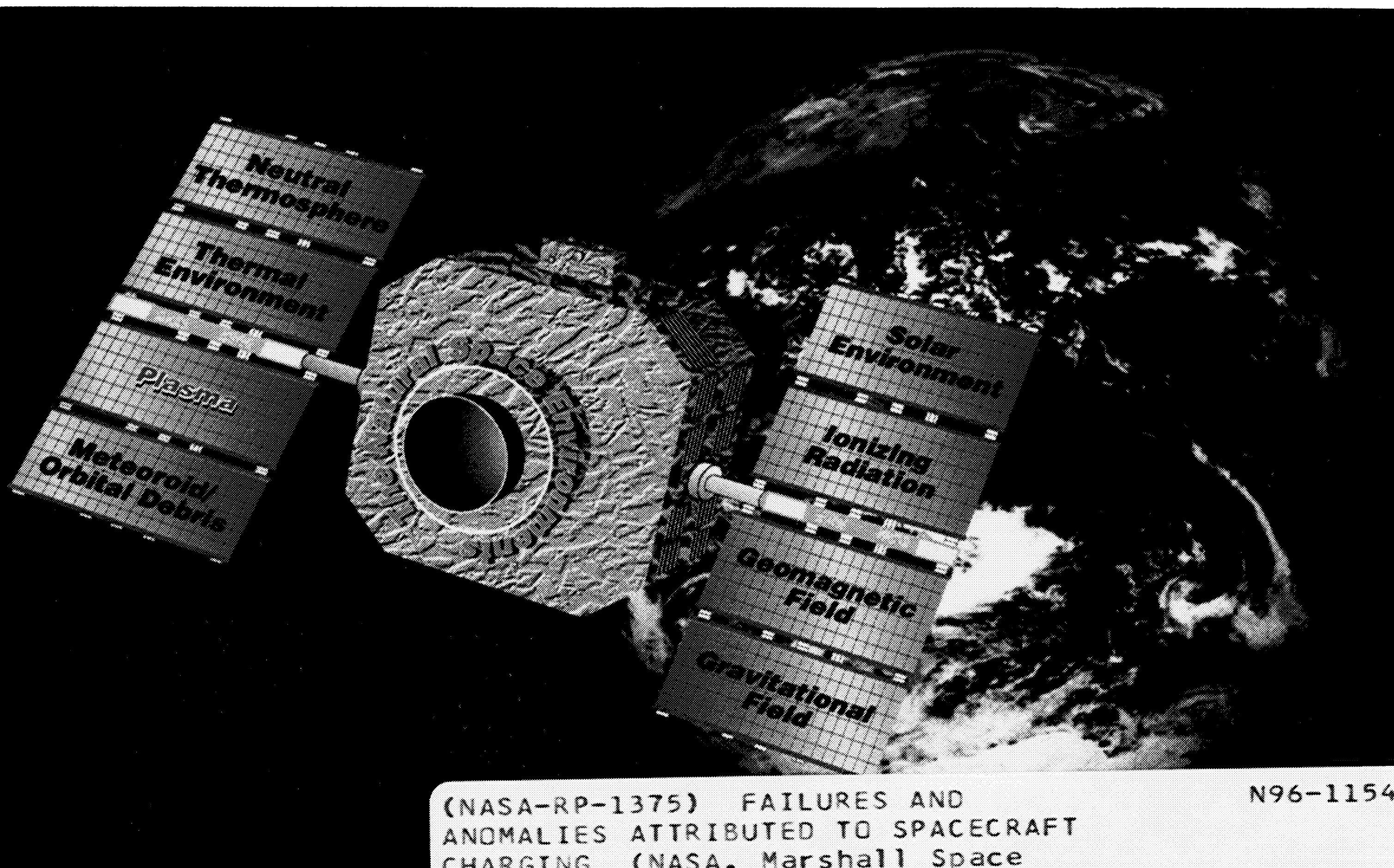
NASA Reference Publication 1375

Failures and Anomalies Attributed to Spacecraft Charging

R.D. Leach and M.B. Alexander, Editor



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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, System Analysis and Integration Laboratory, Marshall Space Flight Center.

This reference publication, third in the series, presents a brief overview of spacecraft charging, acquaints the reader with spacecraft charging history via illustrative cases of anomalies and failures due to spacecraft charging, and introduces current spacecraft charging prevention activities of the Electromagnetics and Environments Branch.

Despite 25 years of study and research into spacecraft charging, occurrences continue to jeopardize space missions. Engineers and managers involved in planning, designing, and operating space missions should be aware of and concerned with the possible consequences of charging to their programs.

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ABBREVIATIONS AND ACRONYMS

AMPTE/CCE	active magnetic particle tracer experiment/charge composition explorer
Arabsat	Arab league communications satellite
AUSSAT	Australian domestic telecommunications satellite
AXAF-I	Advanced X-ray Astrophysics Facility-Imaging
AXAF-S	Advanced X-ray Astrophysics Facility-Spectroscopy
ATS	applied technology satellite
CTS	Canadian-American communications technology satellite
DMSP	defense meteorological satellite program
DSCS	Defense Satellite Communications System
ESD	electrostatic discharge
eV	electron volt
FLTSATCOM	fleet satellite communications
GEO	geosynchronous-Earth orbit
GMS	geostationary meteorological satellite
GOES	geostationary operational environmental satellite
GPB	Gravity Probe B
GPS	global positioning satellite
GSFC	Goddard Space Flight Center
Intelsat	international telecommunications satellite
ISSA	*International Space Station Alpha*
LENA	low-energy neutral atom
LEO	low-Earth orbit
MARECS	Maritime European communications satellite
Meteosat	meteorological satellite

MI	magnetosphere imager
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASACAP/GEO	NASA charging analyzer program for geosynchronous orbit
NASACAP/LEO	NASA charging analyzer program for low-Earth orbit
NATO	North American Treaty Organization
POLAR	potentials of large spacecraft in auroral regions program
SBS	satellite business systems
SCATHA	spacecraft charging at high altitude
SVM	solar vector magnetograph
SXI	Solar X-ray Imager
TDRSS	tracking and data relay satellite system
Telecom	telecommunications

REFERENCE PUBLICATION

FAILURES AND ANOMALIES ATTRIBUTED TO SPACECRAFT CHARGING

INTRODUCTION

Purpose and Scope

Spacecraft charging is expected to have a significant role in future space activities and programs. Objectives of this report are to present a brief background overview of spacecraft charging, to acquaint the reader with charging history, including illustrative cases of charging anomalies, and to introduce current spacecraft charging prevention activities of the Electromagnetics and Environments Branch, Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA). The charging anomaly incidents cited in the report are intended as a representative list—not a complete one—of the nature and severity of problems caused by charging. No special attempt was made to research details from operational reports or project personnel. Events were recorded as they were found in the various sources and only those instances where investigators felt that there was enough evidence to attribute the anomalies to spacecraft charging were included. If the diagnosis of a particular anomaly was listed as unknown or the spacecraft was not identified, the event was not included in this report.

Recent Case

On January 20, 1994, Telsat Canada's Anik E-1 communications satellite suddenly began to spin out of control. Two hours later its sister satellite, Anik E-2, also, without warning, began to spin out of control. Telsat engineers quickly determined that the gyroscopic guidance system on both satellites had mysteriously failed and caused an interruption of cable TV, telephone, newswire, and data transfer services throughout Canada. By activating a backup guidance system, engineers restored Anik E-1 to service in about 8 h. Anik E-2's backup system, however, failed to activate, leaving Telsat with the unpleasant prospect of losing a $228 million asset and revenues of an estimated $3 billion.

The days immediately following these failures were a nightmare for public relations and operations management. Services were switched to other satellites, ground station antennas were realigned, backup transponders were activated, "retired" satellites were recalled to service, backup land links were established, frequencies were changed, and irate customers were reassured that life, as they knew it, was not ending. Eventually when telecommunications were reestablished, service was reduced by 10 full channels and 14 occasional-use channels.[1] In early press accounts, Telsat stated there had never been a satellite failure of this magnitude.[2] Much to their credit, Telsat engineers restored Anik E-2 to service in August 1994. They had developed an innovative first-of-a-kind ground control system that utilizes the 22 thruster motors located on the satellite to reposition the spacecraft. A computer program using data received from onboard sensors automatically determines the thruster firing sequence to maintain proper orientation.

Although Telsat did not lose Anik E-2 and future revenues, an estimated $50 to $70 million in recovery, repair costs, and lost revenues were realized. This included a 1-year decrease in the satellite's projected 10-year-service life caused by an increase in the fuel required to fire the 22 thrusters to keep the satellite stable. This decreases the supply of fuel that can be used for station keeping. Also operating costs over the satellite's remaining 9-year lifetime could be an additional $30 million.[1–4] Because the probability of an on-orbit mission failure is too low to justify the high annual insurance premiums, Telsat does not insure its satellites against on-orbit failures—a position many spacecraft operators take.

A determination was subsequently made that the events of January 20, 1994, were caused by a phenomenon known as spacecraft charging—a process through which a spacecraft charges to an electrical potential relative to its surroundings. In each Anik satellite, electrostatic discharge (ESD) created electromagnetic impulses within the primary gyroscopic guidance system control circuitry that permanently damaged critical components, rapidly degraded the satellites' stability and severely jeopardized their missions.

BACKGROUND

Significance of Spacecraft Charging Phenomenon

For 25 years, spacecraft charging has been researched, and an abundant case history has been documented of spacecraft failures and anomalies attributed to this phenomenon. And, while there has been significant knowledge gained in how to protect spacecraft from charging, continuing technical advancement in electronic systems necessitates the continuing development of improved design and testing to insure spacecraft charging effects will not compromise in-flight experiments and missions.

Modern electronic systems, which utilize low voltage and low currents and are packed into small areas, are more sensitive to space charging effects than older generation equipment.[5] Earlier generations of electronics, because of their size and more distributed layout, provided a certain robustness against the effects of charging, a robustness that modern integrated component technology does not provide. Additionally, with spacecraft flying at higher inclinations and polar orbits, charging caused by high energy particles becomes significant. The increased use of dielectric thermal coatings and composite spacecraft structures not only increases the risk of spacecraft charging, but also results in increased arc discharge damage to surfaces and thermal control coatings.

It will become increasingly important that NASA properly evaluate spacecraft charging due to the increased risk it presents to mission and experiment success. With tighter budgets and closer public scrutiny, successful missions are of paramount importance.

Overview of Spacecraft Charging

Spacecraft charging is the process by which orbiting spacecraft accumulate electric charge from the surrounding natural space plasma. Various effects attributed over 25 years to spacecraft charging are responsible for a number of operating anomalies—some quite serious—and should be of concern to engineers and managers planning, designing, and operating space missions. These effects include the following:

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

(2) Physical spacecraft surface damage (i.e., mirrored thermal control surfaces) as a result of arc-discharging

(3) Degradation of spacecraft surface material thermal and electric properties due to increased surface contamination.

To better understand the causes and characteristics of spacecraft charging, an overview is presented of properties of the natural space plasma, charging phenomenon, and effects of spacecraft charging.

Properties of Natural Space Plasma

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

Exact properties of the natural space plasma depend on several factors. The most dramatic variations are due to changes in altitude and latitude (fig. 1). Properties of the natural space plasma are described by specifying particle density and particle energy. Particle density and energy are nearly the same for electrons and positively charged ions in the various spacecraft orbits. Low inclination, low-Earth orbit (LEO) plasma compared to other plasma surrounding the Earth is relatively dense and has low energy. At high inclination, LEO (POLAR), high-energy electrons, best known for the aurora they produce, are precipitated during these auroral events. At geosynchronous-Earth orbit (GEO), spacecraft frequently encounter high-energy, low-density plasma associated with geomagnetic substorms.

These substorms are a geophysical phenomenon by which electrons, protons, and other ions normally found at altitudes above geosynchronous orbit (where most communication satellites such as Anik E-1 and E-2 are positioned) are accelerated towards Earth, causing an increased flux of high energy electrons. The substorm that affected the Anik satellites started on January 13, 1994, lasted 10 days, and created an environment for the spacecraft charging problems in both satellites.

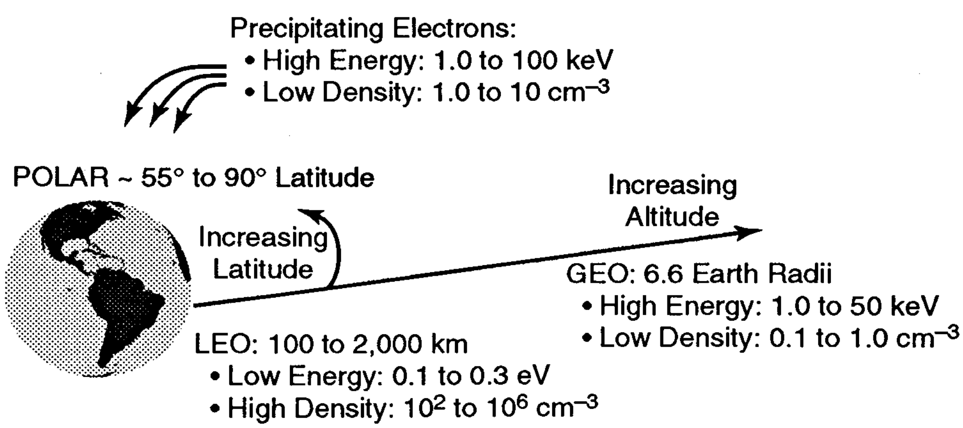


Figure 1. Properties of the natural space plasma.

Charging Phenomenon

Energy in the natural space plasma charged particles causes them to move continuously. Moving charged particles create an electric current; moving electrons create a negative current; moving positively charged ions create a positive current. When a spacecraft orbits the Earth, electric current flows to the spacecraft and causes charge accumulation on exposed surfaces. This phenomenon is known as spacecraft charging.

Various physical environmental parameters of the near-Earth environment interact with spacecraft. These parameters are atmospheric pressure, meteoroids/orbital debris, atmospheric noise, cosmic rays, deep space ions, eclipses (spacecraft entering the Earth's shadow during orbit), electromagnetic interference, geomagnetic storms, plasma, radiation belts, and solar flares. Of these, cosmic rays, eclipses, radiation belts, geomagnetic storms, and solar flares are more closely related to spacecraft charging than the others.

Generally, spacecraft charging is classified as surface charging (external) and dielectric charging (internal or bulk). Both types can produce ESD's that impact space missions. Usually, deep dielectric discharges are more damaging because they occur within dielectric materials or well-insulated conductors inside a spacecraft in close proximity to sensitive electronic circuitry.

1. Surface Charging

Surface charging is produced by interactions between satellite surfaces and space plasma, geomagnetic fields, and solar radiation. These interactions, caused by unequal negative and positive currents to spacecraft surfaces (fig. 2) produce an accumulation of charge on the exposed surfaces of a spacecraft. As a positive or negative charge accumulates, an electric force field is generated that decelerates like-charged particles (decreasing their current positively or negatively) and accelerates oppositely charged particles (increasing their current negatively or positively). The charging process continues until the accelerated particles are collected rapidly enough to balance the currents. At this point, the spacecraft reaches its equilibrium charging level or "floating potential" and no more charge accumulates. The majority of particles affecting the charge level are electrons and ions, with energies from 1 eV to approximately 50,000 eV.

The density and energy of electrons and positively charged ions composing the natural space plasma basically are the same. The mass of the positively charged ions, however, is orders of magnitude greater than the mass of electrons in all spacecraft orbits. Since their energies are equal, the negative electron current is greater than the positive ion current to spacecraft surfaces because lighter particles move faster. Therefore, spacecraft charging occurs in all spacecraft orbits to varying degrees.

Natural space plasma is not the only source of electric current to spacecraft surfaces. Another important one is the photoelectron current that, in some cases, is greater than the natural space plasma current. Photoelectron current, flow of electrons moving away from spacecraft surfaces, consists of electrons liberated from spacecraft surface materials when sufficiently energized by solar radiation. Photoelectron current acts as a positive current since the electrons are leaving the spacecraft surfaces. Because photoelectron current is relatively large, variations in 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 must be considered (fig. 3).

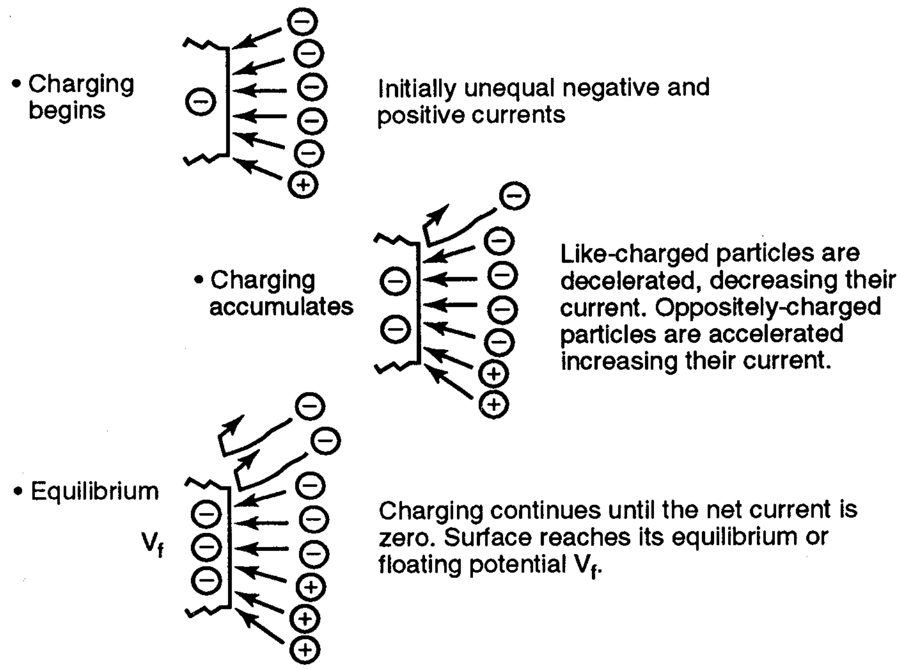


Figure 2. Cause of spacecraft charging.

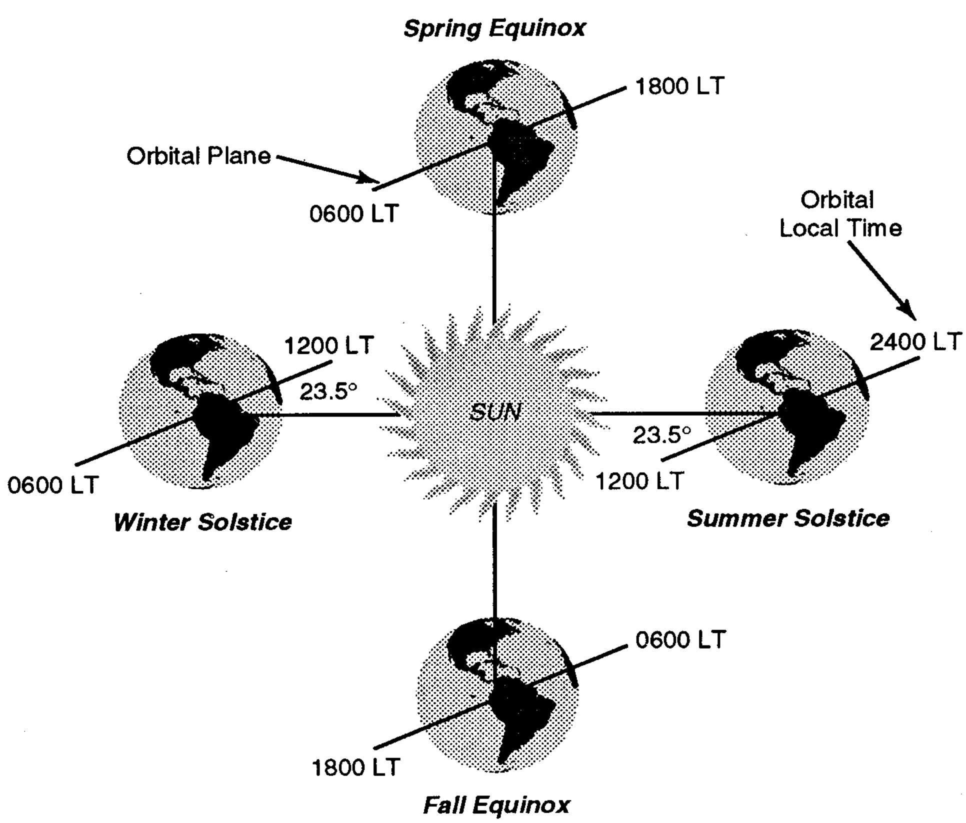
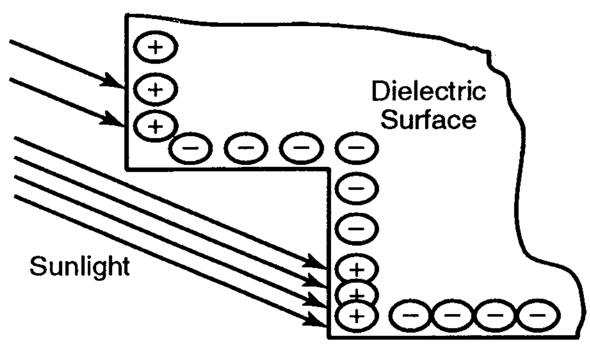


Figure 3. Seasonal, temporal, and orbital variations in the Sun angle.

In a three-axis stabilized spacecraft, 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. Thus, different sides of the spacecraft body are illuminated by the Sun at different points in an orbit. Because each variation in the Sun's angle causes changes in the photoelectron current, determination of the equilibrium or floating potential must consider spacecraft orientation to the Sun.

Since different geometry and material properties form the spacecraft surface, various areas on the surface are charged to different levels. Surface charging is classified into two types based on the spacecraft's acquired relative potential compared with the potential of its surroundings. The two types of surface charging are absolute charging and differential charging.[6]

Absolute charging, sometimes referred to as frame charging, occurs when the satellite, as a whole, acquires a net potential relative to the ambient plasma. If the spacecraft is all metal (i.e., conductive), the entire spacecraft will be charged to the same potential. Absolute charging is nearly instantaneous, with characteristic periods on the order of microseconds. If dielectric surface materials are used on a spacecraft, and the current from surface to surface varies, surfaces may charge to different floating potentials, a process called differential charging (fig. 4).



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.

Differential charging, with periods on the order of seconds to minutes, occurs more gradually than absolute charging. Dielectric materials used on many modern spacecraft (i.e., Kapton™ and Teflon™) are poor distributors of accumulated charge and thereby maintain a portion of the charge deposited on them. A variation in the charged particle flux causes these surfaces to reach different floating potentials. The largest levels of differential charging will typically develop between sunlit and shaded surfaces because the photoelectron current (in some cases 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 potential between two surfaces causes an electric force field to develop between them. Electric force fields can produce stress in spacecraft surface materials and lead to detrimental effects on spacecraft. Differential charging may produce strong local electric fields and affect the absolute charging level of the satellite. From an anomaly effect point of view, differential charging is more significant than absolute charging because it can lead to surface arcing or ESD between satellite surfaces of different potentials. This "arcing and sparking" can result in direct damage to spacecraft components and produce spurious interfering pulses to onboard electronics.[7] In geosynchronous orbit, spacecraft anomalies are often caused by differential charging. Differential charging is particularly common in sunlight, since sunlight tends to keep all illuminated surfaces near the plasma potential, while shaded dielectric surfaces can charge to large negative potentials.

2. Deep Dielectric Charging

Deep dielectric or bulk charging, also referred to as internal charging, is the buildup of charge on and within dielectric materials or on insulated floating conductors inside the spacecraft. Energetic electrons, with energies from approximately 10's of keV to several MeV, can penetrate the surface of the spacecraft and deposit charges inside. Deep dielectric charging depends on four factors: the environment, the shielding thickness of the spacecraft, and the characteristics and shape of the charged material. When the rate at which the energetic electrons deposit on the surface or embed inside a bulk dielectric is greater than the rate at which the charge leaks out, the electric field begins to increase in magnitude. Once the generated electric field reaches the breakdown threshold of the dielectric, an arc discharge occurs. The effects of arc discharges can be very detrimental to spacecraft and spacecraft systems.

Effects of Spacecraft Charging

The primary mechanism by which spacecraft charging disturbs mission activities is arc-discharging. Arc-discharging occurs when generated electric fields from differential or deep dielectric charging exceed breakdown thresholds. Arcs generate a transient broadband electromagnetic pulse that couples into spacecraft electronics and causes operational anomalies such as unintended logic changes, command errors, spurious signals, phantom commands, degraded sensor performance, and component failure. Deep dielectric arc discharges are potentially more serious than surface discharges because the discharge event occurs within the spacecraft in close proximity to sensitive circuits where the probability is higher that the electromagnetic pulse will have a detrimental effect.

Besides generating electromagnetic pulses that can couple with spacecraft electronics, arc-discharging leads to physical damage of surfaces. 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. Solar panels are often affected by arcing, with an accompanying degradation of power to the spacecraft. The ejected material is also a source of contamination for other spacecraft surfaces.

Other spacecraft-charging-related effects of concern include degradation of spacecraft surface material properties due to increased surface contamination and ion sputtering. In 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.

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

SURVEY OF CHARGING ANOMALIES

Garrett[8] points out that the very beginnings of spacecraft charging analysis are traced to early electrostatic probe work by Langmuir in the mid-1920's. As early as the 1940's and 1950's, various studies debated the probable charging potentials that might occur with objects in space. In the early 1950's, rockets equipped with sensors helped initiate spacecraft charging as a technical discipline. In 1955, Johnson and Meadows wrote the first spacecraft charging effects paper. With the launch of *Sputnik* in 1957, a new era of interest in the phenomenon of spacecraft charging began. By 1961, most of the main elements (but not all) of current spacecraft charging theory were in place. By the mid-1960's, it was generally recognized that charging can cause serious problems with spacecraft operations.

The earliest satellite observations of spacecraft charging were on *Sputnik 3* in the late 1950's. The applied technology satellite (ATS-5) launched in 1969 was the first satellite to measure the geomagnetic substorm environments. The Canadian-American communications technology satellite (CTS) was launched in 1976 with instrumentation to monitor transient events. ATS-6 launched in 1974, Meteosat F1 launched in 1977, the spacecraft charging at high altitude (SCATHA) satellite launched in 1979, and the Maritime European communications satellite (MARECS-A) launched in 1981, further aided in the investigation of spacecraft charging phenomenon and its relation to the substorm environment. In 1982 and 1983, two Defense Meteorological Satellite Program (DMSP) satellites were launched into polar LEO orbits to obtain additional information about the low-altitude polar environment.

Perhaps the most significant event in the history of spacecraft charging was the catastrophic failure of the Air Force Defense Space System Communication Satellite (DSCS) 9431 in 1973. The satellite failed when power to its communications system was suddenly interrupted by a high energy discharge due to surface charge buildup during a geomagnetic substorm. This incident resulted in a joint NASA and Air Force spacecraft charging investigation to study and develop technology to control spacecraft charging effects. This program developed a definition of the charging environment, new analytical tools to predict charging of complex spacecraft, design guideline documents, flight and ground-based data, and a general understanding of the charging phenomenon.[9]

Spacecraft continued to experience charging anomalies even after this intense period of study. For 15 years, the subject of spacecraft charging has continued to evolve, with the focus being on identification of environmental stress factors and quantification of engineering effects of discharging on the spacecraft. Today, extensive work is in progress to gain a better understanding of discharge events and the various mechanisms that affect spacecraft electronic circuits.

Spacecraft Charging Anomaly Events

The almost catastrophic events suffered by Telsat's Anik satellites are examples of the many operational anomalies suffered by spacecraft due to spacecraft charging over the last 25 years. Table 1 contains brief descriptions of some of these charging-related anomalies from the many periodicals, journals, papers, and reports dealing with space environmental effects on spacecraft.

Two abundant data sources are the "Spacecraft Anomaly Data Base" maintained by the Solar-Terrestrial Physics Division of the National Geophysical Data Center in Boulder, CO, and a series of yearly orbital anomaly reports for spacecraft compiled by the NASA Goddard Space Flight Center (GSFC). The GSFC reports cover a 17-year period beginning with the report entitled, "Analysis of Spacecraft On-Orbit Anomalies and Lifetimes," PRC R-13579, dated February 10, 1983, which included anomalies from mid-1978 to mid-1982. Both sources address on-orbit anomalies including those believed to be due to spacecraft charging.

Not all the anomalies listed in Table 1 resulted in catastrophic failure of a subsystem or mission. The consequences required, in many cases, reloading memories, tolerating noisy data, switching to redundant systems, reissuing command sequences, and updating real time attitude control commands. All these "small" anomalies, however, required additional operator diligence and operating costs regardless of the nature of the impact to the mission objective. Furthermore, a series of "small" anomalies increases the chances for more significant problems. The despin control problem on Anik D-2 was actually caused by a rapid series of separate anomalies which occurred in one particular sequence and resulted in the data loss event.[10] Any anomaly or series of anomalies carries the potential of turning into serious problems. Therefore, the goal of any mission manager should be to minimize the occurrence of anomalous events due to spacecraft charging.

Table 1. Spacecraft charging anomaly review.

Spacecraft	Launch Date	Anomaly Description
Telstar 401	12/16/93	On October 9, 1994, this AT&T communications satellite experienced a 1-h disruption in service due to an ESD that caused ground controllers to briefly lose stabilization of the satellite[11]
Intelsat K	06/09/92	This satellite is one of 20 communications satellites in geosynchronous orbit owned by the International Telecommunications Satellite Organization. On January 20, 1994, the satellite experienced an ESD resulting from a geomagnetic storm that had started on January 13. The discharge disabled the momentum wheel control circuitry on the satellite causing it to wobble and produce fluctuations in antenna coverage. Full operational status was achieved on the same day after a backup system was activated. The Anik E-1 and E-2 satellites also were affected by this storm on that date.[12]
Anik E-1	09/26/91	On January 20, 1994 this Telsat Canada communications satellite began to spin out of control because of damage to its gyroscopic guidance system (momentum wheel control) due to ESD caused by charge buildup created by the same geomagnetic storm that caused damage to Intelsat K. Backup systems were activated and the satellite was brought under control and stabilized in about 8 h.[13]

Table 1. Spacecraft charging anomaly review (continued).

Anik E-2	04/04/91	About 2 h after Anik E-1 began to spin out of control on January 20, 1994, Anik E-2,also owned by Telsat Canada, began to spin out of control. As with Anik E-1, the gyroscopic guidance system failed due to ESD. Unlike Anik E-1 the backup guidance systems failed to operate and it appeared that Anik E-2 would be a total loss. Telsat engineers, however, devised a ground based control system using the satellite's thruster motors to bring the satellite under control on June 21, 1994, and restore it to useful service in August 1994.[1]
BS-3A	08/28/90	This Japanese broadcasting satellite suffered a 60-min telemetry outage on February 22, 1994 due to an ESD.[12–14]
GMS-4 (Himawari 4)	09/05/89	On this Japanese Geostationary Meteorological Satellite (Himawari 4) the visible infrared spin scan radiometer gain setting experienced an anomalous change in state in January and in July 1991 due to ESD's.[15]
FY-1 (FENGYUN-1)	06/09/88	This Chinese experimental weather satellite failed after 39 days in orbit. It has been postulated that an ESD caused a failure of the attitude control system ending the mission.[15 16]
AUSSAT-A3	09/06/87	This Australian domestic telecommunications Satellite just like AUSSAT-A1 and -A2 suffered anomalous phantom commands that affected the telemetry subcommutator and attitude control system. 19 such events have occurred from October 1987 to October 1990. These anomalous events were reported to be due to electrostatic charging.[15]
FLTSATCOM 6071	03/26/87	This satellite was part of Fleet Satellite Communications constellation of satellites utilized by the U.S. Navy, U.S. Air Force, and the presidential command network. It experienced five deep dielectric charging events that resulted in low level logic anomalies from March to June 1987.[15]
GOES-7	02/26/87	On February 26, 1989, the VAS digital multiplexer bit mode command failed after the satellite came out of eclipse. This was attributed to a discharge event. Also this spacecraft experienced several discharge events in 1987 to 1989 that resulted in phantom commands.[15 17]
AUSSAT-A2	11/28/85	This Australian domestic telecommunications Satellite just like AUSSAT-A1 experienced anomalous phantom commands that have affected the telemetry subcommutator and attitude control system. Thirty-three such events have occurred from May 1986 to June 1990. These events were reported due to electrostatic charging.[15]

Table 1. Spacecraft charging anomaly review (continued).

AUSSAT-A1	08/27/85	This Australian domestic telecommunications Satellite experienced phantom commands events from January 1986 to June 1989 that changed modes in the telemetry system and the attitude control system. These events were reported to be due to electrostatic charging.[15]
Intelsat 511	06/30/85	During the month of August 1993, this communications satellite experienced electrostatic charging events that disrupted the attitude control system and caused uncommanded status changes.[15]
Telecom 1B	05/08/85	On January 15, 1988, this French civil and military satellite experienced a failure of both attitude control systems (prime and backup) and was unable to carry out its mission. Researchers postulated that the anomaly was caused by ESD's coupling with exposed electrical wiring.[18]
Intelsat 510	03/22/85	In August 1993 this International Telecommunications Satellite communications satellite experienced an ESD that affected the attitude control system and produced various uncommanded status changes.[15]
Arabsat 1-A	02/8/85	On March 15, 1985, shortly after launch, this Arab league communications satellite lost power, attitude control, and orbit gyros, necessitating manual North-South station keeping. On June 1, 1986, the satellite experienced loss of Earth lock in the attitude control system and was designated an orbital spare. Investigators believed the problems were due to ESD's.[15] [19]
Anik D2 (ARABSAT 1D)	11/09/84	This Telsat Canada satellite was launched from the Space Shuttle *Discovery* STS-14. On the morning of March 8, 1985, the despin control system malfunctioned and the platform on which the communications antenna was mounted began to spin, interrupting data transmission. The problem was postulated to be a large arc-discharge originating on the reflector at the back of the antenna or on the thermal shield at the front of the antenna. Unusually high activity occurred in the magnetosphere 8 h prior to the anomaly. Although the satellite was eventually brought under control, fuel was used to correct the resulting wobble and a year of station keeping was lost. The satellite also experienced greater than expected degradation to mirrored surfaces which was attributed to surface discharges in the thermal blanket. This satellite was sold to Arabsat in May of 1994 and renamed ARABSAT 1D.[20]

Table 1. Spacecraft charging anomaly review (continued).

AMPTE/CCE	08/16/84	The Active Magnetic Particle Tracer Experiment/Charge Composition Explorer was an international program (United Kingdom, Germany, and the United States) consisting of three satellites launched at the same time. On November 11, 1984, the AMPTE satellite lost data modulation due to a phantom command caused by spacecraft charging. Operating procedures had to be changed to remain operational.[21]
Telecom 1A	08/04/84	This French telecommunications satellite experienced frequent ESD's which interrupted data transmissions causing it to be removed from service and used as a backup. Subsequent testing showed that equipment anomalies were due to ESD's.[18 22]
GMS-3 (Himawari 3)	08/03/84	In December 1984, this Japanese Geostationary Meteorological Satellite (Himawari 3) experienced two anomalous switching events in the accelerometer. This anomaly reoccurred in March and in April 1985. The visible infrared spin scan radiometer experienced anomalous gain level stepping in June, July, and August 1985. All these events were attributed to ESD's.[15]
GOES-6	04/28/83	On September 27, 1986, this GOES satellite, which is operated by NASA for NOAA, experienced an uncommanded shift in its visible infrared spin scan radiometer atmospheric sounder (VAS) Earth window. Also on March 17, 1986, the x-ray scan shifted to calibration mode. These anomalies were judged to be caused by ESD's.[15 23]
TDRSS	04/05/83	The Tracking and Data Relay Satellite System is presently comprised of four satellites: TDRS -1 launched from STS-6 in April 1983, TDRS-3 launched from STS-26 in September 1988, TDRS-4 launched from STS-28 in May 1989, and TDRS-5 launched from STS-42 in August 1991. These spacecraft have experienced arcing anomalies in several different subsystems over their operating life times. The most serious incidents were those related to the attitude control system processor electronics. Rapid manual intervention was required to prevent loss of control of the satellites. Several studies concluded that these anomalies were due to surface charging.[24 25]
DSCS-III (4524)	10/30/82	This Air Force Defense Space Communications Satellite experienced ten deep dielectric charging events that caused glitches in the tachometer system from December 1986 to January 1987.[15]

Table 1. Spacecraft charging anomaly review (continued).

MARECS-A	12/20/81	Soon after this Maritime European Communications Satellite was launched by the European Space Agency, it experienced spurious anomalies in its telemetry system requiring onboard processors to be manually reset. On February 27, 1982, however, the satellite's pointing system suddenly went into an energy conserving "safeing" mode shutting down all communications subsystems. A special team was assigned to investigate for the benefit of future geostationary missions. Electrostatic discharges were determined responsible not only for this incident, but also for the other observed anomalous behavior. These anomaly events corresponded closely with geomagnetic activity studied from 1982 to 1985. Spacecraft charging was deemed responsible for the discharges. On March 25, 1991, MARECS-A was taken out of service due to serious damage to its solar panels. Localized arcing, caused by surface charging while the satellite was in eclipse, degraded the panel surfaces to the point that power output dropped to unacceptable operating levels. This occurred during a period of intense solar and substorm activity. Information gathered in the charging study was used to improve the design of subsequent satellites in this series. These satellites did experience some anomalous behavior, but not to the extent observed on MARECS-A.[26 27 10]
SBS 1	11/15/81	Soon after the launch of this Satellite Business Systems telecommunications satellite, it began to experience ESD's affecting the attitude control electronics. This satellite experienced hundreds of events over an 8-year period.[15]
GOES-4	09/09/80	This Geostationary Operational Environmental Satellite was operated by NASA for NOAA. On March 29,1981, the mirror used with the visible spin scan radiometer-atmospheric sounder (VAS), the principle instrument on the spacecraft, suffered phantom commands that began a sudden, undesired repositioning making it impossible to track the Earth's weather until a new series of commands was issued by controllers on Earth. The satellite continued to experience similar events throughout its operational lifetime. An investigation of these events concluded that a portion of the VAS second stage radiation cooler was ungrounded and built up potential from the surrounding plasma until it discharged, creating a large electromagnetic pulse. This pulse created large current surges that flowed along the wiring to the VAS. On November 25, 1982, the VAS failed completely, requiring the satellite to be taken out of service. It became essentially a standby unit to be replaced

Table 1. Spacecraft charging anomaly review (continued).

GOES-4 (Cont.)	09/09/80	later by GOES-I. The ungrounded radiator was redesigned on GOES-5 before its launch on May 5, 1981. Although similar anomalies due to electrostatic charging did occur on GOES-5, no serious problems were experienced.[28 29]
GPS 5118	02/09/80	This satellite, part of the Global Positioning Satellite System, was launched into a 20,000-km circular orbit and experienced unexpected switch settings within the motor control electronics on July 17, 1985, due to an ESD.[14]
DSCS-II (9443)	11/21/79	This Air Force Defense Space Communications Satellite experienced low level logic glitches in March and July of 1987 due to deep dielectric Charging.[15]
SCATHA (P78-2)	01/30/79	The Spacecraft Charging at High Altitude satellite was launched by the US Air Force in an elliptical orbit 185 by 43,905 km for the purpose of understanding the source of spacecraft charging anomalies. The major impetus for this science mission was the failure of DSCS-II 9431 in 1973. SCATHA's major objectives were to measure charging characteristics and increase the understanding of the relationship between the space plasma environment and spacecraft charging, and to use data gathered to develop computer models of the charging phenomenon. Throughout its operational lifetime, SCATHA experienced many ESD's which scientists studied closely. On September 22, 1982, a particularly large number of arcing events was observed. Three different satellite operational anomalies were observed that day: 1. A 2-min loss of data believed to be caused by a discharge event. 2. A filter change of state in one of the magnetic field monitors. 3. Timing errors in the plasma wave analyzer.[30]
Anik B-1	12/16/78	This satellite was Telsat Canada's first three-axis-stabilized spacecraft. The satellite had only one minor anomalous switching event attributed to spacecraft charging. The satellite did, however, experience a significant increase in the operating temperature of various components. Thermal surfaces (mirrors that radiate heat away from critical electronic components and reflect direct sunlight away from them) were degraded by localized discharges when the satellite was in eclipse.[20]
NATO-3C	11/19/78	This military communications satellite for the North American Treaty Organization experienced five attitude control anomalies similar to those experienced in NATO-3A and 3B from December 1986 to September 1987.[15]

Table 1. Spacecraft charging anomaly review (continued).

NATO-3B	11/28/77	On January 11, 1987, this military communications satellite for the North American Treaty Organization experienced three attitude control anomalies. Also in August and September of that same year, three phantom command anomalies were recorded. All these anomalies were attributed to deep dielectric charging.[15]
Meteosat-F1	11/23/77	The European Space Agency Meteorological Satellite suffered a series of anomalies throughout its operational lifetime. During the first year, 119 anomalies were recorded that interfered with the operation of the radiometer, power system, and the attitude control system. 150 anomalies were recorded in the first 3 years. These anomalies were evaluated by several researchers who concluded that they were being caused by ESD's due to spacecraft charging. Using the information gathered from Meteosat F-1, Meteosat F-2 was modified prior to launch on June 18, 1994, to eliminate some of the problems that F-1 experienced. Additionally, F-2 was equipped with instrumentation to take measurements of electrons in the energy range that could cause spacecraft charging. Although the F-2 experienced fewer but similar anomalies to the F-1, they also were caused by spacecraft charging.[31–33]
DSCS-II (9438)	5/12/77	This Air Force Defense Space Communications Satellite experienced in November and December 1986 low level logic glitches due to deep dielectric charging.[15]
DSCS-II (9442)	12/14/76	This Air Force Defense Space Communications Satellite experienced in November 1986 and March 1987 low level logic glitches due to deep dielectric charging.[15]
NATO-3A	04/20/76	This military communications satellite for the North American Treaty Organization experienced on January 11, 1987, attitude control problems due to deep dielectric charging. A bit flip error was also reported on April 4, 1990.[15]
CTS (Hermes)	01/17/76	The purpose of the Canadian-American Communications Technology Satellite was to demonstrate the technology of using a high power, high frequency transponder in conjunction with small low cost Earth terminals. Because engineers anticipated the possibility of charge buildup on the satellite, it was equipped with a transient event counter (TEC), the first known device of this type on a geosynchronous satellite. The TEC recorded 215 transient events in the wiring harnesses in the first year; 65 percent were multiple transients. Scientists concluded from these data that discharges

Table 1. Spacecraft charging anomaly review (concluded).

CTS (Hermes) (Cont.)	01/17/76	could occur at any time during the local day and that many discharges could occur within a short period of time. The satellite itself did suffer some adverse charging effects when a power diode (exposed directly to the space environment) failed causing a power bus burnout. This event occurred shortly after a moderate substorm.[34 35]
Viking Lander 1	08/20/75	This spacecraft suffered variations in its gas chromatograph mass spectrometer ion pump current due to arcing events. These prompted a modification of its atmospheric analysis experiments.[36]
Symphonie A	12/19/74	This French-German experimental communications satellite, along with its sister satellite Symphonie B launched August 27, 1975, had a history over their operational lifetimes of noncritical anomalies (i.e., modulation losses and logic upsets) attributed to arcing events.[37]
Skynet 2B	11/23/74	This satellite was part of the United Kingdom's Defense Communications Network. Shortly after launch the satellite began experiencing anomalies in the timing circuits of the telemetry and command subsystem. A systematic study of the anomalies concluded they were due to spacecraft charging. In a 2-year period, 1975 to 1976, 300 anomalies were investigated.[38]
DSCS-II (9431)	11/01/71	On June 2, 1973, the Air Force Defense Space Communications Satellite 9431 failed because power to its communications subsystem was suddenly interrupted. The review board found that the failure was due to a high energy discharge caused by spacecraft charging as a result of a geomagnetic substorm. Both 9431 and its sister spacecraft 9432 experienced a series of nuisance electronic anomalies before the failure, but nothing that would have predicted it. This incident resulted in a joint NASA and Air Force spacecraft charging investigation to evaluate and understand the spacecraft charging phenomenon. DSCS-II 9433 and 9434 were launched in 1973 and both experienced arcing anomalies, but suffered no serious consequences.[39 40]

CURRENT ACTIVITIES

Some interesting observations about spacecraft charging anomalies are as follows:

(1) The charging phenomenon, recognized for some 40 years, has been extensively studied for 20 years.[41]

(2) Although some aspects are not understood, much is known about the phenomenon.

(3) Spacecraft over the years have been designed and redesigned to reduce the effects of charging.

(4) The anomaly incidents listed in table 1 suggest that anomalous events in recent years have been, on the average, less serious and less numerous than in earlier years (as you might expect).

As illustrated in recent events with the Anik satellites, however, serious consequences from spacecraft charging continue to occur!

Much scientific and engineering work is in progress to increase the understanding of the environmental factors that cause charging, especially in high-altitude elliptical orbits where little data have been collected. Scientists also desire to obtain a better understanding of the discharge phenomenon and to study what effects new materials, such as composites, will have. Additional investigations are also underway into the computer simulation of plasma environments.

Work is also underway to develop, design, and test an active charge control system to prevent surface charge buildup on spacecraft. The U.S. Air Force plans to launch in early 1995 a prototype system aboard a DSCS satellite. Air Force officials believe their space programs will benefit through reduced life-cycle costs from the enhanced system survivability with decreases in operational disruptions and in-orbit degradation from arc-discharging.[42] Also, proposals have been made to design, develop, and test a compact, lightweight, low-power instrument package to fit to a spacecraft to monitor the space environment around a spacecraft and to provide alerts when the environment is likely to cause anomalies.[42]

Spacecraft Charging Effects Protection Plan

The NASA MSFC Electromagnetics and Environments Branch has developed a methodology to help project engineers protect against the possible detrimental effects of spacecraft charging. This methodology is outlined in a "Spacecraft Charging Effects Protection Plan" that involves defining the natural space plasma in which the spacecraft will operate and developing guidelines to reduce or eliminate the predicted detrimental effects due to spacecraft charging. A computer analysis program models the charging level of the spacecraft and determines how spacecraft charging effects interfere with mission goals and objectives (fig. 5). This analysis is particularly important if some design guidelines were excluded in favor of other design considerations. A complete set of design guidelines and recommendations tailored for a particular mission is provided in the "Spacecraft Charging Effects Protection Plan." A summary of analyses on spacecraft and a description of associated charging effects are also included in the document.

As previously mentioned, an important step in implementing a "Spacecraft Charging Effects Protection Plan" is the application of computer modeling. Three-dimensional computer programs specifically designed for this purpose are: (1) the NASA charging analyzer program for low-Earth orbit (NASACAP/LEO) used to simulate spacecraft charging of low inclination, low altitude Earth spacecraft; (2) the potentials of large spacecraft in auroral regions program (POLAR) used to model spacecraft in low altitude, polar orbit; and (3) the NASA charging analyzer program for geosynchronous orbit (NASACAP/GEO) used to model spacecraft charging by a geomagnetic substorm.

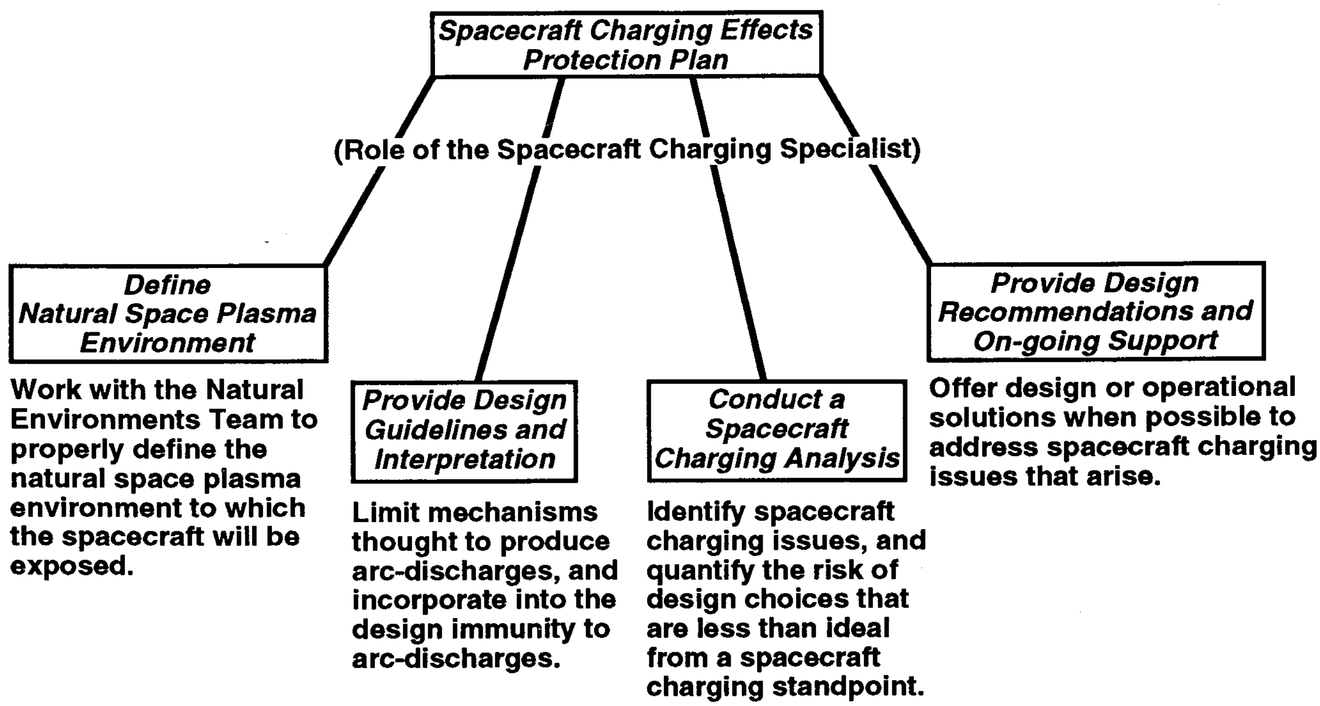


Figure 5. Spacecraft charging effects protection plan.

A NASCAP or POLAR model of a spacecraft is formed by combining various geometric shapes that attempts to simulate the spacecraft structure and by 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. Knowing if, and where, arc discharges are likely to occur allows the charging engineer to aid the project team in planning the mitigation of potential problems.

The "Spacecraft Charging Effects Protection Plan" methodology has been used successfully by the Electromagnetics and Environments Branch for the Solar X-ray Imager (SXI), Advanced X-ray Astrophysics Facility-Spectroscopy (AXAF-S), and other MSFC-managed programs.

The Branch is also currently working to analyze and solve potential charging problems on the Advanced X-ray Astrophysics Facility-Imaging (AXAF-I), Gravity Probe B (GPB), Solar Vector Magnetograph (SVM), Low-Energy Neutral Atom (LENA) Imager, Magnetosphere Imager (MI), and the *International Space Station Alpha* (*ISSA*).

CONCLUSION

The purpose of this report is to make the reader aware of the significant impact the spacecraft charging phenomenon has had in the past and will continue to have in the future. To this end, a history of known spacecraft anomalies and failures was presented. By necessity, a brief overview of the nature of the natural space plasma, the charging phenomenon, and the effects of spacecraft charging were presented to provide a background for reviewing the anomaly listings.

Also presented are current activities in spacecraft charging of the NASA MSFC Electomagnetics and Environments Branch. This Branch has taken a leadership role in modeling charging phenomenon based on a particular orbital environment and translating the results into engineering standards that spacecraft designers can readily apply.

Despite 25 years of study and research into the phenomenon of spacecraft charging, occurrences continue to jeopardize space missions, illustrated most recently by the Anik satellites. These events emphasize the importance of continuing to develop better design procedures and processes to insure that spacecraft charging effects do not compromise in-flight experiments or missions. Engineers and managers involved in the planning, designing, and operating of space missions should be aware of and concerned with the possible consequences of charging to their programs. The continuing evolution of new electronics and materials necessitates a constant study and awareness of the spacecraft charging phenomenon.

If you have any questions or comments about this report, contact the MSFC Systems Analysis and Integration Laboratory, Electromagnetics and Environments Branch, S.D. Pearson at (205) 544–2350.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1995	Reference Publication

4. TITLE AND SUBTITLE

Failures and Anomalies Attributed to Spacecraft Charging

5. FUNDING NUMBERS

6. AUTHOR(S)

R.D. Leach,* Author and M.B. Alexander, Editor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATON REPORT NUMBERS

M-791

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA RP-1375

11. SUPPLEMENTARY NOTES

Prepared by Electromagnetics and Environments Branch, Systems Analysis and Integration Laboratory, Science and Engineering Directorate.
*Computer Sciences Corporation, Huntsville, AL.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The effects of spacecraft charging can be very detrimental to electronic systems utilize in space missions. Assuring that subsystems and systems are protected against charging i an important engineering function necessary to assure mission success.

Spacecraft charging is expected to have a significant role in future space activities and programs. Objectives of this reference publication are to present a brief overview c spacecraft charging, to acquaint the reader with charging history, including illustrati cases of charging anomalies, and to introduce current spacecraft charging prevention activities of the Electromagnetics and Environments Branch, Marshall Space Flight Cente (MSFC), National Aeronautics and Space Administration (NASA).

14. SUBJECT TERMS

plasma, spacecraft charging, spacecraft, electronic systems, anomalies,

15. NUMBER OF PAGES

30

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540 - 01 - 280 - 5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18