft; Potentials of Large spacecraft in Auroral

Regions (POLAR) used to model spacecraft charging in low altitude, polar orbit; and the NASA Charging Analyzer Program for Geosynchronous Orbit (NASCAP/GEO) used to model spacecraft charging by a geomagnetic substorm.

A NASCAP or POLAR model of a spacecraft is formed by combining various geometric shapes which attempts to simulate the spacecraft structure, and then assigning materials to the outer surfaces of the structure. Areas on the model of the spacecraft where large levels of differential charging develop are identified as possible arc-discharge sites. Figure 9 shows the surface charging levels on a model spacecraft obtained using NASCAP/GEO. Regions of sudden color change in a short distance signify a large electric force field and a possible arc-discharge site.

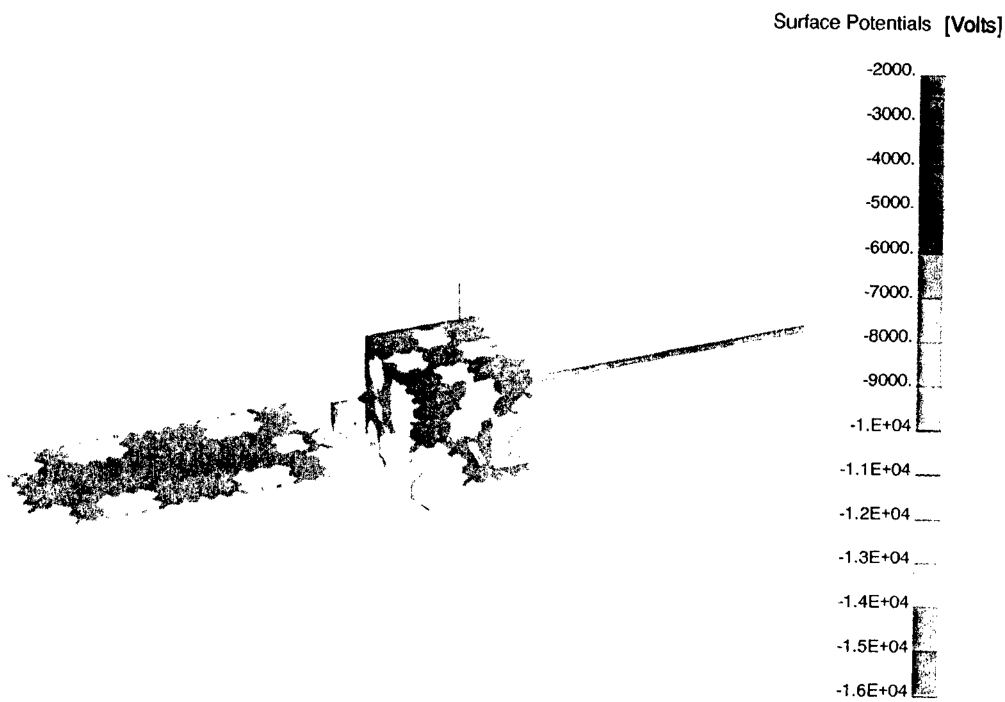


Figure 9. Surface voltage levels obtained by NASCAP/GEO.

CONCLUSION

The purpose of implementing a Spacecraft Charging Effects Protection Plan is to prevent the known spacecraft-charging-related effects from interfering with mission goals and objectives. In the preceding topics, it has been shown that:

- All orbiting spacecraft accumulate electric charge from the natural space plasma by a process called spacecraft charging.
- Arc-discharging, a result of differential charging, is seen as the primary mechanism by which spacecraft charging disturbs missions activities.
- Other spacecraft-charging-related effects of concern include degradation of surface properties due to increased surface contamination and ion sputtering.
- By implementing a Spacecraft Charging Effects Protection Plan, a spacecraft can be designed in such a way as to reduce or eliminate detrimental spacecraft-charging-related effects.

If you have questions or comments, contact the George C. Marshall Space Flight Center's Electromagnetics and Environments Branch (EL54), Steven D. Pearson at 205-544-2350.

APPENDIX

NATURAL SPACE ENVIRONMENTS

	DEFINITION	PROGRAMMATIC ISSUES	MODELS/DATABASES
NEUTRAL THERMOSPHERE	Atmospheric density, Density variations, Atmospheric composition (Atomic Oxygen), Winds	GN&C system design, Materials degradation/ surface erosion (atomic oxygen fluences), Drag/decay, S/C lifetime, Collision avoidance, Sensor pointing, Experiment design, Orbital positional errors, Tracking loss	Jacchia/MET, MSIS, LIFTIM, upper atmospheric wind models
THERMAL ENVIRONMENT	Solar radiation (albedo and OLR variations), Radiative transfer, Atmospheric transmittance	Passive & active thermal control system design, Radiator sizing/ material selection, Power allocation, Solar array design	ERBE database, ERB database, NIMBUS database, ISSCP database, Climate models, General Circulation Models (GCMs)
PLASMA	Ionospheric plasma, Auroral plasma, Magnetospheric plasma	EMI, S/C power systems design, material determination, S/C heating, S/C charging/arcing	International Reference Ionosphere Models, NASCAP/LEO, NASCAP/GEO, POLAR
METEOROIDS AND ORBITAL DEBRIS	M/OD flux, Size distribution, Mass distribution, Velocity distribution, Directionality	Collision avoidance, Crew survivability, Secondary ejecta effects, Structural design/ shielding, Materials/solar panel deterioration	Flux models
SOLAR ENVIRONMENT	Solar physics and dynamics, Geomagnetic storms, Solar activity predictions, Solar/geomagnetic indices, Solar constant, Solar spectrum	Solar prediction, Lifetime/drag assessments, Reentry loads/heating, Input for other models, Contingency operations	EL Laboratory model, NOAA prediction data, Statistical models, Solar database
IONIZING RADIATION	Trapped proton/electron radiation, Galactic cosmic rays (GCRs), Solar particle events	Radiation levels, Electronics/parts dose, Electonics/ single event upset, Materials dose levels, Human dose levels	CREME, AE-8MIN, AE-8MAX, AP-8MIN, AP-8MAX, Radbelt, Solpro, SHIELDOSE
MAGNETIC FIELD	Natural magnetic field	Induced currents in large structures, Locating South Atlantic Anomaly, Location of radiation belts	IGRF85, IGRF91
GRAVITATIONAL FIELD	Natural gravitational field	Orbital mechanics/tracking	GEM-T1, GEM-T2
MESOSPHERE	Atmospheric density, Density variations, Winds	Re-entry, Materials selection, Tether experiment design	Earth-GRAM 90, UARS database, "science" GRAM

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Figure A-1

SPACE ENVIRONMENT EFFECTS

	SPACE ENVIRONMENTS			
SPACECRAFT SUBSYSTEMS	Neutral Thermosphere	Thermal Environment	Plasma	Meteoroids/Orbital Debris
Avionics		Thermal Design	Upsets due to EMI from Arcing, S/C Charging	EMI Due to Impacts
Electrical Power	Degradation of Solar Array Performance	Solar Array Designs, Power Allocations, Power System Performance	Shift in Floating Potential, Current Losses, Reattraction of Contaminants	Damage to Solar Cells
GN&C/ Pointing	Overall GN&C/Pointing System Design		Torques due to Induced Potential	Collision Avoidance
Materials	Material Selection, Material Degradation	Material Selection	Arcing, Sputtering, Contamination Effects on Surface Properties	Degradation of Surface Optical Properties
Optics	S/C Glow, Interference with Sensors	Influences Optical Design	Reattraction of Contaminants, Change in Surface Optical Properties	Degradation of Surface Optical Properties
Propulsion	Drag Makeup/Fuel Requirement		Shift in Floating Potential Due to Thruster Firings Making Contact with the Plasma	Collision Avoidance, Additional Shielding Increases Fuel Requirement, Rupture of Pressurized Tanks
Structures		Influences Placement of Thermally Sensitive Surfaces, Fatigue, Thermally Induced Vibrations	Mass Loss From Arcing and Sputtering, Structural Size Influences S/C Charging Effects	Structural Damage, Shielding Designs, Overall S/C Weight, Crew Survivability
Telemetry, Tracking, & Communications	Possible Tracking Errors, Possible Tracking Loss		EMI Due to Arcing	EMI Due to Impacts
Thermal Control	Reentry Loads/ Heating, Surface Degradation due to Atomic Oxygen	Passive and Active Thermal Control System Design, Radiator Sizing, Freezing Points	Reattraction of Contaminants, Change in absorptance/ emittance properties	Change in Thermal/ Optical Properties
Mission Operations	Reboost Timelines, S/C Lifetime Assessment	Influences Mission Planning/ Sequencing	Servicing (EVA) Timelines	Crew Survivability

MSFC Page 1 of 2 EM & Environments Branch / EL54

Figure A-2

SPACE ENVIRONMENT EFFECTS

	SPACE ENVIRONMENTS				
SPACECRAFT SUBSYSTEMS	Solar Environment	Ionizing Radiation	Magnetic Field	Gravitational Field	Mesosphere
Avionics	Thermal Design	Degradation: SEUs, Bit Errors, Bit Switching	Induced Potential Effects		
Electrical Power	Solar Array Designs, Power Allocations	Decrease in Solar Cell Output	Induced Potential Effects		
GN&C/ Pointing	Influences Density and Drag, Drives Neutrals, Induces Gravity Gradient Torques		Sizing of Magnetic Torquers	Stability & Control, Gravitational Torques	Effect on GN&C for Re-entry
Materials	Solar UV Exposure Needed for Material Selection	Degradation of Materials			Degradation of Materials Due to Atmospheric Interactions
Optics	Necessary Data for Optical Designs	Darkening of Windows and Fiber Optics			
Propulsion	Influences Density and Drag			Influences Fuel Consumption Rates	
Structures	Influences Placement of Thermal Sensitive Structures		Induces Currents in Large Structures	Propellant Budget	Tether Structural Design
Telemetry, Tracking,& Communication	Tracking Accuracy, Influences Density and Drag		Locating South Atlantic Anomaly	May Induce Tracking Errors	
Thermal Control	Influences Reentry Thermal Loads/ Heating				
Mission Operations	Mission Timelines, Mission Planning	Crew Replacement Timelines			

MSFC Page 2 of 2 EM & Environments Branch/EL54

Figure A-3

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