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DEFENCE DÉFENSE

ESA and DREO Space Environment Effects Modelling Tools

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Defence R&D Canada

TECHNICAL REPORT
DREO TR 2001-137
December 2001

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ESA and DREO Space Environment Effects Modelling Tools

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Technical Report
DREO TR 2001-137
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Abstract

This report compares the Space Environment Effects modelling approaches of ESA (SPENVIS) and DREO (VETTE&CREME). Compared are near Earth space radiation and debris environments and their effects on space-borne systems. In general, a similarities and differences exist between the results obtained by the two models. Reasons for agreement/disagreement are explained.

Résumé

Cet état compare des effets d'environnement de l'espace modelant l'approche d'cEsa (SPENVIS) et de DREO (VETTE&CREME). Comparés sont des environnements proches de rayonnement et de débris de l'espace de la terre et leurs effets sur les systèmes capable de supporter l'espace. En général, un accord et les différences existe entre les résultats obtenus par les deux modèles. Des raisons d'agreement/disagreement sont expliquées.

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Executive summary

Attention is being focused on the abundant case history of in-orbit operational anomalies and failures of spacecraft due to the near-Earth space environment in which they are required to operate. It is now well known fact that ionising radiation will have a deleterious effect on electronic and dielectric components of a satellite, such as function upsets, burnouts, electrostatic charging followed by uncontrolled discharging, surface erosion due to sputtering and change of desired material characteristics. The effect of debris and meteorites on space platforms during the collision can result in severe damage or total destruction.

It is therefore important that satellite designers are able to predict the environment in which the satellite will be required to operate. In this work, SEE model SPENVIS developed at ESA, is compared with the model utilized by DREO. Compared are results of space radiation environment space debris modeling at near-Earth orbits. It was observed that, in some cases, there is a good agreement between the results of the two modeling approaches, however there are also differences. These are explained as caused by the continuous development of the existing SEE models.

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Sommaire

L'attention est concentrée sur les antécédents abondants des anomalies opérationnelles d'dans-orbite et les pannes du vaisseau spatial dues au near-Earth espacent l'environnement dans lequel elles sont exigées pour fonctionner. Il est maintenant fait bien connu que le rayonnement s'ionisant aura l'effet délétère sur les composants électroniques et diélectriques d'un satellite, tels que des renversements de fonction, des grillages, du remplissage électrostatique suivi de la décharge non contrôlée, de l'érosion extérieure due à la pulvérisation et du changement des caractéristiques matérielles désirées. L'effet des débris et des météorites sur des plateformes de l'espace pendant le bidon de collision a comme conséquence la destruction grave de dommages ou de total.

Il est donc important, ce les créateurs satellites peuvent prévoir l'environnement dans lequel le satellite sera exigé pour fonctionner. Dans ce travail SEE LE SPENVIS modèle, développé à l'cEsa est comparé au modèle utilisé par DREO. Comparés sont des résultats des débris de l'espace d'environnement de rayonnement de l'espace modelant aux orbites de near-Earth. On l'a observé, cela il y a dans certains cas une bonne concordance entre les résultats des deux approches modelantes, toutefois il y a également des différences. Celles-ci sont expliquées comme provoqué par le développement continu d'exister SEE les modèles

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1. INTRODUCTION

Problems for space missions operating in a space radiation environment are a growing concern. At the design stage, it is therefore important to be able to predict the radiation environment in which the space platform will be operating. This starts with mission specification in which information such as when during the solar cycle the mission will occur, orbit parameters, system deployment timing, and which parts of the system are susceptible to SEE (Space Environment Effects). From the knowledge of the radiation environment, the dose into SEE sensitive parts can be calculated.

Space radiation models are available that allow the system designers to carry out these estimates. Space radiation models that are at the present being used at DREO are the AE8 and AP8 and CREME.[1] AE8 and AP8, the most widespread radiation models, provide orbit-averaged, positional and mission averaged flux vs. energy spectra of geomagnetically trapped electrons and protons. The model is available from National Space Science Data Center at NASA-GFC. The CREME model gives information about GCR (galactic cosmic rays), a stream of singly or multiply ionized heavy particles originating outside the solar system. CREME also returns two types of geomagnetic cut-off coefficients, one for disturbed and one for undisturbed magnetospheric conditions. These particles also contribute to the Earth's radiation environment. The third component, the solar flare protons, can be obtained using KING and JPL92 models. Both models predict the solar flare proton contribution the radiation environment during the mission.

In this work, Space Environment Information System (SPENVIS), an ESA space environment software tool, is used to analyze SEE for two LEO orbits. The main purpose of this work is the results comparison of the DREO approach with the results obtained using SPENVIS. This work is organized as follows: section 2 provides orbital parameters information for LEO 1 and LEO 2, section 3 gives a brief summary of SPENVIS, section 4 is the radiation effects section, section 5 compares space debris results and section 6 shows the results related to spacecraft charging.

2. ORBITAL PARAMETERS

The following two low altitude orbits were used in this comparison study[2]. The orbits in the DREO method were propagated for 6.71 days for the 600km orbit and 7.45 days for the 1100km orbit. Trajectory times for the SPENVIS system were 1.341 days and 1.488 days in one-minute steps to obtain positional fluxes.

LEO 1
Orbit 1: Circular
Altitude: 1100km
Inclination: 85^O

LEO 2
Orbit 2: Circular
Altitude: 600km
Inclination: 98^O

3. SPENVIS PROJECT OPERATIONS

SPENVIS incorporates several SEE models into a unit, which runs behind a user-friendly graphical interface. User registration is required, and login whenever a user wants to access the system. It runs over the WWW (World Wide Web) directly or it can be run in a batch mode. Batch mode is recommended in analysis that requires calculations that might take a considerable amount of time. The program allows the user to create projects, revisit them and manipulate project parameters such as types of analysis, output presentations and others. There are several operations available to the user. Some of these are compulsory, others are not. The following is the list of project operations.

i) Project Creation is required to run SPENVIS. This creates a subdirectory on the hard drive of the SPENVIS system. In this subdirectory, all the input/output parameters / files of the project are stored. Preservation of input parameters, for example, allows re-running of the project without any need of re-entering input.

ii) Project Switching is simply selection of the project to run or edit if several exist under the same user name

iii) Project Deletion erases a project from the SPENVIS hard drive

iv) Edit Project Setting changes settings of the existing project. These can involve changes in input parameters, changes in the type of analysis to be carried out or changes in the form of the output.

v) Project Results provides access to the output files. All output files are in ASCII form.

vi) Project Plots - SPENVIS allows different graphic output plots (GIF, JPEG, and BMP). The graphic format can be selected from the selection menu on the page. These can also be downloaded to the user computer.

There are several types of analysis available to the user of the SPENVIS system:

- Radiation Analysis
- Magnetic Field
- Atmosphere and Ionosphere
- Spacecraft Charging
- Meteoroids and Debris

SPENVIS projects LEO 1 and LEO 2 were created and run in an online mode. LET calculations were run in a batch mode due to extensive time requirements.

4. RADIATION ANALYSIS

4.1 Orbit Creation

The initial step in both methods involves orbit creation. Using the DREO method, the user is required to enter orbit parameters into a program called "ORBIT". The program converts the orbit trajectory from the R-λ coordinate system into B-L coordinate system. Since the spectrum of trapped radiation is mapped in the B-L coordinates, the radiation flux at various points of the trajectory, because of the conversion, is therefore known. With SPENVIS, these actions are similar, but the user utilizes an interactive graphical interface to create orbits. Various orbit plots can also be enabled and are available for inspection or printing from the web page.

4.2 Trapped Radiation

Both SPENVIS and DREO use AE8 and AP8 space radiation models to determine the trapped radiation environment. The AE8 model is applicable to electrons in the energy range from 40keV to 7MeV with L (McIllwain's magnetic shell parameter) values ranging from 1.15R_E (R_E=Earth radius) to 11 R_E. The AP8 model is applicable to protons in the energy range from 100keV to 400MeV. With the DREO method, the program called "VETTE" utilizes the B_L trajectory calculated by the "ORBIT" code and processes the AE8 and AP8 space radiation models, calculating radiation flux at various orbit points. The program output also consists of differential, integral and energy-window binned spectra of trapped radiation, specific to a given orbit. With SPENVIS this action is again hidden from the user. SPENVIS has available additional, more specific radiation models associated with very specific orbits such as the NOAA GOES satellites, the CRESS satellite, MIR orbit to name a few. The differential proton and electron flux for the two orbits are summarized in the Tables 1 and 2 and shown in Figures 1 to 4.

***Table 1**. Calculated relative electron and proton flux ratios at LEO 1*

ENERGY (MEV)	FLUX RATIO (ELECTRONS)	ENERGY (MEV)	FLUX RATIO (PROTONS)
	SPENVIS/DREO		***SPENVIS/DREO***
0.040	0.982676379	1.0000E-01	0.974563467
0.100	0.951979747	5.0000E-01	1.544985222
0.200	0.927850549	1.0000E+00	1.84787027
0.300	0.914792727	2.0000E+00	1.786767568
0.400	0.901065089	3.0000E+00	1.3424516129
0.500	1.102962162	4.0000E+00	1.295688649
0.600	1.073005714	5.0000E+00	1.1844
0.700	0.991115655	6.0000E+00	1.159346939
0.800	1.0328516129	8.0000E+00	1.135968473
1.000	1.042465574	1.0000E+01	1.194171429
1.250	1.019011765	1.2000E+01	1.170327273
1.500	1.005826415	1.5000E+01	1.1422556391
1.750	0.998588698	1.7000E+01	1.18061329
2.000	1.00349313	2.0000E+01	1.182363257
2.250	1.052463158	2.5000E+01	1.159762803
2.500	0.955596992	3.0000E+01	1.173236364
2.750	0.955030331	3.5000E+01	1.221333333
3.000	0.979089443	4.0000E+01	1.168475109
3.250	1.012114286	4.5000E+01	1.158
3.500	0.994300541	5.0000E+01	1.178181818
3.750	1.012450909	6.0000E+01	1.170283146
4.000	1.000441629	7.0000E+01	1.161894479
4.250	1.01772766	8.0000E+01	1.166983784
4.500	1.009774408	9.0000E+01	1.16544
4.750	1.054542857	1.0000E+02	1.160129032
5.000	1.045222642	1.2500E+02	1.159975385
5.500	0.992823952	1.5000E+02	1.163825166
6.000	0.730011738	1.7500E+02	1.162941056
6.500	N/A	2.0000E+02	1.159074783
		3.0000E+02	1.142989944

***Table 2**. Calculated relative electron and proton flux at LEO 2*

ENERGY (MEV)	FLUX RATIO (ELECTRONS)	ENERGY (MEV)	FLUX RATIO (PROTONS)
	SPENVIS/DREO		***SPENVIS/DREO***
0.040	1.139755689	1.0000E-01	1.176264567
0.100	1.084525714	5.0000E-01	1.686043165
0.200	1.07979907	1.0000E+00	2.161925706
0.300	1.133627586	2.0000E+00	2.4624
0.400	1.096009721	3.0000E+00	1.892467005
0.500	1.1974212766	4.0000E+00	1.88352
0.600	1.180666047	5.0000E+00	1.676277551
0.700	1.1214	6.0000E+00	1.571728696
0.800	1.160176656	8.0000E+00	1.448716707
1.000	1.15514085	1.0000E+01	1.518730435
1.250	1.141866667	1.2000E+01	1.519930435
1.500	1.102205607	1.5000E+01	1.42797913
1.750	1.079080851	1.7000E+01	1.436651163
2.000	1.09632	2.0000E+01	1.4406939759
2.250	1.129687372	2.5000E+01	1.4328
2.500	1.066878505	3.0000E+01	1.413560656
2.750	1.0584	3.5000E+01	1.438612048
3.000	1.0824	4.0000E+01	1.429476923
3.250	1.107	4.5000E+01	1.435885714
3.500	1.069170889	5.0000E+01	1.444731429
3.750	1.087545852	6.0000E+01	1.427873684
4.000	1.072340426	7.0000E+01	1.436487805
4.250	1.087466667	8.0000E+01	1.427873684
4.500	1.084253829	9.0000E+01	1.427657143
4.750	1.1332097561	1.0000E+02	1.399975831
5.000	1.1238084507	1.2500E+02	1.378467762
5.500	0.980142408	1.5000E+02	1.387465327
6.000	0.986896552	1.7500E+02	1.383919121
6.500	N/A	2.0000E+02	1.347314917
		3.0000E+02	1.332934351

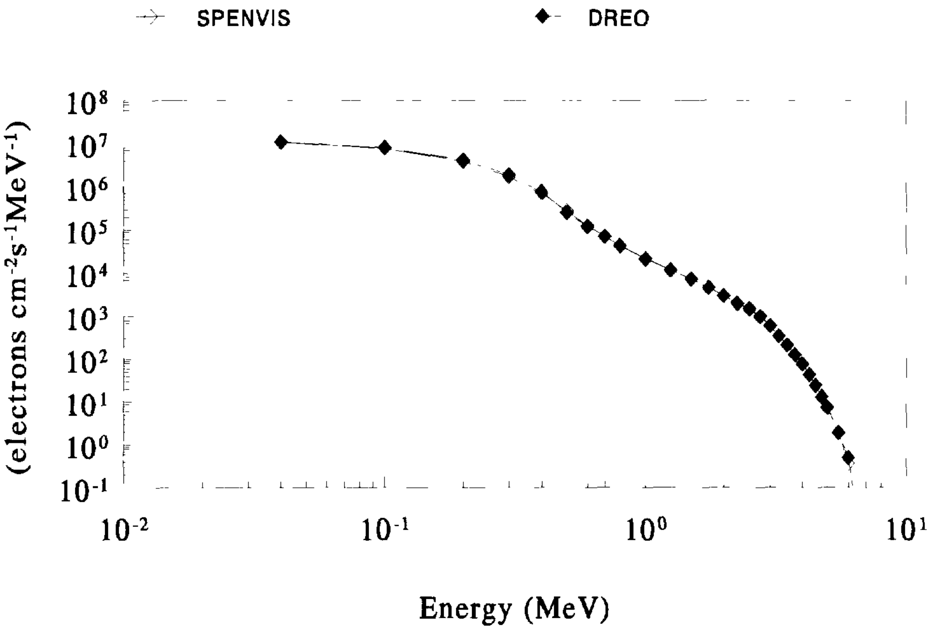

Figure 1. *SPENVIS and DREO differential electron spectra for LEO 1*

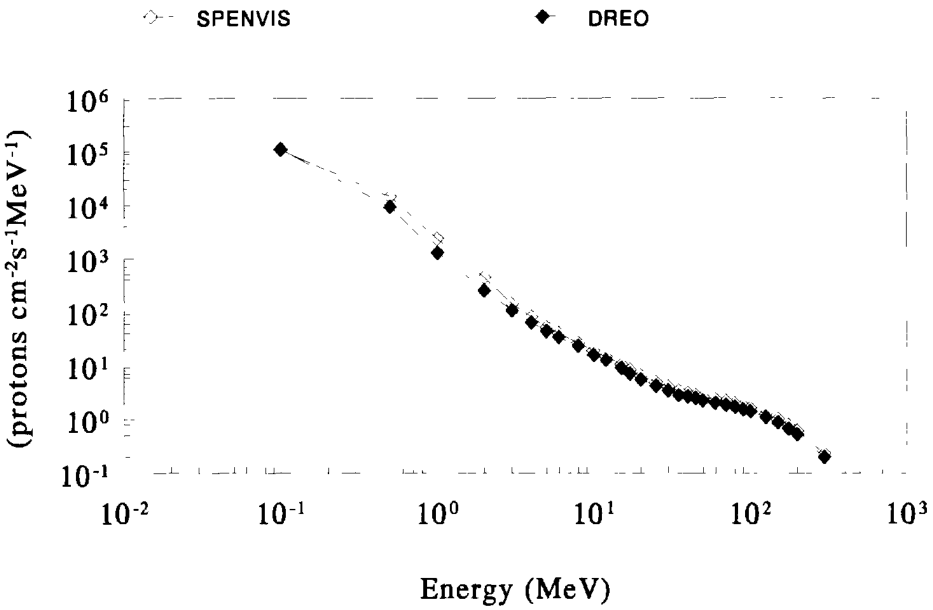

Figure 2 *SPENVIS and DREO differential proton spectra for LEO 1*

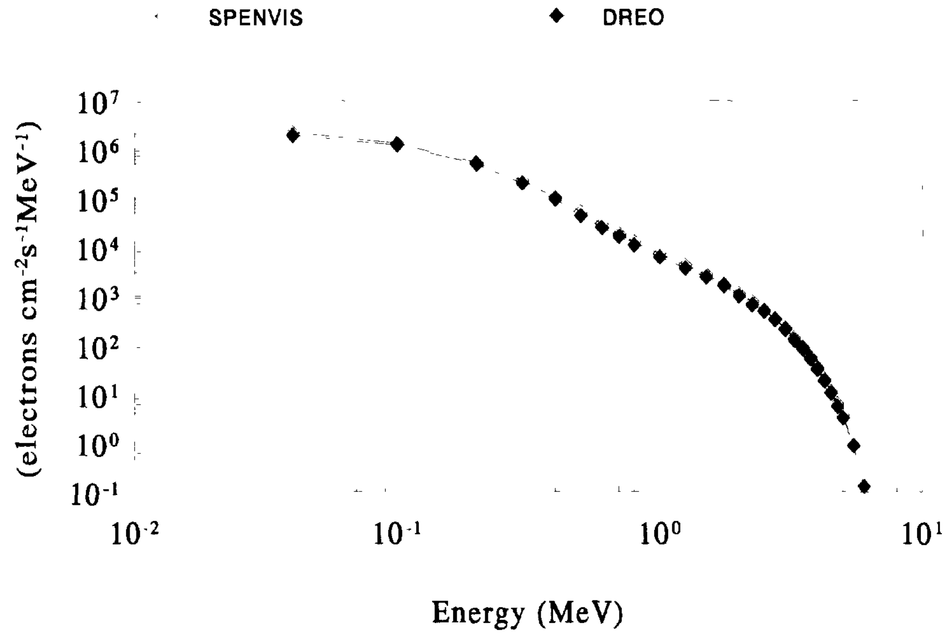

Figure 3. *SPENVIS and DREO differential electron spectra for LEO 2*

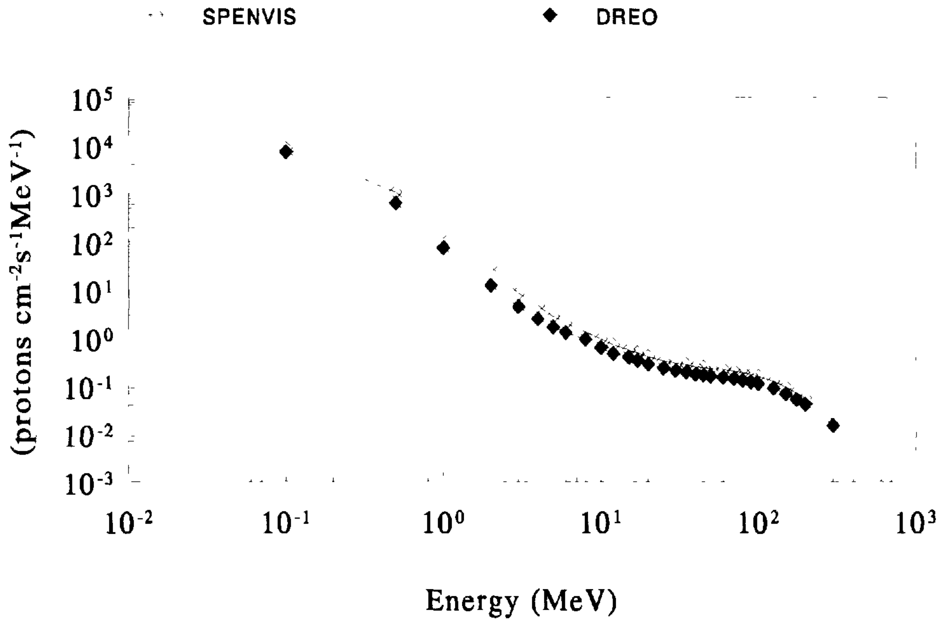

Figure 4. *SPENVIS and DREO differential proton spectra for LEO 2*

4.3 LET Spectra

Both DREO and SPENVIS use the CREME code to obtain LET spectra. Specifically, it is the LET program module within the CREME code that calculates differential and integral LET spectra for the given orbit, range of elements, solar activity represented by IWI (Interplanetary Weather Index) and thickness of shielding. The LET spectral plots are shown below, the SPENVIS results are shown in Figures 5 and 6 and DREO results are shown in Figures 7 and 8 for both LEO 1 and LEO 2 orbits. The LET spectra change with the Interplanetary Weather Index, which is influenced by the solar activity. These indices can be set from 1 to 12 in the DREO method and in SPENVIS. Indices 1,3,5 and 7 have been selected as they relate to ever increasing solar flare activity. Higher indices were omitted because they represent a specific case of solar flare activity. Zero shielding has been assumed.

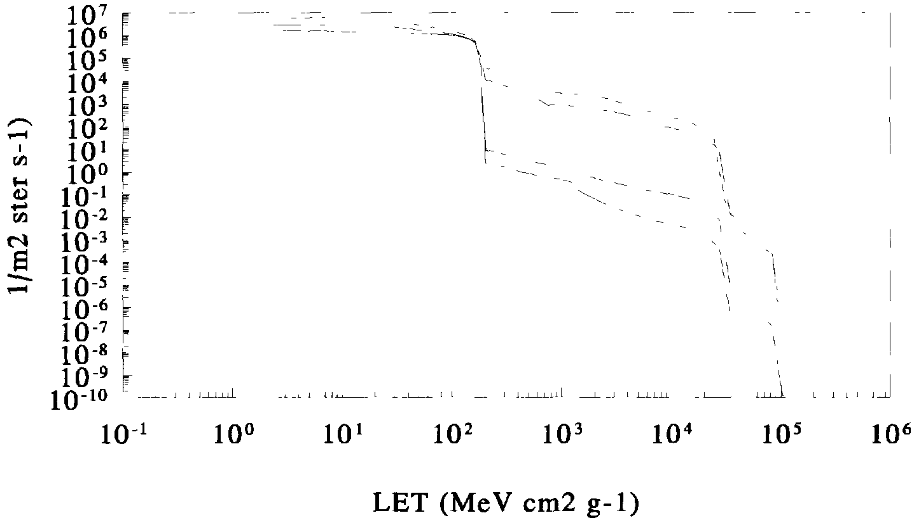

Figure 5. Integral LET spectrum at LEO 1 obtained by SPENVIS for various levels of solar flare activities

4.4 Total Dose

The absorbed dose in silicon as a function of Aluminum shielding was calculated for a five-year mission for LEO 1 and LEO 2, using both approaches. SPENVIS utilized the SHIELDOSE program to calculate dose deposition into a silicon detector with Al shielding ranging from 1mm to 10mm. Three detector geometries were investigated, namely: infinite plane, semi-infinite plane and spherical geometry. For both orbits, the profiles are shown in Figures 8 and 9.

For comparison, the dose calculations with the DREO method are also given. The DREO method uses the ITS 3.0 3-D Monte Carlo code for electrons and the TRIM code for protons and heavy ions. These calculations do not involve the heavy ion contribution to the total dose.

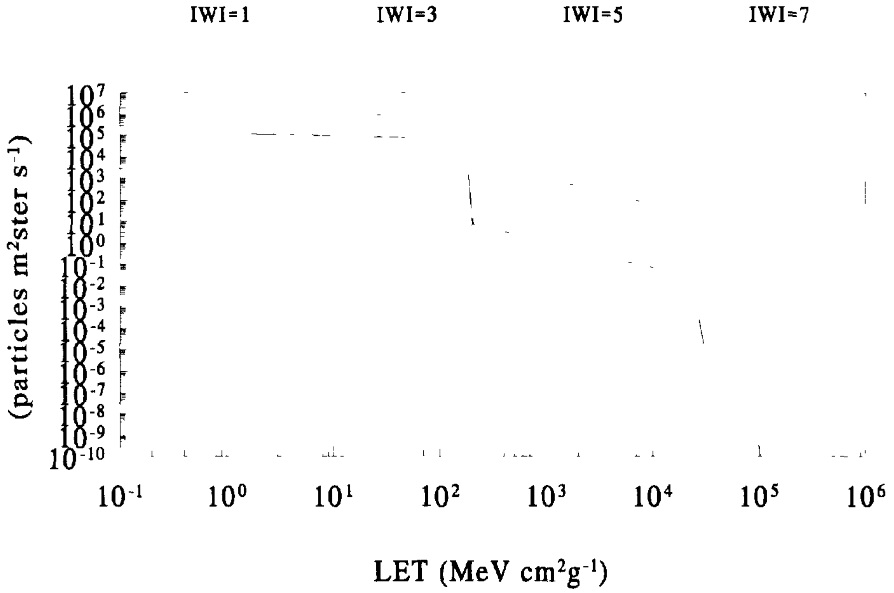

Figure6. *Integral LET spectrum at LEO 2 obtained by SPENVIS for various levels of solar flare activities*

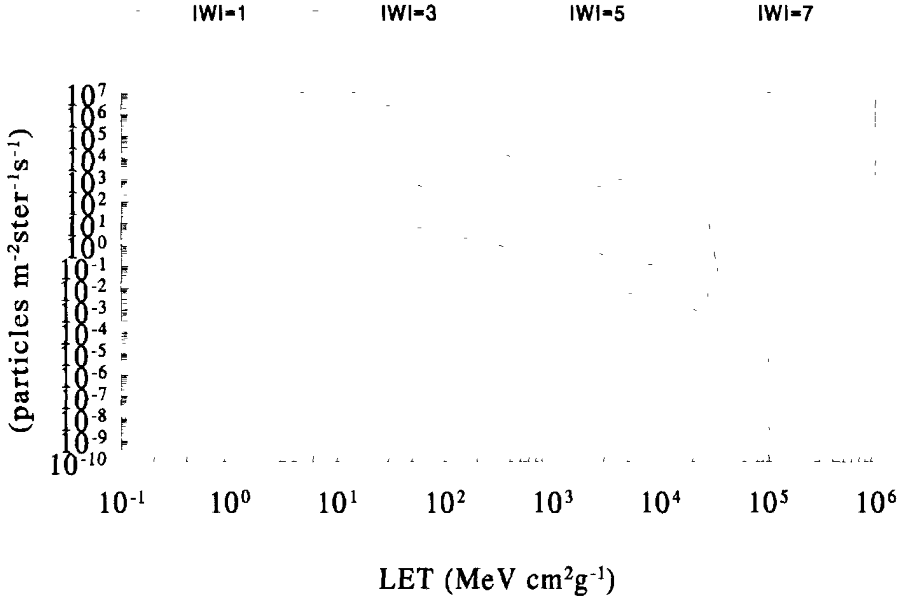

Figure 7. *Integral LET spectrum at LEO 1 obtained by DREO method for various solar flare activities*

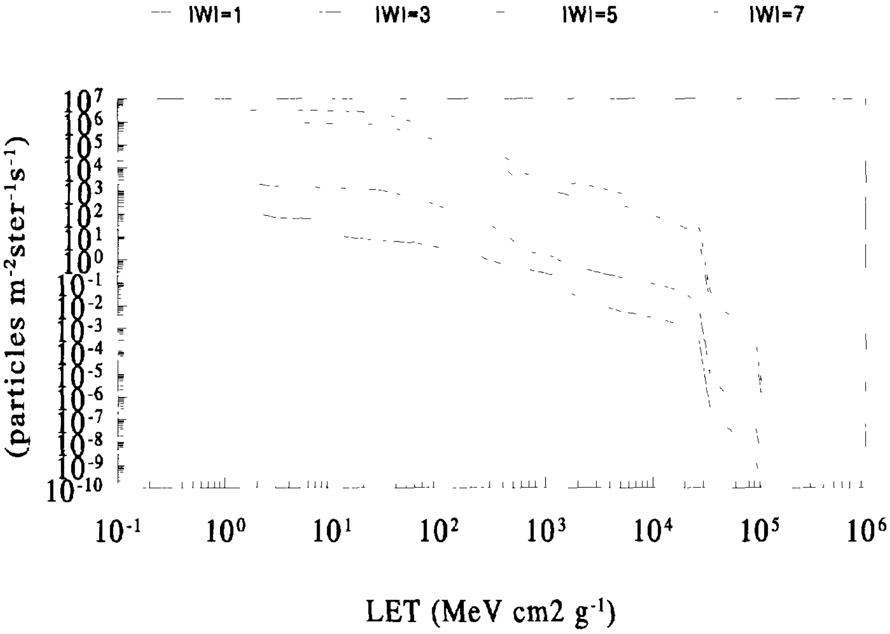

***Figure* 8.** *Integral LET spectrum at LEO 1 obtained by DREO method for various solar flare activities*

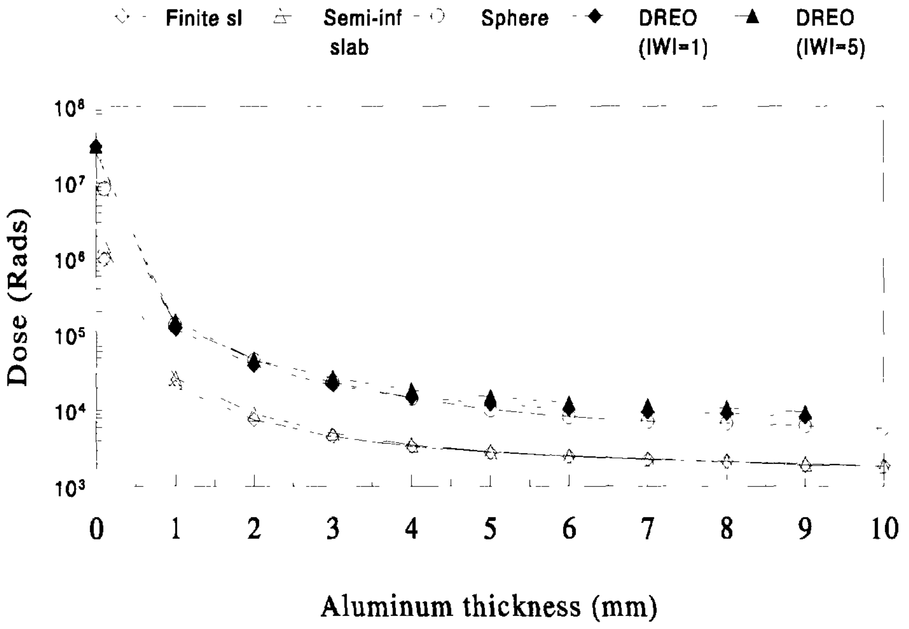

***Figure* 9.** *Total dose deposition as a function of Aluminum shielding thickness for LEO 1 Both SPENVIS and DREO results are shown A much better agreement between the two approaches is observed with the spherical detector of SPENVIS.*

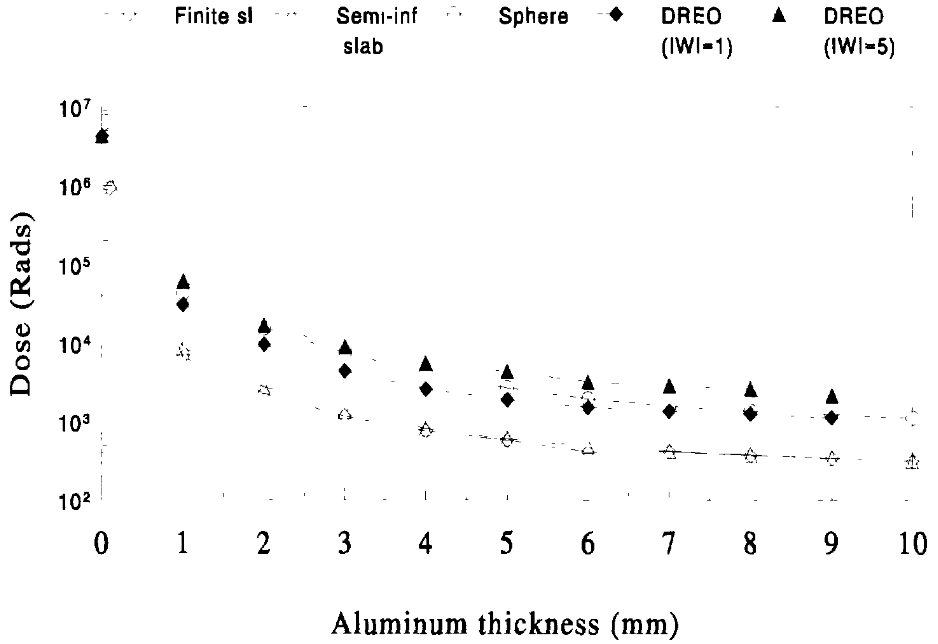

***Figure* 10.** *Total dose deposition as a function of Aluminum shielding thickness for LEO 2* Both SPENVIS and DREO results are shown A much better agreement between the two approaches is observed with the spherical detector of SPENVIS

4.5 SEU Rates

The space radiation environment is highly structured and dynamic. The temporal modulation of this environment is caused by the variations in solar activity. Both SPENVIS and CREME use a parameter called IWI (Interplanetary Weather Index) to take solar activity into consideration. These indexes vary from 1 to 12, representing various levels of solar activity, some of which are also special events that had occurred at some specific date in the past, such as the August 1972 solar flare. Solar activity affects the SEU rates in space-borne electronic systems. Both SPENVIS and the DREO system calculate SEU events caused by direct ionization and nuclear interaction. In Figure 10, SEU calculations using both systems are compared for various IWI indexes. IWI =1 represents no solar activity, only galactic cosmic rays (GCR). With increasing IWI index, the solar contribution to SEU increases. As Figure 10 shows, there is a disagreement between the methods; SPENVIS consistently returns smaller SEU rate values.

SEU rates caused by direct ionization are compared in Figure 11. These rates, in addition to solar flare activity, also depend on the dimensions of the sensitive volume of the device, especially on the depth. This is also evident in Figure 11.

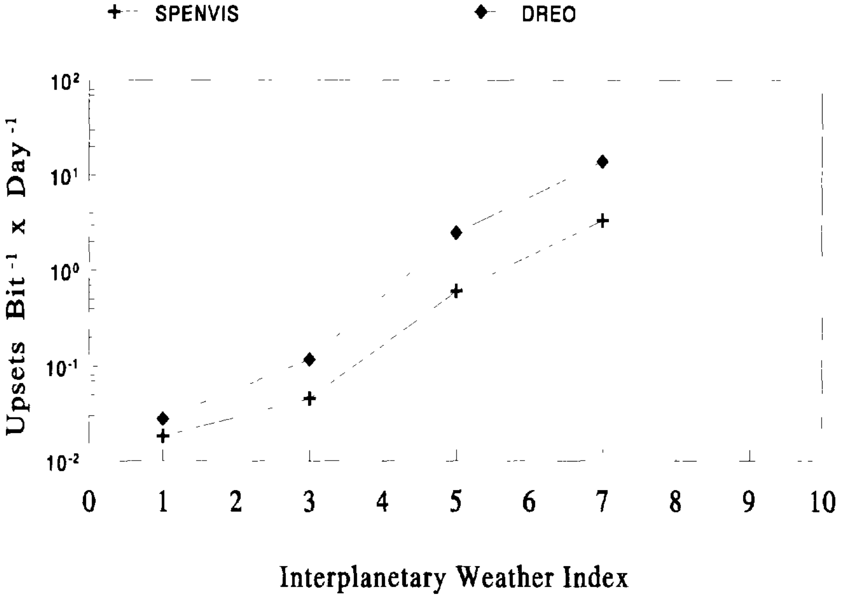

Figure **11.** *Nuclear reaction-induced SEU rate comparison between SPENVIS and DREO model. Four levels of solar activity are shown.*

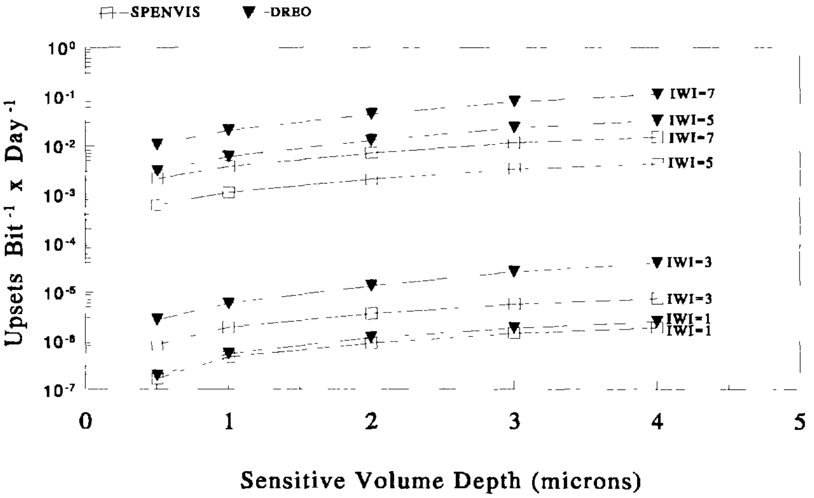

***Figure* 12.** *Direct ionization induced SEU rate comparison between SPENVIS and DREO model as a function of device sensitive volume depth. Four levels of solar activity are shown.*

5. METEOROIDS AND SPACE DEBRIS

The following parameters were use to determine the size distribution of space debris at LEO 1.

Altitude: 1100.0 km
Satellite velocity: 7.3 km/s
Inclination: 85.0 deg
Epoch: 2001
Solar radio flux: 140.0
Mass growth rate: 0.05
Fragment growth rate: 0.02
Density: 2.80 g/cm3

SPENVIS presently uses the NASA90 flux model while DREO uses the SE code, which is based on Kessler's 1990 debris model. This model is applicable directly for circular orbits, however, for elliptical orbits an orbit integration procedure is to be used to account for the altitude distribution. The SE code is a space environment code also containing a space debris module. The SE code also provides velocity distribution, which is not available with the NASA90 code. The results from the two methods are compared in Figure 11.

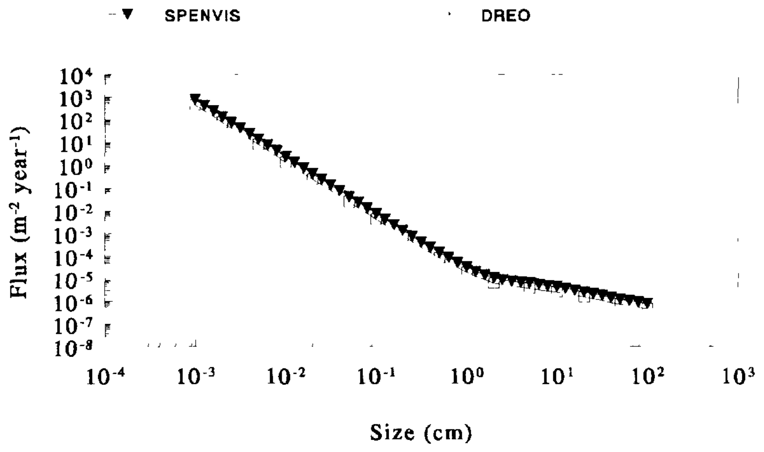

Figure 13. *Space debris flux vs size comparison for LEO 1 obtained by SPENVIS and by DREO model.*

6. SPACECRAFT CHARGING

The natural trapped electron environment has a component in the energy spectrum that can penetrate deep into the interior of a satellite. These high energy electrons will, over a period of time, charge dielectric components of a satellite to a high voltage. High electric fields can develop that exceed the breakdown electric field of a dielectric, usually around several Megavolts / m. When this happens, uncontrolled discharge occurs, which can cause severe spacecraft anomalies. SPENVIS utilizes an internal charging prediction tool DICTAT, developed at DERA. DREO utilizes a Monte Carlo code to predict the likelihood of discharge occurrence. The DREO method is much more elaborate because after charge distribution is known (output file of the Monte Carlo code), the potential distribution is obtained by solving Poisson's equation in 3D. In DICTAT, this is done internally and analytically in 1D. Both methods are compared in Figure 14, which is a simple case of Plexiglas slab charging.[3] The experimental data are not shown. The specimen has a rectangular geometry with dimensions 50mm x 50mm x 5mm with three probes, one at the surface, one at the depth of 2mm and the third at the depth of 4mm. From DICTAT we have only one point to compare because the potential due to charge deposition in this tool is taken with respect to the surface of the specimen. Figure 15 shows the charge distribution inside the specimen as calculated by the DREO method.

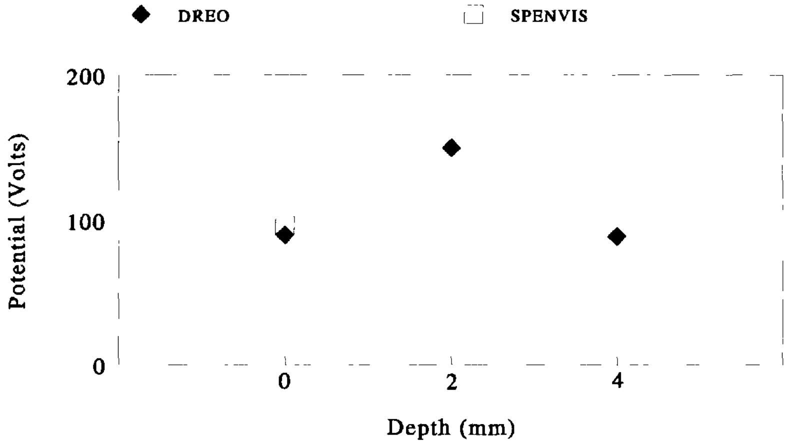

Figure 14 Calculated potentials obtained by DICTAT (SPENVIS) and ITS Monte Carlo code (DREO model). DICTAT provides information only about the surface potential, therefore only results at the 0 mm depth are compared

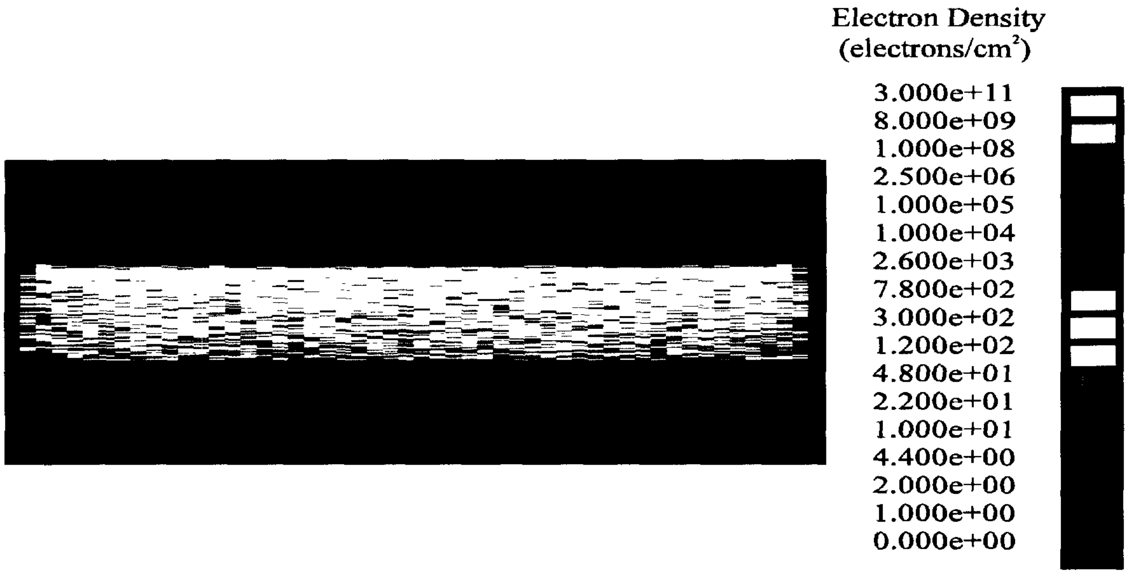

Figure 15. *Charge distribution inside the Plexiglas specimen after a 50 minutes irradiation by a 100mCi Sr^{90} source. The potentials due to this charge distribution are shown in Figure 12*

In the experimental setup, the source of radiation was a 100mCi Sr^{90} radioactive source located at 70cm above the specimen, thus the specimen subtended an 8-degree opening angle. From this the flux impinging on the specimen was determined. The electron spectrum was binned into 7 energy windows. The spectrum used in both methods is shown in Table 3.

Table 3 *Sr/Y^{90} beta spectrum used in charging analysis*

ENERGY (MEV)	FLUX ($CM^{-2}\,S^{-1}$)
0.1	4.936E6
0.25	7.597E6
0.45	7.379E6
0.70	2.876E6
1.00	3.145E6
1.35	3.460E6
1.75	3.004E6
2.3	1.99E6

6.DISCUSSION

SPENVIS, ESA's space environment effects (SEE) model, and the DREO SEE model were tested on several key SEE events and the results compared. There are several key models in both systems that are common; for example, both systems use the AP8 and AE8 trapped radiation models that originate from The National Space Science Data Center at NASA-GFC. The results of trapped proton and electron spectrum calculations were compared and shown in Figures 1 to 4 and Tables 1 and 2. It is evident that there are some differences, although not major. It is important to remember that the results do not come just straight from the environment codes (AP8, AE8), but there is also processing involved which is different between the two systems.

To obtain the trapped component of the space radiation, DREO uses a program called VETTE, which returns a desired output, either for protons or electrons taking also into consideration solar max or solar min scenarios. Running this program, the user must have first an AP8min or AP8max input file set up for protons and similarly AE8min or AE8max for electrons, which then serves as an input file for the VETTE program. In these files, the user sets up the energies as well as the desired output. The type of output depends on the "tabcons" selected in these files. There are 5 tabcons and the desired output is selected by setting these to either "T" (True) or "F" (False). The most frequently utilized output is a tabular output of differential, integral and difference spectra. This is, for example, obtained by setting tabcon #3 to "T" and the rest to "F". In SPENVIS, the action of obtaining the desired output is hidden behind the graphical interface. The differences in results can be explained by the differences in the smoothing algorithm, applied due to irregularities or missing electron or proton data at locations of the inner magnetosphere. VETTE uses the original TRARA algorithm while SPENVIS uses an upgraded version. Other differences will also arise from the difference in smoothing algorithm, such as in the LET spectrum, and SEU rates when trapped protons are included. It should be noted that SPENVIS is the updated version of the existing SEE models and has undergone numerous upgrades and expansions in various sections of SEE. For example, some of those expansions include spectra for specialized orbits. LEOPOLD is a model of the space environment for Low Earth Orbits, which provides the user with such parameters as particle densities and average temperatures of the neutral atmospheric constituents. Additional parameters are then derived from this information. LEOPOLD does not exist with the DREO modeling approach.

Both SPENVIS and DREO use CREME to obtain SEU rates and LET spectra. In the DREO approach, the user runs the individual modules in the DOS environment; in SPENVIS, the modules are executed behind the user interface. One advantage, observed with the DREO approach, was that additional information also becomes available to the user, information such as solar and galactic cosmic ray spectra, which seem to be used only internally for determination of SEU rates or LET in SPENVIS. Running LET with SPENVIS was observed to be slower than with the DREO model. However, this is not serious because, executions can be carried out in the background and therefore will not inhibit other CPU usage. It was observed that using a Monte Carlo code, such as is used with the DREO approach for calculating transport of ionizing radiation through materials, is more time-consuming then using DICTAT or SHIELDOSE in SPENVIS. However, both DICTAT and SHIELDOSE are approximations in comparison with the Monte Carlo approach, which has an excellent track record when it comes to comparison with experiments. It is also becoming clearer that there are increasing requirements to be able to provide more precise analysis of SEE. Radiation models are improving and therefore other tools utilizing these models should improve as well. Round Table discussions on utilization of Monte Carlo Methods for simulations of radiation hazards on space electronics and other applications have been initiated.[4]

List of symbols/abbreviations/acronyms/initialisms

LEO	Low Earth Orbit
SEU	Single Event Upset
LET	Linear Energy Transfer
SEE	Space Environment Effect

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Abstract

This report compares the Space Environment Effects modelling approaches of ESA (SPENVIS) and DREO (VETTE&CREME). Compared are near Earth space radiation and debris environments and their effects on space-borne systems. In general, a similarities and differences exist between the results obtained by the two models. Reasons for agreement/disagreement are explained.

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