Abstract

This paper describes an integrated, comprehensive tools for analysis of environmental related spacecraft hazards for use in spacecraft analysis and design, mission planning and operations. This analysis is extremely important for small satellites since they are often at higher risk due to a number of physical, economic and operational constraints. These constraints may limit the ability to mitigate the natural and man-made hazards resulting from the space environments the satellite will be operating in. The SEAT software tool addresses hazards and effects related to solar activity, magnetic fields, radiation, thermal exposure, impact from small particles, plasma and neutral atmosphere exposure. SEAT is integrated with a commercial-off-the-shelf orbit analysis package. It is designed to be useable by spacecraft engineers and operators who may not have expertise in space environmental effects and their analysis.

Introduction

Small satellites are often more greatly constrained by physical, economic and operational considerations than larger spacecraft.1 These constraints may limit the ability to mitigate the natural and man-made hazards resulting from the space environments the satellite will be operating in. For example, small satellites are more likely to fly without radiation tolerant (rad-tol) and/or radiation hardened (rad-hard) components because the shorter operational lifetime, budget and schedule constraints may not allow for the higher cost and longer lead time for obtaining rad-tol and rad-hard parts. Size and mass limitations may also the limit the amount of shielding allowed to
protect components. In such situations, it is critical to know the types and characteristics of space environmental hazards to maximize the effectiveness of the available mitigation strategies, such as parts selection and placement.

The space environment hazards that spacecraft and mission designers and operators need to be concerned with are:

- Solar Environment
- Magnetic Environment
- Radiation Environment
- Thermal Environment
- Impact Environment
- Plasma Environment
- Neutral Atmospheric Environment

More information on these environments is given in the following section of this paper.

Unfortunately, satellite designers and operators have had very limited choices in tools for performing the analysis tasks related to space environmental effects. Most of the available tools are hard to obtain in useable formats, are poorly documented and are difficult to use for the non-specialist. In addition, these tools are usually stand-alone programs that address a single type of effect and do not easily integrate, interface or share data with each other and other software tools commonly used by satellite designers and operators, such as orbital analysis software.

In order to address these shortcomings and limitations, an integrated Space Environmental Analysis Tool (SEAT) has been developed. SEAT determines the environmental interactions and effects from solar, radiation, thermal, impact, plasma and neutral atmospheric exposure. SEAT is designed to transparently interface with STK, the orbit analysis software tool from Analytical Graphics, Inc. and uses this interface to obtain information on the timeframe and orbit of interest. This information is used to automatically select the appropriate environmental models and determine input and control variable values to use with the different models. Where possible, these controls are configured in accordance with existing Air Force, NASA and ESA guidelines for environmental effects analysis.

**Space Environment Overview**

**SOLAR ENVIRONMENT**

The solar environment, directly or indirectly, effects all the other hazard environments. The solar activity levels, which follows an 11-year cycle, directly is a directly contributing factor interacts to the radiation, thermal and plasma environments. The increased energy output from the Sun during its active periods heats the Earth's atmosphere and causes it to expand, which can effect the impact and neutral atmosphere environments, as well.

SEAT includes a database of archival (actual) and predicted solar environment parameters. Figure 1 shows the actual and predicted activity levels, based on the smoothed sunspot number (SSN) for the Cycle 23, the current cycle. The database includes F10.7 solar flux value and solar activity state indicators. Figure 2 shows the actual and predicted F10.7 profile for Cycle 23. This information is used by a number of the environmental analysis models for analyzing the conditions the spacecraft is exposed to. Unlike most other analysis software, which support only static input values, it can automatically adjust these parameters over the time period of interest to more accurately determine the space environment effects as solar activity level, geomagnetic field strength and other coupled parameters change over time. Periodic updates of the archival and predicted data will be available over the Internet as needed.

**MAGNETIC ENVIRONMENT**

The fields generated by the magnetic environment can directly interact with spacecraft. This is often taken advantage of in the attitude control subsystems, which can employ magnetometers and magnetic torque rods. The magnetic environment is also a major factor in determining the radiation and plasma environments around the Earth.

SEAT incorporates the Olsen-Pfitzer magnetic field model. This model includes an external field component as well as the internal field. The internal field is modeled using a spherical harmonic expansion of the magnetic potential using the standard IGRF coefficients. Since the magnetic field (and the IGRF coefficients used to express it) change over time, the current and past epochs are included in the environmental database. The software will automatically select the appropriate dataset and in the case where no data is available (such as the future), the standard method of linearly extrapolating the values from the IGRF data is used.

The external field results from the interaction between the solar wind, the magnetosphere and the interplanetary magnetic field. For low earth orbit, the external field influence is negligible, but can be a significantly contributing factor for higher altitude orbits.
The radiation environment is principally composed of naturally occurring charged particles trapped in the Earth's magnetic field (also known as the Van Allen belts). Energetic solar particles and galactic cosmic rays also contribute to the natural radiation environment. The Van Allen radiation is usually responsible for most of the ionizing dose damage to electronics and materials, though energetic solar particles can also be a significant source during solar storms. Solar particles, cosmic rays and trapped protons with energies greater than 50 MeV can also cause single event effects (SEE) that disrupt electronics. The total ionizing dose, the exposure dose rates and SEE must be considered in the spacecraft design and component selection.

Several radiation environment models are incorporated into SEAT. These include the models developed by the Air Force Research Lab (AFRL) using data from the CRRES and APEX satellite missions. The NASA AP-8 proton model and AE-8 electron model are also included. In the cases where the model reports fluence instead of ionizing dose, the SHIELDOSE radiation transport model is used to convert.

The thermal environment consists of thermal energy flux from the sun, the solar energy reflected back into space (and towards the spacecraft) from the Earth, referred to as albedo and the direct long wave thermal emission of the Earth due to its temperature, sometimes referred to as Earthshine. This energy, combined with any internal heat dissipation requirements must be accounted for in the satellite thermal management subsystem design and operations.

SEAT determines the thermal of the spacecraft and treats the spacecraft as a single isothermal node to determine the steady-state temperature. It does not provide the multi-nodal thermal and heat transfer analysis available from such tools as SINDA, FLUINT, Radcad and Nevada/Vegas. Since the Earth albedo varies, the software performs the calculations for three cases - nominal, hot and cold albedo. A value for the internal heat dissipation can also be specified. The steady-state temperature is computed using user provided values for the surface area and absorptance and emissivity properties.

The impact environment consists of material from natural occurring micrometeoroids and from man-made debris flux. Due to the high relative velocities, even tiny particles can cause direct physical damage to the satellite structure and solar panels and can also induce damaging electrostatic discharges.

The "modified Kessler" method is used for determining the man-made debris flux. This model accounts for the effects of the solar activity level on the atmosphere, which in turn, effect the population of particles at low altitudes and also accounts for expected growth in the number of particles due to rocket launches, satellite deployments and break-ups. The Grun et al. model is used for naturally occurring micrometeoroids. The earth shielding factor is accounted for in the model in reducing the number of particles encountered versus exposure in interplanetary space. The value for the spacecraft cross-sectional area needs to be provided and is used to generate statistics of the number and size of impacts expected to occur.

This feature complements the STK Close Approach Tool, which analyzes the impact hazards from large objects appearing in the USSPACECOM catalog.

The plasma environment is mostly composed of charged particles (electrons) with energies too low to be a radiation hazard. However, these particles can strike and deposit themselves on external surfaces of the spacecraft or penetrate through the surface and deposit on internal components, causing electrostatic charge build-up. This charge can build up to high enough levels to create electrostatic discharge hazards that can damage spacecraft electronic components.

The neutral atmospheric environment is the residual atmosphere remaining at spacecraft altitudes. The neutral atmosphere can contain atomic oxygen, which can damage the materials used on the spacecraft. Other residual atmospheric chemicals can also react with materials or be a source of contamination for optical systems.

The initial release of SEAT provides the following analysis:

- Radiation Dose
- Impact
Additional functionality planned for future releases of SEAT include:

- Enhanced ionizing dose analysis, including provision of fluence data, as well as dose data and improved radiation transport analysis.
- Incorporation of CHIME for single event effect analysis resulting from high energy trapped protons, solar protons and cosmic rays.
- Incorporation of neutral thermosphere modeling for analysis of chemical contamination and atomic oxygen effects on Low Earth Orbiting (LEO) spacecraft.
- Incorporation of plasma environment modeling for analysis of plasma, charging and localized electromagnetic phenomena.

SEAT is expected to be commercial available in the 4th quarter of 1999. Most of the additional functionality is expected to be available in SEAT within the first year of its release.

**RADIATION DOSE**

The Radiation Dose functionality determines the total ionizing dose exposure for the spacecraft over the course of the mission time span. SEAT also provides information on the ionizing dose rate, since some classes of electronic devices have been recently shown to be more susceptible to damage at low exposure rates, whereas testing has traditionally been done at high rate. An example dose graph is shown in Figure 3. SEAT provides the option of using the NASA AP-8 and AE-8 radiation models, or it can be configured to automatically select the appropriate radiation models. In the automatic selection mode, the AFRL CRRES and APEX radiation models may be used instead of or together with the AP-8 and AE-8. The selection is made based on the satellite orbit and timeframe relative to the solar activity cycle. This information is also provided to the user. A sample report is shown in Figure 4.

**IMPACT**

The Impact functionality determines the spacecraft exposure to impact hazards from natural occurring micrometeoroid and man-made orbital debris flux. The values are reported as integral number of impacts greater than a given mass at the end of the time period of interest. The values are calculated for a randomly oriented surface. Figure 5 shows the output of an impact report. Figure 6 shows the corresponding graph. This information can be used in determining the need for shielding and the likelihood of catastrophic collision over the spacecraft lifetime.

**TEMPERATURE PROFILE**

The Temperature Profile functionality determines the spacecraft exposure to thermal loads from the direct solar, albedo (Earth reflected solar) and Earth outgoing long-wave radiation. SEAT treats the spacecraft as a single isothermal node and determines the steady-state temperature for the nominal, hot and cold albedo cases. A value for the internal heat dissipation can also be specified. The steady-state temperature is computed using user provided values for the surface area and absorptance and emissivity properties. Different values can be specified for the surface area for thermal emission and absorption.

A temperature profile report is shown in Figure 7. A temperature plot is shown in Figure 8.

**SOUTH ATLANTIC ANOMALY TRANSIT**

The South Atlantic Anomaly Transit functionality determines the entry and exit times and related statistics for spacecraft passages through the South Atlantic Anomaly (SAA). The SAA is a region of space where the Earth's magnetic field is weakest, resulting in heightened exposure to protons with energies greater than 50 MeV which can result in increased numbers of single event effects (upsets and latchups).

The SAA Transit analysis can be useful in component selection. For example, previous versions of the ITHACO SCANWHEEL, found in the attitude control subsystem of several small satellites, were shown to be susceptible to proton radiation, before additional shielding was added by ITHACO. The SAA Transit analysis provides information on the percentage of time that the spacecraft will be operating in the SAA, allowing for appropriate component selection or shielding decision to be made. In addition, this function can also be useful for operational mission planning. It can be used to provide predictions of SAA fly-through. This knowledge can then be used to schedule critical spacecraft so they don't occur during periods of higher vulnerability.

An example SAA transit report is shown in Figure 9.
Small Satellite Analysis Results

This section contains a typical analysis as an example. It is often the case in the spacecraft business that missions are delayed and can launch months and even years after their originally intended launch date. The analysis was performed to determine the results of potential launch slips for a mission scheduled for launch in summer of 1998. The example spacecraft has a nominal design life of 6 months with a 1 year goal. The orbit information and SEAT input parameters are shown in Table 1.

A set of analysis runs was performed for a 1 year period, with the start date slipping by 6 months in each successive run. It can be seen in Figure 1 that Solar Cycle 23 is expected to peak during this period at a level potentially twice that of the original launch date. Figure 10 shows the graphs for the Dose result for 4 of the runs. It can be seen that there is a significant increase, approximately 50% in the dose between the original date and a year later, which then increases slowly. The implications are clear if 1.5x was used as the design margin for total dose.

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References


5. ESA Space Environmental Standard, ECSS E-10-04 Draft 02

6. MIL-STD 1809 - Space Environment, 1993


Figure 1: Solar Cycle 23 Activity Level, Predicted and Actuals - Sunspot Number
(http://www.sunspotcycle.com/)

Figure 2: Solar Cycle 23 Activity Level, Predicted and Actuals - F10.7 Radio Flux
(http://science.msfc.nasa.gov/ssl/pad/solar/predict.htm)
Figure 3: Ionizing Dose and Dose Rate Graph (24 Hour period, 1000 km Sun Synchronous Orbit)
Figure 5: Example Impact Report

Figure 6: Example Impact Graph
Figure 7: Example Temperature Profile Report

Figure 8: Example Temperature Profile Graph
Figure 9: Example SAA Transit Report

Table 1: Example Analysis Satellite Orbit

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<th>Parameters</th>
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<td>Perigee Altitude</td>
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<tr>
<td>Longitude of Ascending Node</td>
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</table>

Figure 10(a): Total Ionizing Dose (Original Mission Time Span - Launch in June 1998)
Figure 10(b): Total Ionizing Dose (Six Month Slip - Launch in Dec 1998)

Figure 10(c): Total Ionizing Dose (One Year Slip - Launch in June 1999)
Figure 10(d): Total Ionizing Dose (Two Year Slip - Launch in June 2000)