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CONSIDERATIONS FOR MICRO- AND NANO-SCALE SPACE PAYLOADS

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Abstract

This paper collects and summarizes many of the issues associated with the design, analysis, and flight of space payloads. However, highly miniaturized experimental packages, in particular, are highly susceptible to the deleterious effects of induced contamination and charged particles when they are directly exposed to the space environment. These two problem areas are addressed and a general discussion of space environments, applicable design and analysis practices (with extensive references to the open literature), and programmatic considerations is presented.

Introduction

The use of advanced micro- or nano-technology in space payloads will increasingly provide a highly visible avenue by which to advance the state-of-the-art in ultra-large-scale integrated systems. Just as the aerospace industry fueled the development of integrated microelectronics over twenty-five years ago, the unique requirements of space systems to minimize weight and maximize performance will undoubtedly contribute to the extension of our engineering capabilities to the nano-scale. Since launch systems are not expected to employ these new technologies initially, flight experiment payloads (and vehicle diagnostic systems) will provide the first opportunities to demonstrate the practicality of these new technologies.

This paper collects and summarizes many of the issues associated with the design, analysis, and flight of highly miniaturized space payloads. Space environments, applicable design and analysis practices, and programmatic considerations will be discussed. Since many advanced micro- and nano-technology development activities exist outside the mainstream aerospace community, the information related here may serve as a useful introduction to potential payload designers and managers interested in flying space payloads.

Because studies of space environments, design and analysis strategies, and launch vehicle program requirement documents comprise a large body of literature, only a top-level overview of space flight in low earth orbit (LEO) will be given here and extensive reference will be made to the detailed literature.

Space Environment

Radiation

Thermal radiation is the primary mechanism for heat transfer in space. As a result, exposed payloads may be susceptible to very large temperature gradients. In predicting the operating temperatures of space hardware, a detailed numerical analysis is usually performed taking into account material optical properties and sun angles. The tailoring of surface properties for radiative heat transfer is an especially important element of payload design. However, it should be noted that these surface properties may be susceptible to changes due to contamination or interactions with photons, nuclear particles, or electrons, which will be discussed later [1].

In calculating temperatures, an accepted value for the solar heat flux is 1371 W/m^2 with a variance of $\pm$10 W/m^2 [2]. As a result of this flux, spacecraft in LEO typically experience naturally-induced surface temperatures ranging from -150 F to 250 F.

Some of the solar flux is reflected by a planet and is referred to as albedo. Albedo forms a secondary contribution to the heat flux incident upon spacecraft and is highly dependent upon time of day and other orbital parameters. Calculations of albedo can be made using specialized computer programs. References 3 and 4 are good resources for the thermal analysis of spaceflight systems and orbital thermal analysis software is available through the COSMIC software repository located at the University of Georgia.

Other forms of radiation, such as ultraviolet (UV), nuclear, and cosmic radiation, may also drive important considerations during design. For short duration micro- or nano-scale payloads, UV radiation, in particular, plays a significant role in the degradation of spacecraft materials and has special implications for thermal control. For example, the synergistic effects of UV radiation and induced contaminant films have been known to cause the darkening of optical, electronic, and thermal control equipment [5,6]. For longer duration missions, higher energy photons , such as x-rays, become more important and the fluence of these quanta is such that physical damage to materials can occur.

Upper Atmosphere

Typically, vacuum levels in LEO lie generally between 10^{-6} and 10^{-10} torr largely depending whether the control surface of interest is towards the ram or wake direction of flight. A lesser source of variability is due to fluctuations in solar activity. However, levels of vacuum as high as 10^{-14} torr are possible with the Wake Shield Facility (WSF), for example, which is a free-flying payload experiment carrier which has been flown aboard the Shuttle. For the simulation of on-orbit conditions, MSIS-90, an upper atmospheric database also available through COSMIC, has been widely employed in analyses of flight hardware with the LEO environment.

For payloads mounted on launch or re-entry vehicle external surfaces (such as data acquisition , a standard atmospheric model may be useful in approximating the ambient pressure and gas species to which payloads will be subjected. For modeling re-entry conditions, the GRAM-90 atmospheric model has been widely used and is available through COSMIC [7]. The Space Shuttle program also uses the Revised Range Reference Standard Atmosphere and the 1963 Patrick Air Force Base Standard Atmosphere to represent launch ascent conditions.

Induced Contamination

The contamination of payloads can be significant, especially for highly miniaturized payloads whose operation are more likely to suffer from relatively small contaminant depositions. Optics, radiators, sensors, and antennas are especially at risk since the accidental deposition of foreign materials on their surfaces may impair the successful operation of these devices (see refs. 8 and 9). Material surface properties may also be affected by contamination which has implications for thermal control [10]. Gases evolved (i.e., outgassed) from spacecraft materials are often the source of contamination for which the judicious selection of materials during design is the best prevention.

Material selection should be based on experimentally measured outgassing levels of the candidate materials (see ref. 11). ASTM E 1559-93 is a particularly attractive method for the testing of spacecraft materials [12]. However, it can be said that anodized aluminum and quartz are routinely employed for exposed spacecraft surfaces and may represent convenient materials for the packaging of micro- and nano-scale payloads. In contrast, silicones are problematic from the standpoint of contamination and should be avoided. In many cases, material outgassing may be minimized by conditioning the hardware to vacuum or a purging flow of inert gas prior to assembly (see ref. 13).

An appropriate design analysis may also involve the accounting of the outgassing species based on experimentally measured mass fluxes and a simulation of their interactions with the natural environment and spacecraft surfaces. MOLFLUX (available through COSMIC) is a software package that has been especially useful to this end [14]. However, several detailed assessments of contamination environments are already available for the Shuttle, International Space Station Alpha (ISSA), and Spacelab platforms (e.g., refs. 15, 16, and 17).

Plasmas and Charged Particles

While traveling through the ionosphere which begins approximately 50 to 70 km above the Earth's surface, a spacecraft will encounter effects due to plasma [2]. This plasma is created by the photo ionization of the ambient neutral atmosphere. Charged particles are present in the form of positively charged ions and free electrons that may contain enough energy to penetrate several centimeters of metal. However, charged particles with such high energies are not dominant at LEO altitudes. Nonetheless, the number of charged particles at LEO may be enough to confuse or blind certain sensors.

The characteristics of plasmas are dependent upon plasma density which is expressed as the electron number density. This density is defined by altitude, local time, season, and amount of solar activity. Some variations in plasma density are shown in Figure 1.

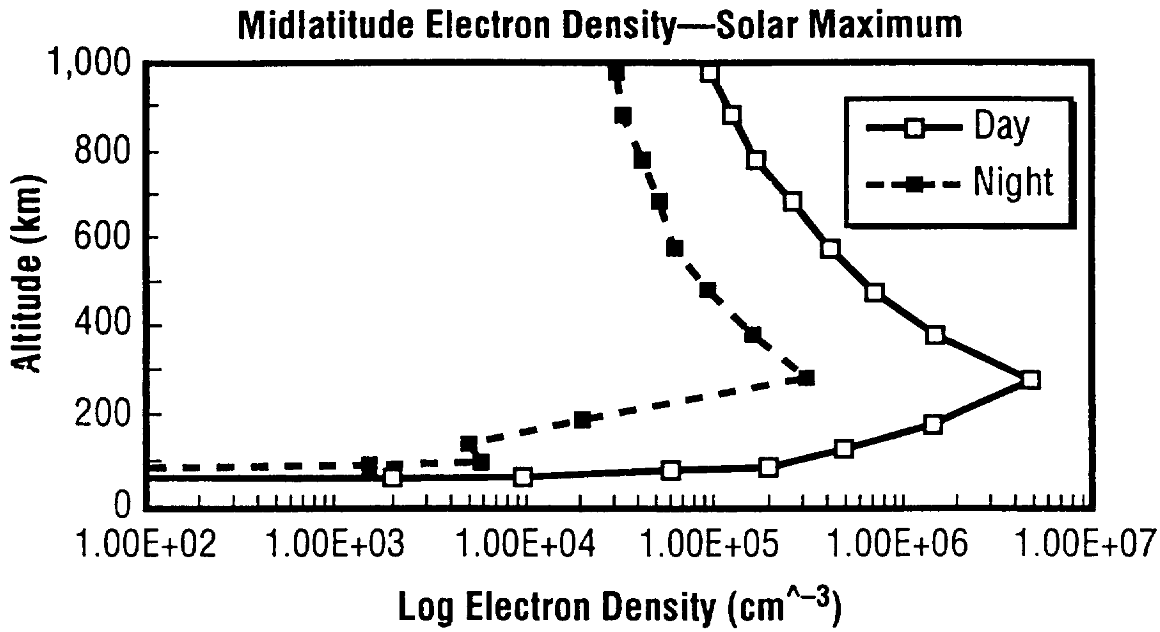

Figure 1. LEO Plasma Density at Solar Maximum [19].

Plasma can result in spacecraft charging, electromagnetic interference (such as radio frequency signals), as well as the erosion of spacecraft surfaces [18]. These phenomena may drive special considerations for the design of micro- and nano-scale payloads even in LEO (see ref. 20). However, through the careful selection of materials, the effects of charging and material erosion can be mitigated. The electrical biasing or shielding of electronic equipment, too, can be of significant help for this area of concern.

Another significant photo ionization effect at LEO altitudes (130 to 190 km) is the splitting of diatomic oxygen into monatomic oxygen. Monatomic oxygen is highly reactive and is responsible for the degradation of many nonmetallic spacecraft materials. To minimize these effects, it is preferable to locate payloads on the wake side of the host spacecraft where the exposure to the monatomic oxygen flux is less [5]. Reference 21 provides an assessment of atomic oxygen and ultraviolet exposures aboard the Shuttle (STS-46) and reference 22 presents an overview of the measured material reactivities for that flight.

Magnetic Fields

The Earth's magnetic field traps charged particles and deflects low-energy cosmic rays. The magnetic field consists of dipoles that result in a field strength at Earth's surface of 0.3 gauss at the equator and 0.6 gauss at the poles [2]. Currents from the magnetosphere cause deviations from the near-Earth field at altitudes greater than 2000 kilometers. Geomagnetic storms caused by solar activity result in fluctuations in the magnetic field strength. However, magnetic fields can be determined for orbital spacecraft by using a spherical harmonic expansion model:

$$\vec{B} = -\nabla\vec{U}$$

for which various expressions for U, the magnetic potential, are available in the literature [e.g., ref. 2].

Microgravity

Gravitational forces upon spacecraft can be approximated to within 0.1 percent using the central-force model:

$$\vec{F} = \frac{\mu_E m}{r^2} \cdot \hat{r}$$

where,

μ_E = Earth's gravitational constant = 3.986012×10^{14} N m^2/kg
m = Mass of spacecraft
r = Distance from center of Earth

However, gravitational models are available that offer accuracies of a few parts in a million (e.g., ref. 23).

Usually, high frequency accelerations induced by the host spacecraft are of more serious concern for the design of highly miniature payloads. Fortunately, the primary vibrational modes of most spacecraft structures lie in the range of 5 to 200 Hz and are too low to affect the operation of most micromechanical devices. However, more significant vibrations in the range of 200 to 2000 Hz may arise as a result of acoustic noise in the payload compartment [24,25]. Unfortunately, detailed vibroacoustic data is usually not comprehensive for most commercial payload environments and, oftentimes, only a few data points are available from the commercial launch vehicle operator in order to characterize a launch vehicle's vibrational environment. However, microgravity assessments are available for the Shuttle (e.g., refs. 26 and 27).

Orbital Debris

Meteroids pose a threat to orbiting spacecraft especially at geosynchronous altitudes (800 to 1000 km) and higher orbital inclinations [19]. In many cases, the concern over orbital impact damage from natural sources will be negligible especially if shielding is employed in some way. However, artificial sources of particle impacts, such as waste water dumps for example, may be of larger concern (see ref. 28). However, the probability of particle impacts is inversely proportional to the size of the particle and, therefore, degradation of micro- and nano-scale payloads is more likely to occur due to impacts of very small (i.e., less than 100 μm) particles. The size of these small payloads offers an additional advantage in that the probability of an impact is further reduced due to their low visibility as a target.

For payloads for which orbital impacts remain a consideration, numerous models are available for predicting the vulnerability of such a threat. Reference 29 is a well-accepted model that characterizes the population of orbital debris. A caveat that has been noted, however, in that this model may underestimate particles larger than 2 cm [30].

Accessing Space

Space Shuttle

Shuttle payloads may be either in the mid-deck or in the payload bay depending on whether access to open space is required. For payload bay payloads, the period between 1998 and 2002 will be marked by Space Shuttle missions dedicated to the delivery of space station elements. These missions will maximize the capacity of the payload bay thereby displacing the smaller packages traditionally used for scientific experimentation in the open space environment. However, by designing ultra small payloads that do not require Shuttle utilities and are largely unobtrusive, the micro- and nano-scale payload designer will have a unique opportunity to couple space science experimentation in the payload bay with the technological advancement of highly miniaturized integrated systems in spite of the hardships that conventional payloads will face.

International Space Station Alpha

At this time, payload manifesting for the International Space Station Alpha (ISSA) has not yet begun. However, the idea of micro- and nano-payloads is being promoted at NASA and, at this time, remains largely conceptual with a significant degree of enthusiasm.

Expendable Launch Vehicles

An important consideration when developing highly miniaturized payloads, especially for flight on commercial launch vehicles, is to employ a high degree of autonomy that minimizes (or eliminates altogether) the need for utilities supplied by the launch vehicle (i.e., power, thermal control, data acquisition and telemetry). It is also important to make sure that payloads do not adversely affect other payload customers by inducing excessive contamination or electromagnetic interference.

Summary

An overview of the LEO space environment and its effects upon spacecraft and space payloads has been given. Also, selected design and analysis guidelines have been referenced and the importance of designing small, unobtrusive micro- and nano-scale payloads has been emphasized. In conclusion, Table I outlines some possible space environmental effects and influences that should be considered during the development of highly miniaturized space systems.

Table I. Possible Space Environment Effects and Influences on Micro- and Nano-Scale Payloads.

	Micromechanical Systems	**Micro- Electronics and Photonics**	**Microfluidic Systems**
Radiation	fatigue;cross-linking/brittle transitions; thermally-induced vibrations; solid diffusion	semiconductor transitions; dielectric properties; solid diffusion	fluid viscosity; surface tension; Brownian motion; Marangoni flow
Upper Atmosphere	pressure equalization; outgassing	pressure equalization; outgassing	pressure equalization; outgassing
Induced Contamination	mass changes; changes in dynamic response; changes in surface properties	changes in surface properties	changes in surface properties
Plasma and Charged Particles	static charging	static charging; electromagnetic interference	static charging
Microgravity	minor effects	negligible effects	minor effects
Orbital Debris	structural damage (minor concern)	structural damage (minor concern)	structural damage (minor concern)

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