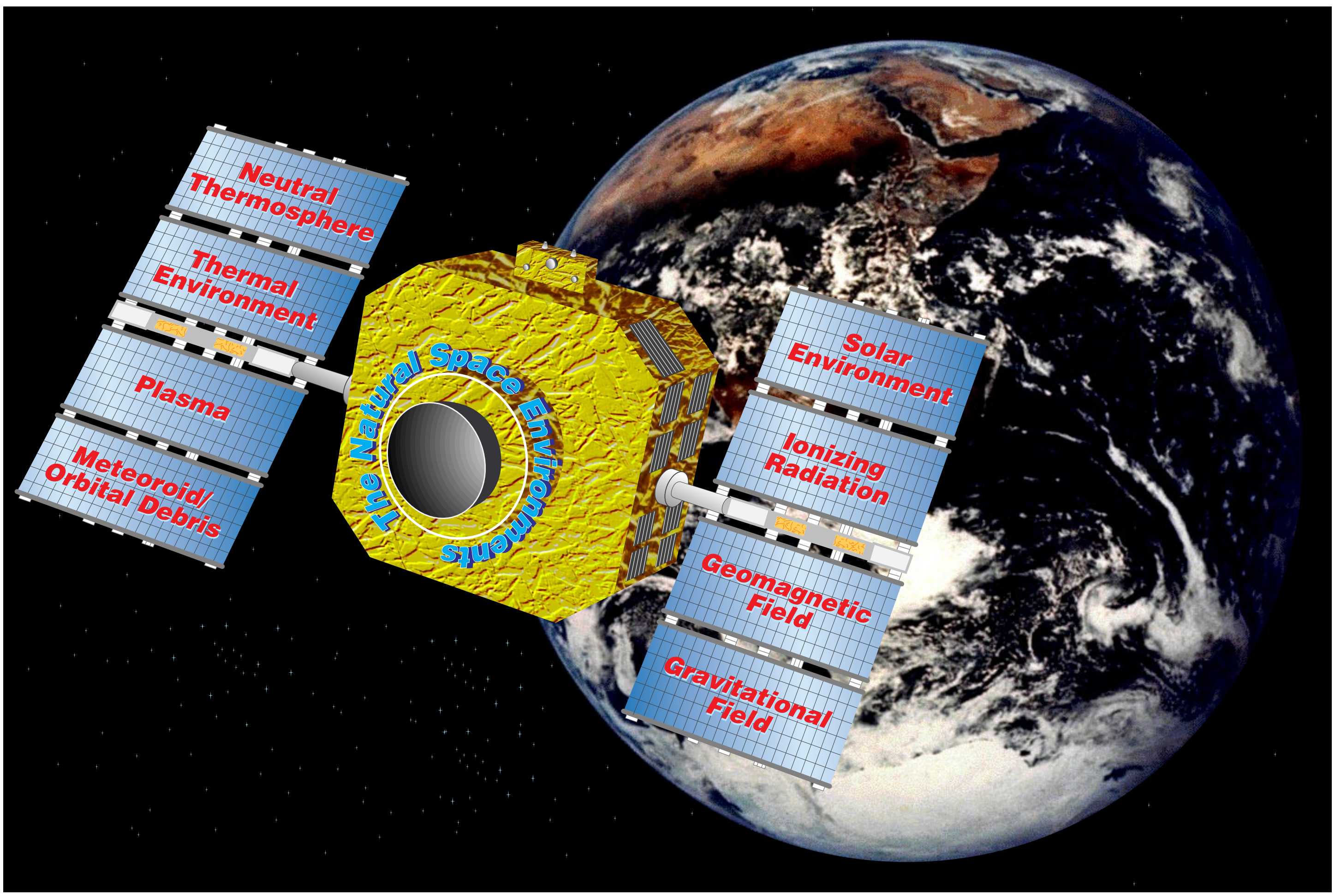
NASA Reference Publication 1390

Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment

K.L. Bedingfield, R.D. Leach, and M.B. Alexander, Editor



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PREFACE

The effects of the natural space environment on spacecraft design, development, and operation are the topic of a series of NASA Reference Publications currently being developed by the Electromagnetics and Aerospace Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center.

This primer provides an overview of seven major areas of the natural space environment including brief definitions, related programmatic issues, and effects on various spacecraft subsystems. The primary focus is to present more than 100 case histories of spacecraft failures and anomalies documented from 1974 through 1994 attributed to the natural space environment. A better understanding of the natural space environment and its effects will enable spacecraft designers and managers to more effectively minimize program risks and costs, optimize design quality, and achieve mission objectives.

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ABBREVIATIONS AND ACRONYMS

AO	atomic oxygen
CDA	command and data acquisition
CRRES	Combined Release and Radiation Effects Satellite
CTU	central telemetry unit
DC	direct current
DCPI	data collection platform interrogation
EL23	mail code for Electromagnetics and Aerospace Environments Branch
EMI	electromagnetic interference
ESA	European Space Agency
ESD	electrostatic discharge
ETS	Engineering Test Satellite
EUV	extreme ultraviolet
FGS	fine guidance system
GN&C	guidance, navigation, and control
GOES	Geostationary Operational Environmental Satellite
HST	Hubble Space Telescope
IGRF	International Geomagnetic Reference Field
IR	infrared
JSC	Johnson Space Center
kHz	kilohertz
LDEF	Long Duration Exposure Facility
LEO	low-Earth orbit
MARECS	Maritime European Communications Satellite
MJ	megajoule(s)
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense Command
NSE	natural space environment
OLR	outgoing long-wave radiation
PMT	photomultiplier tube
RAM	random access memory
SAA	South Atlantic Anomaly
SEU	single event upset
STS	Space Transportation System
TDRS	Tracking and Data Relay Satellite
USA	United States of America

REFERENCE PUBLICATION

SPACECRAFT SYSTEM FAILURES AND ANOMALIES ATTRIBUTED TO THE NATURAL SPACE ENVIRONMENT

INTRODUCTION

Purpose and Scope

Because of the significant impact the natural space environment (NSE) is likely to have in future space programs, this primer presents a brief overview of the natural space environment, illustrative case histories of spacecraft failures and anomalies attributed to the natural space environment, and associated activities of the Electromagnetics and Aerospace Environments Branch, NASA Marshall Space Flight Center. The primary focus is to catalog more than 100 case histories of spacecraft failures and anomalies that occurred from 1974 through 1994 due to the effects of the natural space environment.

The natural space environment refers to the environment as it occurs independent of the presence of a spacecraft. It includes both naturally occurring phenomena such as atomic oxygen (AO) and radiation and man-made factors such as orbiting debris. Specifically, the natural space environment includes nine environments: the neutral thermosphere, thermal environment, plasma, meteoroids and orbital debris, solar environment, ionizing radiation, geomagnetic field, gravitational field, and the mesosphere. Illustrative case histories of failures and anomalies associated with seven of these environments are reviewed and listed in the appendix.

Figures 1 and 2 break out the natural space environment into the nine major areas. For each area, specific environmental parameters of interest to spacecraft designers are cited and affected programmatic issues listed. Also shown are models and data bases used to establish environmental criteria for spacecraft design and summaries of major effects the nine areas have on major spacecraft subsystems.

Recent Case Histories

Environmental Effects on Communication Satellites

On January 20, 1994, Telsat, Canada's Anik E-1 communications satellite, suddenly began to spin out of control.[1] Two hours later its sister satellite, Anik E-2, also, without warning, began to spin out of control.[2] 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 hours. 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.

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 and 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 (GCM's)
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	MSFC EL Laboratory model, NOAA prediction data, Statistical models, Solar database
IONIZING RADIATION	Trapped proton/electron radiation, Galactic cosmic rays (GCR's), Solar particle events	Radiation levels, Electronics/parts dose, Electronics/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 95, UARS database, Mars-GRAM 3.34

Figure 1. A breakout of the natural space environments and typical programmatic concerns.

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	Materials 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	Degredation 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

Figure 2. Space environments effects on spacecraft subsystems (page 1 of 2).

SPACE ENVIRONMENT EFFECTS

	SPACE ENVIRONMENTS				
SPACECRAFT SUBSYSTEMS	**Solar Environment**	**Ionizing Radiation**	**Magnetic Field**	**Gravitational Field**	**Mesosphere**
Avionics	Thermal Design	Degradation: SEU's, 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, & Communications	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			

Figure 2. Space environment effects on spacecraft subsystems (page 2 of 2).

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.[3] In early press accounts, Telsat stated there had never been a satellite failure of this magnitude.[4] 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.[3–6] 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.

Solar-Terrestrial Phenomena

An intense period of solar activity in March 1991 initiated a sequence of major terrestrial effects that included the generation of a second inner radiation belt, satellite anomalies, and power surges on electrical power grids. The rapidly changing geophysical environment in late March was the result of a severe storm in space that began in the outer atmosphere of the Sun. A giant loop of hot ionized gas (plasma) many times larger than Earth, arched high above the solar corona, expanded slowly, gained speed, and blasted outward through interplanetary space toward the Earth.

During this powerful solar X-ray event, the sunlit ionosphere was strongly ionized; i.e., atoms had electrons ejected from their outer shells. This increase in electron density resulted in degradation of short-wave radio frequency communication. With the arrival of high energy solar radiation, a disruption in high latitude point-to-point communication occurred and solar panel degradation was evident on Geostationary Operational Environmental Satellites (GOES)-6 and -7. The GOES-7 power degradation translated to a decrease of 2 to 3 years in expected satellite lifetime. Also, the presence of high energy solar particles increased the frequency of single event upsets (SEU) recorded by spacecraft. These upsets are aberrations in analog, digital, or even power circuits caused by the interaction of a single solar particle within the circuit. Six geostationary satellites, including GOES-6 and -7, and the Tracking and Data Relay Satellite (TDRS)-1 had 37 reported single event upsets during the major part of the solar activity.

Additional problems occurred during the geomagnetic storm portion of this period. The combination of solar events mentioned previously resulted in an interplanetary magnetic shock traveling from the Sun to Earth. Within seconds of the arrival of the interplanetary disturbance, an immediate influx of electrons and protons into the Earth's magnetosphere, measured by the Combined Release and Radiation Effects Satellite (CRRES), created a second and long lasting (i.e., months) inner radiation belt.

With the arrival of the interplanetary shock and the ensuing geomagnetic disturbance, auroral sightings were reported in the Northern Hemisphere as far south as the state of Georgia, United States of America (USA), and in the Southern Hemisphere as far north as the Blue Mountain region of New South Wales, Australia. This resulted in low-latitude communication disruption as the polar ionospheric conditions extended to mid and low latitudes. Hydro-Quebec experienced several power surges in its power grid. Tripping of power relay systems and damage to electrical distribution transformers and equipment in the eastern United States and Canada caused major power outages.

In addition, a loss of automatic attitude control of the National Oceanic and Atmospheric Administration (NOAA)-11 satellite occurred, and increased satellite drag due to the heated atmosphere necessitated a massive update of the North American Air Defense Command (NORAD) catalog of orbiting objects. Of more serious consequence was the complete failure of the geosynchronous orbiting Maritime European Communication Satellite (MARECS)-1 on March 25, 1991, due to serious damage to its solar panels that occurred during this period of intense solar activity.[3]

These cases show some of the effects of the natural space environment on spacecraft and ground operations. The remainder of this primer will be devoted to additional case histories associated with the different areas of the natural space environment.

SPECIFIC ENVIRONMENTS

Neutral Thermosphere

Environment Definition

The region of the Earth's atmosphere containing neutral atmospheric constituents and located above 90 km is known as the neutral thermosphere, while that region above 600 km or so is known as the thermosphere (fig. 3). The thermosphere is composed primarily of neutral gas particles that tend to stratify based on their molecular weight. AO is the dominant constituent in the lower thermosphere, with helium and hydrogen dominating the higher regions. As figure 3 shows, the temperature in the lower thermosphere increases rapidly with increasing altitude from a minimum at 90 km. Eventually, it becomes altitude independent and approaches an asymptotic temperature known as the exospheric temperature. Thermospheric temperature, as well as density and composition, is very sensitive to the solar cycle because of heating by absorption of the solar extreme ultraviolet (EUV) radiation. This process has been effectively modeled using a proxy parameter, the 10.7-cm solar radio flux ($F_{10.7}$).

Spacecraft Effects

Density of the neutral gas is the primary atmospheric property that affects spacecraft orbital altitude, lifetime, and motion. Even though space is thought of as a vacuum, there is enough matter to impart a substantial drag force on orbiting spacecraft. Unless this drag force is compensated for by the vehicle's propulsion system, the altitude will decay until reentry occurs. Density effects also directly contribute to the torques experienced by the spacecraft due to the aerodynamic interaction between the spacecraft and the atmosphere, and thus, must be considered in the design of the spacecraft attitude control systems.

Many materials used on spacecraft surfaces are susceptible to attack by AO, a major constituent of the low-Earth orbit (LEO) thermosphere region. Due to photodissociation, oxygen exists predominantly in the atomic form. The density of AO varies with altitude and solar activity and is the predominant neutral species at altitudes of about 200 to 400 km during low solar activity. Simultaneous exposure to the solar ultraviolet radiation, micrometeoroid impact damage, sputtering, or contamination effects can aggravate the AO effects, leading to serious deterioration of mechanical, optical, and thermal properties of some material surfaces. A related phenomenon that may be of concern for optically sensitive experiments is spacecraft glow. Optical emissions are generated from metastable molecules that have been excited by impact on the surface of the spacecraft. Investigations show that the surface acts as a catalyst, thus the intensity is dependent on the type of surface material.

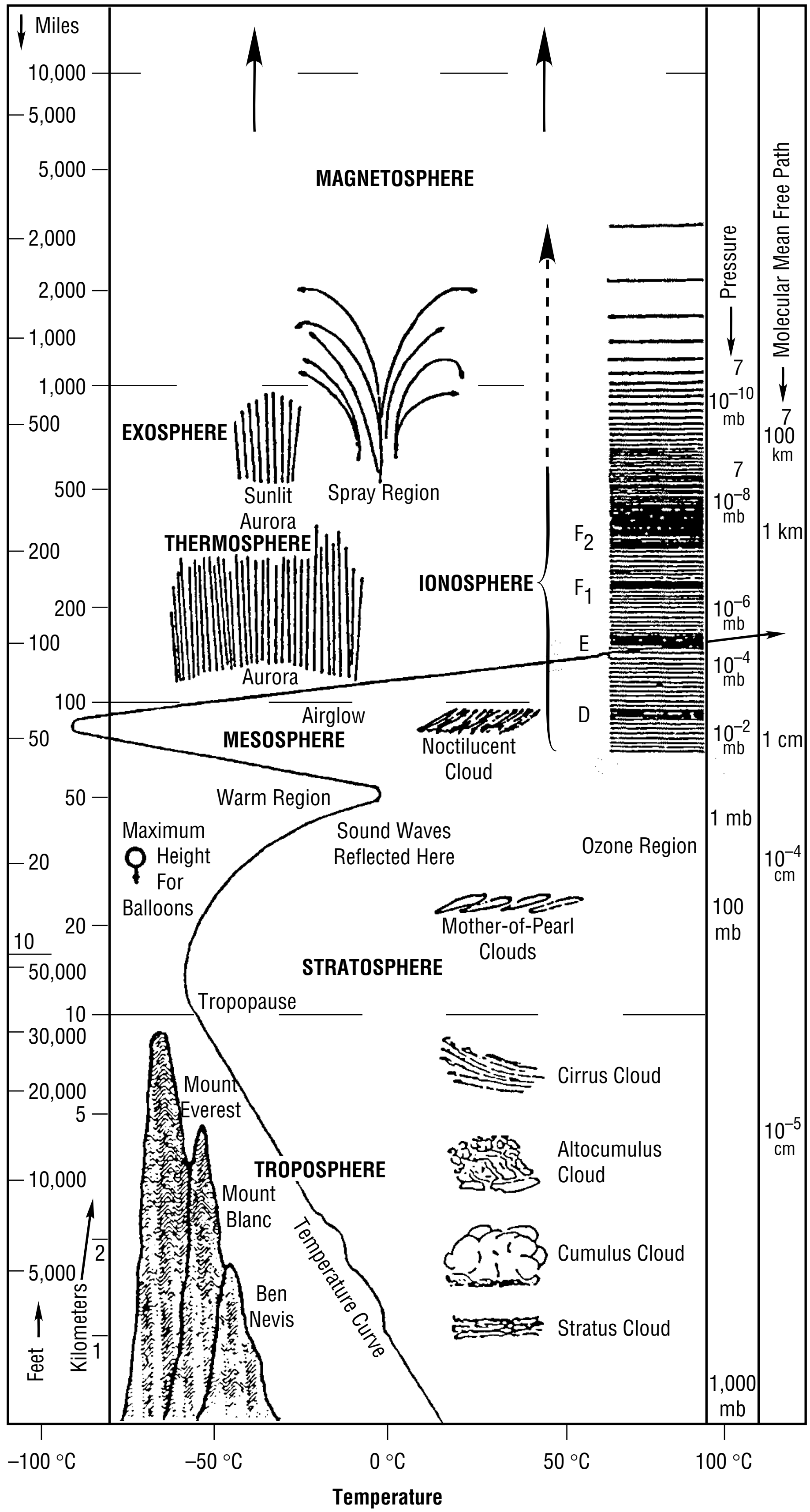

Figure 3. The layers of the Earth's atmosphere.

Representative Cases

Skylab

On July 11, 1979, *Skylab* (fig. 4) prematurely reentered the Earth's atmosphere. This orbiting laboratory, the first of its kind, experienced the density effects of the neutral thermosphere. As atmospheric drag increased, the spacecraft reached the point at which it could no longer stay in orbit, and before a rescue mission could be launched, it fell to Earth.[4]

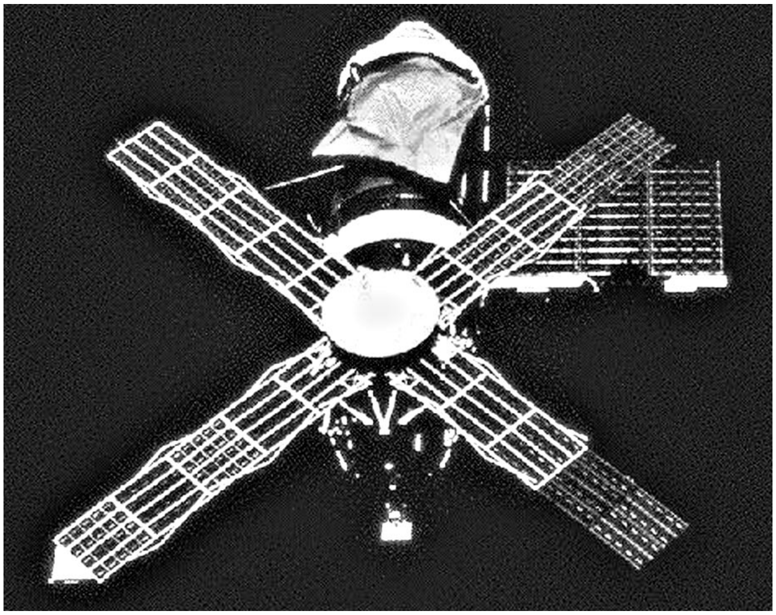

Figure 4. *Skylab*.

Long Duration Exposure Facility (LDEF)

Aluminized-polyimide Kapton™ multilayer insulation samples, located on the leading edge of the LDEF, experienced significant AO undercutting. This phenomenon, a potential threat to vulnerable spacecraft materials, causes degradation of mechanical and optical properties that affect systems performance. If the protective coating tears or curls when undercut, additional degradation to the coating may occur.[5]

These anomalies and one other associated with the neutral thermosphere are listed in the appendix.

Thermal

Environment Definition

Spacecraft may receive radiant thermal energy from three natural environment sources: (1) incoming solar radiation (solar constant), (2) reflected solar energy (albedo), and (3) outgoing longwave radiation (OLR) emitted by the Earth and atmosphere. If one considers the Earth and its atmosphere as a whole and averages over long time periods, the incoming solar energy and outgoing radiant energy are essentially in balance; the Earth/atmosphere is nearly in radiative equilibrium with the Sun. However, it is not in balance everywhere on the globe and there are important variations with local time, geography, and atmospheric conditions. A space vehicle's motion with respect to the Earth results in its viewing only a "swath" across the full global thermal profile, so it sees these variations as a function of time in accordance with the thermal time constants of its hardware systems (figs. 5 and 6).

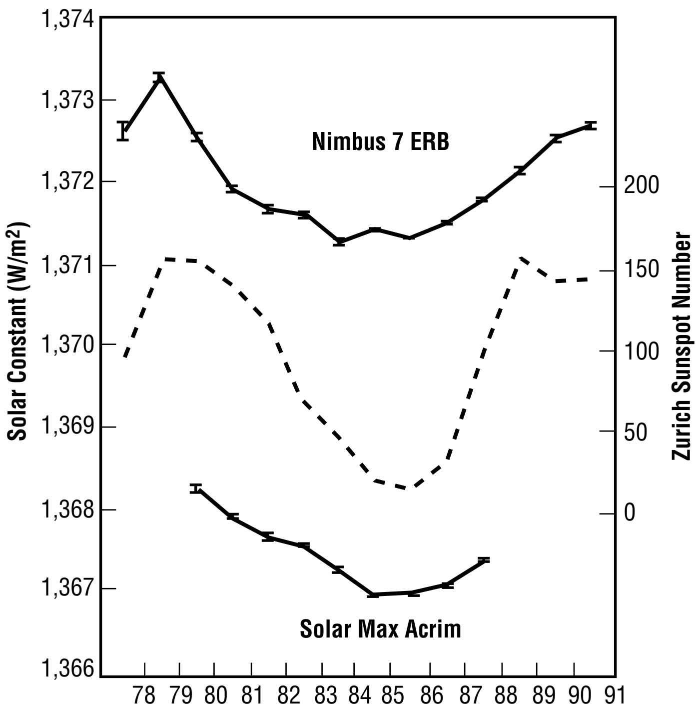

Figure 5. A sample of the solar constant measurements from an instrument on the Solar Max satellite and an instrument flying on a Nimbus satellite. (The dashed line represents the trend in sunspot number.)

Spacecraft Effects

Correct definition of the orbital thermal environment is an integral part of an effective spacecraft thermal design. This thermal environment varies over orbits and over mission lifetime, while typical temperature control requirements for spacecraft components cover a predetermined range of temperatures. Changes in temperature need to be minimized because they may lead to system fatigue. An issue frequently encountered is the ability to provide adequate capability to cool sensitive electronic systems. Temperature fluctuations may fatigue delicate wires and solder joints, promoting system failures. Also, the selection of lubricants is dependent on expected thermal conditions. Failure of lubricants to function properly can also lead to system failures. Abrupt changes in the thermal environment may cause excessive freeze-thaw cycling of thermal control fluids. Too extreme an environment may require oversizing of radiators or possibly cause permanent radiator freezing. The thermal environment is also an important factor in considering lifetimes of cryogenic liquids or fuels.

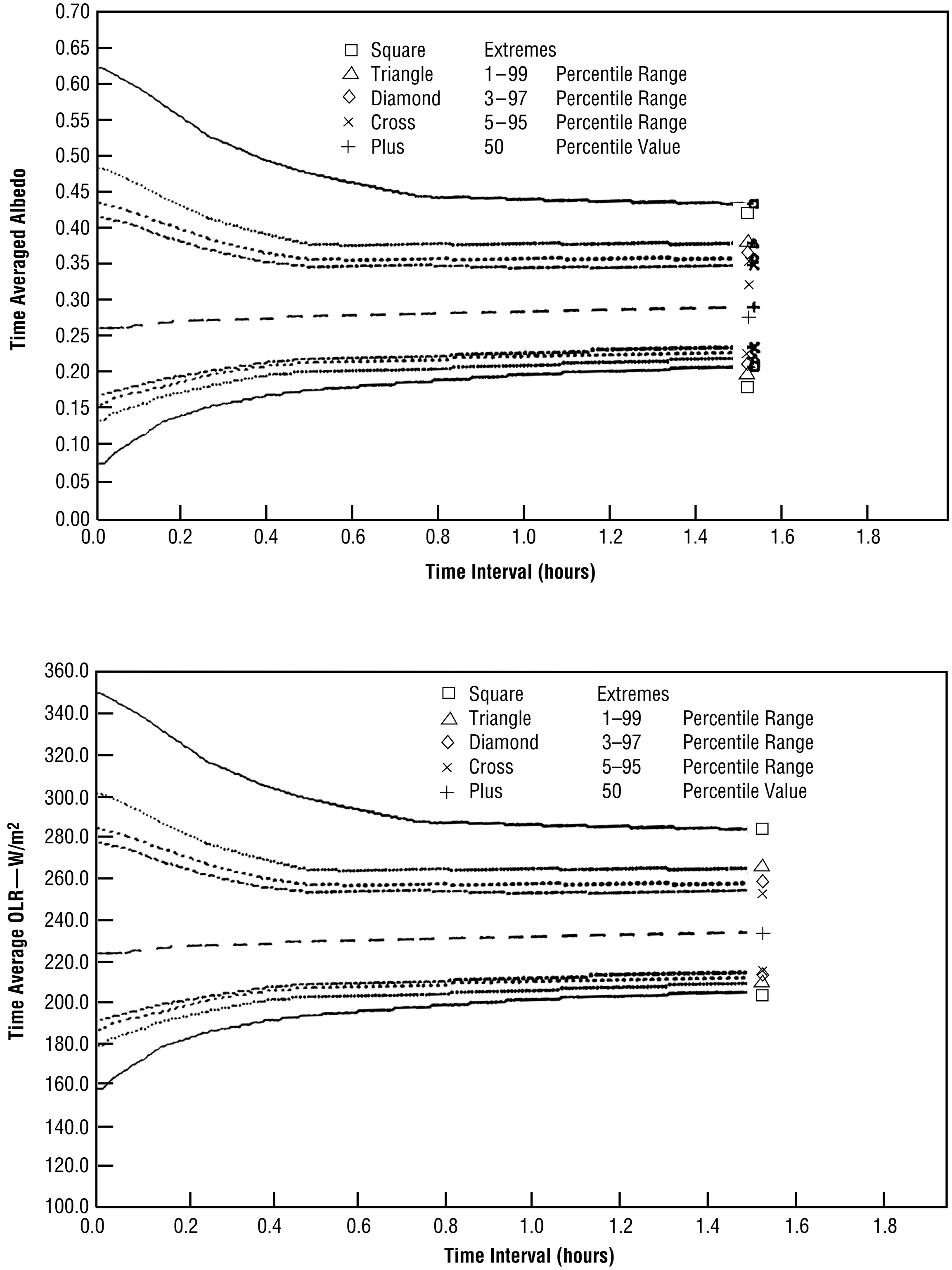

Figure 6. New engineering thermal model results for polar orbits.

Representative Cases

Hubble Space Telescope (HST)

Before the December 1993 HST service mission, the solar arrays vibrated severely each time the observatory emerged from shade into sunlight. Active vibration cancellation using the onboard gyros was implemented before the service mission to minimize the problem. Thermal expansion of the support poles (also called bistems) was blamed for the vibrations, which interfered with deep-space observations. The new arrays installed during the service mission had sleeves over the bistems to provide jitter-free imagery[7] (fig. 7).

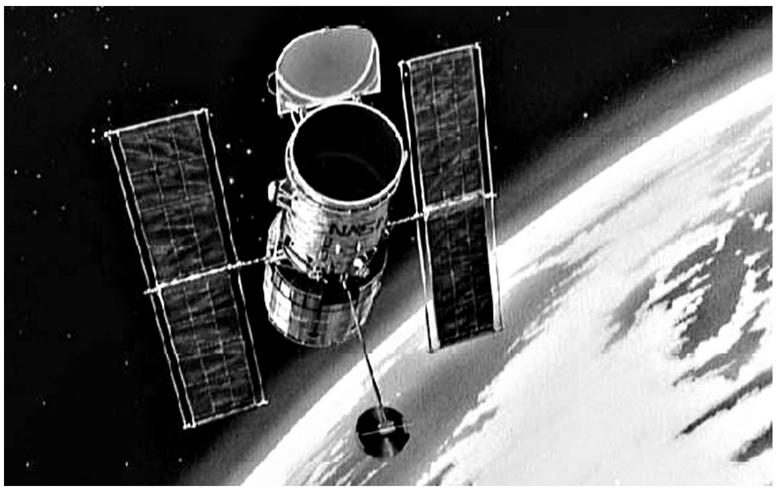

Figure 7. HST.

Galileo

Despite rigorous ground testing, the onboard antenna of the *Galileo* Jupiter probe, launched from the Space Shuttle *Atlantis*, failed to properly deploy. Operators concluded that this was due to the failure of a lubricant used on the mechanical joints to function in the ambient thermal environment. The result of this anomaly was degraded data transfer back to Earth.[8]

GOES-7

In early April 1993, a minor anomaly occurred involving the data collection platform interrogation (DCPI) system. The No. 1 S-band receiver could not acquire interrogation frequency from the command and data acquisition (CDA) station for an hour after the daily eclipse period. The receiver's frequency stability exceeded the required ±5 kHz limits, due to cold post-eclipse temperatures.[1] Although no immediate detrimental effects to the mission occurred, mission personnel were required to monitor transmissions to prevent possible data loss.

These anomalies and others associated with the thermal environment are listed in the appendix.

Plasma

Environment Definition

The major constituents of the Earth's atmosphere remain virtually unchanged up to an altitude of 90 km, but above this level the relative amounts and types of gases are no longer constant with altitude. Within this upper zone of thin air, shortwave solar radiation causes various photochemical effects on the gases. A photochemical effect is one in which the structure of a molecule is changed when it absorbs radiant energy. One of the most common of these effects is the splitting of diatomic oxygen into atoms. Another common effect is that atoms will have electrons ejected from their outer shells. These atoms are said to be ionized. A small part of the air in the upper atmosphere consists of these positively charged ions and free electrons which cause significant physical effects. The electron densities are approximately equal to the ion densities everywhere in the region. An ionized gas composed of equal numbers of positively and negatively charged particles is termed a plasma. The electron and ion densities vary dramatically with altitude, latitude, magnetic field strength, and solar activity.

Spacecraft Effects

As a spacecraft flies through this ionized portion of the atmosphere, it may be subjected to an unequal flux of ions and electrons and may develop an induced charge. Plasma flux to the spacecraft surface can charge the surface and disrupt the operation of electrically biased instruments. In LEO, vehicles travel through dense but low-energy plasma. These spacecraft are negatively charged because their orbital velocity is greater than the ion thermal velocity but slower than the electron thermal velocity. Thus, electrons can impact all surfaces, while ions can impact only ram surfaces. LEO spacecrafts have been known to charge to thousands of volts; however, charging at geosynchronous orbits is typically a greater concern. Biased surfaces, such as solar arrays, can affect the floating potential. The magnitude of charge depends on the type of grounding configuration used. Spacecraft charging may cause biasing of spacecraft instrument readings, arcing which may cause upsets to sensitive electronics, increased current collection, reattraction of contaminants, and ion sputtering which may cause accelerated erosion of materials. High-magnitude charging will cause arcing and other electrical distrubances on spacecraft (figs. 8, 9, and 10).

Spacecraft charging is presented in detail in NASA Reference Publication 1354, "Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging," and NASA Reference Publication 1375, "Failures and Anomalies Attributed to Spacecraft Charging." Also, numerous case histories of spacecraft failures and anomalies attributed to electromagnetic interference (EMI) due to the effects of spacecraft charging, are presented in detail in NASA Reference Publication 1374, "Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference."

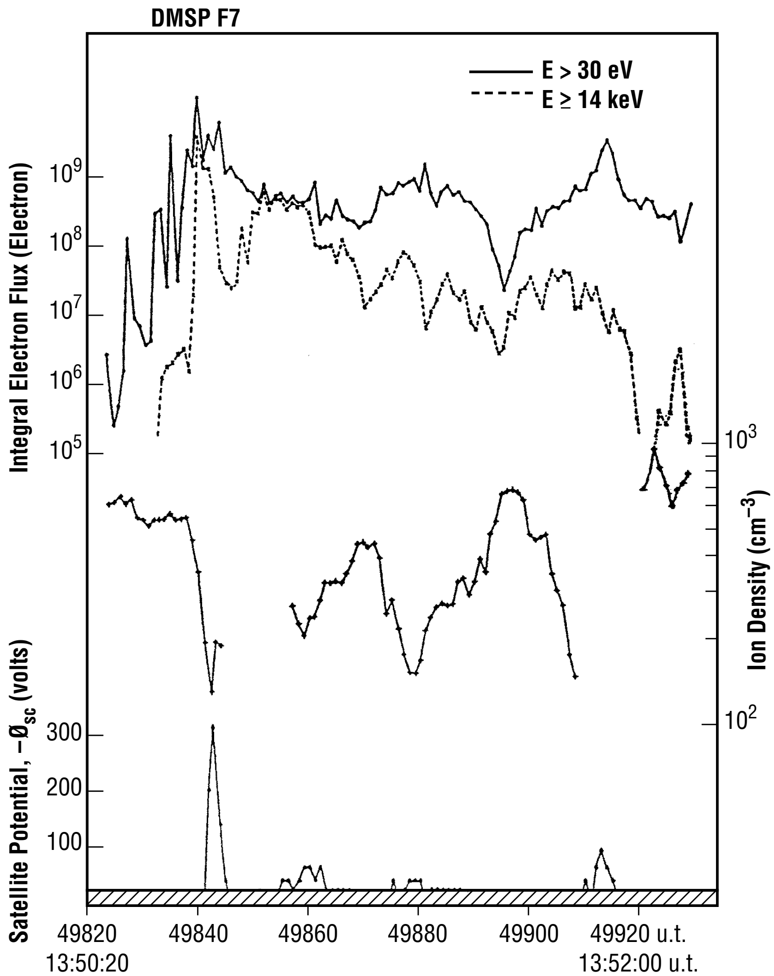

Figure 8. An example of the type of charging events encountered by the DMSP satellite F7 on November 26, 1983. DMSP 7 is a defense meteorological satellite flying LEO/polar.

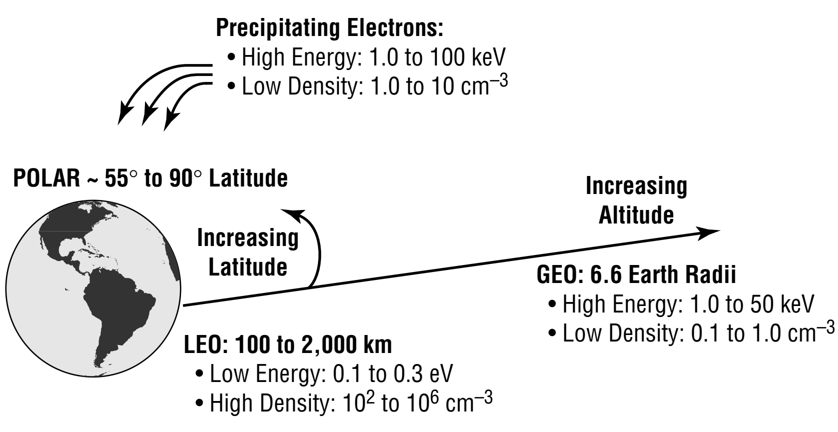

Figure 9. Properties of the natural space plasma.

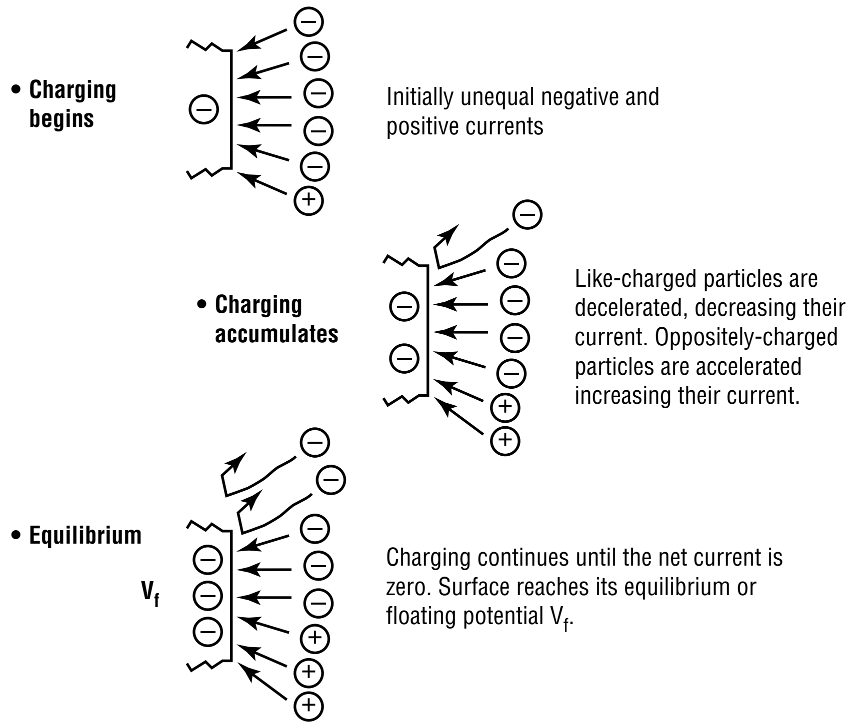

Figure 10. Cause of spacecraft charging.

Representative Case

Intelsat K

Intelsat K is one of 20 communications satellites in geosynchronous orbit owned by the International Telecommunications Satellite Organization. On January 20, 1994, the satellite experienced an electrostatic discharge resulting from the geomagnetic storm that started January 13th. The discharge disabled the momentum wheel control circuitry on the satellite, causing it to wobble and produce fluctuations in antenna coverage. After a backup system was activated, full operational status was achieved on the same day.[10] Failure to correct the wobble would have resulted in severe deterioration of data transfer, causing disruption of service for the satellite's many customers.

This anomaly and others associated with plasma and spacecraft charging are listed in the appendix.

Meteoroids/Orbital Debris

Environment Definition

The meteoroid population consists primarily of the remnants of comets. As a comet approaches perihelion, the gravitational force and solar wind pressure on it are increased, resulting in a trail of particles in nearly the same orbit as the comet. When the Earth intersects a comet's orbit, there is a meteor shower, and this occurs several times per year. The Earth also encounters many sporadic particles on a daily basis. These particles originate in the asteroid belt, and are themselves the smallest asteroids. Radiation pressure from the Sun causes a drag force on the smallest particles in the asteroid belt. In time, these particles lose their orbital energy and spiral into the Sun.

Since the beginning of human activity in space, there has been a growing amount of matter left in orbit (figs. 11 and 12). In addition to operational payloads, there exist spent rocket stages, fragments of rockets and satellites, and other hardware and ejecta, many of which will remain in orbit for hundreds of years. Currently, the U.S. Air Force Space Command tracks over 7,000 large objects (>10 cm) in LEO, and the number of smaller objects is known to be in the tens of thousands. Since the orbital debris population continually grows, it will be an increasing concern for future space operations.

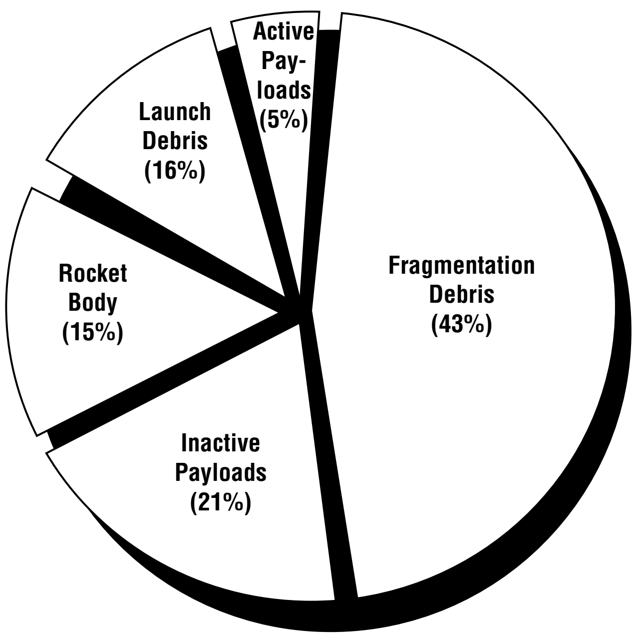

Figure 11. Sources of the catalogued debris population.

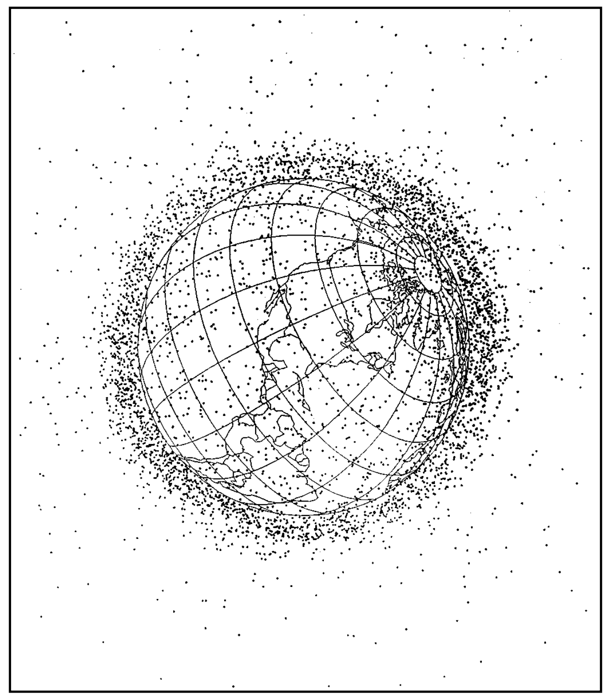

Figure 12. The state of the Earth debris environment is illustrated in this snapshot of all catalogued objects in July 1987.

Spacecraft Effects

Meteoroids and orbital debris pose a serious damage and decompression threat to space vehicles. In the orbital velocity regime, collisions are referred to as hypervelocity impacts. Such an impact, for example, by a 90-gram particle, will impart over 1 MJ of energy to the vehicle. Thus, practically any spacecraft will suffer catastrophic damage or decompression if it receives a hypervelocity impact from an object larger than a few grams. Collisions with smaller objects cause serious surface erosion with subsequent effects on the surface thermal, electrical, and optical properties. Net risk to a mission depends on the orbit duration, vehicle size and design, launch date (solar cycle phase), orbit altitude, and inclination. Protective shielding is often necessary to minimize the threat from the meteoroid/orbital debris environment. If a system cannot be shielded, operational constraints or procedures may be imposed to reduce the threat of damage. The debris threat is highly directional, so risk can also be mitigated by careful arrangement of critical components.

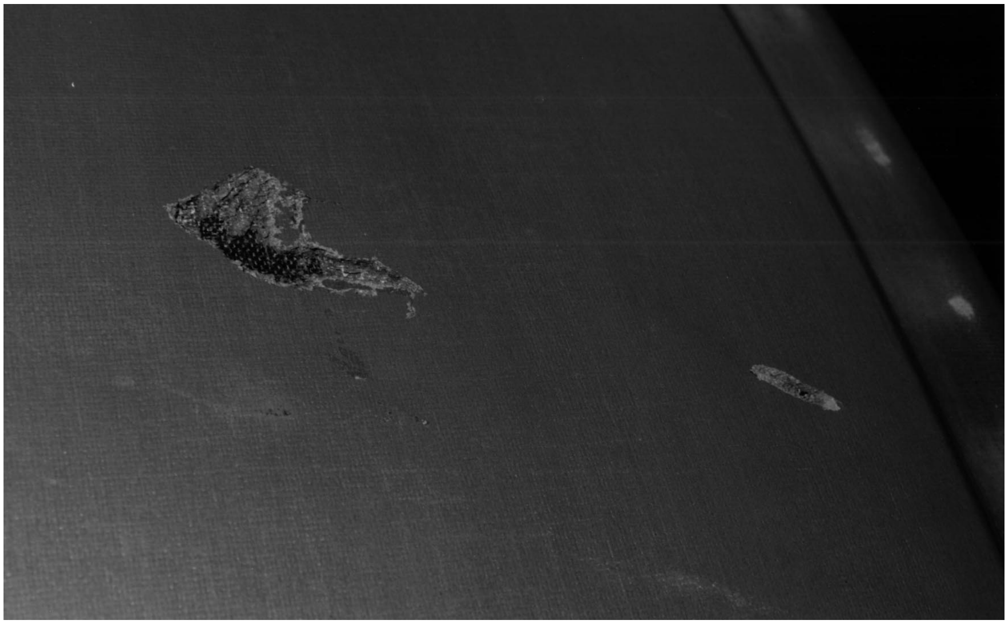

Figure 13. Orbiter *Atlantis* (STS-45) right wing leading edge gouges.

Representative Cases

Space Shuttle (STS-45)

On Space Shuttle mission STS-45, launched March 24, 1992, the orbiter *Atlantis* suffered two gouges, (1.9 by 1.6 in. and 0.4 by 1 in.), on the upper portion of the right wing leading edge (fig. 13). The most probable cause was a low-velocity (relative to the spacecraft) debris impact on orbit or during reentry. However, Johnson Space Center (JSC) engineering has not ruled out prelaunch or ascent debris as the cause of the damage. This particular event raised concern about the consequences of a higher energy impact to the integrity of the spacecraft.[11]

Shuttle Windshield Replacement

The shuttle program has had to replace 46 orbiter windshields due to impact pits (total through STS-68 launch in September 1994). While no impact has been mission critical, collected data indicate that the threat from meteoroids and orbital debris is real and must be accounted for in mission planning guidelines, flight rules, and operating procedures. NASA is currently reevaluating orbiter meteoroid and orbital debris risk-reduction strategies, including predictive modeling of impacts not only to windshields but also to radiators and other surfaces. These risk reduction strategies also include improved inspection and repair techniques and development of techniques and materials to provide better impact protection.

HST (STS-31)

After the December 1993 Hubble service mission, British Aerospace inspection of the retrieved HST array revealed that the whole wing suffered between 5000 and 6000 micrometeoroid impacts in its 4-year life. The effect of these impacts range from slight grazing to puncture of cells and blankets.[12]

KOSMOS-1275

At an altitude of 977 km on July 24, 1981, the Russian satellite Kosmos-1275 broke up into over 200 trackable fragments. Speculation is it was the result of a hypervelocity collision with a piece of space debris. This was based on the following: this type satellite has shown no capability to maneuver and may have been a gravity gradient stabilized spacecraft, no pressurized vessels or onboard propellants are standard on this type, the satellite resided in the altitude region most densely populated with debris from earlier satellite breakups, and the satellite was in a high inclination orbit (83 degrees), which suggests higher relative velocities between a satellite and the general debris population.[13]

These anomalies and others associated with meteoroids and orbital debris are listed in the appendix.

Solar

Environment Definition

The Sun emits huge amounts of mass and energy. This tremendous emission of energy has important consequences to spacecraft design, development, and operation. Over short periods of time and in certain locations, solar intensity can fluctuate rapidly. It is thought that a major factor causing these fluctuations is the distortion of the Sun’s large magnetic field due to its differential rotation. Two of the most common indicators of locally enhanced magnetic fields are sunspots and flares. Sunspots are probably the most commonly known solar activity feature. The average sunspot number is known to vary with a period of about 11 years (fig. 14). Each cycle is defined as beginning with solar minimum (the time of lowest sunspot number) and lasting until the following solar minimum. For example, cycle 22, which began in late 1986, reached solar maximum in 1991. A solar flare is a highly concentrated explosive release of energy within the solar atmosphere. The radiation from a solar flare extends from

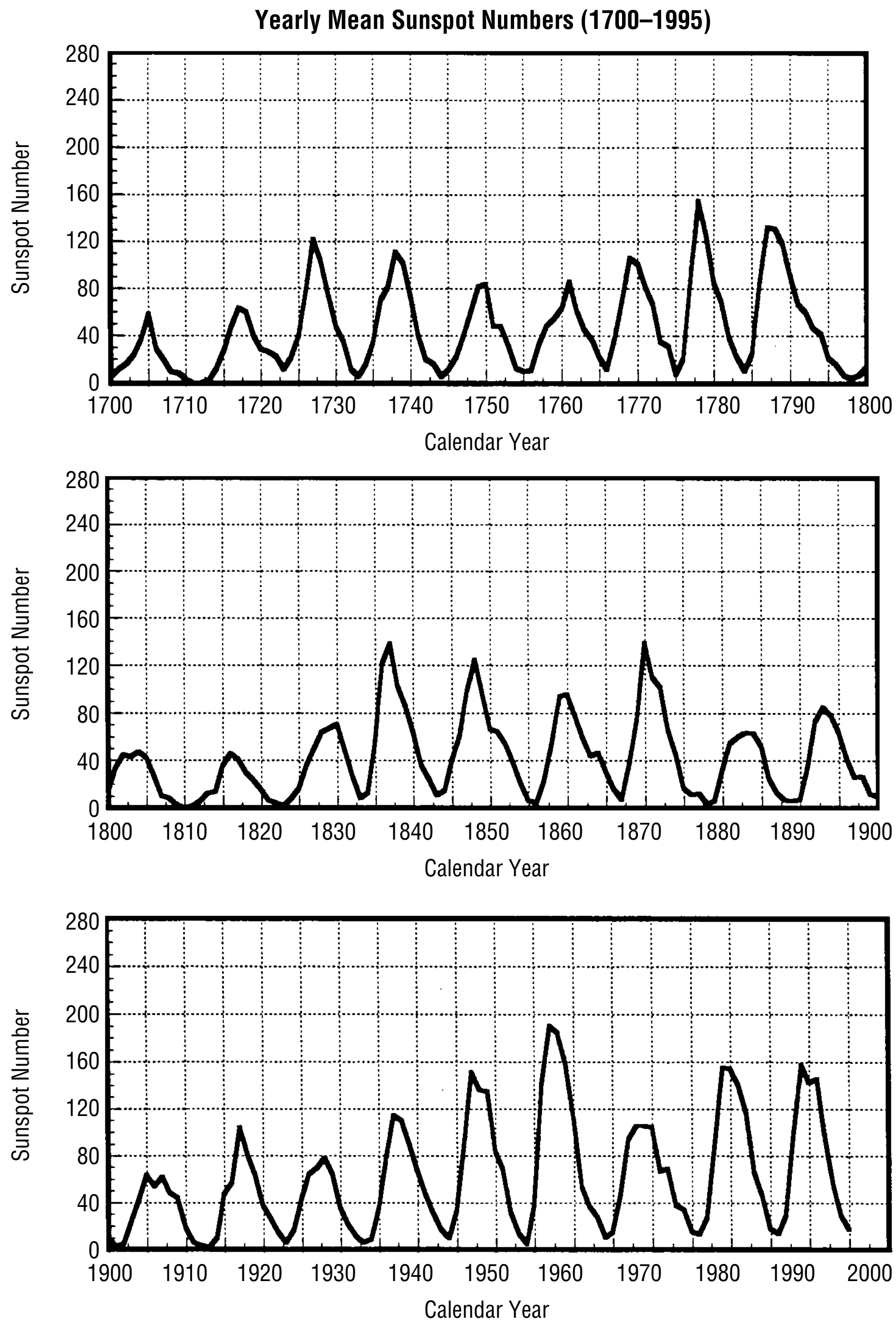

Figure 14. Solar cycle history. Of interest is that the dawn of the space age in the 1950's occurred during the "largest" cycle on record, cycle number 19. Space travel has been faced with dramatic solar cycle characteristics since that time.

radio to X-ray frequencies. Solar flares are differentiated according to total energy released. Ultimately, the total energy emitted is the deciding factor in the severity of a flare's effects on the space environment.

Spacecraft Effects

The solar environment has a critical impact on most elements within the natural space environment. Variations in the solar environment impact thermospheric density levels, overall thermal environment a spacecraft will experience, plasma density levels, meteoroids/orbital debris levels, severity of the ionizing radiation environment, and characteristics of the Earth's magnetic field. The solar cycle also plays an important role in mission planning and operations activities. For instance, when solar activity is high, ultraviolet and extreme ultraviolet radiation from the Sun heats and expands the Earth's upper atmosphere, increasing atmospheric drag and orbital decay rate of spacecraft. Solar flares are a major contributor to the overall radiation environment and can add to the dose of accumulated radiation levels and to single event phenomena that can greatly affect electronic systems.

Representative Cases

GOES-7

During a period of intense solar X-rays from March 22 to 24, 1991, researchers found evidence of solar panel degradation on GOES-7. The spacecraft is designed to accommodate a gradual decline in solar panel power output caused by the space environment. The intense high-energy radiation from this particular solar event permanently damaged solar panel electronics and caused an accelerated power degradation above design expectations that decreased the life expectancy of the satellite by 2 or 3 years.[3]

NOAA-10

On March 13, 1989, this NOAA satellite experienced excessive x-axis gyro speeds due to magnetic momentum unloading that caused the roll/yaw coil to switch into backup mode. Operators suspected the anomaly was caused by solar activity.

On October 1, 1989, a 28-volt power switch indicated an undesired "on" reading requiring controllers to reset the switch. Solar influence was determined to be a probable cause.[14]

GOES-5

The central telemetry unit (CTU) of this geostationary satellite experienced 10 SEU's during 1989, six of which were associated with solar flares. Also, a major solar flare on October 19, 1989, damaged solar array electronics and decreased by 0.5 amps current output of the array.

These anomalies and others associated with the solar environment are listed in the appendix.

Ionizing Radiation

Environment Definition

The particles associated with ionizing radiation are categorized into three main groups relating to the source of the radiation: trapped radiation belt particles, cosmic rays, and solar flare particles. Results from recent satellite studies suggest that the source of the trapped radiation belt (or Van Allen belts) particles seems to be from a variety of physical mechanisms: from the acceleration of lower-energy particles by magnetic storm activity, from the trapping of decay products of energetic neutrons produced in the upper atmosphere by collisions of cosmic rays with atmospheric particles, and from solar flares. Solar proton events are associated with solar flares. Cosmic rays originate outside the solar system from other solar flares, nova/supernova explosions, or quasars.

The Earth's magnetic field concentrates large fluxes of high-energy, ionizing particles including electrons, protons, and heavier ions. The Earth's magnetic field provides the mechanism that traps these charged particles within specific regions, called the Van Allen belts. The belts are characterized by a region of trapped protons, an inner, and outer electron belt. The radiation belt particles spiral back and forth along the magnetic field lines (fig. 15). Because the Earth's approximate dipolar field is displaced from the Earth's center, the ionizing radiation belts reach their lowest altitude off the eastern coast of South America. This means as particles travel into the region, they reach lower altitudes, and particle densities are anomalously high. This area is termed the South Atlantic Anomaly (SAA). In this document, the term "cosmic rays" applies to electrons, protons, and the nuclei of all elements from other than solar origins. Satellites at low inclination and low altitude experience a significant amount of natural shielding from cosmic rays due to the Earth's magnetic field. A small percentage of solar flares are accompanied by the ejection of significant numbers of protons. Solar proton events occur sporadically, but are most likely near solar maximum. Events may last for hours or up to more than a week, but typically the effects last 2 to 3 days. Solar protons add to the total dose and may also cause single event effects in some cases.

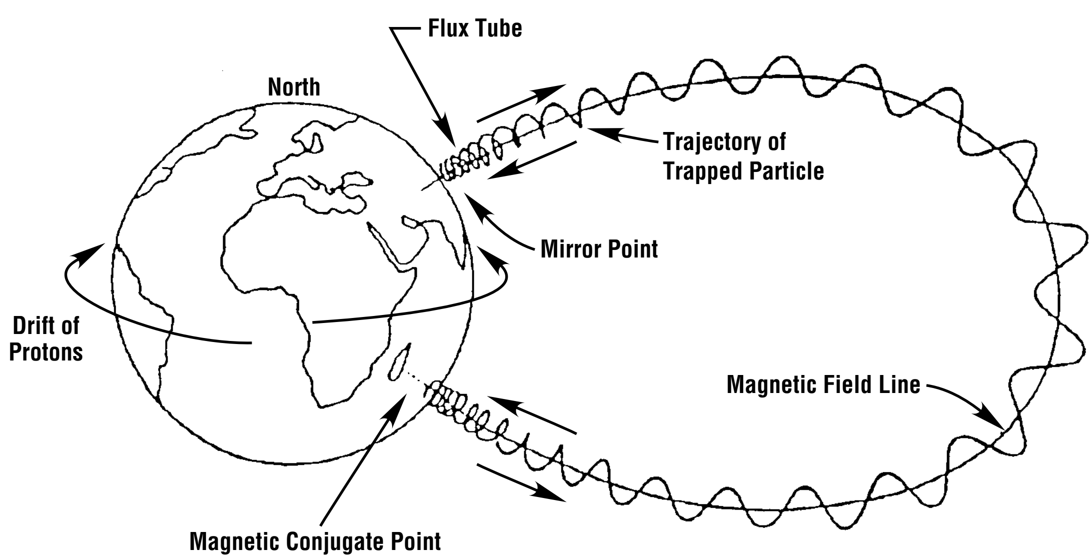

Figure 15. Trapped particles spiral back and forth along magnetic field lines.

Spacecraft Effects

The high-energy particles comprising the radiation environment can travel through spacecraft material and deposit kinetic energy. This process causes atomic displacement or leaves a stream of charged atoms in the incident particles' wake. Spacecraft damage includes decreased power production by solar arrays, failure of sensitive electronics, increased background noise in sensors, and radiation exposure to the spacecraft crew. Modern electronics are becoming increasingly sensitive to ionizing radiation.

Representative Cases

Hipparcos

After more than 3 years of efficient and successful operations, communications with the European Space Agency (ESA) Hipparcos astronomy satellite were terminated on August 15, 1993. In June 1993, the satellite experienced difficulties in communications between the ground and the onboard computer. Cause of the problem was attributed to radiation damage to certain components. After attempts to restart operations proved unsuccessful, mission operations were terminated.[15]

ETS-6

Because solar radiation reduced the effectiveness of its solar panels, Japan's Engineering Test Satellite (ETS-6) faced failure within a year. The $415-million satellite did not reach its geostationary orbit because its apogee kick motor failed to achieve proper pressure. Its 98-ft solar array was deployed on September 3, 1994, as were six antennas, including one with a 12-ft diameter dish. High radiation levels from the Van Allen belts, however, quickly eroded efficiency of the solar panels. The panels produced 5800 watts of power on deployment day, but 10 days later this dropped to 5300 watts. Projections were a power drop to 4700 watts by the end of September 1994, and below 2000 watts in a year—too low to support experiments.[16]

HST (STS-31)

On May 7, 1990, bit flips occurred in the random access memory (RAM) of the fine guidance electronics and affected the guidance system while HST was passing through the SAA. The onboard software was modified to compensate for the flips. On June 20, 1990, the SAA also caused high photo-multiplier tube (PMT) counts in the fine guidance system (FGS). This resulted in guide star acquisition failures. Subsequently, FGS use was suspended in the SAA. Both incidents are suspected to be due to increased radiation effects.[17]

These anomalies and others associated with ionizing radiation are listed in the appendix.

Geomagnetic Field

Environment Definition

The Earth's magnetic field exerts a strong influence on space environmental phenomena such as plasma motions, electric currents, and trapped high-energy charged particles. This influence has important consequences on spacecraft design and performance. The Earth's natural magnetic field comes from two sources: (1) currents inside the Earth that produce 99 percent of the field at the surface, and (2) currents in the magnetosphere. The magnetosphere is the outer region in the Earth's atmosphere where the Earth's magnetic field is stronger than the interplanetary field. The dipole is about 436-km distance from the center of the planet. The geomagnetic axis is inclined at an 11.5˚ angle to the Earth's rotational axis. The International Geomagnetic Reference Field (IGRF) predicts the Earth's equatorial magnetic field to decrease by 0.02 percent each year. The IGRF prediction of the Earth's magnetic field is shown in figures 16 and 17.

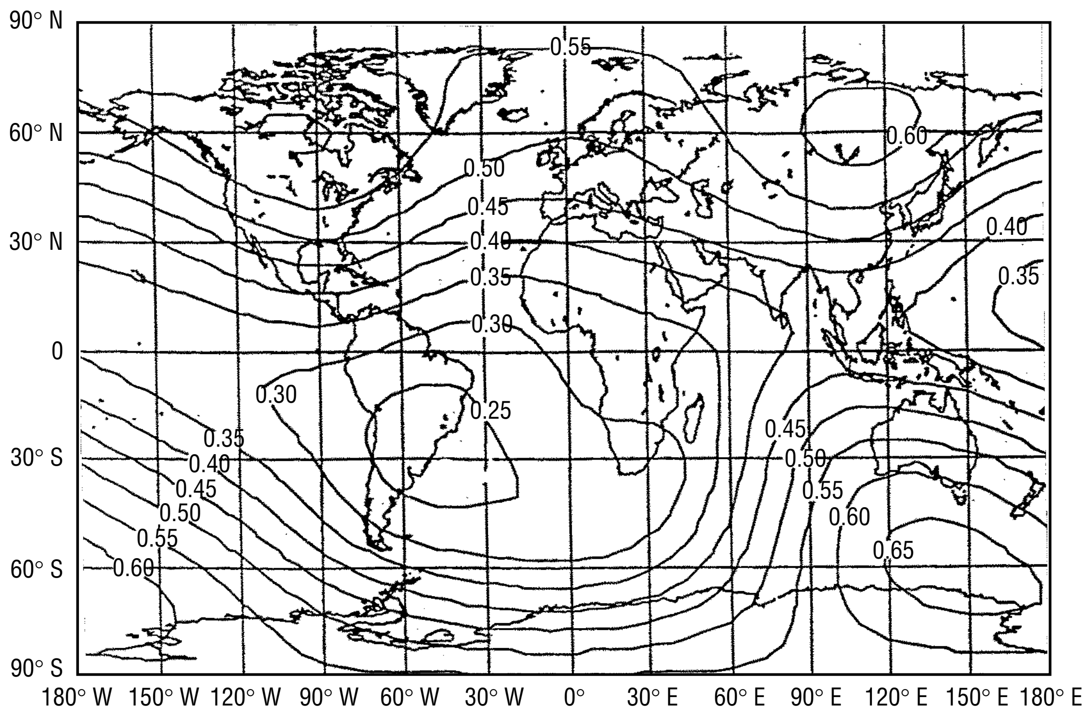

Figure 16. Geomagnetic field at sea level.

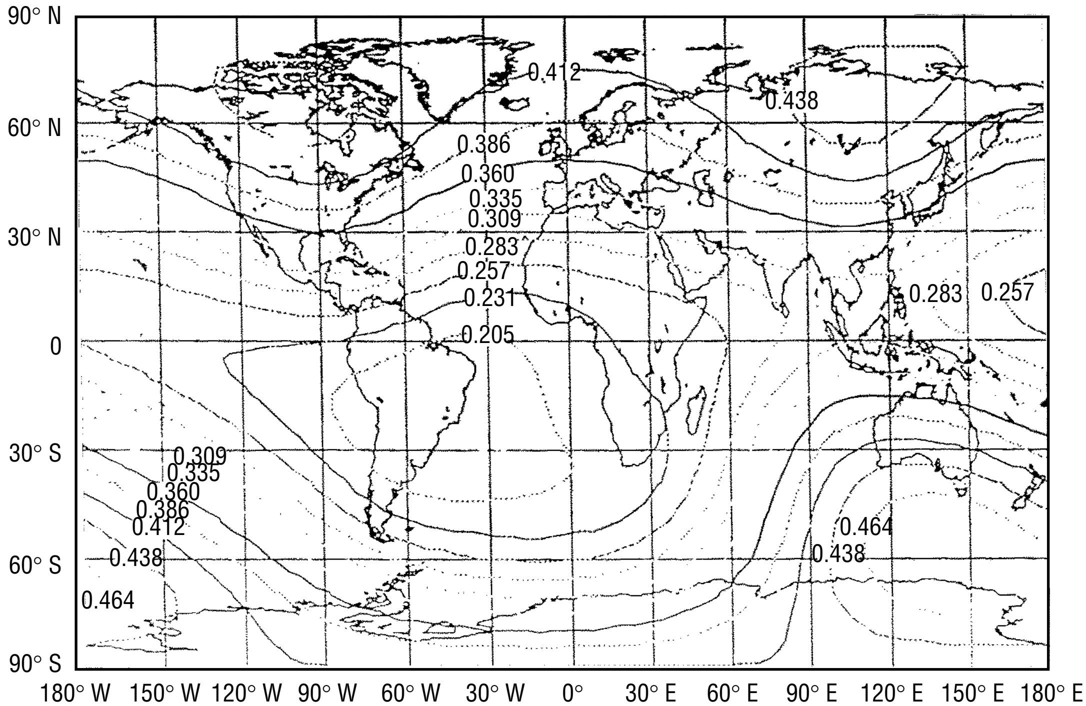

Figure 17. Geomagnetic field at 650-km altitude.

Spacecraft Effects

The geomagnetic field influences the motions of particles within the Earth's orbital environment and deflects incoming high-energy particles associated with cosmic rays. These high-energy particles may charge spacecraft surfaces, causing failure of, or interference with, spacecraft subsystems. Due to dipole field geometry, the magnetic field strength is lowest over the southern Atlantic Ocean, which leads to a higher concentration of trapped radiation in this region (figs. 16 and 17). It is in the vicinity of the SAA that a spacecraft may encounter electronics "upsets" and instrument interference. An accurate depiction of the geomagnetic field is needed to properly size magnetic torquers used in guidance, navigation, and control (GN&C) systems.

Geomagnetic storms may affect orbiting spacecraft. Disturbances in the geomagnetic field lasting one or more days are called geomagnetic storms. When a geomagnetic storm occurs, large numbers of charged particles are dumped from the magnetosphere into the atmosphere. These particles ionize and heat the atmosphere through collisions. Heating is first observed minutes to hours after the magnetic disturbance begins. Effects of geomagnetic heating extend from at least 300 km to well over 1000 km and may persist for 8 to 12 hours after the magnetic disturbance ends.

Representative Cases

Anik-B

Operation of Telsat's Anik-B satellite can be heavily influenced by the magnetospheric environment. Control of the roll and yaw of the satellite requires electromagnetic torquing coils. Direct current (DC) passed through the coils is controlled by a circuit that switches the current on with the appropriate polarity when the roll sensor output exceeds a preset threshold. The system's electromagnetic field interacts with the Earth's magnetic field to provide the necessary control torques about the roll and yaw axes. After a large disturbance in the Earth's field, especially a field reversal, these coils can drive the satellite to an increasing roll error instead of correcting it. Such an event occurred on February 8, 1986, when K-indices recorded at Anchorage, Alaska, USA, remained at eight for about 18 hours. This has occurred only twice during more than 7 years of Anik-B service. In each case, roll control was maintained using thrusters when necessary.[18]

Landsat-3

The multispectral scanner on board the Landsat-3 satellite experienced extra scan monitor pulses that caused early line starts or extra end-of-line codes. These events, attributed to magnetic anomalies, make it difficult for operators to supply high-quality, reliable images to customers.[6]

These anomalies associated with the geomagnetic field are listed in the appendix.

CONCLUSION

Documented episodes of disrupted communications, major power losses, and satellite failures show that the natural space environment has caused adverse effects in orbiting spacecraft and ground operations. Major perturbations in the near-Earth space environment have adversely affected space and ground based systems for years. Substantial research into the consequences of the natural space environment on programs and numerous case histories, emphasize the importance of continuing the development of better design procedures and processes to ensure successful in-flight experiments and missions.

Because of known effects the natural space environment has on spacecraft, this primer was prepared by the Universities Space Research Association and Computer Sciences Corporation to address concerns of the Marshall Space Flight Center's Electromagnetics and Aerospace Environments Branch, Code EL23. A brief overview of the natural space environment and illustrative case histories of anomalies attributed to this environment are presented. This primer is to reinforce the importance of proper consideration of the natural space environment, to provide a better understanding of failures, anomalies, and related cause(s), and to assist NASA engineers and program managers in effectively minimizing program risks and costs, optimizing design quality, and achieving mission objectives. As use of composite materials and smaller, faster electronincs increases, spacecraft systems are becoming more complex and susceptible to the potentially catastrophic effects of the natural space environment. Also, tighter program budgets and closer public scrutiny make mission failures not an option.

If you have questions or comments, contact the MSFC Systems Analysis and Integration Laboratory, Steven D. Pearson at 205–544–2350.

REFERENCES

1. “Orbital Anomalies in Goddard Spacecraft for CY 1992.” Office of Flight Assurance, Goddard Space Flight Center, October 1993.

2. Knapp, B.: “Telsat Ponders Using Thrusters To Salvage Anik.” *Space News*, vol. 5, No. 5, January 31–February 6, 1994, p. 1.

3. Shea, M.A., Smart, D.F., Allen, J.H., and Wilkinson, D.L.: “Spacecraft Problems in Association with Episodes of Intense Solar Activity and Related Terrestrial Phenomena During March 1991.” IEEE Transactions in Nuclear Science, vol. 39, December 1992.

4. Tribble, A.C.: “Spacecraft Interactions with the Space Environment.” AIAA 33rd Aerospace Sciences Meeting and Exhibit, January 9–12, 1995, Reno, NV.

5. De Groh, K.K., and Banks, B.A.: “Atomic Oxygen Undercutting of Long Duration Exposure Facility Aluminized-Kapton Multilayer Insulation.” Journal of Spacecraft and Rockets, vol. 31, No. 4, July–August 1994, pp. 656–664.

6. “Analysis of Spacecraft On-Orbit Anomalies and Lifetimes.” Goddard Space Flight Center, February 10, 1983.

7. Carts, Y.A.: “Astronomers Report Benefit of Hubble Fix.” *Laser Focus World*, September 22, 1994, pp. 15–17.

8. Freeman, M.T.: “Spacecraft On-Orbit Deployment Anomalies: What Can be Done?” IEEE AES *Systems Magazine*, April 1993, pp. 3–15.

9. Hughes, D.: “Telsat Succeeds in Anik E2 Rescue.” *Aviation Week & Space Technology*, July 4, 1994, p. 32.

10. “Electromagnetic Storm Hits Intelsat Satellite.” *Space News*, vol. 5, No. 5, January 31–February 6, 1994, p. 3.

11. STS-45 In-Flight Anomaly Report.

12. Hempsell, M.: “Hubble Array Impacts.” *Spaceflight*, vol. 36, November 1994.

13. McKnight, D.: “Determining the Cause of a Satellite Fragmentation: A Case Study of the Kosmos 1275 Breakup.” 38th Congress of the International Astronautical Federation, Brighton, United Kingdom, October 10–17, 1987.

14. Elsen, W.G.: “Orbital Anomalies in Goddard Spacecraft for CY 1989.” Office of Flight Assurance, Goddard Space Flight Center, July 1990.

15. "ESA Bulletin." August 1993, No. 75, p. 14.

16. "Solar Radiation Strikes Another Blow to ETS-6." *Aviation Week & Space Technology*, October 3, 1994, p. 66.

17. Elsen, W.G.: "Orbital Anomalies in Goddard Spacecraft for CY 1990." Office of Flight Assurance, Goddard Space Flight Center, September 1991.

18. Wadham, P.N.: "The Effects of Electrostatic Discharge Phenomena on Telesat's Domestic Communications Satellites." Satellite Engineering Group, Telesat Canada, pp. 25-1 to 25-5, November 1992.

BIBLIOGRAPHY

Herr, J.L., and McCollum M.B.: “Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging.” NASA Reference Publication 1354, Marshall Space Flight Center, November 1994.

James, Bonnie F., Norton, O.A., Jr., and Alexander, M.B.: “The Natural Space Environment: Effects on Spacecraft.” NASA Reference Publication 1350, Marshall Space Flight Center, November 1994.

Leach, Richard D., and Alexander, M.B.: “Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference.” NASA Reference Publication 1374, Marshall Space Flight Center, July 1995.

Leach, Richard D., and Alexander, M.B.: “Failures and Anomalies Attributed to Spacecraft Charging.” NASA Reference Publication 1375, Marshall Space Flight Center, August 1995.

Wong, Yan Chun: “Satellite Anomalies and Electrostatic Surface Discharges.” Thesis, Naval Post Graduate School, Monterey, California, September 1991.

APPENDIX

As part of the efforts of the MSFC Electromagnetics and Aerospace Environments Branch to make engineers and managers aware of the importance of the space environment, a list of documented anomalies and failures attributed to the natural space environment is presented in this appendix to illustrate the consequences of ignoring the environment.

The anomalous incidents listed are intended as a representative list—not a complete one—of the nature and severity of problems caused by the natural space environment. 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. Only included are those instances investigators felt sufficient evidence existed to attribute the anomaly to the space environment. If a particular anomaly cause was listed as unknown or the spacecraft unidentified, the event was not included. In some cases, a listed incident may illustrate a design or operational accommodation to the effects of the environment. While these are not anomalies per se, they illustrate the importance of environmental effects.

Not all anomalies listed herein caused catastrophic failure of subsystem or mission. In many cases these anomalies required the reloading of memories, tolerating noisy data, switching to redundant systems, reissuing command sequences, and updating real-time attitude control commands. All these “small” anomalies, however, require additional operating costs which in the current climate of better, cheaper, faster could jeopardize funding for future projects. Furthermore, a series of “small” anomalies increases the chances for more significant problems. Any anomaly or series of anomalies carries the potential of turning into serious problems. Hence a goal of mission managers should be to hold to a minimum all anomalous events attributed to the natural space environment.

SPACECRAFT FAILURES AND ANOMALIES DUE TO THE NATURAL SPACE ENVIRONMENT

Record Layout:
Spacecraft **Type of Anomaly** Launch Date

Anomaly Description

Type Code:
P-Plasma/**M/OD**-Meteroid & Orbital Debris/**N-** Neutral Thermosphere/**R**-Radiation/**S**-Solar/**T**-Thermal / **G**-Geomagnetic

Telstar 401 **P** 12/16/93
On October 9, 1994 this AT&T communications satellite experienced a 1-hour disruption in service due to an electrostatic discharge that caused ground controllers to briefly lose stabilization of the satellite [1] .

Intelsat K **P** 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 electrostatic discharge resulting from a geomagnetic storm that had started on January 13th. 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 [2].

Anik E-1 **P** 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 electrostatic discharge 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 hours [3,4].

Anik E-2 **P** 04/04/91
About 2 hours 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 electrostatic discharge. 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 [3].

BS-3A **P** 08/28/90
This Japanese Broadcasting satellite suffered a 60-minute telemetry outage on February 22, 1994 due to an electrostatic discharge [2,5,6].

GMS-4 (Himawari 4) **P** 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 electrostatic discharges [7].

FY-1 (FENGYUN-1) **P** 06/09/88
This Chinese experimental weather satellite failed after 39 days in orbit. It has been postulated that an electrostatic discharge caused a failure of the attitude control system ending the mission [7,8].

AUSSAT-A3 **P** 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 [7].

FLTSATCOM 6071 **P** 03/26/87
This satellite was part of Fleet Satellite Communications constellation of satellites utilized by the US Navy, US 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 [7].

GOES-7 **P** 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 1987-89 that resulted in phantom commands [7,9].

AUSSAT-A2 **P** 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. 33 such events have occurred from May 1986 to June 1990. These events were reported due to electrostatic charging [7].

AUSSAT-A1 **P** 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 [7].

Intelsat 511 **P** 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 [7].

Telecom 1B **P** 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 electrostatic discharges coupling with exposed electrical wiring [10].

Intelsat 510 **P** 03/22/85

In August 1993 this International Telecommunications Satellite communications satellite experienced an electrostatic discharge that affected the attitude control system and produced various uncommanded status changes [7].

Arabsat 1-A **P** 02/08/85

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 electrostatic discharges [7,11].

Anik D2 (ARABSAT 1D) **P** 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 eight hours 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 [12].

AMPTE/CCE **P** 08/16/84

The Active Magnetic Particle Tracer Experiment/Charge Composition Explorer was an international program (U.K., Germany, and the US) 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 [13].

Telecom 1A **P** 08/04/84

This French telecommunications satellite experienced frequent electrostatic discharges 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 electrostatic discharges [10,14].

GMS-3 (Himawari 3) **P** 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 electrostatic discharges [7].

GOES-6 **P** 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 electrostatic discharges [7,15].

TDRSS **P** 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 [16,17].

DSCS-III (4524) **P** 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 [7].

MARECS-A **P** 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 [18,19].

SBS 1 **P** 11/15/81

Soon after the launch of this Satellite Business Systems telecommunications satellite, it began to experience electrostatic discharges affecting the attitude control electronics. This satellite experienced hundreds of events over an eight year period [7].

GOES-4 **P** 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 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 [20,21].

GPS 5118 **P** 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 electrostatic discharge [6].

DSCS-II (9443) **P** 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 [7].

SCATHA(P78-2) **P** 01/30/79

The Spacecraft Charging at High Altitude satellite was launched by the US Air Force in an elliptical orbit 185 x 43905 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 electrostatic discharges 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-minute 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 [22].

Anik B-1 **P** 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 [12].

NATO-3C **P** 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 [7].

NATO-3B **P** 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 [7].

Meteosat -F1 **P** 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 electrostatic discharges 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 [23,24,25].

DSCS-II (9438) **P** 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 [7].

DSCS-II (9442) **P** 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 [7].

NATO-3A **P** 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 [7].

CTS (Hermes) **P** 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% were multiple transients. Scientists concluded from this data that discharges 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 [26,27].

Viking Lander 1 **P** 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 [28].

Symphonie A **P** 12/19/74

This French-German experimental communications satellite, along with its sister satellite Symphonie B launched 8/27/75, had a history over their operational lifetimes of non-critical anomalies (i.e., modulation losses and logic upsets) attributed to arcing events [29].

Skynet 2B **P** 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, 1975-76, 300 anomalies were investigated [30].

DSCS-II (9431) **P** 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 [31,32].

SEDS-2 **M/OD** 03/10/94

This Small Expendable Deployer Satellite (SEDS) deployed a tether some 20 km in length. On the fourth day after launch, the tether was severed by particle impact ending the experiment prematurely [62].

MSTI-2 **M/OD** 05/8/94

On 9/5/94 contact was lost to this Miniature Sensor Technology Integration (MSTI) satellite. While the actual cause of the failure may never be known, the failure assessment and follow-up indicated that probability existed for the failure to have been caused by orbital debris impact to a wire bundle causing an electrical short. There was also the possibility that spacecraft charging caused the failure. One proposed failure mechanism suggested that the debris impact allowed charge that had been stored in the Teflon™ coating on the wire to discharge causing a transient current that damaged the satellite beyond repair [67].

SAMPEX **M/OD** 07/03/92

In mid-August 1993, the door of the Heavy Ion Large Telescope (HILT) instrument was closed for a few hours while the spacecraft was exposed to the Perseid Meteor Shower. No known meteor hits were encountered by the spacecraft [33].

STS-45 **M/OD** 03/24/92

The Space Shuttle *Atlantis* suffered two gouges, (1.9 in × 1.6 in and 0.4 in × 1 in), on the upper portion of the right wing leading edge. It has been determined that the most probable cause was a low velocity (relative to the spacecraft) debris impact on-orbit or during re-entry. However, JSC Engineering has not ruled out prelaunch or ascent debris as being the cause of the damage. This particular event raised concern about the consequences of a higher energy impact to the integrity of the spacecraft [64].

STS-49 **M/OD** 05/07/92

The crew documented a chip in the upper right hand corner of the thermal window pane. The crew reported that impact occurred on or around flight day 8 [34].

Solar A (Yohkoh) **M/OD** 08/30/91

This Japanese Solar x-ray telescope mission satellite experienced a micrometeoroid hit on the thin film membrane covering its optical system. This impact caused a 0.05 mm hole that resulted in the loss of the visual portion of the telescope [63].

HST (STS-31) **M/OD** 04/24/90

In order to protect the Hubble Space Telescope (HST) from any possible damage during the annual Perseid Meteor Shower (mid-August, 1993), it was placed in an attitude that minimized the possibility of damage. The solar arrays were also adjusted to minimize their exposure to possible meteors. Apparently no meteor hits were encountered [33].

HST (STS-31) **M/OD** 04/24/90

British Aerospace inspection of the old HST array indicated that the whole wing suffered between 5000 and 6000 micrometeoroid impacts in its four year life. The effect of these impacts range from slight grazing to the puncture of the cells and blankets [35].

***Mir* SS** **M/OD** 02/19/86

The Russian space station Mir has had chronic power shortages due, primarily, to its aging solar panels, which have been battered over the years by tiny meteorites, space debris and atomic oxygen particles [36].

KOSMOS-1275 **M/OD** 06/04/81

Kosmos-1275 broke up into over 200 trackable fragments on 7/24/81 while at an altitude of 977 km. It has been highly speculated that this was the result of a hypervelocity collision with a piece of space debris. This conclusion was based on the following factors: This type of satellite has not shown any capability to maneuver and may have been a gravity gradient stabilized spacecraft. It appears that no pressurized vessels or onboard propellants are standard on these types of Soviet satellites. The satellite resided in the altitude region most densely populated with debris from earlier satellite breakups. The satellite was in a high inclination orbit (83 degrees), which suggests higher relative velocities between a satellite and the general debris population [37].

ISEE-1 **M/OD** 10/22/77

The detector window of this low energy cosmic ray experiment aboard the International Sun Earth Explorer (ISEE) was punctured due to micrometeroid impact. This resulted in a 25% data loss. (No dates were given) [38].

ANIK-B **G** 12/16/78

The operation of Telsats' ANIK-B satellite can be heavily influenced by the magnetospheric environment. This involves the control of the roll and yaw of the satellite by electromagnetic torquing coils. These are coils about the roll and yaw axes through which DC current is passed and controlled by a circuit which switches the current on with the appropriate polarity when the roll sensor output exceeds a preset threshold. The systems electromagnetic field interacts with the earth's magnetic field to provide the necessary control torques about the roll and yaw axes. Where there is a large disturbance in the earth's field, especially a field reversal, these coils can drive the satellite to an increasing roll error instead of correcting it.

Such an event occurred on 2/8/86, when the k-indices recorded at Anchorage remained at 8 for about 18 hours. This type of event has occurred only twice over the more than 7 years that ANIK-B has been in service. In each case, roll control was maintained, using thrusters if necessary [39].

Landsat-3 **G** 03/05/78

The multispectral scanner on board the Landsat-3 satellite experienced extra scan monitor pulses that caused early line starts or extra end-of-line codes. These events occurred over magnetic anomalies. (No dates were given) [38].

LDEF (STS-41C) **N** 04/06/84

An aluminized-polyimide Kapton™ multilayer insulation sample was located on the leading edge of the Long Duration Exposure Facility (LDEF) and was subjected to low Earth orbit atomic-oxygen undercutting [40].

Landsat-3 **N** 03/05/78

Landsat-3 experienced degradation to onboard sensors which was attributed to contamination from residual gas molecules. This resulted in the loss of IR data. (No dates were given) [38]

Skylab **N** 05/14/73

On 7/11/79 Skylab re-entered the earth's atmosphere prematurely as the result of atmospheric drag [41].

ETS-6 **R** 08/28/94

Japan's Engineering Test Satellite-6 (ETS-6) could fail within a year because solar radiation has reduced the effectiveness of its solar panels. The $415-million satellite was unable to reach its geostationary orbit when its apogee kick motor failed to achieve proper pressure. Its 98-ft. solar array was deployed on 9/3/94, as were its six antennas, including one with a 12 ft. diameter dish. But high radiation levels from the Van Allen belt are quickly eroding the efficiency of its solar panels. They produced 5,800 w. of power on 9/3/94, but 10 days later this dropped to 5,300 w. Projections are that power will drop to 4,700 w. by the end of September 1994 and could be below 2,000 w. in a year—too low to support experiments [42].

STS-61 **R** 12/02/93

On 12/6/93 the Y star tracker failed to acquire navigation stars for approximately 5 hours. Following a power cycle, the star tracker successfully passed a self test and functioned nominally for the remainder of the mission. The cause of the failure is believed to be a single event upset. The time noted for the beginning of the anomalous behavior of the tracker coincides with the Orbiter passing through the South Atlantic Anomaly (SAA), an area of high radiation. The high altitude flown on STS-61 resulted in increased radiation exposure when compared with flights at lower altitudes [43].

TDRS-6 **R** 01/13/93

On 7/10/93 this Tracking and Data Relay Satellite (TDRS) Earth Sensor Assembly A Pitch Channel output cautioned at 0/.3199 deg. for one update period. The cause was probably due to a single event upset (SEU) in Command and Telemetry Electronics (CTE) buffer [33].

EUVE **R** 06/07/92

In early November 1993 the Extreme Ultra Violet Explorer (EUVE) satellite experienced a "clam-up" (all detector doors shut). This was probably caused by a SEU. Things were restored to normal in four hours. Later that same month another suspected SEU occurred in the Central Data Processor (CDP) which put the payload into a pre-launch mode (i.e. Ion Pumps On). Systems were restored to normal the same day with no damage done [33].

TDRS-5 **R** 08/02/91

On 8/10/91 an apparent SEU-event on this tracking and data relay satellite caused a control sensor parameter to momentarily exceed its caution limit. This "pitch glitch" was probably caused by hit in the CTE buffer [44].

TDRS-5 **R** 08/02/91

On 12/12/93 normal mode outputs from the Control Processing Electronics (CPE) on this tracking and data relay satellite went into disabled state, with numerous Attitude Control System (ACS) parameters out of limits. The cause was determined to most likely be a SEU in the CPE processor [33].

ERS-1 **R** 07/17/91

A Precision Range and Range Rate Equipment (PRARE) instrument failed on this European Space Agency Remote Sensing Satellite (ERS) following a transient high current event. The failure was found to have occurred close to the center of the South Atlantic Anomaly. Ground tests showed certain memories to be sensitive to proton induced latch-ups. It was concluded that the failure was due to latch-ups during exposure to South Atlantic Anomaly protons. This is believed to be the first time a verified proton-induced latch-up in space was reported [45].

CRRES **R** 07/25/90

Analysis of SEU data from the Chemical Realease Radiation Effects Satellite (CRRES) Microelectronics Package Space Experiment (MEP) from 7/27/90 to 3/26/91 showed that upsets were observed each orbit with the 93422 and 93L422 bipolar random access memories (RAM) being the most sensitive devices [46].

HST (STS-31) **R** 04/24/90

On 5/7/90 bit flips occurred in the RAM of the Fine Guidance Electronics when the telescope was passing through the South Atlantic Anomaly (SAA) which affected the guidance system. On 6/20/90 the SAA caused high photomultiplier tube (PMT) counts in the fine guidance system. This resulted in guide star acquisition failures. Both incidents were suspected to be due to increased radiation effects [47].

HST (STS-31) **R** 04/24/90

On 7/4/91 six of the telescopes' status monitors failed in the SAA due to possible radiation damage [44].

HST (STS-31) **R** 04/24/90

On 12/9/93 the Data Interface Unit-2 (DIU-2), 'A' side presented faulty telemetry readings for specific HST parameters. The suspected cause was radiation damage [33].

Hipparcos **R** 08/08/89

Communications with the European Space Agency (ESA) Hipparcos astronomy satellite was terminated on 8/15/93 after more than three years of efficient and successful operations. At the end of June 1993, the satellite experienced further difficulties in communications between the ground and the onboard computer. This was attributed to radiation damage to certain components. Attempts to restart operations proved unsuccessful, and mission operations were terminated [48].

TDRS-4 **R** 03/13/89

On 5/8/89 a possible SEU caused an Earth Sensor Assembly (ESA) roll output alarm [49].

TDRS-4 **R** 03/13/89

On 8/1/93 telemetry indicated erratic ACS data and the spacecraft slowly started to diverge from earth pointing. The cause was determined to be an SEU in one of the control processing or command and telemetry chips [33].

TDRS-4 **R** 03/13/89

On 8/26/93 an earth sensor assembly roll & pitch "glitch" occurred lasting 2 seconds which caused ESA "Fail-Safe" to occur. One possible cause was suspected to be an SEU [33].

GOES-7 **R** 02/26/87

In early June 1988, the first and only SEU anomaly occurred on Geostationary Operational Environmental Satellite - 7 (GOES-7) when the REPLY BUS switched uncommanded from A to B channel in the Central Telemetry Unit (CTU-1) [50].

ERBS **R** 10/05/84

On 11/1/84 the Earth Radiation Budget Satellite (ERBS) experienced radiation that caused bit changes in block (delta time) section of both command memories. Ther were 142 "hits" recorded to date [51].

ERBS **R** 10/05/84

On 7/22/93 anomalous changes occurred in chips located in the in Command. Storage Memory. It was believed that these chips were susceptible to noise and radiation [33].

AMPTE/CCE **R** 08/16/84

On 9/11/84 the magnetometer of the Active Magnetic Particle Traces Explorer/Charge Composition Explorer (AMPTE/CEE) Satellite changed modes on 4 occasions. Operators determined these incidents to be due to external radiation "hits".

17 temperature measuring devices also failed on this satellite. evidence indicates that these failures were due to radiation [51].

AMPTE/CCE **R** 08/16/84

In April 1988 the Command Processor System (CPS) No. 1 failed, resulting in a switch to CPSNo. 2 by the operators. The cause of this failure is thought to be the failure of a CMOS PROM, caused by cumulative radiation damage after over 3.5 years in orbit [50].

UOSAT-2 **R** 03/02/84

SEUs occured in large dynamic NMOS and static CMOS memories on-board this low altitude, polar orbiting satellite. The strong localization of these upsets to the South Atlantic region lead to the conclusion that the majority of the upsets were caused by nuclear reactions involving energetic radiation-belt protons encountered in the South Atlantic Anomaly [52].

GOES-6 **R** 04/28/83

On 7/7/84 This satellite experienced the loss of pulse code modulated telemetry due to an SEU. This was a first time occurrence time occurrence on GOES-6 [51].

GOES-6 **R**
04/28/83
On 3/9/88 the telemetry system of the satellites was permanently degraded due to an SEU. Five SEU's had preceded this one, all being corrected by ground command. The degradation consisted of the loss of several analog and digital channels [50].

TDRS-1 **R**
04/04/83
The systematic recording of Single Event Upsets on TDRS-1 from 1984 to 1990 allowed correlations to be drawn between those upsets and the space environment. During the transfer orbit, the first anomalous responses were observed in the Attitude Control System (ACS). These anomalies were traced to state changes in the Random Access Memory (RAM) in the ACS caused by SEUs. The most serious ACS anomalies were considered mission-threatening by operators because they could cause the satellite to tumble. Ground control was required to maintain the satellite's proper attitude [53].

TDRS-1 **R** 04/04/83
On 11/2/89 command processor electronics of this tracking, data, and relay satellite had a probable SEU, causing temporary loss of attitude control [49].

TDRS-1 **R** 04/04/83
On 4/1/92 the Control Processing Electronics (CPE) stopped running due to CPE/CTE sync failure. Operators felt that the most likely cause was an SEU in the CPE chip [54].

INSAT-1 **R** 04/10/82
From 9-13-87 to 4-26-88 this satellite experienced a total of 6 bit flip errors most likely due to radiation [55].

DE-1 **R** 08/03/81
At the beginning of 1982 the Dynamic Explorer (DE-1) satellite was operating in a slightly degraded mode due to failure of the high voltage power supply on the High Altitude Plasma Indicator (HAPI). Probably the most significant anomaly was the effect of periodic "radiation" hits which caused periodic "glitches" in spacecraft operations [56].

DE-1 **R** 08/03/81
There was an unexplained 7 to 10 watt power increase on spacecraft bus and apparent loss of microprocessor in the command and telemetry processor due to radiation "hits" impinging spacecraft clock, etc.(No dates were given) [38].

SMM **R** 02/14/80
A possible SEU reported on the Solar Maximum Mission (SMM) in 1985 caused an anomaly in the On Board Computer (OBC), placing the spacecraft in a "safe hold" condition that interrupted science data for 8 days [57].

SMM **R** 02/14/80
In early January 1986 there were some "safe-holds" during spacecraft operation due to problems in the OBC . Evidence indicates that 8K of memory (out of 48K total) was lost due to "hard hits" by cosmic rays [58].

SMM **R** 02/14/80
The C Gyro failed due to the transient radiation susceptibility of complementary MOS semi-conductors in the electronics. Control was regained and the B Gyro was used. (No dates were given) [38].

NIMBUS-7 **R** 10/24/78
A digital data channel became noisy and went into saturation. Operators speculated on the possibly that high energy particles caused electrical component damage [54].

Voyager-1 **R** 09/05/77
An on board clock lost 8 seconds due to 40 spurious power-on reset signals which were probably caused by Jovian radiation. (No dates were given) [38].

Voyager-1 **R** 09/05/77
Star tracker #2 could not be commanded into cone angle settings 3, 4 or 5. Possibly due to transistor leakage caused by 2 or more Delrin insulating sleeves decomposing due to high intensity radiation. (No dates were given) [38].

ATS-6 **R** 05/30/74
On this American Test Satellite (ATS) the heat pipe gas reservoir ran hotter than normal due to degradation of the second surface mirrors (optical solar reflectors) that cover the reservoir's radiation. No dates were given) [38].

GPS 9521 **R**
From 1-30-87 to 7-5-90 this global positioning satellite experienced a total of 62 bit flip errors [55].

GPS 9783 **R**
From 12-27-84 to 7-1-90 this global positioning satellite experienced a total of 113 bit flip errors [55].

GPS 9794 **R**
From 1-13-85 to 8-6-90 this global positioning satellite experienced a total of 123 bit flip errors [55].

GOES -7 **S** 02/26/87
During a period of intense Solar x-rays which occurred from March 22 to 24, 1995, researchers found evidence of solar panel degradation. This power degradation translated to a 2 to 3 year decrease in the expected life of the satellite [61].

NOAA-10 **S** 09/17/86
On 3/13/89 this National Oceanic and Atmospheric Agency (NOAA) satellite experienced excessive x-axis gyro speed after magnetic momentum unloading. This caused the roll/yaw coil to switch to backup mode. Operators suspected the anomaly was caused by solar activity.

On 10/1/89 the SCU 28 volt switch power indicated an on reading. Command line glitch or solar influence was the possible cause [49].

NOAA-9 **S** 12/12/84
High solar activity in mid-March 1989 caused unusual momentum wheel activity that resulted in the roll/yaw coil switching to its backup mode. However, proper attitude control was maintained throughout the event. The mid-March high solar activity also affected NOAA-10 and NOAA-11 in the same way [49].

NOAA-7 **S** 06/23/81
Magnetic coil unloadings were not completely effective. This was attributed to higher than expected torque from solar pressure. (No dates given) [38].

GOES-5 **S** 05/22/81
The Central Telemetry Unit (CTU) experienced ten SEU's during 1989, six of which were associated with solar flares. A major solar flare on 10-19-89 degraded the solar array by about 0.5 amps [49].

GOES-5 **S** 05/22/81
Solar array output dropped abruptly due to high level solar particle event. (No date given) [38].

Meteosat 6 **T** 11/20/93
This European meteorological satellite (Meteosat) has experienced continuing problems with its radiometer. Operators feel that the problem is caused by ice forming on the instrument and contaminating the optical surfaces [65].

JERS-l **T** 02/11/92
The Radar antenna failed to deploy in this Japanese Earth Resources Satellite (JERS). It was determined that cold welding of the deployment pins due to faulty lubrication caused the failure [66].

HST (STS-31) **T** 04/24/90
Before the December 1993 service mission, the solar arrays vibrated severely every time the observatory emerged from shade into sunlight. Active vibration cancellation using the gyros had been implemented before the mission to minimize the problem. Thermal expansion of the support poles (also called bistems) was blamed for the vibrations, which interfered with observations [59].

HST (STS-31) **T** 04/24/90
On 5/1/90, a low frequency vibration manifested itself. This vibration was determined to be thermally induced, involving the solar array during the transition from day to night and night to day. This anomaly affected gyro operations [47].

Galileo **T** 10/18/89
Despite rigorous ground testing, the on board antenna of the *Galileo* Jupiter probe, launched from the Space Shuttle *Atlantis*, failed to properly deploy. Operators concluded that the failure was due to the failure of a lubricant used on the mechanical joints. This resulted in degraded data transfer back to Earth [66].

GOES-7 **T** 02/26/87
In early April 1993 there was a minor anomaly involving the Data Collection Platform Interrogation (DCPI) System. The No. 1 S-Band Receiver could not acquire interrogation frequency from the Command and Data Acquisition (CDA).

Station for an hour after the daily eclipse period. It was found that Receiver's frequency stability exceeded the required +/- 5 KHz limits, due to cold post-eclipse temperatures [60].

Insat IB **T** 08/31/83
The solar sail failed to deploy on this Indian communication satellite launched from the Space Shuttle *Challenger.* The failure was due to thermal binding of the deployment mechanism caused by failure of the lubricant [66].

Landsat-4 **T** 07/16/82
Power cables on two of the four solar arrays failed. The problem began as an intermittent power loss in one of the four cables on 3-18-83. By mid-May, one cable had failed and a second was intermittent. The cause of the problem was attributed to stresses in the conductors due to thermal cycling. By 6-5-83, the second array had also failed [56].

MAGSAT **T** 10/30/79
This spacecraft suffered the loss of star camera data for periods of 30-40 minutes due to direct sunlight on the sides of the sunshades that penetrated their black plastic skin. (No date given)[38].

NIMBUS-7 **T** 10/24/78
Unexpected high temperature of the Coastal Zone Color Scanner cooler door and cone occurred. Operators concluded this could have been caused by a higher earth albedo in orbit than was simulated during design. (No date given) [38].

IUE **T** 01/26/78
The on-board computer of the International Ultraviolet Explorer experienced a 4k and 8k memory crash, due to possible faulty thermal design. (No date given) [38].

Landsat-2 **T** 01/22/75
Array current notching was attributed to sets of parallel solar cells with intermittent electrical connections in an area of probable high temperature. (No date given) [38].

Appendix References

1. *The Space Review*, Airclaims, October 25, 1994, p. ATLAS 5/D

2. "Electromagnetic Storm Hits Intelsat Satellite," Space News, Vol. 5, No 5, January 31-February 6, 1994, p. 3.

3. Knapp, Bill, "Telsat Ponders Using Thrusters To Salvage Anik," *Space News*, Vol. 5, No. 5, January 31- February 6, 1994, p. 1.

4. Hughes, David, "Telsat Succeeds in Anik E2 Rescue," *Aviation Week & Space Technology*, July 4, 1994, p. 32.

5. "Mobile Satellite Reports," Vol. 15, No. 12, June 21,1991

6. *The Space Review*, Airclaims, September 21, 1994, p. N&H 4/B.

7. Spacecraft Anomaly Database, Version. ANOM5I, National Geophysical Data Center, Solar-Terrestrial Physics Division, Boulder CO, March 1994.

8. Garret, Henry, Berry, "The Charging Of Spacecraft Surfaces," *Reviews of Geophysics and Space Physics*, Vol. 19, No. 4, November, 1981, p. 577-616.

9. Elsen, William, G., *Orbital Anomalies in Goddard Spacecraft for CY 1989*, Assurance Requirements Office, Office of Flight Assurance, NASA Goddard Space Flight Center, July 1990.

10. *DBS News*, Phillips Publishing Co.. February 1, 1988.

11. Lenorovitz, Jeffrey, M., "Arabsat Communications Satellite Experiences Cryo-Control Problems," Aviation Week & Space Technology, March 25, 1985, p. 22.

12. Wadham, P., N., " *The Effects of Electrostatic Discharge Phenomena on Telsat's Domestic Communications Satellites*," *AGARD, The Aerospace Environment at Altitude and Its Implications for Spacecraft Charging*," 1987, p. 21-18.

13. Shockley, Edward, F., *Orbital Anomalies in Goddard Spacecraft 1984*, Assurance Requirements Office, Office of Flight Assurance, NASA Goddard Space Flight Center, September 1985.

14. *The Space Review*, Airclaims, October 25, 1994, p. ARIANE 3/A.

15. Elsen, William, G., *Orbital Anomalies in Goddard Spacecraft for CY 1986*, Assurance Requirements Office, Office of Flight Assurance, NASA Goddard Space Flight Center, April 1987.

16. Garret, H., and Whittlesey, "Environment Induced Anomalies on the TDRSS and the Role of Spacecraft Charging," 28th Aerospace Sciences Meeting, January 8-11, Reno, Nevada.

17. Orbital Anomalies in Goddard Spacecraft annual reports prepared for the System Reliability and Safety Office, NASA Goddard Space Flight Center, 1983-1993.

18. Capart, J., J., and Dumesnil, J., J., "The Electrostatic Discharge Phenomena on Marces-A," *ESA Bulletin*, No. 34, May 1983, p. 22-27.

19. Frezet, M., et.al., "Assessment of Electrostatic Charging of Satellites in the Geostationary Environment," *ESA Journa*l, Vol. 13, No. 2, 1989, p.89-116.

20. Farthing, Winifred, H., Brown, James, P., and Bryant, William, C., *Differential Spacecraft Charging on the Geostationary Operational Environmental Satellites*, NASA Technical Memorandum 83908, Goddard Space Flight Center, Greenbelt Maryland, March 1982.

21. Shockley, Edward, F., *Orbital Anomalies in Goddard Spacecraft 1982-1983*, Assurance Requirements Office, Office of Flight Assurance, NASA Goddard Space Flight Center, July 1984.

22. Koons, Harry, C., and Gorney, David, J. "Relationship Between Electrostatic Discharges on Spacecraft P78-2 and the Electron Environment," *Journal of Spacecraft and Rockets*, Vol. 28, No. 6, November-December 1991, p. 683-688.

23. Hodge, D., and Leverington, D., "Investigation of Electrostatic Discharge Phenomena on the Meteosat Spacecraft," *ESA Journal*, Vol. 13, 1979, p. 101-113.

24. Frezet, M., et.al., “Assessment of Electrostatic Charging of Meteosat Satellite in the Geostationary Environment,” *IEEE Transactions on Nuclear Science*, Vol. 35, No. 6, 1988, p. 1400-1406.

25. Sims, Andrew, J., *Electrostatic Charging of Spacecraft in Geosynchronous Orbit*, Defense Research Agency Tech. Memo SPACE 389, Fambough, Hampshire, U.K., December 1992.

26. Stevens, N., John, “Preliminary Report on the CTS Transient Event Counter Performance through the 1976 Spring Eclipse Season,” *Proceedings of the Spacecraft Charging Technology Conference*, NASA Lewis Research Center, February, 1977, p.81-105.

27. Gore, J., Victor, “Design Construction and Testing of the Communications Technology Satellite Protection Against Spacecraft Charging,” *Proceedings of the Spacecraft Charging Technology Conference*, NASA Lewis Research Center, February, 1977, p.773-787.

28. Bloomquist, Charles, and Graham, Winifred, *Analysis of Spacecraft On-Orbit anomalies and Lifetimes*, NASA Contract NAS-27229, NASA Goddard Space Flight Center, February 10,1983.

29. Dechezelles, J.,J., “ Some Knowledge of Dynamics and Space Materials Derived from InFlight Performance of Symphonie Satellites,” *International Astronautics Federation International Astronautics Congress*, *27th*, Anaheim, CA, October 10-16, 1976.

30. Robbins, A., and Short, C., D., “Space Environmental Effects in the SKYNET 2B Spacecraft,” *Proceedings of the Spacecraft Charging Technology Conference*, NASA Lewis Research Center, February, 1977, p.853-863.

31. Inouye, George, T., “Spacecraft Charging Anomalies on the DSCS II Launch 2 Satellites,” *Proceedings of the Spacecraft Charging Technology Conference*, NASA Lewis Research Center, February, 1977, p. 829-852.

32. Stevens, N., John; Rosen, Alan, and Inouye, George, T., “Communication Satellite Experience in the Seventies,” *AIAA 25th Aerospace Sciences Conference*, Reno, Nevada, January, 1987.

33. “Orbital Anomalies in Goddard Spacecraft for CY 1993,” Office of Flight Assurance, Goddard Space Flight Center, June 1994.

34. “STS-49 In-Flight Anomaly Report, # STS-49-V-36.

35. Hempsell, M., “Hubble Array Impacts,” *Spaceflight*, Vol. 36, November 1994.

36. Iannotta, B., “Power Shortage Forces Crew at Mir to Rely on Backup, “*Space News*, October 24-30 1992.

37. McKnight, D., “Determining the Cause of a Satellite Fragmentation: A Case Study of the Kosmos 1275 Breakup,” 38th Congress of the International Astronautical Federation, Brighton, United Kingdom October 10-17, 1987.

38. “Analysis of Spacecraft On-Orbit Anomalies and Lifetimes,” Goddard Space Flight Center, February 10, 1983.

39. Wadham, P.N., “The Effects of Electrostatic Discharge Phenomena on Telesat’s Domestic Communications Satellites, “Satellite Engineering Group, Telesat Canada, pp. 25-1/25-5.

40. De Groh, Kim K., Banks, Bruce A., “Atomic Oxygen Undercutting of Long Duration Exposure Facility Aluminized-Kapton Multilayer Insulation,” Journal of Spacecraft and Rockets, Vol. 31, No. 4, July-August 1994 pp. 656-664.

41. Tribble, A. C., “Spacecraft Interactions with the Space Environment,” AIAA 33rd Aerospace Sciences Meeting and Exhibit, January 9-12, 1995, Reno, NV.

42. “Solar Radiation Strikes Another Blow to ETS-6,” *Aviation Week & Space Technology*, October 3, 1994. p. 66.

43. “STS-61 (OV-105, FLT #5) Official InFlight Anomaly Report.

44. Elsen, William G., “Orbital Anomalies in Goddard Spacecraft for CY 1991,” Office of Flight Assurance, Goddard Space Flight Center, October 1992.

45. Adams, L.,"A Verified Proton Induced Latch-Up in Space," *IEEE Transactions on Nuclear Science* NS-39, pp. 1804-1808.

46. Campbell, A. B., "SEU Flight Data From CRRES MEP, "*IEEE Transactions on Nuclear Science*, Vol. 38, No. 6, December 1991, pp. 1647-1654.

47. Elsen, William G., "Orbital Anomalies in Goddard Spacecraft for CY 1990," Office of Flight Assurance, Goddard Space Flight Center, September 1991.

48. "ESA Bulletin," August 1993, #75, p. 14.

49. Elsen, William G., "Orbital Anomalies in Goddard Spacecraft for CY 1989," Office of Flight Assurance, Goddard Space Flight Center, July 1990.

50. Elsen, William G., "Orbital Anomalies in Goddard Spacecraft for CY 1988," Office of Flight Assurance, Goddard Space Flight Center, November 1989.

51. Shockey, Edward F., "Orbital Anomalies in Goddard Spacecraft 1984," Office of Flight Assurance, Goddard Space Flight Center, September 1985.

52. Adams, L., "Proton Induced Upsets in the Low Altitude Polar Orbit," *IEEE Transations on Nuclear Science*, Vol. 36, No. 6, December 1989, pp. 2339-2343.

53. Wilkinson, D., "TDRS-1 Single Event Upsets and the Effect of the Space Environment," *IEEE Transactions on Nuclear Science*, Vol. 38, No. 6, December 1991.

54. "Orbital Anomalies in Goddard Spacecraft for CY 1992," Office of Flight Assurance, Goddard Space Flight Center, October 1993.

55. "Spacecraft Anomaly Database," *National Oceanic & Atmospheric Administration*, National Geophysical Data Center, Solar-Terrestrial Physics Division.

56. Shockey, Edward F., "Orbital Anomalies in Goddard Spacecraft 1982-1983," Office of Flight Assurance, Goddard Space Flight Center, July 1984.

57. Elsen, William G., "Orbital Anomalies in Goddard Spacecraft 1985," Office of Flight Assurance, Goddard Space Flight Center, September 1986.

58. Elsen, William G., "Orbital Anomalies in Goddard Spacecraft for CY 1986," Office of Flight Assurance, Goddard Space Flight Center, April 1987.

59. Carts, Yvonne A., "Astronomers Report Benefit of Hubble Fix," *Laser Focus World*, September 22, 1994. P.15-17.

60. "Orbital Anomalies in Goddard Spacecraft for CY 1992," Office of Flight Assurance, Goddard Space Flight Center, October 1993

61. Shea, M.A., Smart, D.F., Allen, J.H. and Wilkinson, D.L., "Spacecraft Problems in Association with Episodes of Intense Solar Activity and Related Terrestrial Phenomena During March 1991," IEEE Transactions in Nuclear Science, Vol. 39, No., December 1992.

62. *Space Flight Environment International Engineering Newsletter*, Vol. VI, No. 2, May-June, 1995, p. 9.

63. Internal Memorandum, Jeff Anderson to Richard Leach, NASA Marshall Space Flight Center, February 24, 1995.

64. STS-45 In-Flight Anomaly Report

65. *Space News*, December 12-18, 1994, p. 23.

66. Freeman, Michael, T., "Spacecraft On-Orbit Deployment Anomalies: What Can be Done?" IEEE AES *Systems Magazine*, April, 1993, p. 3-15.

67. Herr, Joel, L., *Review and Comments On MSTI-2 Failure Report*, NASA Marshall Space Flight Center, Report No. 212-010-94-017, Sverdrup Corporation, December 1994.