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Introduction

1.1 Introduction

Before the space age began, it was realized that space was not empty. Comet tails, meteors, and other extraterrestrial phenomena demonstrated the presence of a "space environment." Much as an aircraft operates in and interacts with the atmosphere (indeed the air is necessary for lift), so a spacecraft operates in and interacts with this space environment. The environment can, however, limit the operation of the spacecraft and in extreme circumstances lead to its loss. Concern over these adverse environmental effects has created a new technical discipline – spacecraft–environment interactions. The purpose of this text is to describe this new field and introduce the reader to its many different aspects.

Historically, the field of spacecraft–environment interactions has developed primarily as a series of specific engineering responses to each interaction as it was identified. Consider the discovery of the radiation belts and their effects on electronics. This led to the development of radiation shielding and microelectronic-hardening technology. Similarly, in the early seventies, the loss of a spacecraft apparently due to spacecraft charging from the magnetospheric plasma led to intense efforts to understand charge accumulation on surfaces in space and to methods for mitigating the effects. Ultimately, these efforts culminated in the 1979 launch of a dedicated spacecraft, *SCATHA* (Spacecraft Charging at High Altitudes), into a near geosynchronous orbit for studying this interaction. Likewise, in the eighties, certain materials were found to erode rapidly in the low-Earth space environment because of chemical interactions with atomic oxygen. This led to the development of complex ground simulation facilities and to the flight of numerous *Shuttle* experiments aimed at characterizing the phenomenology associated with the erosion. Thus, the study of environment interactions can be characterized largely as a response to problems – it has seldom anticipated them.

The next generation of spacecraft likely will be much longer-lived, more sensitive to environmental effects, and more environmentally active. They will be active in the sense that they may emit particulates, gases, plasma, or possibly radiation (electromagnetic and corpuscular) in sufficient quantities to substantially modify the ambient environment in their vicinity. These spacecraft will possess increasingly more complex, sensitive, and, by inference, expensive instruments. A good example is the *Shuttle*, around which the neutral pressure has often been measured to be over an order of magnitude or larger than the ambient environment. The enhancement is due to outgassing, water releases, and thruster firings. It and similar self-generated environments may significantly alter the radiation and plasma components. These in turn could pose serious problems for the operation of sensitive optical and electrical/electromagnetic sensors or threaten the long-term integrity of the spacecraft structures and electronic systems. The greatly increased cost of future systems such as the *space station* will require a long operational lifetime to amortize the costs. This may mean that even seemingly innocuous interactions could, through cumulative effects, reduce the lifetime of the system rendering it uneconomical or unfeasible. No longer will the space engineer have the luxury of fixing problems after the fact; they must be anticipated in the original design.

In addition, for the new class of vehicles, many of the interactions may be synergistic, greatly enhancing their impact. That is, relatively weak individual interactions could couple in such a way as to have a nonlinear effect on the spacecraft, becoming strong enough to be design limiting. For example, the choice of a negative ground for the high-voltage power system on the *space station* may increase the probability of arcing on the structure. This arcing may erode thermal control coatings and increase the contamination in and near the station. For this reason, a plasma contactor has been incorporated into the station design to eliminate such arcing. To understand and control such environmental interactions, it has become critically important to develop a unified description of the spacecraft, the environment, and the interactions. That description forms the basis of a new engineering and scientific discipline – spacecraft–environment interactions.

Since interactions and their effects can depend on the environment, the spacecraft, and the spacecraft subsystems, it is important to properly define these variables. Based on these definitions, it is possible to systematically organize and describe the basic interactions. This procedure is followed in the next section.

1.2 Classification of Spacecraft Environments

The environment to which a spacecraft is subject consists of the combination of the ambient (typically a function of the orbit) and that generated by the spacecraft itself. The combination of these environments may not be their simple sum but a more complex environment brought about by a synergistic, nonlinear interaction. In fact, the self-generated environment of a spacecraft may substantially differ from the ambient, suggesting that the orbit may not always be a primary consideration in characterizing the in-situ spacecraft environment. In any event, in this book, the term "spacecraft environment" always means the combination of the ambient and the induced environments.

It is useful to characterize the environment in terms of four physical components: the neutral environment, the plasma environment, the radiation environment, and the particulate environment. The neutral environment includes the ambient gas and that released by the spacecraft surface materials through outgassing or decomposition, deliberately vented from the spacecraft, or emitted during thruster firings. The plasma environment includes the ambient plasma; that released from plasma thrusters; that created by ionization of or charge exchange with, the neutral gas; that generated by arc discharges; or that created by hypervelocity impacts with the spacecraft surfaces. The radiation environment has two components: electromagnetic and corpuscular. The electromagnetic radiation environment includes the ambient solar photon flux, that reflected (and emitted) from the Earth, and the electromagnetic interference (EMI) generated by the operation of spacecraft systems or arcing. It also includes electromagnetic waves generated by the plasma environment and photons emitted from spacecraft nuclear sources. The corpuscular radiation environment consists of the ambient flux of particles (electrons, protons, heavy ions, and neutrons) and any high-energy particles emitted by nuclear sources or reactors. The particulate environment consists of ambient meteoroids, orbital debris, and particulates released by the spacecraft. These are from a number of sources ranging from dust on the surfaces to material decomposition under thermal cycling and exposure to ultraviolet radiation.

1.3 Spacecraft Orbits and the Ambient Space Environment

Spacecraft orbits typically fall into specific families based on the intended use of the spacecraft. In addition to defining the interactions in terms of specific environmental conditions, it is therefore useful to consider the cumulative effects along these common orbital paths. There are five families of orbits that are of particular relevance for spacecraft interactions near the Earth. Other planets have the same components to the environment but different characteristics. These are: low Earth orbit (LEO), medium Earth orbit (MEO), polar orbit (PEO), geosynchronous orbit (GEO), and interplanetary orbit. Although a given spacecraft mission may have a more complex trajectory than represented by these orbits, it is still common to refer to the interactions that the spacecraft will see in terms of the five families. The characteristics of the five orbits are listed in Table 1.1.

Table 1.1. *Classification of orbits*

Name	Altitude (km)	Inclination to equator (deg)
Low Earth orbit	100–1,000	<65
Medium Earth orbit	1000–36,000	<65
Polar orbit	>100	>65
Geostationary orbit	~36,000	0
Interplanetary orbits	Outside magnetosphere	N/A

Table 1.2. *Description of orbits*

Name	Description
Low Earth orbit	Cold, dense, ionospheric plasma; dense, supersonic neutral atmosphere; solar ultraviolet (uv); orbital debris; South Atlantic anomaly (SAA)
Medium Earth orbit	Solar uv; trapped radiation belts; plasmasphere
Polar orbit	Solar uv; cold, dense ionosphere; supersonic neutral atmosphere; orbital debris; auroral particles; solar flares; cosmic rays; SAA; horns of radiation belt
Geosynchronous orbit	High-energy plasmasheet; substorm plasma; uv radiation; outer radiation belts; solar flares; cosmic rays
Interplanetary orbits	Solar-wind plasma; solar flares; cosmic rays

The primary physical components of the environment associated with each of the orbit families are described qualitatively in Table 1.2 (quantitative values are given in later sections). As an example of this classification scheme, consider a nominal *space station (SS)* orbit of 28.5° and *Earth Observing System (EOS)* satellite orbit. Their orbits are described in Table 1.3 and can be classified as being affected by the LEO or LEO/PEO orbital environments, respectively. Of course, there are highly elliptical orbits that span all five orbital environments. In such cases, a designer has to consider the characteristic interactions for each

Table 1.3. *Assumed* Space Station *(*SS*) and* Earth Observing System *(*EOS*) orbits*

Orbit	Spacecraft *SS*	Spacecraft *EOS*
Inclination (deg)	28.5	98.25
Altitude (km)		
Minimum	463	400
Nominal	500	705
Maximum	555	900
Orbit type	LEO	LEO/PEO

orbital segment as the vehicle passes through the different orbital regions along its trajectory.

1.4 Spacecraft Systems

Spacecraft require many different types of systems for their successful operation. Each system may affect or be affected by the environment. The systems also may add to the induced environment around the spacecraft. Typical systems are: power, propulsion, attitude control, structure, thermal control, avionics, communications, and the payload. A brief description of each of these components follows (for a complete description of spacecraft systems, see Agrawal (1986) and similar references).

Power System: The power system provides the electrical power for the spacecraft and its payload. For spacecraft with orbits inside the asteroid belts, the power source is usually solar arrays, although it can be fuel cells as on the *Shuttle*. For missions to the outer planets, nuclear sources such as radioisotope thermal generators (RTGs) are required. The power system also includes the power processing units and the power distribution subsystem (i.e., the cables, relays, and electronics necessary to get the power to where it is to be used) and the power storage system (usually batteries).

Propulsion System: The propulsion system is responsible for providing the velocity increments (or Δv) needed to maneuver and boost or reboost the spacecraft. The propulsion system is generally the chemical or plasma thrusters along with the associated tanks, propellant, and plumbing.

Attitude Control System: The attitude control system senses the spacecraft orientation relative to some reference system (e.g., the Earth, fixed stars, or the Sun) and maintains a desired attitude. It is composed of sensors such as star trackers or horizon sensors and inertial measurement units (IMUs) and actuators such as control moment gyroscopes, control thrusters, magnetic torquers, and flywheels.

Structure: The spacecraft structure physically houses all the systems of the spacecraft and includes the internal structure (e.g., plates, decks), external appendages, and the surface materials that make up the spacecraft skin. For understanding interactions with the environment, this book is concerned mainly with the external structure and the spacecraft skin. The structure or some part of it is usually taken as the electrical reference (i.e., the spacecraft ground).

Thermal Control System: The thermal control system is responsible for maintaining the temperature of the spacecraft within acceptable limits. It can be active, passive, or some combination of the two. A typical system is composed of heaters, coolers, radiating surfaces, and means for conducting heat around the spacecraft. Examples of the latter are heat sinks or heat pipes. Surface materials are often selected for their thermal properties, and thermal blankets or coatings frequently dominate the spacecraft exterior surfaces.

Avionics System: The avionics system has the task of controlling the functions of all the other systems and operating the spacecraft. It is composed of the electronics as well as the software necessary to run the spacecraft.

Communications System: The communications system provides the two-way command and data relay link with the ground station. It is composed of the transmitters, receivers, spacecraft antennas, and actuators necessary to orient them.

Payload: The spacecraft payload typically has many functions. For the purpose of studying interactions, however, the major payload components considered will be limited to different types of sensors and communications devices.

1.5 Interactions between the Environment and a Spacecraft

In this section, as an overview, the effects of the environmental components are summarized. Each of the four environmental components can affect the design and operation of a space vehicle or its systems. The effects may not be constant over time and will often change as the vehicle ages. Even on very short time scales (a fraction of the orbital period), the effects of an environmental interaction can vary substantially. In addition, although each environmental component has a unique effect on the spacecraft, it will be instructive to group their effects in terms of the five orbit families.

Consider first the neutral gas environment. This component has a number of potentially adverse effects on spacecraft. The ambient neutral environment in LEO below $\sim$800 km is dominated by the Earth's residual atmosphere, which is primarily monatomic oxygen over most of the altitude range (see Section 3.2). The atmosphere exerts an aerodynamic drag force on spacecraft. This drag force arises from the impact of the atmospheric particles on the spacecraft surfaces. Although the drag force is typically antiparallel to the spacecraft velocity vector, for large asymmetric spacecraft, aerodynamic torques become an issue. They must be taken into account by the attitude control system and can cause long-term problems for a large vehicle such as the *space station*. For LEO, the aerodynamic drag will eventually deorbit the spacecraft if it is not countered by periodic reboosting of the spacecraft. For example, the *space station* will require one logistics *Shuttle* flight a year to replace the propulsion modules and keep the station in orbit.

The impact of the atmospheric molecules on the spacecraft in LEO can initiate physical and chemical changes to the materials making up the structure of the spacecraft. The mean kinetic impact energy of the dominant atomic oxygen impinging on frontal or ram surfaces is 5 eV. Although generally this is not energetic enough to physically remove material from the surface, it is energetic enough to initiate chemical reactions on certain materials at the spacecraft surface that can lead to material loss. The flux of atomic oxygen to spacecraft surfaces at low-Earth orbital conditions (with a speed relative to the ambient atmosphere in the 7- to 8-km/s range) is approximately a monolayer per s. This flux has been shown to lead to surface erosion of materials such as Kapton or silver. For example, unprotected Kapton, a material often used as an external thermal control surface, was completely eroded from exposed surfaces on the Long Duration Exposure Facility (*LDEF*) spacecraft. The *LDEF* was placed in LEO orbit by the *Shuttle* and orbited for six years before being retrieved. Even on the short *Shuttle* missions, exposed Kapton samples have been found to erode measurably in a few days. In another example, one of the early designs of the *space station* was to have used a carbon–carbon composite for the truss as a mass-saving material relative to aluminum. It was determined that such a composite would erode significantly after only five years in space. Even if the flux of atomic oxygen does not erode the surface, oxidation of the surface may change the thermal properties of the surface layer. This must be considered in the design of the spacecraft thermal control system.

The LEO ambient neutral component is also a direct contributor to the diffuse UV–visible–IR glows that have been observed to occur above surfaces oriented toward the spacecraft ram direction. These complex glow phenomena, which include surface-catalyzed, excited recombination, appear to be functions of the spacecraft altitude, attitude, materials, surface temperature, time in orbit, nature of the orbit (including sunlight conditions), and vehicle size.

The induced neutral environment around a spacecraft arises from the release of neutral gas from sources on the spacecraft. Many materials are known to release absorbed gas on exposure to the space environment because the ambient neutral gas pressure in space is so low relative to that of the Earth. Additionally, materials may release gas through decomposition or sublimation. Neutral gas is generated through backflow from thruster firings, incomplete ionization of ion thruster gases, and effluent dumps. Over time, these gaseous products can coat and contaminate sensitive sensors and surfaces, seriously degrading their performance or rendering them useless. Optical sensors may be affected on the payload as well as thermal control surfaces and coverslides on solar arrays. One example of how interactions with supposedly neutral gases can drive the spacecraft design is given by the *Hubble Space Telescope* (*HST*). For the *HST*, the desire to protect the mirror from contamination led to the decision not to place attitude control thrusters on the spacecraft. Instead, the attitude is controlled by momentum wheels and magnetic torquers.

The plasma component of the environment represents a current flow to the spacecraft skin and the exposed parts of the power subsystem. Intrinsic imbalances in this current flow result in the buildup of charge on all surfaces exposed to the plasma. Charging also can be caused by the photoelectric effect, which causes surfaces to emit low-energy electrons when they are illuminated by the Sun. For large spacecraft in LEO, currents may be induced by the motion of the spacecraft across the geomagnetic field. The current flow to the spacecraft also may be significantly modified by the electric fields generated by a high-voltage power system exposed to the space environment.

The effects of current flow to the spacecraft can be profound because it can cause differential charge accumulation on the spacecraft surfaces. This charge, in turn, produces potential gradients between electrically isolated surfaces of the spacecraft and relative to the spacecraft ground and space plasma. At a minimum, any shift in potential relative to the spacecraft ground or to the space plasma can affect the operation of instruments designed to collect or emit charged particles. Beyond that, the buildup of differential potentials on the surface of the spacecraft or on the power system can give rise to destructive arc discharges or microarcs that generate electromagnetic noise and erode surfaces. This surface erosion contributes to the gas and dust environments near the spacecraft. For highly biased solar arrays (generating greater than 1,000 volts), it has been found that the arcing induced by the LEO plasma for conventionally designed solar cells is so severe that it destroys the array. Even for much lower voltages, the desire to avoid microarcs and the associated electromagnetic interference has been a design-limiting factor for solar arrays. Indeed, the *space station* solar arrays were chosen to operate at 160 volts to stay comfortably below an empirically determined arcing threshold of 200 volts. This lower voltage increased the weight of the power distribution compared to that for the higher operating voltages originally envisioned (higher voltages equate to lower line losses for the same thickness of wire).

For spacecraft in GEO, the charging environment can be much more severe than in LEO because the plasma, though much more tenuous, is very energetic.

This plasma can sustain surface potential differences of several thousands of volts between the spacecraft structure, its surfaces, and the space plasma. The arcing associated with the appearance of such large potential differences is believed to have been directly responsible for the failure of at least one and perhaps several GEO satellites as well as anomalous behavior on many others. To mitigate the effects of the charging, detailed design guidelines and computer codes have been developed by NASA to determine the type and placement of materials on the spacecraft surface, grounding schemes, and circuit filters. Although necessary, the synergistic relationship between these charge control design considerations, the thermal control design, and, in some cases, the meteoroid protection system can greatly complicate the design of a spacecraft.

One active way to mitigate the effects of surface charging is to emit a dense, cold plasma from a source on the spacecraft. The dense plasma supplies the charge required to neutralize the differential charge buildup on the surface and to balance the currents due to the ambient plasma while maintaining a desired frame potential. This technique was successfully demonstrated on the Advanced Technology Satellite, *ATS-6*, and will be used on the *space station* to suppress arcing on the habitation module. Besides arcing, the charge buildup on the spacecraft can attract charged contaminants to sensitive surfaces. This contamination, in turn, can alter the properties of the surface (e.g., making a conducting surface less conducting) and change the charging characteristics. This is known to occur on satellites at GEO and is one example where the synergism of the plasma and the neutral environment can produce an effect that enhances both interactions. Another example is that the flux of these neutral species to a surface can enhance the possibility of arcing associated with exposed parts of the power system by providing a source of electrons through ionization (i.e., Paschen breakdown or multipacting).

The corpuscular (particle) radiation component of the environment can affect the vehicle systems by direct radiation damage as well as by deep dielectric charging. The latter process is the result of high-energy electrons that can penetrate into the interior of a vehicle, deposit charge, and, ultimately, induce arcs inside the vehicle on electrically isolated components. The direct radiation damage can be either temporary or permanent. Temporary damage occurs when the state of an electronic component is momentarily modified by the passage of a high-energy particle through the component. This is known as a single-event effect (SEEs) and can reset a spacecraft clock, change the state of a random access memory, increase the noise levels in charge-coupled devices, and induce other false signals. In particularly severe cases, the SEE can cause a 'latchup,' where permanent damage can result from burnout of the integrated circuit. More common interactions are associated with the long-term buildup of the total ionizing dose (TID). The slow accumulation of charge or physical damage to the material because of the passage of high-energy particles leads to power loss in solar cells, degradation and failure of microelectronics, and darkening of optical components. Indeed, radiation damage to solar cells is one of the most important life-limiting factors in power system design for spacecraft. The design solution of choice is to oversize the solar array so that it will still be producing the desired power levels at the end of the life of the spacecraft. Clearly, such a solution is wasteful of weight and hence costly for the spacecraft program. Proper design to protect the spacecraft and its systems from the effects of corpuscular radiation can be extremely expensive, particularly for the new, more susceptible microelectronic components coming on the market. It is a major driver in the study of spacecraft interactions.

In addition to the effects of radiation due to particles, photon radiation effects also can adversely affect spacecraft systems. At the lowest frequencies, radio frequency interference affects the electronic systems while infrared from the Earth or other celestial body can alter the thermal balance of an orbiting spacecraft. Visible light glinting off surfaces or dust in the vicinity of sensors can create false images. At the other end of the frequency band, the ultraviolet radiation environment in space can directly degrade the properties of many of the materials used on spacecraft surfaces. As mentioned before, it can modify the charging of a spacecraft through photoemission or by photochemically bonding contaminants to sensitive surfaces. X rays and gamma rays, primarily from man-made sources, can penetrate surfaces and generate charged particles inside the spacecraft shielding, greatly enhancing their effect on sensitive systems.

Finally, impacts by the meteoroid or space-debris particulate environments can damage or totally destroy a spacecraft. The kinetic energy of even small particles moving at low-Earth-orbital velocities is so large that severe damage can result (the impact of an object the size of a pea moving at low-Earth-orbital velocities of 7 km/s is comparable to a bowling ball moving at 60 mph). Micrometeoroid impact velocities are typically 15 to 20 km/s and can be as large as 70 km/s. For example, a paint fleck struck a *Shuttle* window with sufficient energy to cause a large enough pit to require window replacement. The issue of damage from orbital debris has become one of the driving issues for the design of the *space station*. In addition, impacts can induce arcing on structures and surface materials under voltage stresses of less than 100 volts.

Besides the obvious potential for damage from particles moving at a large relative velocity with respect to the spacecraft, near-field particulate contamination can seriously degrade the performance of spaceborne optical systems. Small particulates trapped near the vehicle radiate or scatter enough energy to overload sensitive sensor systems. A particle in the near field that radiates may exceed the signatures of targets that are in the far field. Consequently, the particles will appear as clutter in the field of view of the sensor system. Dust or particulates around a spacecraft