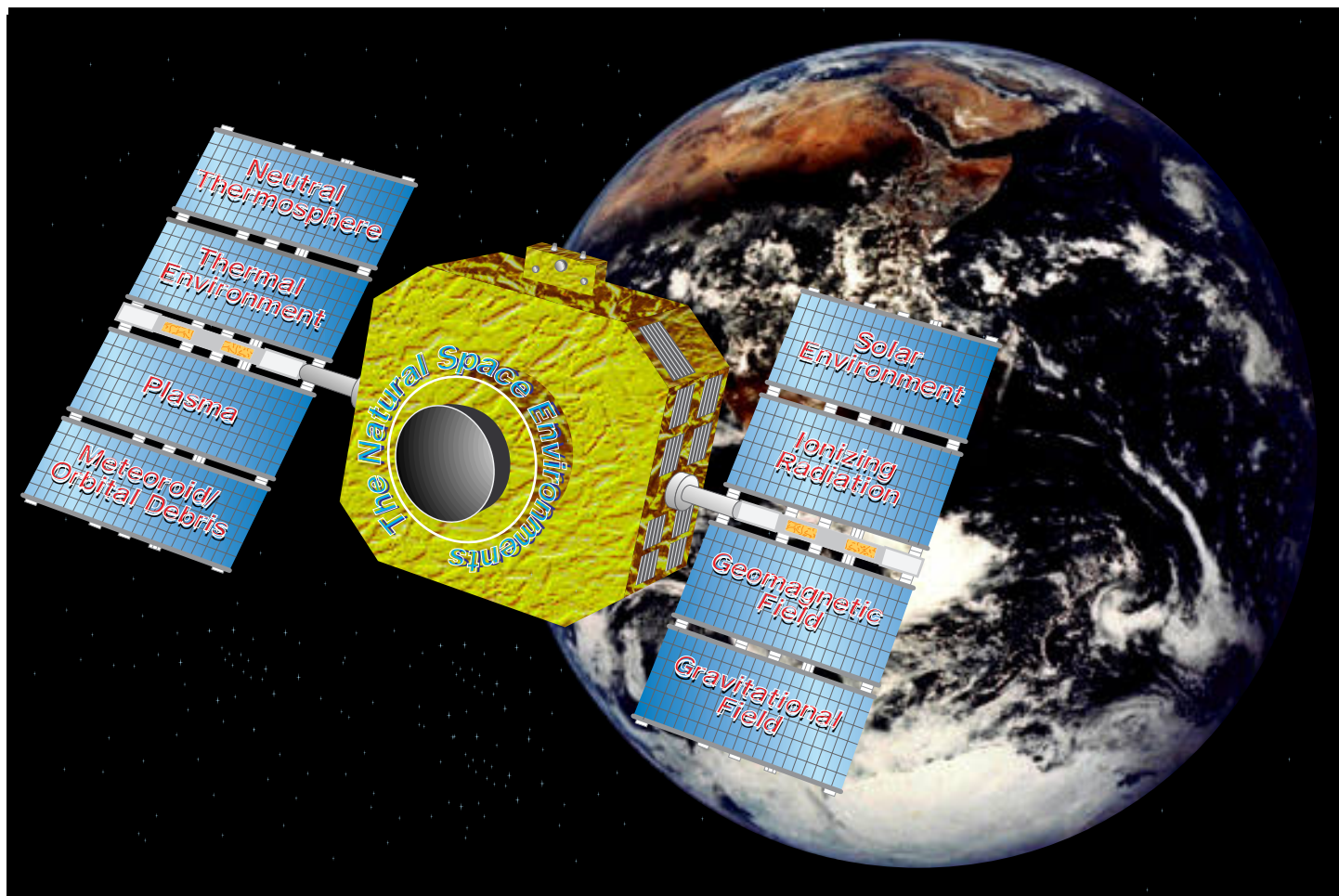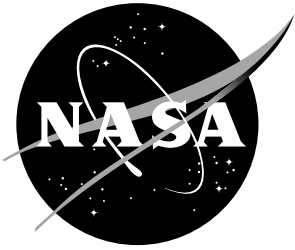# The Natural Space Environment: Effects on Spacecraft

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The Natural Space Environment: Effects on Spacecraft

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PREFACE

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

This primer provides an overview of the natural space environment and its effects on spacecraft design, development, and operations, and also highlights some of the new developments in science and technology for natural space environment. It is hoped that a better understanding of the space environment and its effects on spacecraft will enable program management to more effectively minimize program risks and costs, optimize design quality, and successfully achieve mission objectives.

TABLE OF CONTENTS

LIST OF ACRONYMS

AO	atomic oxygen
CRRES	combined release and radiation effects satellite
DMSP	defense meteorological satellite program
EMI	electromagnetic interference
ERBE	Earth radiation budget experiment
EUV	extreme ultraviolet
GCM	general circulation model
GCR	galactic cosmic rays
GN&C	guidance, navigation, and control
IGRF	international geomagnetic reference field
IRI	international reference ionosphere
LEO	low-Earth orbit
MET	Marshall engineering thermosphere
M/OD	meteoroid/orbital debris
MSFC	Marshall Space Flight Center
MSIS	mass spectrometer incoherent scatter
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense Command
OLR	outgoing long-wave radiation
POLAR	potential of large spacecraft in auroral regions (computer model)
SAMPEX	solar, anomalous, and magnetospheric particle explorer
S/C	spacecraft
SAA	South Atlantic anomaly
UV	ultraviolet

THE NATURAL SPACE ENVIRONMENT: EFFECTS ON SPACECRAFT

INTRODUCTION

The natural space environment refers to the environment as it occurs independent of the presence of a spacecraft; thus, it includes both naturally occurring phenomena such as atomic oxygen (AO) and atmospheric density, ionizing radiation, plasma, etc., and a few man-made factors such as orbital debris. Figures 1 through 3 list the breakout of the natural space environments and their major areas of interaction with spacecraft systems.

This primer provides an overview of these natural space environments and their effect on spacecraft design, development, and operations, and it also highlights some of the new developments in science and technology for each space environment.

Understanding these natural space environments and their effect on spacecraft enables program management to more effectively optimize the following aspects of a spacecraft mission:

- Risk—Increasingly, experience on past missions is enabling NASA to provide statistical descriptions of important environmental factors, thus enabling the manager to make informed decisions on design options.

- Cost—Selection of design concepts and missions profiles, especially orbit inclination and altitude which minimizes adverse environmental impacts, is the first important step toward a simple, effective, high-quality spacecraft design and low operational costs.

- Quality—New environment simulators and models provide effective tools for optimizing subsystem designs and mission operations.

- Weight—Consideration of environmental effects early in the mission design cycle helps to minimize weight impacts at later stages. For example, early consideration of directionality effects in the orbital debris and ionizing radiation environments could lead to reduced shielding weights.

- Verification—A unified, complete environments description coupled with a clear mission profile provides a sound basis for analysis and test requirements in the verification process and eliminates contradictory, unnecessary, and/or incomplete performance assessments.

- Science and Technology—The natural space environment is not static. Not only is our understanding improving, but new things occur in nature which have not been observed before (for example, a new transient radiation belt was recently encountered). Perhaps more importantly, engineering technology is constantly changing and with this the susceptibility of spacecraft to environmental factors. Early consideration of these factors is key to converging quickly on a quality system design and to successfully achieving mission objectives.

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, Seconary ejecta effects, Structural design/ shielding, Materials/solar panel deterioration	Flux models
SOLAR ENVIRONMENT	Solar physics and dynamics, Geometric storms, Solar activity predictions, Solar/geomagnetic indices, Solar constant, Solar spectrum	Solar prediction, Lifetime/drag assessments, Reentry loads/heating, Input for other models, Contingency operations	EL Laboratory model, NOAA prediction data, Statistical models, Solar database
IONIZING RADIATION	Trapped proton/electron radiation, Galactic cosmic rays (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 90, UARS database, "science" GRAM

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

Space Environment Effects

SPACECRAFT SUBSYSTEMS	SPACE ENVIRONMENTS			
	Neutral Thermosphere	Thermal Environment	Plasma	Meteoroids/Orbital Debris
Avionics		Thermal Design	Upsets due to EMI from Arcing, S/C Charging	EMI Due to Impacts
Electrical Power	Degradation of Solar Array Performance	Solar Array Designs, Power Allocations, Power System Performance	Shift in Floating Potential, Current Losses, Reattraction of Contaminants	Damage to Solar Cells
GN&C/Pointing	Overall GN&C/Pointing System Design		Torques due to Induced Potential	Collision Avoidance
Materials	Material Selection, Material Degradation	Material Selection	Arcing, Sputtering, Contamination Effects on Surface Properties	Degradation of Surface Optical Properties
Optics	S/C Glow, Interference with Sensors	Influences Optical Design	Reattraction of Contaminants, Change in Surface Optical Properties	Degradation of Surface Optical Properties
Propulsion	Drag Makeup/Fuel Requirement		Shift in Floating Potential Due to Thruster Firings making Contact with the Plasma	Collision Avoidance, Additional Shielding Increases Fuel Requirement, Rupture of Pressurized Tanks
Structures		Influences Placement of Thermally Sensitive Surfaces, Fatigue, Thermally Induced Vibrations	Mass Loss From Arcing and Sputtering, Structural Size Influences S/C Charging Effects	Structural Damage, Shielding Designs, Overall S/C Weight, Crew Survivability
Telemetry, Tracking, and 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

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Figure 2. Space environment effects on spacecraft subsystems.

Space Environment Effects

SPACECRAFT SUBSYSTEMS	SPACE ENVIRONMENTS				
	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 and 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			
Structures	Influences Density and Drag				
Propulsion	Influences Placement of Thermal Sensitive Structures		Induces Currents in Large Structures	Influences Fuel Consumption Rates	
Telemetry, Tracking and Communication	Tracking Accuracy, Influences Density and Drag		Locating South Atlantic Anomaly	Propellant Budget	Tether Structural Design
Thermal Control	Influences Reentry Thermal Loads/Heating			May Induce Tracking Errors	
Mission Operations	Mission Timelines, Mission Planning	Crew Replacement Timelines			

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Figure 3. Space environment effects on spacecraft subsystems.

NEUTRAL THERMOSPHERE

Environment Definition

The region of the Earth's atmosphere containing neutral atmospheric constituents and located between about 90 and 600 km is known as the neutral thermosphere, while that region above 600 km or so is known as the exosphere (fig. 4). The thermosphere is composed primarily of neutral gas particles which 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 4 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, are 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 a spacecraft's 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 (fig. 5). 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 which may be of concern for optically sensitive experiments is spacecraft glow. Optical emissions are generated from metastable molecules which 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.

New Developments

Two important extensions to the Marshall engineering thermosphere (MET) model were developed in 1992–93 (fig. 6). One provides a statistical definition of density variations in the day-to-week time scales for all LEO applications; the other is a simulation model for very short time scale variations which impact guidance, navigation, and control (GN&C) design, microgravity, and torque equilibrium attitude calculations, applicable to low inclination orbits.
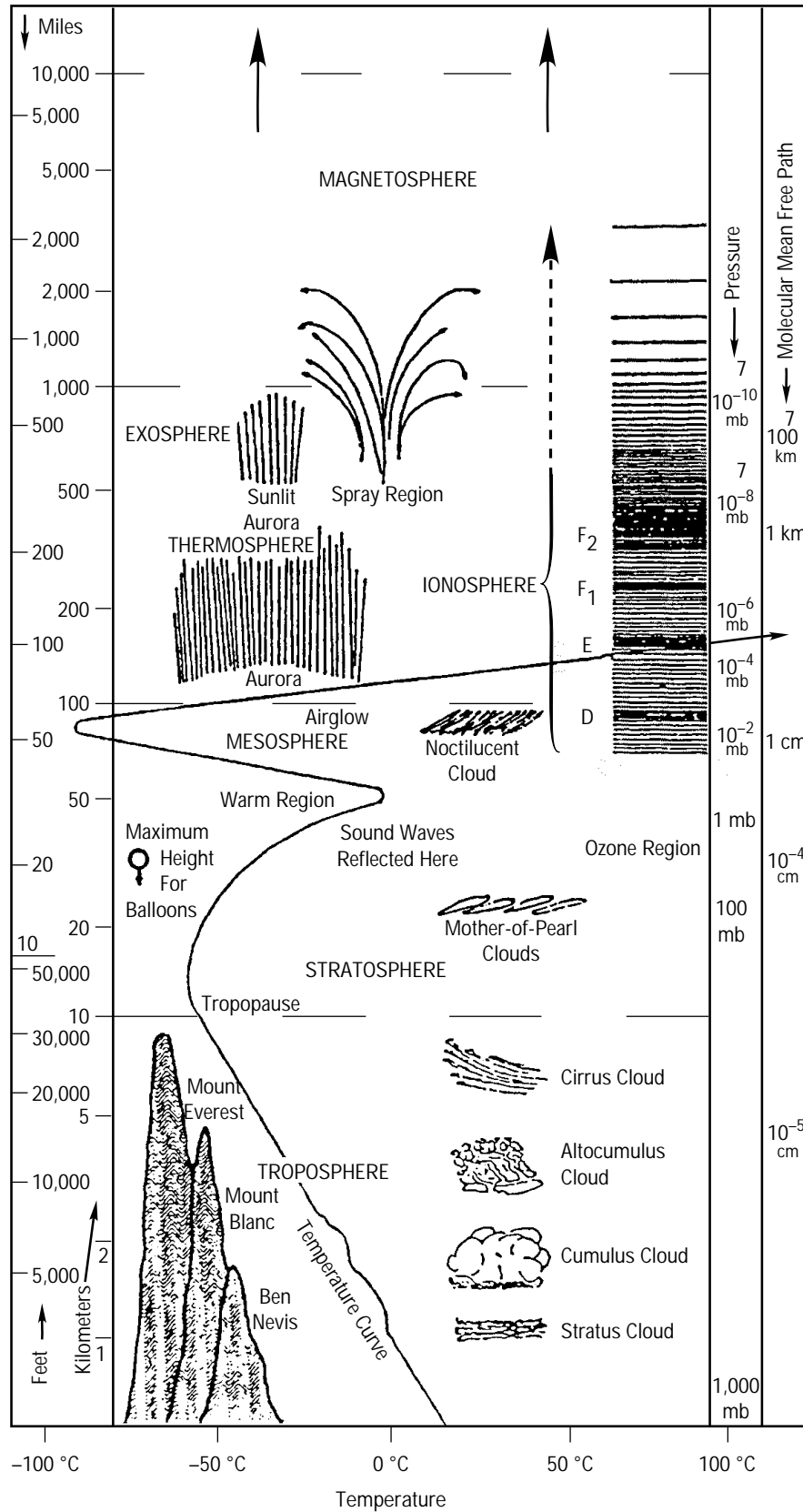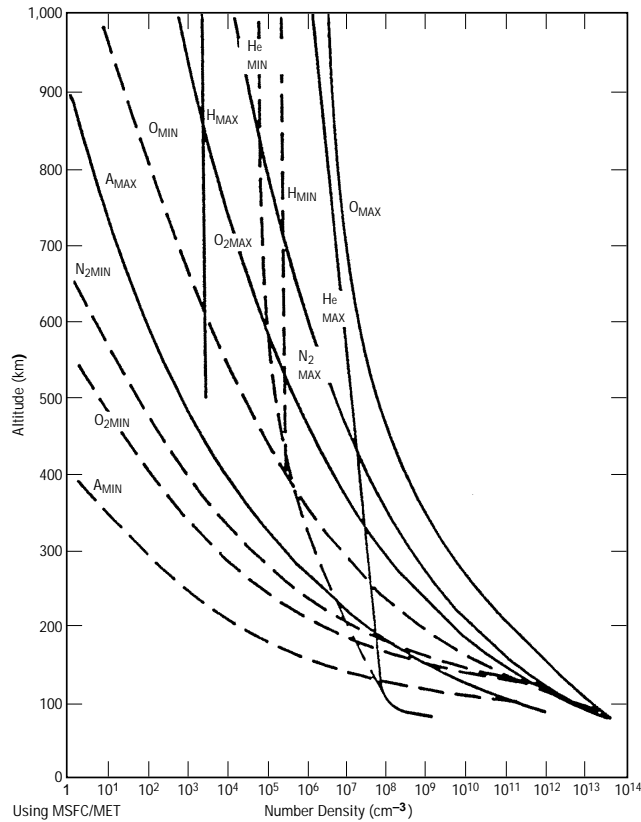
Figure 4. The layers of the Earth's atmosphere.

Figure 5. Variations of neutral species concentration as a function of altitude. Neutral atmospheric constituent densities vary with solar conditions also. Typically, AO is the constituent of concern at orbital altitudes. (MAX refers to solar maximum and MIN to solar minimum.)
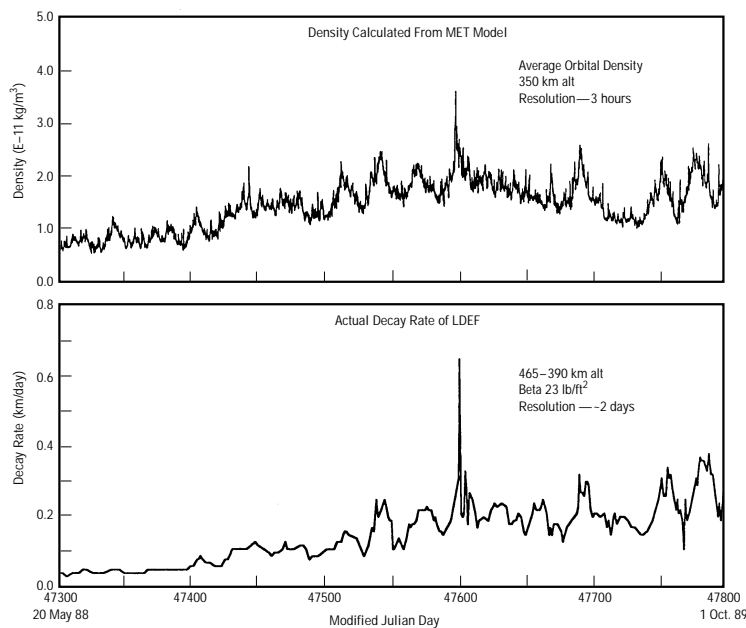

Figure 6. Comparison of calculated and measured thermosphere drag. MSFC can now provide statistical descriptions of these rapid density fluctuations to support control system design.

THERMAL ENVIRONMENT

Environment Definition

Spacecraft may receive radiant thermal energy from three sources: (1) incoming solar radiation (solar constant), (2) reflected solar energy (albedo), and (3) outgoing long-wave 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. 7 and 8).

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. 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.

New Developments

Advances in technology have led to stronger material bonding which has provided the space community with stronger flight materials at much reduced weight. These lightweight materials, however, are more susceptible to changes in the thermal environment of space. This has led to a need for a much more accurate description of thermal environment variations. Previously, the design engineer had only long-term, global mean thermal parameters to aid in the design process. Marshall Space Flight Center (MSFC) has completed analysis of data from the Earth radiation budget experiment (ERBE) which provides a significant advancement in the description of this near-Earth thermal environment. The new results provide thermal environment parameters which vary with orbit inclination and can be matched to a system's thermal response time. The new thermal environment description has already been incorporated in the space station program and other NASA programs.
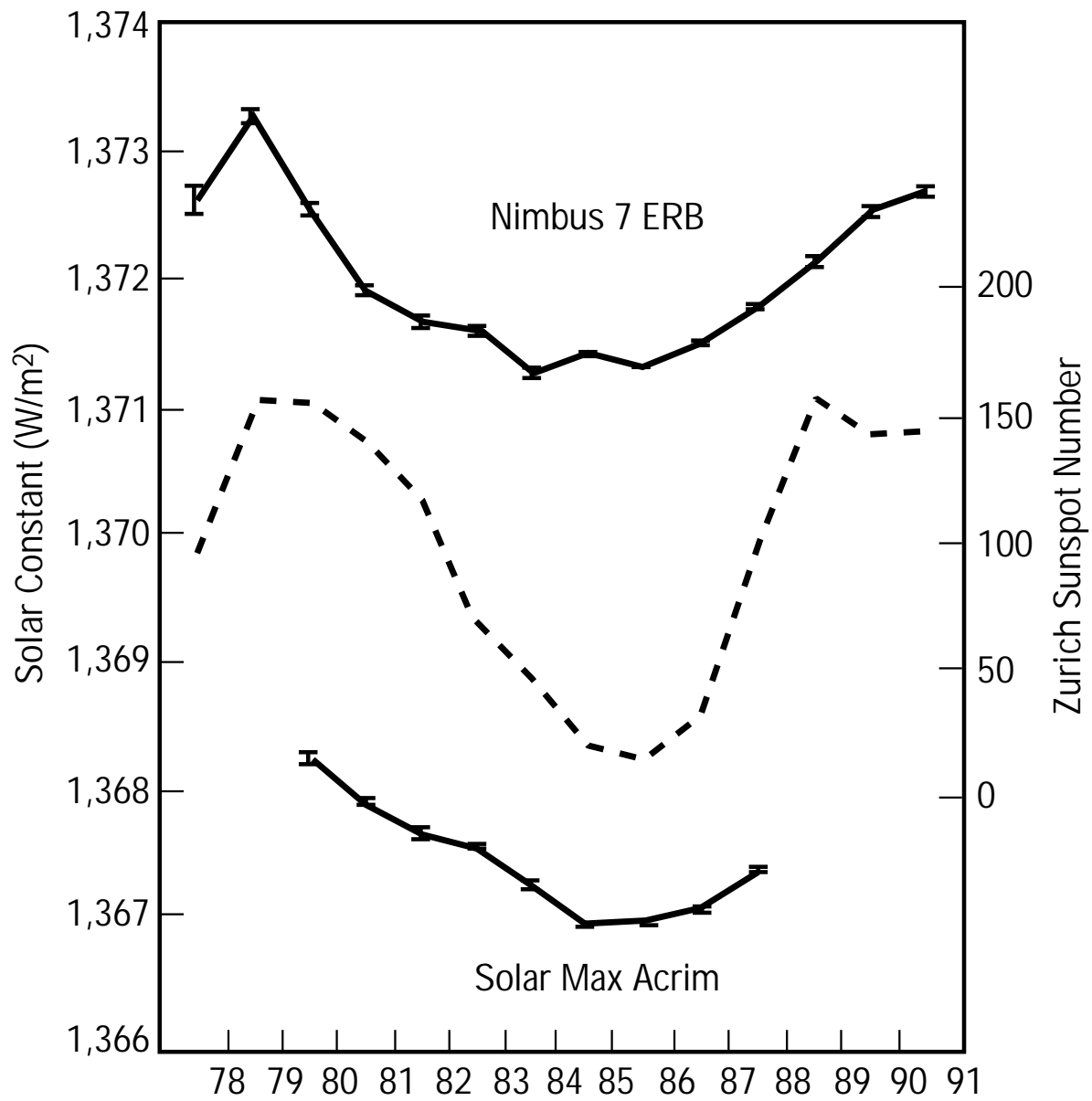
Figure 7. A sample of the solar constant measurements from an instrument on the solar maximum satellite and an instrument flying on a Nimbus satellite. (The dashed line represents the trend in sunspot number.)
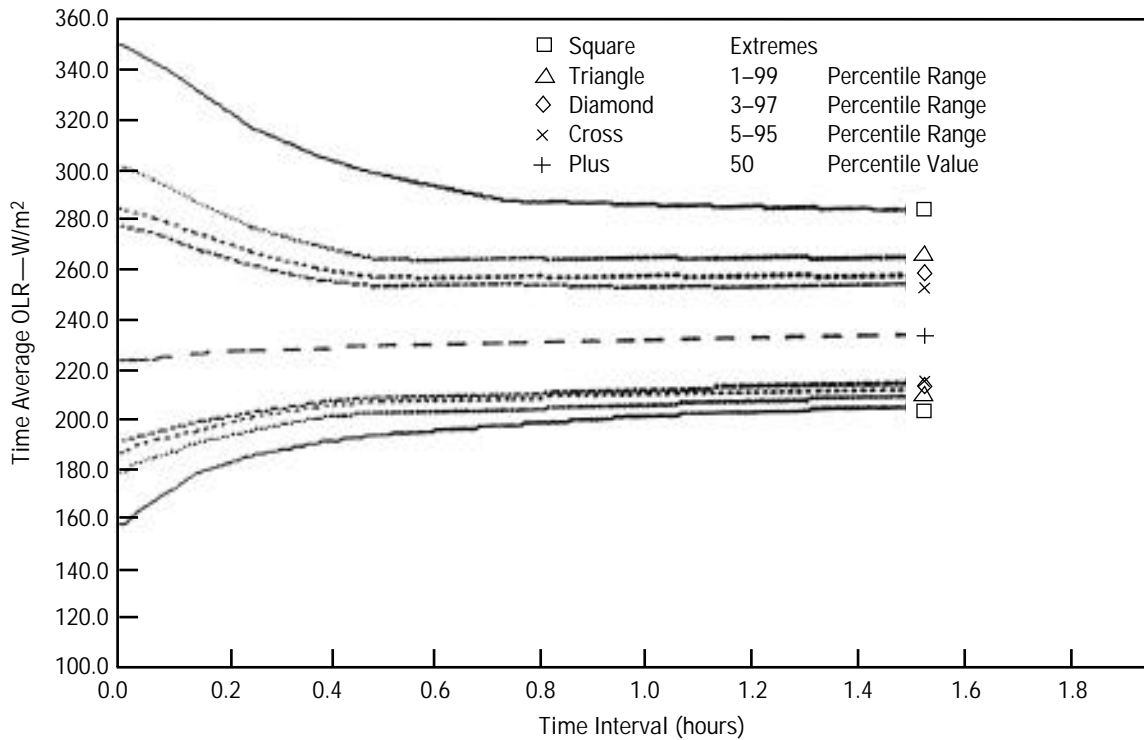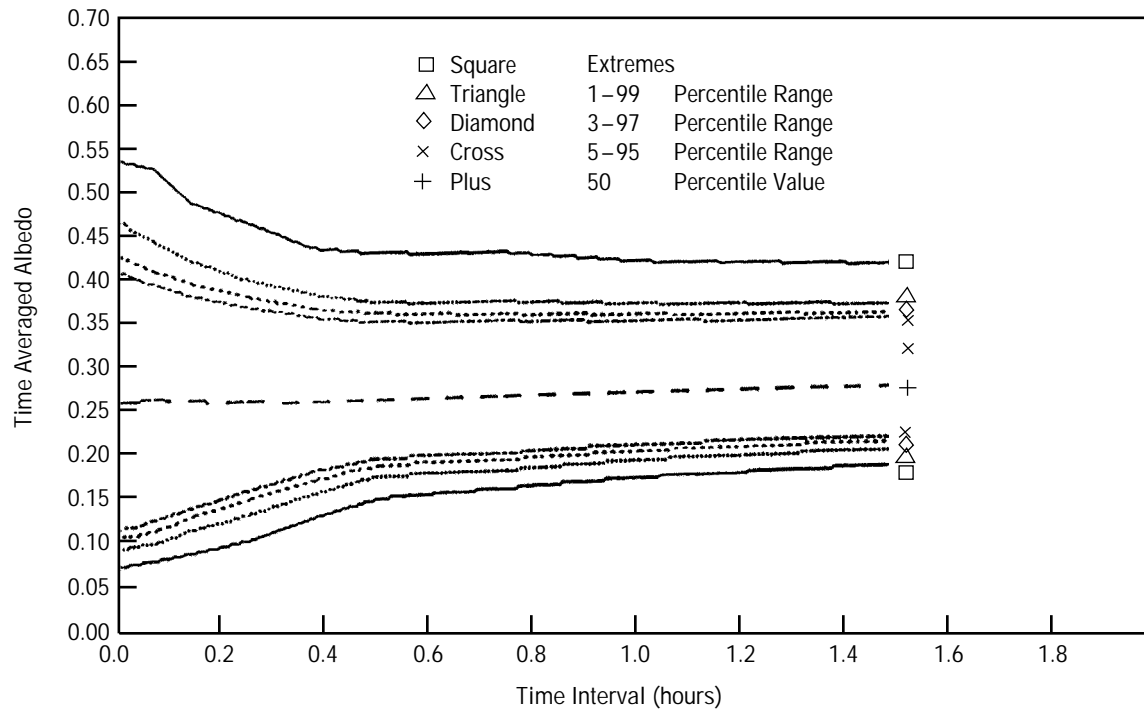
Figure 8. New engineering thermal model results for polar orbits.

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. Therefore, it is because of these characteristics that this electrically charged portion of the atmosphere is known as the ionosphere, and the gas within this layer is referred to as the ionospheric plasma. The electron and ion densities vary dramatically with altitude, latitude, magnetic field strength, and solar activity (figs. 9 and 10).

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 (fig. 11). 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 disturbances on spacecraft. Figure 12 shows some typical charging events that have occurred on a polar orbiting spacecraft. A listing of some of the disturbances that have been noted by spacecraft charging is provided in figure 11.

New Developments

Spacecraft charging due to plasma interactions has been studied for some time for spacecraft at geosynchronous altitudes. Recently, however, there has been a new emphasis on studying charging effects on LEO spacecraft, especially those in polar orbits. A new computer model called POLAR has been developed to analyze spacecraft charging in low-Earth polar orbit. POLAR provides detailed information on charging potentials anywhere on the spacecraft structure.
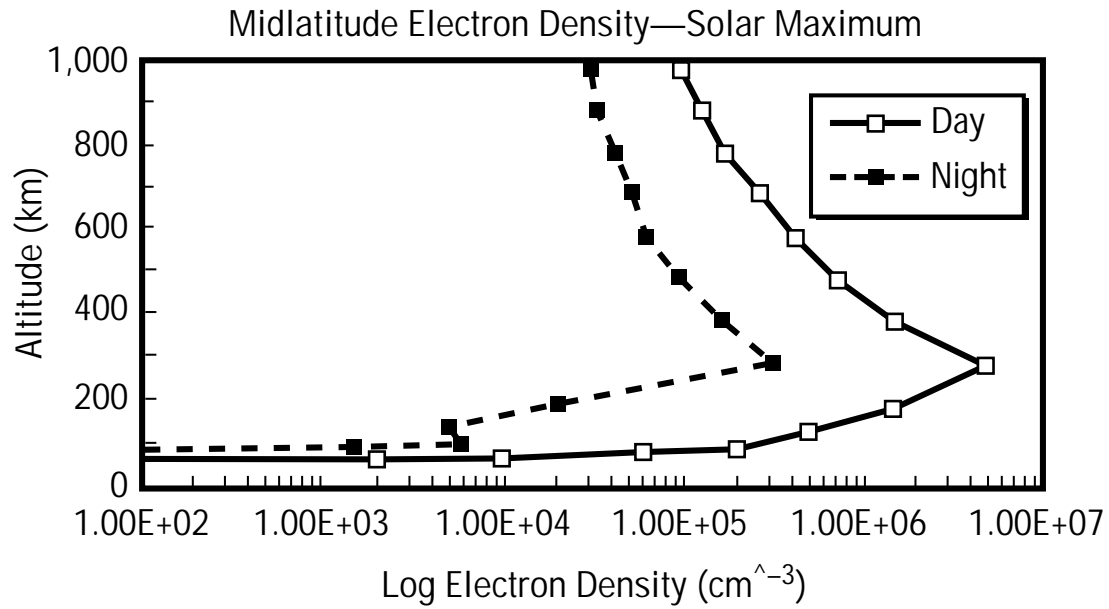
Midlatitude Electron Density—Solar Maximum

Figure 9. LEO plasma density at solar maximum.
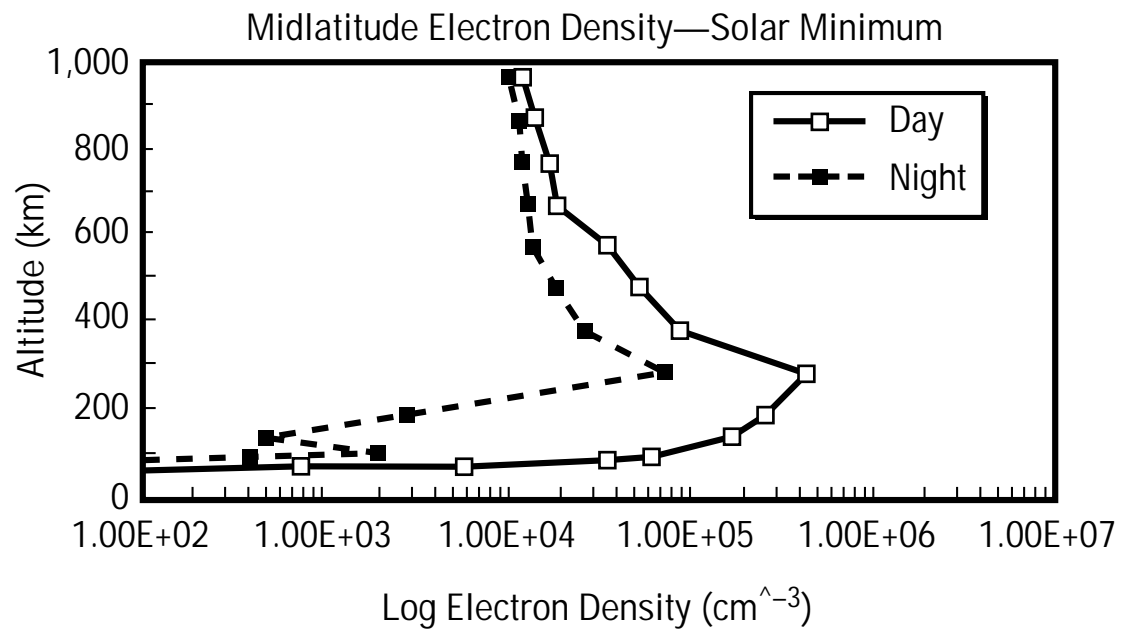
Midlatitude Electron Density—Solar Minimum

Figure 10. LEO plasma density at solar minimum

Effects attributed to spacecraft charging can be of serious engineering concern:
- Increased surface contamination
- Compromised scientific missions
- Physical surface damage
- Operational anomalies ranging from "minor irritations to the fatally catastrophic"

Arc discharging is seen as the primary mechanism by which spacecraft charging disturbs mission activities
- Occurs when generated electric fields exceed a breakdown threshold
- Results in a rapid release of large amounts of charge
- Coupling of generated structural transients into spacecraft electronics

Types of discharges are:
- "flashover"   discharge from one surface to another
- "punch-through"   discharge through surface material from underlying structure
- "discharge to space"   discharge from spacecraft to ambient plasma

| Spacecraft	Known Anomaly	Spacecraft	Known Anomaly
Voyager I	Power-on resets	**Intelsat 3 and 4**	Spin up
SCATHA	34 pulses detected	**Skynet 2B**	Telemetry problems
DSP	False flags from star sensor	**ANIK**	Power downs
DSCS II	Spin up, amplifier gain change, power switching events	**CTS**	Short circuit
		Meteosat	Status changes
GPS	Clock shift, false commands	**GOES 4 and 5**	Upsets and failure

Figure 11. Spacecraft charging.
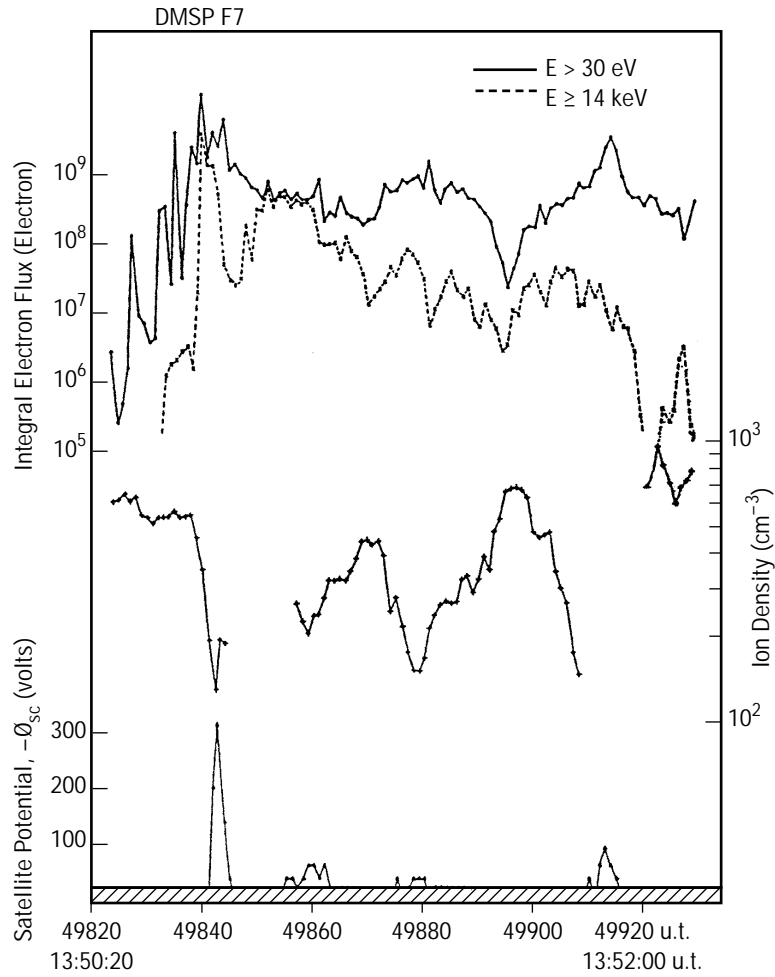
Figure 12.   An example of the type of charging events encountered by the DMSP satellite F7 on November 26, 1983. DMSP 7 is a defense meteorological satellite flying in LEO/polar.

METEOROID/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. 13 through 16). 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 many 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.

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.

New Developments

The orbital debris environment continues to increase because of continued activity in space and continued on-orbit fragmentation events. New data from radar measurements confirm the current NASA models, in general, and will lead to improved descriptions of the altitude, inclination, and velocity distributions of the debris environment.
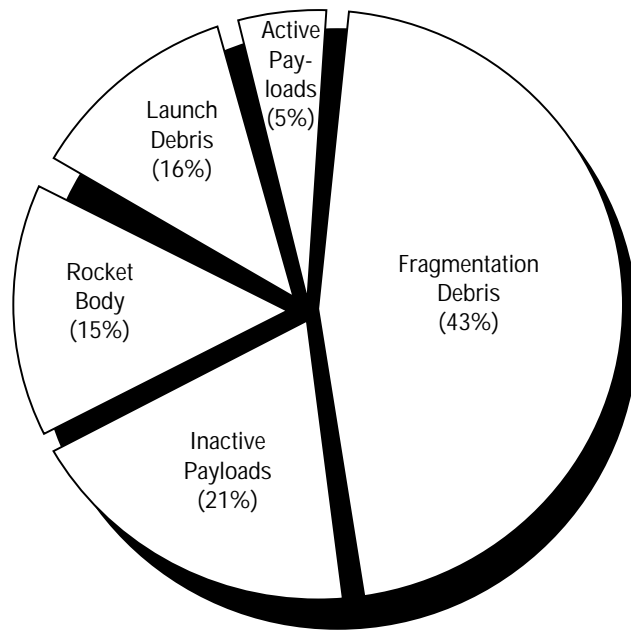
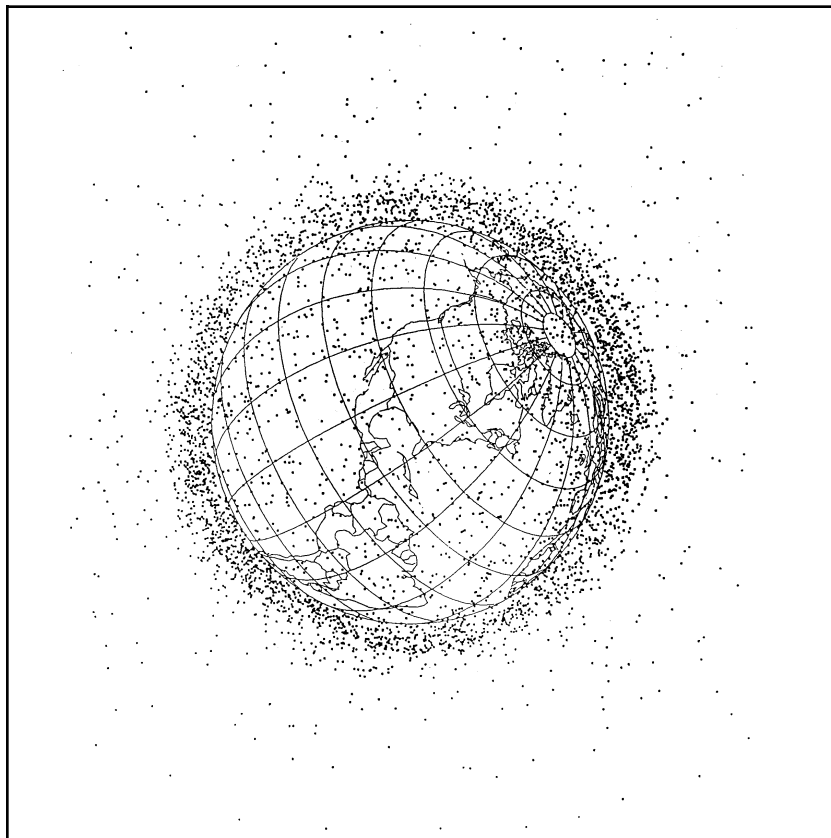Figure 13. Sources of the catalogued debris population.

Figure 14. The state of the Earth debris environment is illustrated in this snapshot of all catalogued objects in July 1987.
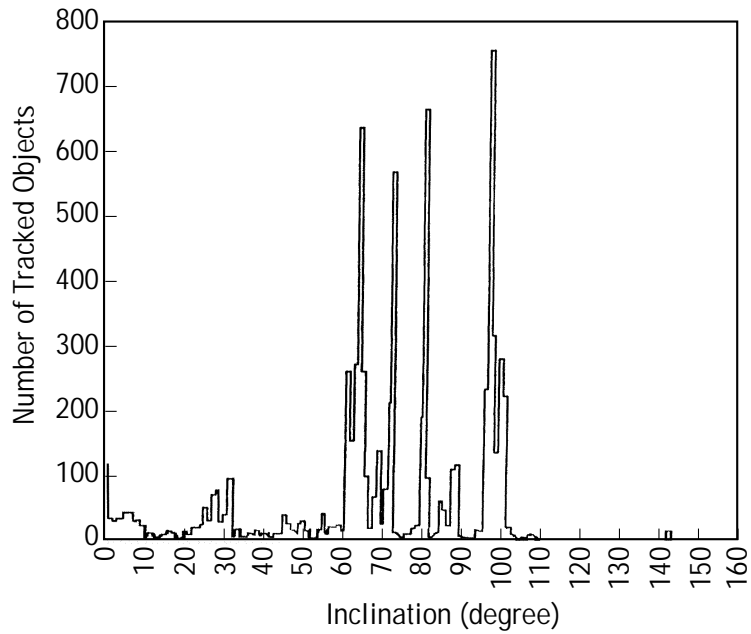
Figure 15. Inclination distribution of the USSPACECOM tracked objects,
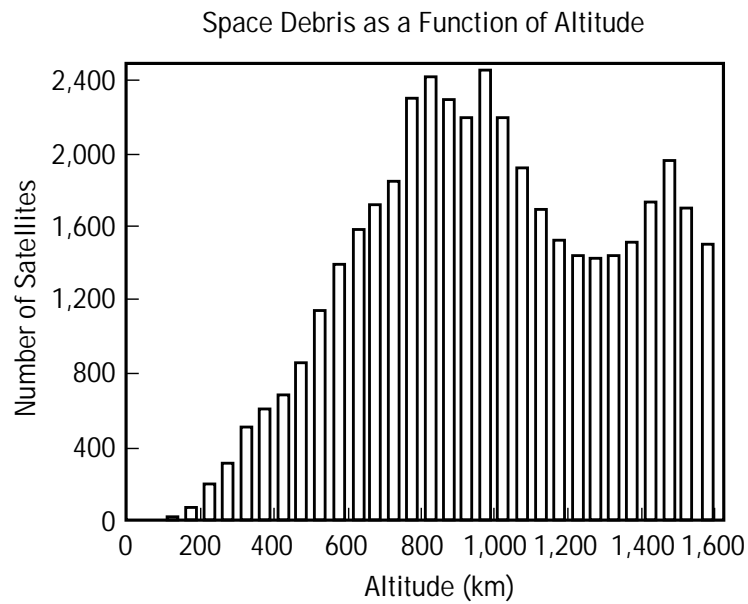August 1988—all altitudes.

Figure 16. Based on data from the January 1987 NORAD satellite catalog,
the altitude regime between 800 and 1,000 km is the most populous.

SOLAR ENVIRONMENT

Environment Definition

The Sun emits huge amounts of mass and energy; enough energy in 1 second to power several million cars for over a billion years. This tremendous emission of energy has important consequences to spacecraft design, development, and operations. 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. 17). 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 radio to x-ray frequencies. Solar flares are differentiated according to their 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, the overall thermal environment a spacecraft will experience, plasma density levels, meteoroids/orbital debris levels, the 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 mission 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 the 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 which affect electronic systems.

New Developments

The variability of the solar cycle has been effectively modeled using a proxy parameter, the 10.7-cm solar radio flux (F10.7). The Environments Team at the Marshall Space Flight Center currently predicts and publishes a monthly solar activity memorandum which gives long-range estimates of both the F10.7 index and the geomagnetic activity index, Ap. Also, solar science is making progress toward predicting the sites for flare activity on the Sun in much the same way as meteorologists have developed criteria for probable tornadic activity within the Earth's atmosphere. As more is learned about the Sun's behavior, more realistic modeling of the Sun is possible and more accurate predictions of the Sun's future behavior can be made.
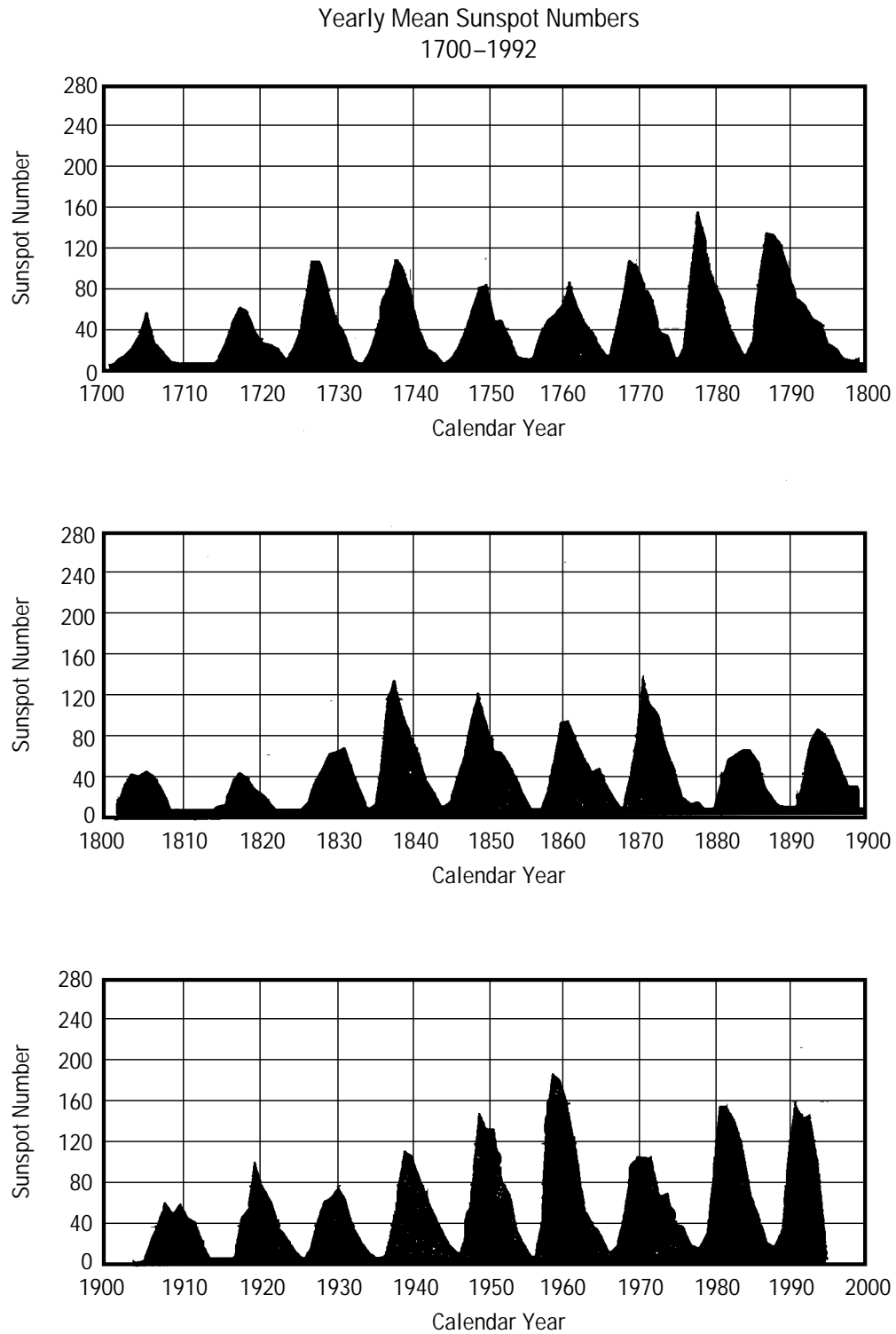
Yearly Mean Sunspot Numbers
1700–1992

Figure 17. 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.

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 belts (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 from 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 some heavier ions. The Earth's magnetic field provides the mechanism which traps these charged particles within specific regions, called the Van Allen belts. The belts are characterized by a region of trapped protons and both an inner and an outer electron belt. The radiation belt particles spiral back and forth along the magnetic field lines (fig. 18). 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 this region they will reach lower altitudes, and particle densities will be anomalously high over this region. This area is termed the South Atlantic Anomaly (SAA). For the purpose of 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 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 (figs. 19a and 19b).

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 particle's wake. Spacecraft damage includes decreased power production by solar arrays, failure of sensitive electronics, increased background noise in sensors, and radiation exposure of the spacecraft crew. Modern electronics are becoming increasingly sensitive to ionizing radiation.

New Developments

A new transient radiation belt containing large numbers of highly energetic electrons was recently encountered by the combined release and radiation effects satellite (CRRES). The solar anomalous and magnetospheric particle explorer (SAMPEX) satellite recently discovered a belt of trapped anomalous ray particles that will effect LEO missions. Also, it is now realized that many heavy ion cosmic rays are only partially ionized so that geomagnetic shielding of these particles is not as effective as once thought.
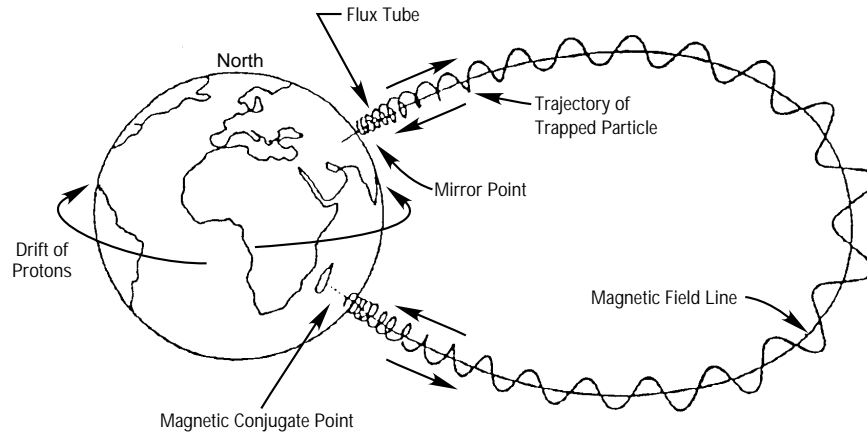
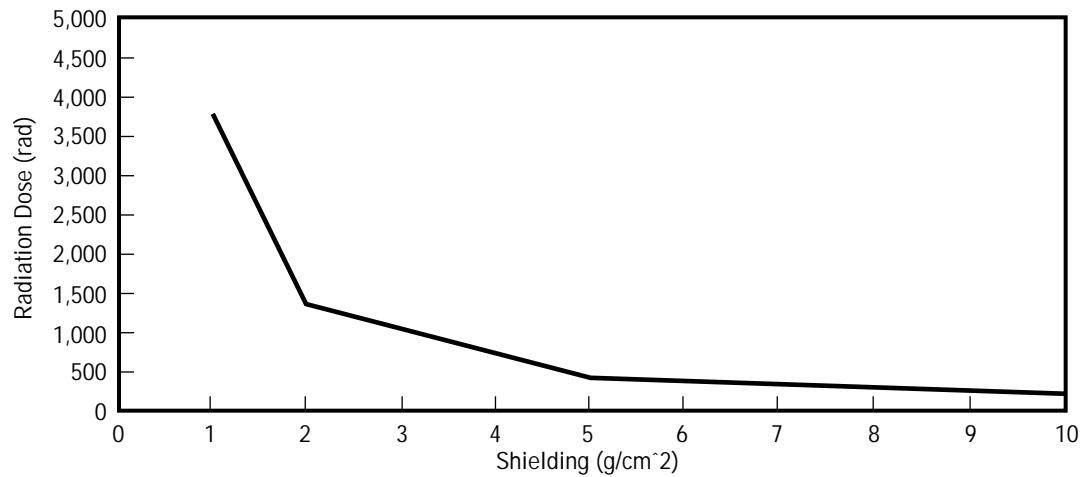Figure 18. Trapped particles spiral back and forth along magnetic field lines.

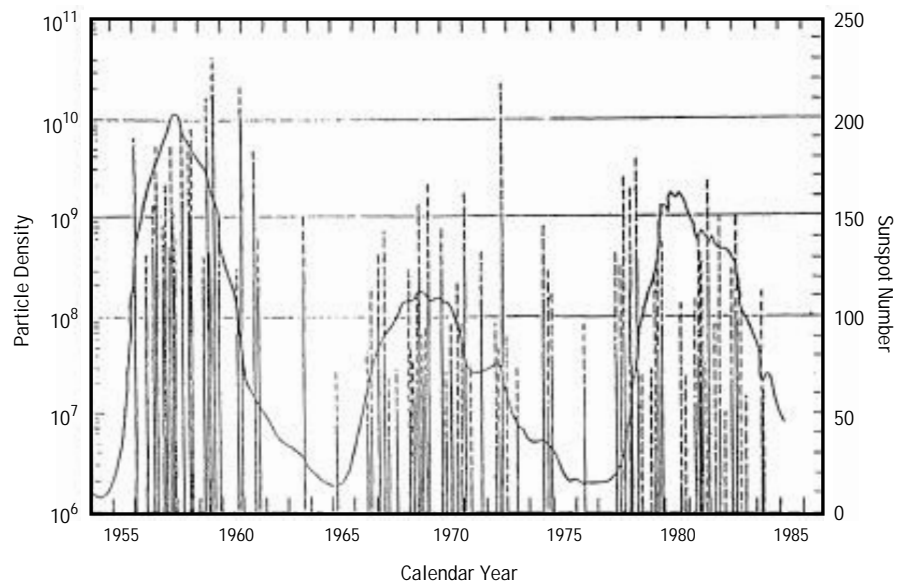Figure 19a. Average radiation dose from a large solar proton event.

Figure 19b. Variation of solar flare proton events as a function of solar activity.

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 to spacecraft design and performance. The Earth's natural magnetic field comes from two sources: (1) currents inside the Earth which 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 20 and 21.

Spacecraft Effects

The geomagnetic field influences the motions of particles within the Earth's orbital environment and also deflects incoming high-energy particles such as those associated with cosmic rays. These high-energy particles may charge spacecraft surfaces causing failure of or interference with spacecraft subsystems. Due to the 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. 20 and 21). 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 also needed to properly size magnetic torquers, which are used in GN&C systems.

Geomagnetic storms may also affect orbiting spacecraft. Disturbances in the geomagnetic field which last 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. The heating is first observed minutes to hours after the magnetic disturbance begins. The effects of geomagnetic heating extend from at least 300 km to well over 1,000 km and may persist for 8 to 12 hours after the magnetic disturbance ends.

New Developments

Technology advancements have provided electronics which are far more sophisticated, but at the same time are far more vulnerable to radiation damage. Therefore, correct determination of the SAA has become essential to successful spacecraft design and to successful mission operations. The IGRF is updated with new coefficients approximately every 5 years. The most recent revision was in 1991, but the model allows projection of future trends.
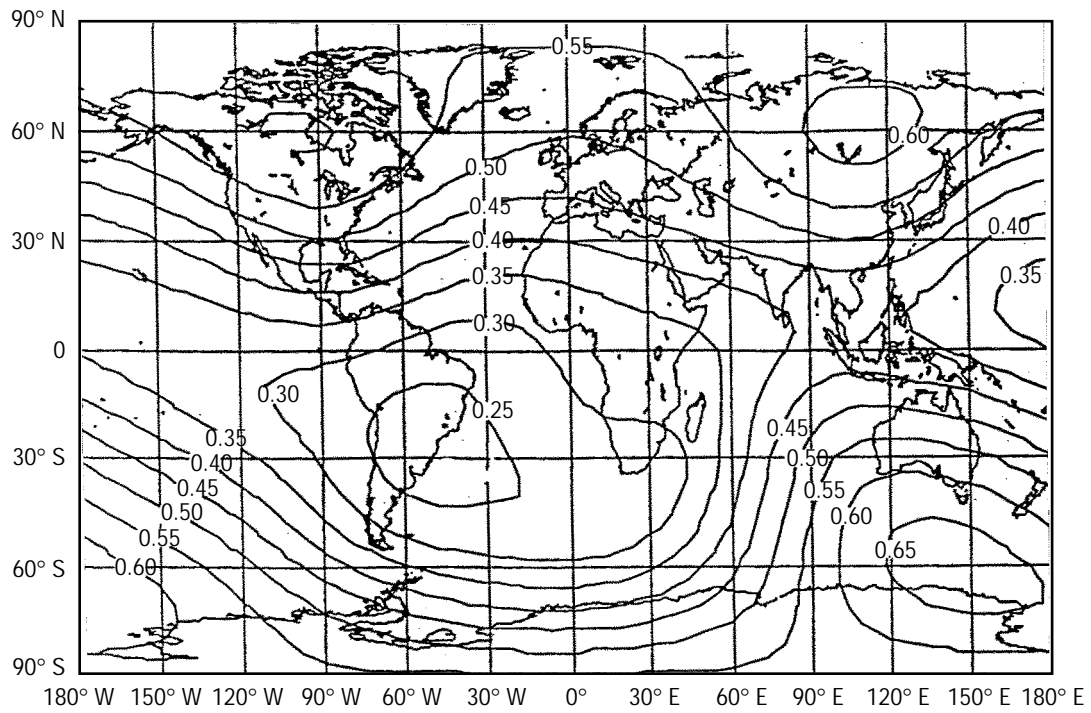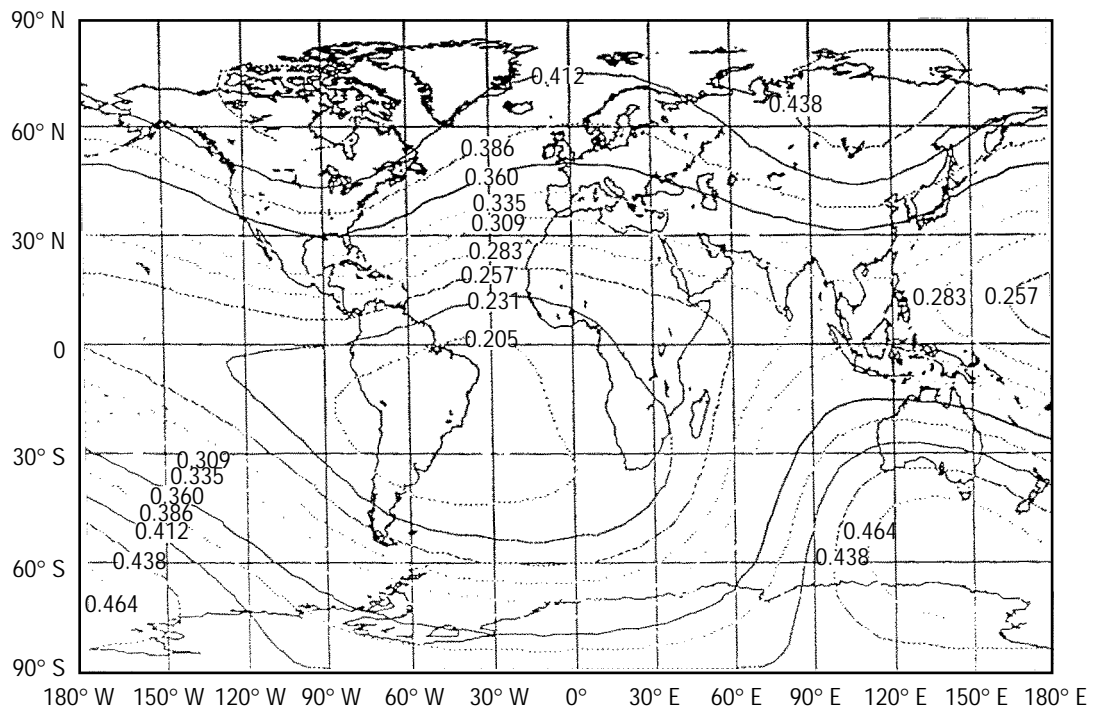
Figure 20. Geomagnetic field at sea level.

Figure 21. Geomagnetic field at 650 km-altitude.

GRAVITATIONAL FIELD

Environment Definition

Since the advent of Earth satellites, there has been a considerable advancement in the accurate determination of the Earth's gravitational field. The current knowledge regarding the Earth's gravitational field has advanced far beyond the normal operational requirements of most space missions. Adequate accuracy for determining most spacecraft design values of gravitational interactions is obtained with the central inverse square field:

$$\vec{F} = -\frac{\mu_E m}{r^2}\,\hat{r}\quad.$$

The above central force model accurately represents the gravitational field to approximately 0.1 percent. If this accuracy is insufficient for particular program needs, a more detailed model of the gravitational field can be used that accounts for the nonuniform mass distribution within the Earth. This model gives the gravitational potential, *V*, to an accuracy of approximately a few parts in a million. The gravitational acceleration is expressed in terms of the negative gradient of the potential. The potential is then expressed using harmonic expansion:

$$\vec{F} = m\vec{g} = m(-\vec{\nabla}V)\quad.$$

Spacecraft Effects

Accurate predictions of the Earth's gravitational field are a critical part of mission planning and design for any spacecraft. The Earth's gravitational field will affect spacecraft orbits and trajectories. Gravity models are used to estimate the gravitational field strength for use in designing the GN&C/pointing subsystem, and designing the telemetry, tracking, and communications. The available gravitational models have sufficient accuracy for estimating the gravitational field strength for spacecraft planning and design.

New Developments

Gravitational models of the Earth are continually being updated and upgraded. Currently, gravitational models are available for varying degrees of accuracy. For operational applications and other situations where computer resources are a premium, "best fit" approximations to the highest accuracy model may be utilized which minimize the computational requirements yet retain the required accuracy for the specific application.

CONCLUSION

For optimum efficiency and effectiveness, it is important that the need for definition of the flight environment be recognized very early in the design and development cycle of a spacecraft. From past experience, the earlier the environments specialists become involved in the design process, the less potential for negative environmental impacts on the program through redesign, operational work-arounds, etc. The key steps in describing the natural space environment for a particular program include the following:

- Definition of the flight environment is the first critical step. Since the environment depends strongly on orbit and phase of the solar cycle, environment effects should be reviewed prior to final orbit selection.

- Not all space environments will have a critical impact on a particular mission. It is the role of the environments specialists to find all the environmental limiting factors for each program and to offer design or operational solutions to the program where possible. This typically requires a close working relationship between the environments specialists, members of the design teams, and program management. Typically, once the limiting factors are established, trade studies are usually required to establish the appropriate environmental definition.

- After definition of the space environment is established including results from trade studies, the next important step is to establish a coordinated set of natural space environment requirements for use in design and development. These requirements are derived directly from the definition phase and again, typically are derived after much interaction among the design development engineering staff, program management, and environments specialists.

- Typically, the space environment definition and requirements are documented in a separate program document or are incorporated into design and performance specifications.

- The environments specialist then helps insure that the environment specifications are understood and correctly interpreted throughout the design, development, and operational phases of the program.

This primer has provided an overview of the natural space environments and their effect on spacecraft design, development, and operations. It is hoped that a better understanding of the space environment and its effect on spacecraft will enable program management to more effectively minimize program risks and costs, optimize design quality, and successfully achieve mission objectives. If you have further questions or comments, contact the MSFC Systems Analysis and Integration Laboratory's Electromagnetics and Environments Branch, Steven D. Pearson at 205–544–2350.