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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
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ABSTRACT

This report summarizes the analytical approach developed to estimate the total ionizing radiation dose received by Earth-orbiting satellites. The analytical tools and methodology utilized in this work represent a departure from the more traditional, "industry standard" approaches. The approach developed was applied to the problem of determining the mission total dose for the Swedish satellite ODIN.

RÉSUMÉ

Ce rapport résume l'approche analytique développée pour estimer la dose ionizante totale reçue par les satellites terrestres. Les outils et la méthodologie analytique utilisés dans ce travail se distance de l'approche plus traditionelle de standard industriel. L'approche analytique ainsi développée a été appliquée au problème de la détermination de la dose totale du satellite Suédois ODIN.

EXECUTIVE SUMMARY

All space-based platforms must be designed to withstand the rigours of the space radiation environment. In general, every space vehicle encounters a unique radiation environment, due to the temporal and spatial variation of the radiation fields in the near-earth environment. One of the critical engineering tasks in satellite system design is the determination of the mission specific radiation environment and how it will impact on satellite performance over the expected mission lifetime. The work presented in this report reflects the ongoing DND/DREO R&D effort to develop the methodology and, where necessary, the computational tools to allow system engineers to design space-based platforms which can successfully complete their mission objectives in the near-earth space radiation environment.

The methodology and computational tools (i.e. codes) developed or acquired by Defence Research Establishment Ottawa, are applied to obtain an estimate of the total radiation dose due to electrons and protons for the Swedish scientific satellite "ODIN", which is scheduled for launch in 1997. Radiation dose estimates were obtained for spacecraft shielding thicknesses ranging from 0 mm to 5 mm of aluminum. The dose estimates are compared with data obtained via different calculation techniques performed by the European Space Agency.

CONTENTS

1.0 Introduction

Critical to the survivability and mission success of any space-based platform, is that it be able to withstand the deleterious effects of ionizing radiation on the system's electronics. The radiation environment that a space-platform is subjected to is orbit specific; the earth's magnetosphere, for example, greatly affects the charged particle fluxes encountered in near-earth orbits. The radiation environment also has temporal variations, as evidenced by cyclical variation in solar flares. It is desirable, therefore, to have a means of predicting the radiation environment that a spacecraft will encounter over the duration of its mission. This information can then be utilized during the specification, design and testing phases of a space vehicle's development, to ensure that radiation hardness survivability criteria can be met.

Total dose effects and single-event upsets are the primary radiation effects on electronics of interest to the spacecraft system designer. Space radiation environmental models and computational methods for estimating total dose and single-event upset (SEU) rates have been developed and in use for several decades. However, many of these programs require expert application in order to obtain meaningful results. The problem is exacerbated by the lack of user manuals, detailed technical reports and the fact that the programs were developed primarily by their authors for in-house use and hence contain little or no useful comments in the Fortran program source code.

As part of the development of in-house expertise in Space Radiation Effects at Defence Research Establishment Ottawa (DREO), a project was initiated to develop the computational capability for estimating radiation effects on space-based electronic platforms, for arbitrary orbits. To this end, publicly available computer codes (primarily from NASA) applicable to space radiation effects were surveyed and technically evaluated. Computer codes were selected for use based upon the following criteria; a) the codes must be successfully compiled in a PC environment with little or no modification b) the input/output parameters and requirements could be understood (considering the lack of documentation previously mentioned) and verified and c) the codes should employ the most recent data sets, radiation environmental models and radiation transport methodology available. Alternative, state-of-the art computer codes were obtained to replace computer codes that did not fulfil the above criteria and in one instance, a computer code was developed in-house at DREO.

In this report we describe the computer programs and the data processing steps and procedures that were used in determining the mission total dose for the Swedish research satellite ODIN, which is tentatively planned for launch in 1997. This work was performed in support of ODIN developmental activities carried out by DND/DREO and the Canadian Space Agency (CSA). In addition, the data generated by this study was requested by and supplied to the Neptec Design Group Inc., Kanata, Ontario, in support of their system development for ODIN.

2.0 The Space Environment

The space radiation environment is generally composed of a variety of energetic charged particles. The energy of these particles can range from a few eV to TeV and beyond. These charged particles can either become trapped by the earth's magnetic field or can pass through it. The main constituents of the space radiation environment are:

1. Galactic cosmic rays. The relatively low fluxes of these ions can extend to energies beyond the TeV energy range and include all elements found in the periodic table.
2. Solar cosmic rays. Solar eruptions (flares) produce energetic protons, with a minor component of alpha particles, heavy ions and electrons. The maximum energy is several hundred MeV.
3. Trapped radiation. This comprises the earth's radiation belts and consists of a broad spectrum of energetic particles (mainly protons and electrons) trapped by the earth's magnetic field.

Trapped radiation and solar flares are usually the primary contributor to total dose. Cosmic rays are generally the primary source of SEUs, due to the large linear energy transfer (LET) and ion range in semiconductors.

2.1 Trapped Radiation.

Energetic charged particles, primarily protons and electrons, trapped by the earth's magnetic field, can pose a significant radiation hazard to the electronics on-board of orbiting satellites. The charged particles drift longitudinally and travel in a complex trajectory along the magnetic field lines.

The motion of charged particles in the earth's magnetosphere is governed by the magnitude and direction of the earth's magnetic field. In order to describe the distribution of trapped radiation, a "B-L coordinate system" was introduced by McIlwain, et al[1]. The coordinate L is called McIllwain's magnetic shell parameter and B is the magnetic field strength. The parameter L has units of Earth's radii (R_E) and represents a magnetic field line that passes through the equatorial plane at a distance of $L*R_E$. For example, L=1 is the location of the Earth's surface. The advantage of using this coordinate system is that the distribution of trapped radiation can be systematically mapped. Figure 1 is an example of such distribution[2] for trapped electrons as function of L-shell parameter and energy.

Models of the trapped radiation environment have been developed which permit satellite system engineers to quantitatively estimate the radiation levels likely to be encountered during space missions. The trapped electron model, designated AE8, is applicable to trapped electrons in the energy range of 40 keV to 7 MeV with L-values ranging from L=1.15 R_E to L=11 R_E. The trapped proton model, designated AP8, is applicable to trapped protons in the energy range of 100 keV to 400 MeV. Both the electron and the proton models have been implemented in Fortran computer programs which output particle fluence estimates for both solar minimum and solar maximum conditions. The computer programs which implement these models are available from The National Space Science Data Center at NASA-GFC and have been aptly named AE8MIN, AE8MAX, AP8MIN and AE8MAX.

To apply the above computer models, the user is required to enter the satellite's orbital parameters into a program called "ORBIT". This program converts the satellite's trajectory from R-λ coordinates to the B-L coordinate system. Since the spectrum of the trapped radiation is mapped in the B-L coordinates, the total radiation flux traversed by the satellite per orbit as it is passing through various radiation zones can be determined. The computer program designated "VETTE" uses the B-L trajectory of the satellite and trapped electron and proton model data (contained in the AE8 and AP8 codes for solar maximum and solar minimum conditions) to obtain the total radiation fluence impinging on the satellite. The program output consists of differential, integral and energy-window binned spectra of trapped radiation, specific to a given orbit.

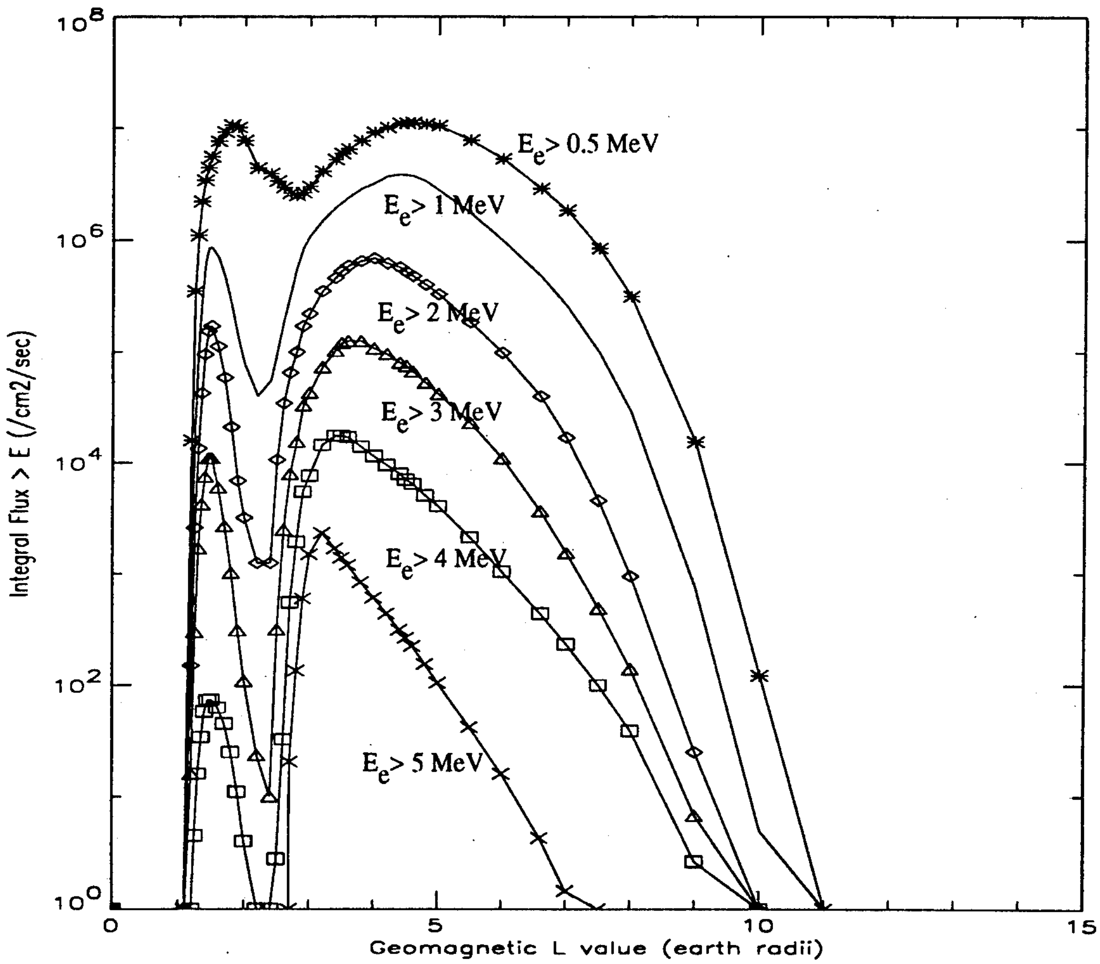

Figure 1. Omnidirectional flux of trapped electrons for various L - shell parameters.

2.2 Cosmic Ray Component

Cosmic rays are singly-ionized or multi-ionized elements with energies that can extend beyond 1 TeV. There are two cosmic ray components which affect the total radiation dose received by an earth-orbiting spacecraft, namely the galactic component and solar component. Galactic cosmic rays originate outside the solar system and in general, their flux is anti-correlated with the flux of solar cosmic rays (blocking effect). The solar cosmic rays are of solar flare origin.

The cosmic ray radiation contribution to the total dose received by an earth-orbiting satellite platform can be predicted with the use of the CREME code[3]. CREME is composed of several code modules that determine various orbit-dependent particle spectra and other related parameters. For each ion species, these include the energy spectra (i.e. fluence versus energy), LET spectra and estimates of the bit-upset rate for a particular semiconductor device. The CREME code also incorporates several auxiliary modules to include trapped radiation components into spectral calculations. Additional sub-programs provide the user with the capability of including various physical phenomena which can influence the results of the various spectral calculations. These factors include geomagnetic shielding effects, inclusion of various "interplanetary weather conditions", spacecraft shielding and earth shadowing effects. The reader is urged to consult Adams[3] for details on these code modules (subroutines) and their calling sequence from the main program. In section 4.2, the use and application of the CREME code to obtain an estimate of the total mission radiation dose for a specific spacecraft are demonstrated.

In the determination of the various particle spectra, CREME makes use of experimental data from a variety of sources. For example, in-situ measured spectra of cosmic ray protons and alpha particles are scaled by appropriate factors[3] to determine particle spectra for heavier elements, up to Ni in the periodic table. The values of these scaling factors were deduced from the element-abundance measurements originating from a French-Danish experiment[4], taken on-board HEAO-3. To obtain spectra of ionized elements heavier than Ni, scaling factors are also applied to measured iron spectra and other heavy nuclei, from the heavy nuclei experiment[5,6,7], also taken on-board HEAO-3.

During the CREME run, the analyst selects one of twelve (enumerated one through twelve in the CREME code) interplanetary cosmic ray weather conditions, known as the "Interplanetary Weather Index" (IWI). Three of the weather indices (1, 2 and 4 in the CREME code) pertain only to galactic cosmic rays. The other 9 indices (3 and 5 to 12, inclusive) include solar flare cosmic rays of various compositions and intensities[3].

The number and magnitude of solar flares experienced by a satellite can significantly influence estimates of both the SEU rates and the total mission radiation dose. Various probability distributions for predicting flare activity during future solar cycles have been derived, based open the analysis of flare activity during previous solar cycles[8,9]. As a rule-of-thumb, a solar cycle is considered to be comprised of seven years of high flare activity, followed by four "quiet" years. The following equation represents one such example of an empirical relationship that yields the probability of having more than a given number of "ordinary" or "anomalously large" flares during a given time period.[3]

$$P(n,t,N,T) = 1 - \sum_{i=0}^{n} \frac{(i+N)! \left(\frac{t}{T}\right)^{i}}{i!\; N! \left(1+\frac{t}{T}\right)^{1+i+N}} \qquad (1)$$

In the above expression, n is the number of solar flare events expected over the mission duration t, and N is the number of expected solar flares over the period T. For example, the values of N and T for a case of ordinary solar flares for the active years in the solar cycle #21 (1974-1985) were 24 and 7. For the quiet years, N and T are valued 6 and 4 respectively. For the case of an anomalously large event, N=1 and T=7.

3.0 Computer Methods for Radiation Transport

In the space radiation effects field, the calculation of total dose (from electrons and protons) delivered to spacecraft electronics has traditionally been performed via the computer code SHIELDOSE[10]. This computer code employs a "look-up table" based approach to solving total dose distributions in simple (e.g. slab and spherical) geometries. SHIELDOSE was abandoned in favour of other computer codes for three reasons;

1. A lack of user documentation.
2. The availability of a much more recent "state-of-the-art" Monte Carlo electron/photon radiation transport code, with an updated reaction cross-section database for elemental materials and the latest numerical radiation transport methods.
3. Inflexibility in assessing the total dose delivered to the target material (e.g. Si).

The first two of these three points are self-explanatory, however, the last point requires further explanation. SHIELDOSE provides an estimate of the absorbed dose, in a small volume of a target material as a function of shielding thickness. The small target volume is either located within the bulk of the shielding material (a very non-realistic case), or at the transmission surface of the shielding material (i.e. the surface dose). Neither of these scenarios provides a realistic dose estimate for a semiconductor device, because the dose delivered to the active layer can vary considerably from the surface dose, or from the absorbed dose to the target volume within the shielding material. With the alternate method employed in this work, not only is the surface dose data available, but the dose versus depth is calculated for 1000 μm (or greater, if required) of target material depth. This allows the analyst the option of selecting the target material depth which accurately reflects the semiconductor technology of interest, thus resulting in a more accurate estimate of absorbed dose.

A suite of computer codes, designated ITS 3.0[11] (Integrated Tiger Series of electron/photon Monte Carlo transport codes) was selected for use in determining the electron depth/dose profiles in silicon. As mentioned previously, this suite of computer codes represents the "state-of-the-art" in Monte Carlo electron/photon radiation transport. The ITS codes are very well documented, are relatively easy to use and, most importantly, have been extensively benchmarked against a diversified range of experimental data in radiation physics. The ITS codes can accommodate one, two and three dimensional geometries of arbitrary material composition (i.e. shielding layers and "target" material), however, in this work, all simulations were restricted to 1-dimensional (1-D), finite-thickness, slab geometries. The limitation of being restricted to 1-D geometries was due to the unavailability of physical satellite data such as where the electronics of interest would be located on-board the satellite, hence there was no requirement to perform a three-dimensional analysis. Had this and other information regarding the structural make-up of the satellite been known, a more accurate total dose analysis could have been performed. This analysis, known as sector analysis, would have included effects such as satellite self-shielding, which could have been accounted for in a realistic manner.

For the computation of total distribution due to protons in 1-D, slab geometries, a computer code "PROTDOSE" was developed in-house at Defence Research Establishment Ottawa. This code shares similar analytical methodologies with SHIELDOSE, but incorporates more recent and accurate stopping power data. It is also much more versatile in that it permits the user an unlimited selection of shielding layers, composition and "target materials" (other than aluminum or silicon) and determines depth/dose distributions, rather than a single dose estimate. This code was developed to compute depth/dose profiles for one-dimensional (i.e. slab) geometries only, for reasons outlined above.

3.1 Calculation of Electron Contribution to Mission Total Dose

The one-dimensional electron/photon transport code "TIGER", from the ITS suite of radiation transport codes, was utilized to determine depth/dose profiles in silicon for various shielding configurations. In order to perform a 1-D depth/dose simulation using the TIGER code, a photon/electron cross-section data file was created first, consisting of data for both the shielding and target materials. A separate simulation was conducted for each change in shielding configuration (e.g. thickness of Al) and/or source (i.e. electron) energy spectrum. The simulations performed in this study included dose deposition due to primary electrons, bremsstrahlung, x-ray production and generation of secondary particles (e.g. Compton electrons). The ITS codes allow the analyst to selectively enable or disable each of these types of radiation, in order to investigate the individual dose contributions, but this feature was not utilized in this work.

The source electron energy spectrum input to TIGER was the binned electron energy spectrum generated by AE8, for a given set of orbital parameters. The ITS codes provide for a user-defined source spectrum, however, the integral flux (normalized to unity) must be input rather than the differential flux. As the electron flux in space is considered isotropic[12], the source spectrum was defined as an isotropic source in the TIGER problem input file.

The thickness of the shielding layer (given in cm of aluminum) was specified in the input file. The thickness of silicon used for the simulations was 1000 μm, which is thicker than the active regions of the majority of semiconductor devices in use today. The silicon was sub-divided into 100 equal thickness layers (by specifying the parameter NZONES in the input file) and the deposited dose calculated for each layer. The absorbed dose in silicon as a function of depth generated via the simulation represents the dose to a given 10 μm segment, normalized to one incident electron. In order to obtain the mission dose, these values must be multiplied by the integral electron flux that the spacecraft is subject to over the duration of the mission.

3.2 Calculation of Proton Contribution to Mission Total Dose

The computer code "PROTDOSE" was used to calculate the contribution to mission dose due to protons, in an analogous fashion to that for electrons. The code calculates the depth-dose profile in silicon (or any other material) for planar geometries, for multi-layer shielding of arbitrary composition and thickness, as shown in Figure 2.

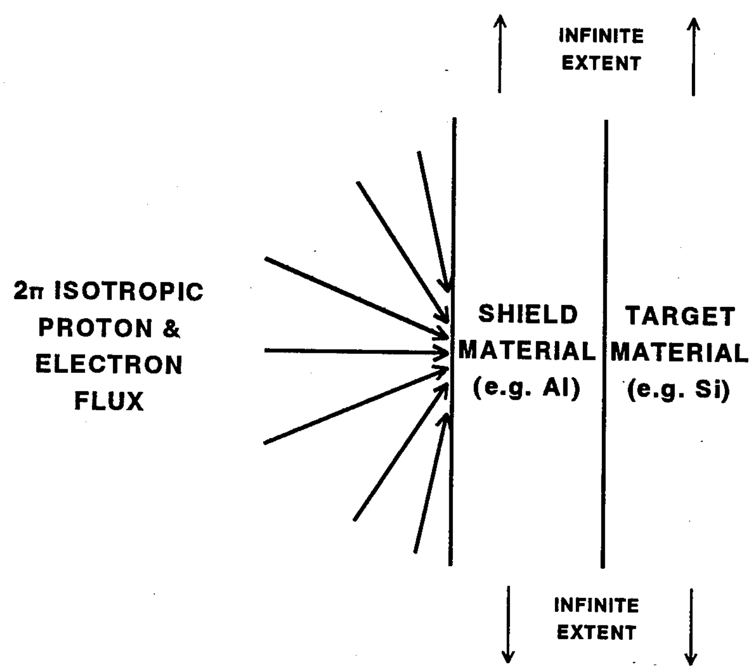

Figure 2. Geometry employed by PROTDOSE code to simulate proton depth-dose profiles in spacecraft materials, for multi-layer shielding of arbitrary composition.

The code is based upon the straight-ahead, continuous slowing-down approximation[13] of energy loss for protons, i.e.:

$$\Delta E(E, \Delta x) = \int_{x_0}^{x_0+\Delta x} \left[\frac{dE}{dx}\right] dx \qquad (2)$$

where, $\Delta E(E,\Delta x)$ is the energy deposited in a material for a proton of initial energy E, travelling a straight-line distance Δx (from x_0 to $x_0+\Delta x$) and [dE/dx] is the stopping power for the proton in the given material.

The stopping powers used by the program for the target material (e.g. Si) and the various shielding materials (such as aluminum) were generated by the TRIM-92 (TRansport of Ions in Materials) computer code[14]. The code is based upon the straight-ahead, continuous slowing-down approximation[13] of energy loss for protons. TRIM-92 was used to generate stopping powers for protons in the energy range of 1 keV to 2 GeV. Above 2 GeV proton energy, the stopping power was considered constant.

PROTDOSE models a 2π (solid angle) isotropic flux of protons incident on planar shielding material. The energy spectrum of protons for use in the simulation is defined by the user. The (default) number of angles of incidence used in this work was ten and this parameter can also be altered by the user. These angles are not uniformly spaced; the angles are computed internally within PROTDOSE so as to provide a constant solid angle for all angles of incidence. This was necessary to ensure that the weight attributed to the depth-dose profile for each angle of incidence is the same, since the flux is isotropic.

The user is required to input the following data to PROTDOSE, for a typical simulation:

a) The proton energies (MeV) required for the simulation and the corresponding proton fluence for each energy "bin", i.e. an energy spectrum.
b) The thickness/composition (if any) of the shielding layer(s).
c) The appropriate TRIM stopping power data file(s) corresponding to the target and shielding materials, for the appropriate range of proton energies.

The code's output consists of:

a) The depth-dose curve for protons in silicon, for the entire proton energy spectrum.
b) The depth-dose curve (for protons in Si) for each individual proton energy that was input. Each of these curves <u>is not</u> weighted by the proton fluence for their respective energy bin, i.e. the curves are normalized to 1 proton cm^{-2}, for the respective energy bin.

The potential utility of this feature for saving computational time while conducting an extended analysis is described subsequently.

The depth-dose curves for protons in silicon (for both cases described above) are output as ASCII tables, with the absorbed dose expressed in rad(Si) and depth increments given in microns. The data is also graphically displayed. The dose in silicon is scored up to a maximum depth of 1000 microns, in 1 micron increments. The maximum thickness used in the simulation greatly exceeds the extent of the thickness of the active regions (including oxide and passivation layers) of the majority of semiconductor devices in use today. The maximum depth parameter can be increased by the analyst, if the need arises.

As was indicated earlier, a unique feature of this code is that once a simulation has been performed for a given problem set (i.e. a given shielding/target geometry and material composition), the effect of the shape of the energy spectrum on the absorbed dose (in Si) can be investigated easily, if the proton energy binning remains the same. This may be an important design consideration, as the energy spectra for protons generated by AP8 or CREME are estimated. The analyst may also wish to investigate the sensitivity of the absorbed dose on orbital parameters, which might cause the proton energy spectrum to vary. Instead of having to re-run the code "from scratch" for each change in the energy spectrum, the code has been written so as to make use of appropriate intermediate results from previous calculations, stored on disk. The intermediate results used are the individual depth-dose profiles saved for each proton energy. These curves are simply weighted by the proton energy spectrum and added up to yield the new depth/dose data. This reduces greatly the length of CPU time required to obtain a result.

4.0 Mission Total Dose Calculation for ODIN

Figure 3 illustrates the typical data processing flow and computational steps for radiation transport analysis. In the following sub-sections, the analysis of the mission total dose for the Swedish scientific satellite ODIN is documented. The steps in the analysis are presented in a logical sequence, as they were actually performed. The analytical procedures used and the order in which they were performed are not unique to the ODIN mission; a similar analysis can be performed for any space mission.

In the analysis reported here, it should be noted that only the contribution to total mission dose from protons and electrons was considered. When this independent study was initiated, the Neptec Design Group offered to obtain the results of similar analysis provided by others [Note that we did not have access to this data until after our study had been completed], which included only the electron and proton dose. DREO and the Neptec Design Group both wished to have an independent validation of the data sets. The mission dose for ODIN, due to heavy ions ($A \geq 2$), was not determined for this reason. The heavy ion dose, however, can be determined using the same analytical procedures as were used for protons. This is not normally done in this type of study however, because both the heavy ion fluence and the resulting total dose delivered to the spacecraft are *assumed* to be insignificant when compared to the proton fluence and dose, respectively.

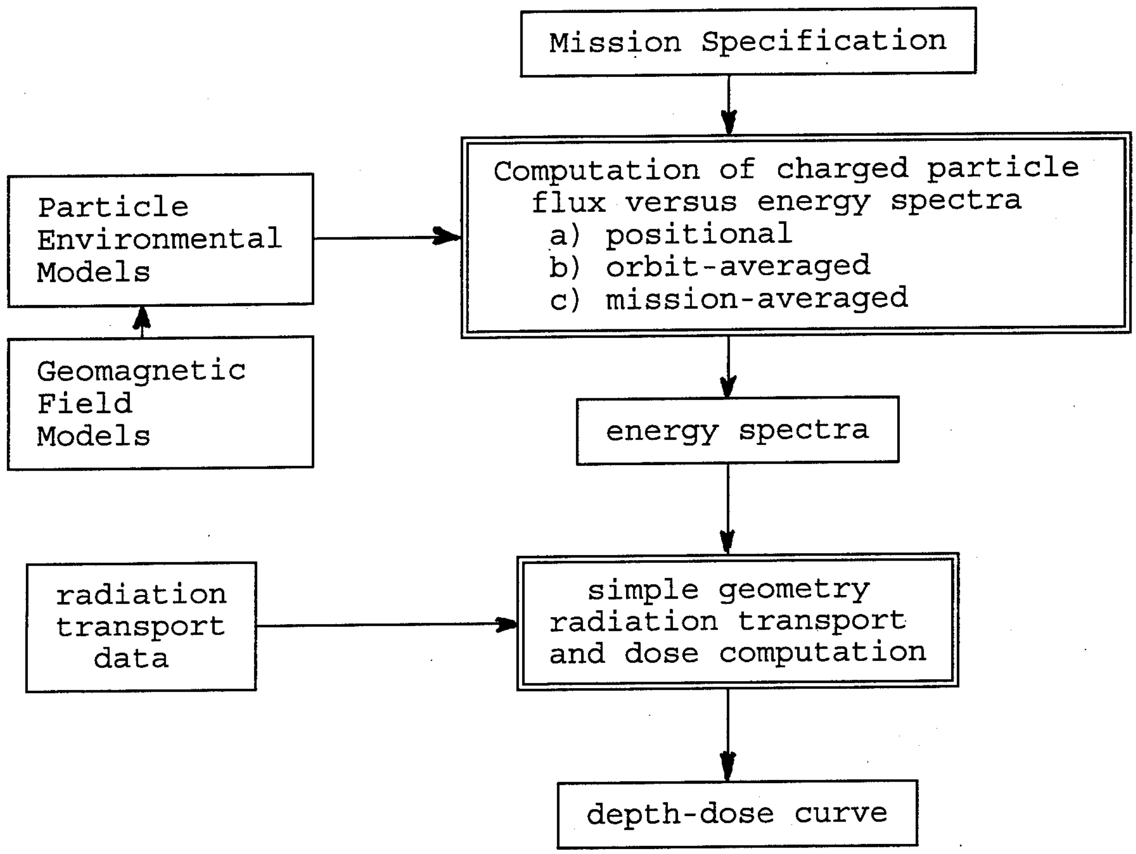

Figure 3. Data processing flow chart and computational steps used for determination of the total mission dose, for a given space platform and mission.

4.1 Orbital Parameters

The Swedish scientific research satellite ODIN is tentatively scheduled for launch in 1997 and the design criteria specifies a two year minimum lifetime. The design specifications indicated that the spacecraft electronics would be shielded by the equivalent thickness of 5 mm aluminum. The satellite will be flown in a circular polar orbit (i.e. 90 degree inclination) at a mean altitude of 650 km.

4.2 The Radiation Environment

To obtain an estimate of the mission total dose, the radiation environment must first be determined. It was first necessary to carry-out orbital radiation analysis. For the task at hand, this radiation was considered to be an omnidirectional flux of protons and electrons. The proton component of the orbital radiation environment for the satellite was composed of geomagnetically trapped protons, cosmic ray protons and solar-flare protons. The electron spectrum of the environment was entirely due to the geomagnetically trapped electrons.

The cosmic ray component of the proton spectrum was determined using the CREME code. Both solar minimum and solar maximum were considered in this exercise. This selection is enabled by a choice of the appropriate IWI value. For the solar minimum case, IWI=1 was selected. Using this index, CREME returns only the galactic component of the cosmic ray model. The proton spectrum of this component is shown in Figure 4. For the solar maximum case, in addition to the galactic cosmic ray component, the model also takes into an account solar flare activity. In this case, IWI=3 was selected. This weather condition does not include the occurrence of any major solar flare, however, the proton fluxes are severe enough that there is only 10% chance of being surpassed. It is evident from Figure 4 (compare the min/max curves) that the solar flares contribute to the proton flux at the soft-end of the cosmic ray spectrum. Figure 4 also shows the effect of the geomagnetic cut-off on the cosmic ray spectrum. CREME returns two types of geomagnetic cut-off coefficients, one for the disturbed and one for the quiet geomagnetic condition. The difference between the two values of geomagnetic cut-off coefficients reflects the change in the geomagnetic field which occurs during magnetospheric storms.

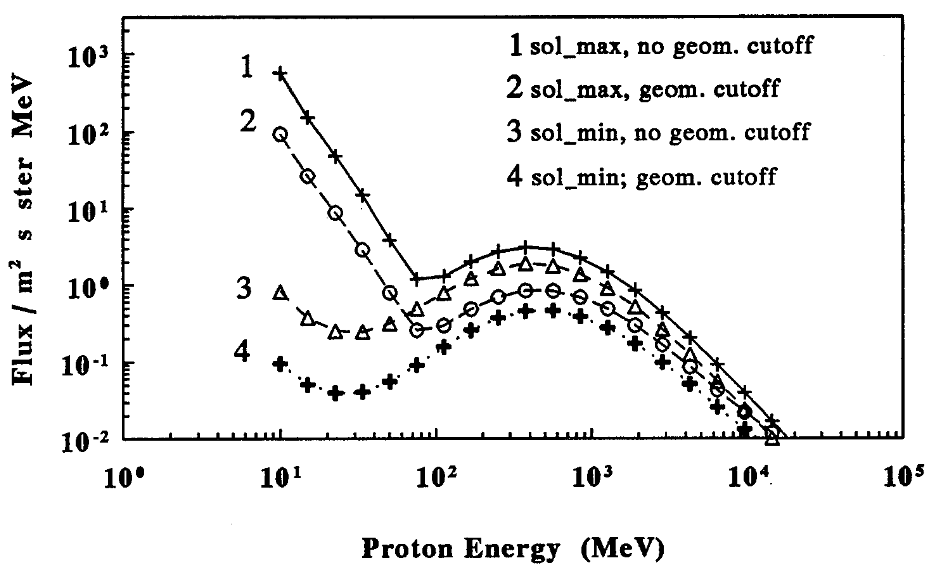

Figure 4. The cosmic ray component of the proton energy spectrum, as determined by the CREME code.

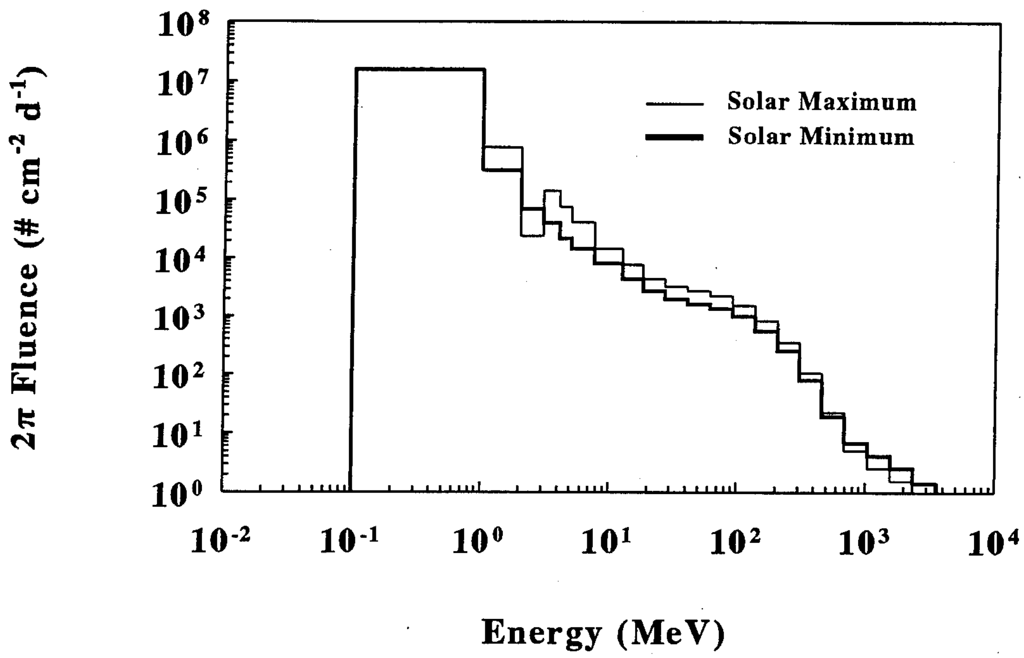

Figure 5. The composite proton energy spectrum, during solar minimum and solar maximum, for the ODIN mission.

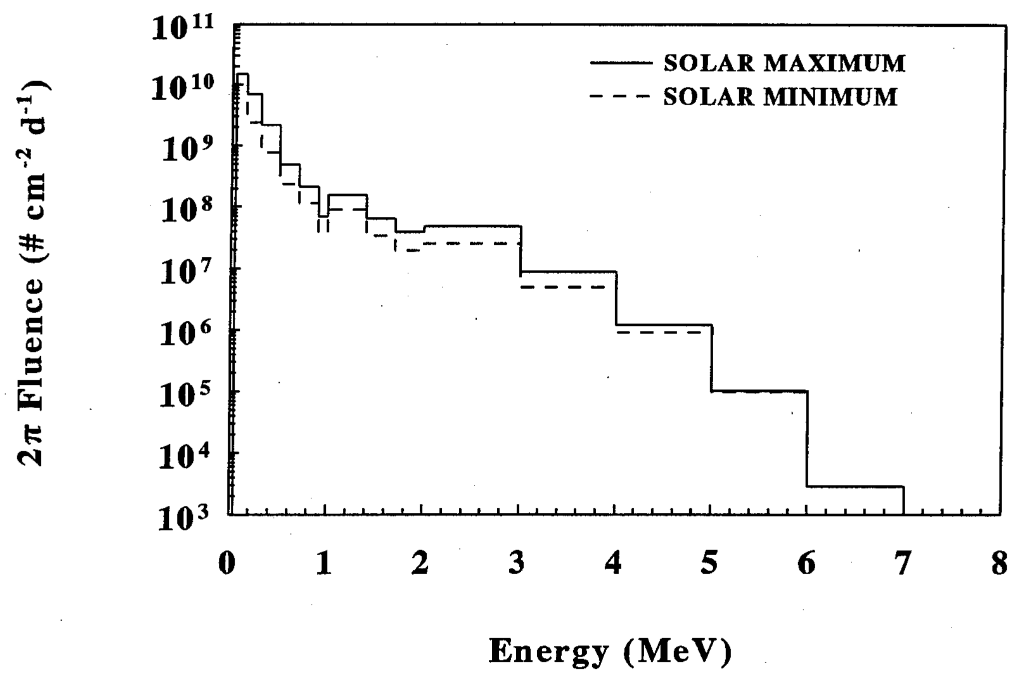

Figure 6. The trapped electron spectra predicted by the AE8 computer code, during solar maximum and solar minimum, for the ODIN mission.

The trapped proton spectral data was obtained using the AP8 trapped proton model environment. The data output for the trapped proton component flux for ODIN was the energy-binned data given in particles cm^{-2} day^{-1} $window^{-1}(4\pi$ $ster)^{-1}$. The trapped proton component was determined for both solar minimum and solar maximum conditions. The width of the energy bins used were the same as that used with the CREME code. This code returns a differential spectrum (particles m^{-2} s^{-1} MeV^{-1}) that was converted to energy-binned data. This was required to make the data compatible with the output data format of the AP8 code and so that it would also be in a compatible input data format for the radiation transport codes. The widths of the energy bins were obtained using the energy differences in the differential spectrum. For example, for the i'th energy bin, the lower energy limit is located half way between E_{i-1} and E_i while the upper energy limit is in the middle of the E_i to E_{i+1}. This results in the energy windows not having the same width. The flux for each individual energy point was multiplied by the appropriate conversion factor to derive the binned flux in units of particles cm^{-2} $ster^{-1}$ s^{-1}. The values of the energies used to define the boundaries of the energy windows were also used when running the AP8 codes. Figure 5 shows the energy-binned composite proton spectrum for solar maximum and minimum. The data in this form are suitable for the total mission dose determination. The electron spectrum of the orbital radiation environment was obtained directly from the AE8 code, for both solar maximum and solar minimum. The electron spectra are presented in Figure 6.

4.3 Radiation Transport

ITS 3.0 TIGER simulations were performed for trapped electron energy spectra and fluences generated by AE8 for conditions of solar maximum and solar minimum, using the ODIN orbital specifications. Simulations were conducted for shielding thicknesses ranging from 0 mm Al to 5 mm Al, in 1 mm increments.

Two electron depth/dose curves obtained for different shielding configurations are shown in Figure 7. This data represents solar maximum conditions. Both curves represent the dose deposited per day (rad(Si) d^{-1}) as a function of depth in silicon, for planar geometries. In Figure 7, the depth/dose simulation results for the minimum shielding (0 mm Al) and maximum shielding (5 mm Al) conditions are illustrated.

From the two depth/dose curves of Figure 7, a difference in both the depth/dose profile and the magnitude of the peak dose can be observed. For the case of 0 mm shielding, the surface dose is approximately 25% less than the peak dose, located approximately 10-15 μm below the surface. If the SHIELDOSE code had been used to perform the simulation, only the surface dose data would have been available to the analyst. It is obvious that a different conclusion might be drawn regarding the absorbed dose.

The summary data for the daily electron contribution to mission dose is presented in Table 1, for conditions of solar maximum and solar minimum. The absorbed dose per day shown in these tables represents the maximum dose in the first 100 microns in Si. It can be

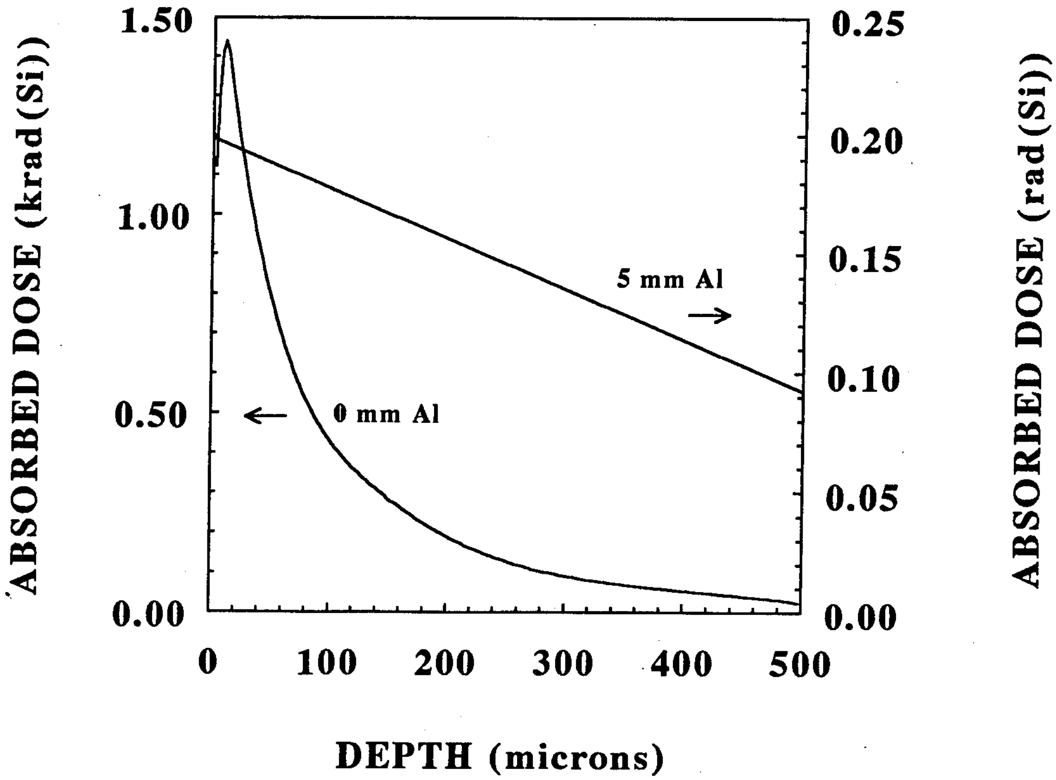

Figure 7. Absorbed dose (rad(Si)) versus depth in silicon due to electrons, for 0 mm and 5 mm aluminum shielding thickness, at solar maximum.

Al Shield Thickness (mm)	SOLAR MAXIMUM		SOLAR MINIMUM	
	Electron Dose rad(Si)/d	Proton Dose rad(Si)/d	Electron Dose rad(Si)/d	Proton Dose rad(Si)/d
0	1.41E3	1.27E3	5.64E2	1.27E3
1	10.30	0.753	5.62	1.21
2	3.04	0.559	1.57	0.932
3	1.11	0.494	0.431	0.794
4	0.486	0.398	0.226	0.615
5	0.199	0.361	0.107	0.552

Table 1. Daily radiation absorbed dose contribution by trapped electrons and protons for the ODIN mission.

observed that the electron doses are higher, for the same shielding configuration, during the period of solar maximum. It can also be seen that the use of a moderate thickness of Al shielding results in a significant reduction in the electron contribution to total dose. For example, during solar maximum, the use of 5 mm of Al shielding versus no shielding results in a reduction in the absorbed dose by an approximate factor of 7000.

PROTDOSE simulations were also conducted using trapped proton energy spectra and fluences generated by AP8, for conditions of solar maximum and solar minimum, using the ODIN orbital specifications. Simulations were conducted for shielding thicknesses ranging from 0 mm Al to 5 mm Al, in 1 mm increments.

Two trapped proton depth/dose curves obtained for different shielding configurations are shown in Figure 8. This data represents solar maximum conditions. Both curves represent the dose deposited per day (rad(Si) d^{-1}) as a function of depth in silicon, for planar geometries. In Figure 8, the depth/dose curves for minimum shielding (0 mm Al) and the maximum shielding (5 mm Al) conditions are illustrated.

From these two trapped proton depth/dose curves, an erroneous conclusion might be made regarding the effectiveness of the aluminum shielding in reducing the proton dose. From the depth/dose curve for 0 mm shielding, it is evident that the majority of the dose deposition occurs in the first 10 microns of silicon. The dose deposition in this region is due primarily to relatively low energy protons (i.e. with an energy of several tens of MeV, or less), which are also the most abundant (see Figure 5). Even if there was not any Al shielding present, the protons would have to penetrate the semiconductor device package material. This is unlikely, even if the protons are normally incident, when one considers that the range of a 10 MeV proton in epoxy is about 660 μm [TRIM]. For higher energy protons (e.g. for proton energies in excess of 100 MeV), device packaging materials generally provide little attenuation.

The effect of packaging materials on absorbed dose is *not* modelled in SHIELDOSE, unless the thickness of the packaging material can be expressed as an equivalent thickness of Al shielding material. This is generally *not* done. Our simulation work did not include semiconductor device packaging either, although PROTDOSE can accommodate this requirement, if needed.

The summary data for the daily trapped proton contribution to the mission dose is presented in Table 2, for conditions of solar max and solar min. The absorbed dose per day shown in these tables represents the maximum dose in the first 100 microns of Si. It can be observed that the proton doses are higher, for the same shielding configuration, during the period of solar minimum. This is opposite to the trend for trapped electrons. From this data it is evident that once the low energy portion of the proton spectrum is removed (as was previously discussed), with the first 1 mm of Al shielding, increasing the shielding has very little effect on the absorbed dose. This is a result of higher energy protons losing a very small fraction of their incident energy in the maximum amount (5 mm) of Al shielding and

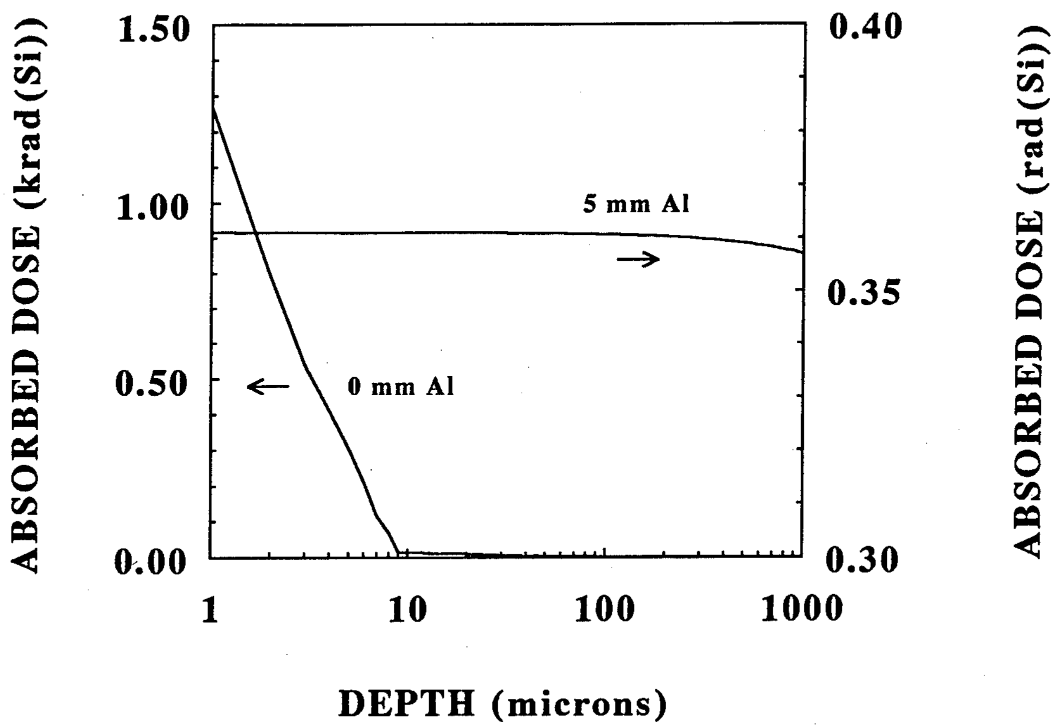

Figure 8. Absorbed dose (rad(Si)) versus depth in silicon due to trapped protons, for 0 mm and 5 mm aluminum shielding thickness, at solar maximum.

Al Shielding Thickness (mm)	CONTRIBUTION TO MISSION DOSE rad (Si)/solar flare
0	9.94E3
1	2.08E3
2	1.09E3
3	708
4	528
5	452

Table 2. An estimate of the contribution to the ODIN mission radiation dose, due to protons generated from one solar flare. The data is based upon King's solar flare model in the CREME code and is applicable only to the period of solar maximum.

their stopping powers in Si remaining relatively constant.

The dose contribution to the ODIN mission, due to protons originating from major solar flares, was also simulated using PROTDOSE. Solar flare generation only contributes to the proton flux during the solar maximum period. The proton energy spectrum and fluence values were generated via the CREME code, using King's solar flare model[8]. This data was input into PROTDOSE and the corresponding depth/dose curves were obtained for the range of Al shielding thickness of 0-5 mm. Table 2 summarizes the *total* absorbed dose *per flare*, which contributes to the mission dose for ODIN. Using statistical models[15], we estimate that at the 95% confidence level that there will be no more than 2 major solar flares during the 2 year ODIN mission. The dose contribution from 2 major solar flares, therefore, were factored into the estimate of the ODIN mission dose, which is detailed in the next section.

4.4 Mission Dose

The estimate of the total absorbed radiation dose for the ODIN mission is presented in Table 3, for conditions of solar maximum and solar minimum. The contribution to the mission dose is the sum of trapped proton, trapped electron and solar flare proton doses. From the data, it is evident that the solar maximum conditions yield the highest total dose conditions for the electronics on-board ODIN, over the range of Al shielding thickness of 0-5 mm.

Al Shielding Thickness (mm)	SOLAR MAXIMUM MISSION DOSE krad (Si)	SOLAR MINIMUM MISSION DOSE krad (Si)
0	1.98E3	1.34E3
1	12.2	4.99
2	4.8	1.83
3	2.6	0.894
4	1.7	0.614
5	1.3	0.481

Table 3. Estimates of the two year total mission radiation dose that ODIN's electronics would be subjected to, as a function of Al shielding thickness, for both solar minimum and solar maximum.

5.0 Discussion

The CREME, AE8 and AP8 computer codes were utilized to determine the mission radiation environment for the ODIN satellite. These codes predict the so called "radiation climate", which might be encountered in a given orbit in space. The geomagnetic field that a satellite traverses is not only orbit dependent, but can also fluctuate greatly even within a given orbital period. Since the geomagnetic shielding is the major factor that determines the radiation climate that the satellite is exposed to, it follows that the mission dose for a satellite is generally very orbit-dependent.

Geomagnetic shielding modifies the spectrum of the radiation that originates outside the Earth's magnetosphere, namely the components of the cosmic radiation. This can be significant as is evident from Figure 4. Since ODIN's orbital plane is perpendicular to the Earth's equatorial plane, the satellite will pass through large gradients in magnetic field intensity, especially in the vicinity of the South Atlantic Anomaly (SAA). It can, therefore, be expected that the satellite will also pass through ionizing radiation belts of varying composition. In Figure 9a, a contour map of the Earth's magnetic field, traversed by the ODIN at 650 km altitude, is shown. The South Atlantic Anomaly region is also indicated. Since the satellite's orbit plane sweeps about 22 degrees of longitude per rotation, the investigator should use minimum of 16 orbits to generate a 360° map. If fewer than this number of orbits were used, an under- or over-estimate of the radiation flux could result. Figure 9b illustrates the corresponding contour map of L-shell parameters.

The integral flux of protons (E>0.1 MeV) encountered by the satellite traversing the SAA is shown in Figure 10a. The presence of proton fluxes at this low altitude is due to the weak magnetic field present in the SAA region. The relatively weak magnetic field causes the mirror points of trapped protons to be shifted to lower altitudes, which intercept ODIN's orbit. The proton flux apparently originates from the equatorial distance of 3 to 7 Re (L=3 to L=7, Figure 9b). It should be noted that the SAA region is the only significant source of trapped protons in ODIN's orbit.

The trapped electron flux distribution, shown in Figure 10b, indicate that the highest electron fluences will be encountered in both the SAA region and in the auroral zone regions. This zone is clearly seen as a continuous band in the northern hemisphere above the 50 degree latitude (see Figure 10b). A similar band of relatively higher electron fluence can also be observed in the southern hemisphere. The total dose that is encountered by a satellite for a given orbit-mission also depends on the transient radiation fluxes. Although CREME, AE8 and AP8 models provides both quiet and disturbed radiation environments, the anomalously large transient events had to be considered separately. When a large transient proton event is considered, a reference is usually made to the fluence level of the solar flare of August 1972.

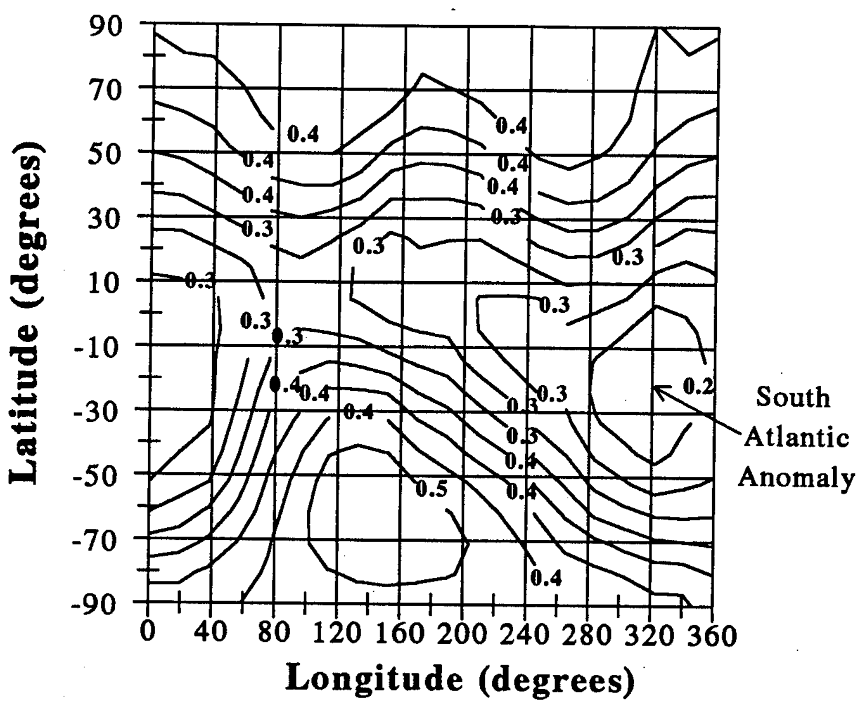

Figure 9a. Contour map of the Earth's magnetic field intensity (units of gauss) at a 650 km polar circular orbit.

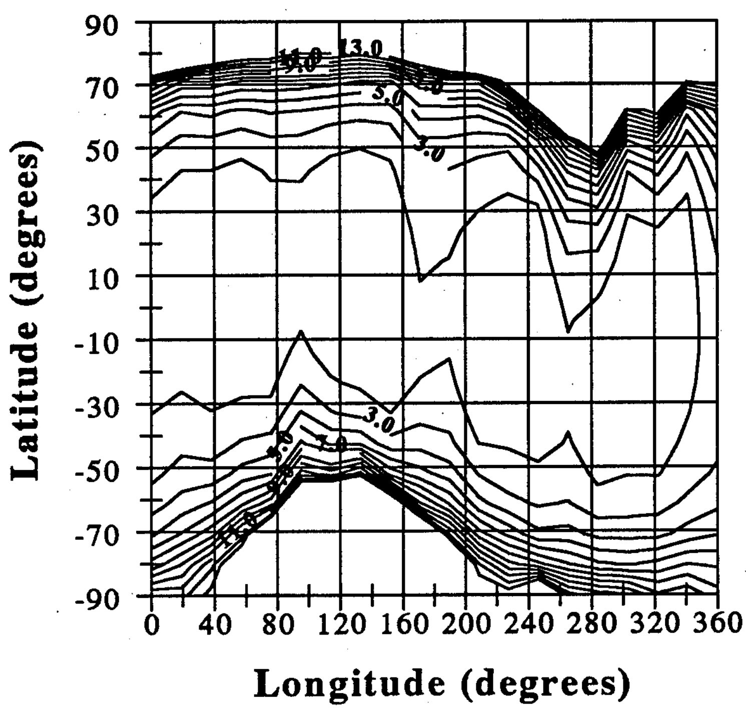

Figure 9b. Contour map of the magnetic L-shell parameters at a 650 km circular polar orbit.

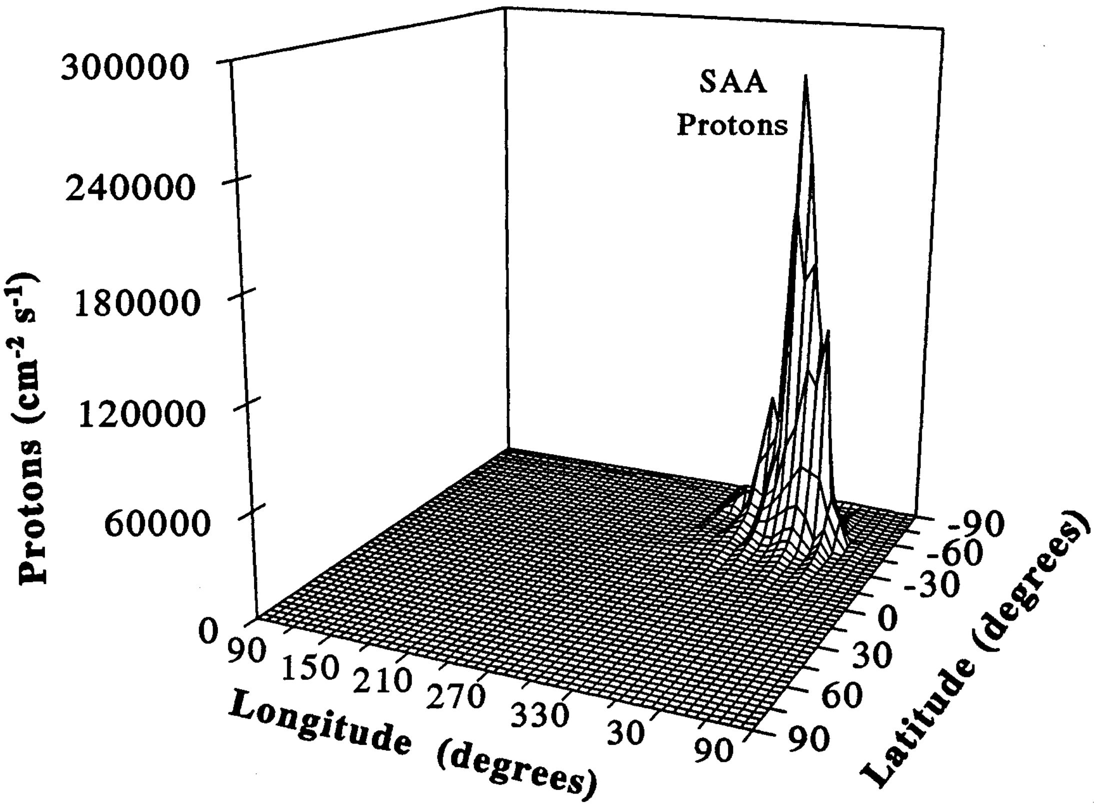

Figure 10a. Trapped proton distribution flux at a 650 km circular polar orbit.

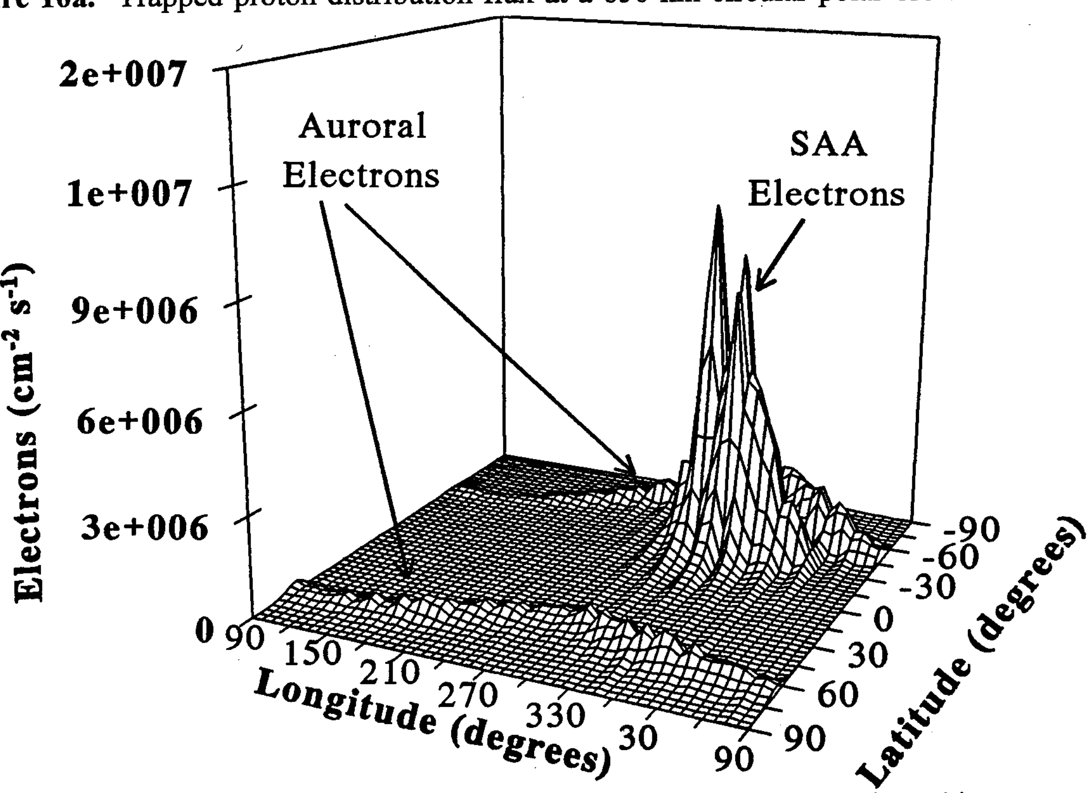

Figure 10b. Trapped electron flux distribution at a 650 km circular polar orbit.

In our application of the CREME code, we have adopted King's model for predicting the proton fluence for transient events, in conjunction with a galactic cosmic ray background weather index equal to one (IWI=1). This also served as a model for cosmic ray flux during solar minimum. For modelling purposes, a solar cycle is divided into 7 active and 4 quiet years[15]. Based on the observation of solar cycle #20, King's model predicts that 1 large solar flare will occur during a 7 year period. Using Burrell-modified Poisson statistics[15], one can calculate the confidence levels associated with the number of very large solar flares expected during the duration of the mission. Table 4 summarizes the confidence levels associated with the maximum number of flares expected over the 2 year ODIN mission.

Number of Events	Confidence Level (%)
0	40
1	87
2	95
3	98

Table 4. Confidence levels for the maximum number of very large flares expected during the ODIN mission.

In our estimation of the solar flare proton contribution to ODIN's mission dose, we have assumed that there would be no more than 2 solar flares occurring, at the 95% confidence level (by specifying IWI=9 in the CREME code).

6.0 Conclusions

In this report, we have used the AE8, AP8 and Creme codes to obtain an estimate of the electron and proton fluence that the Swedish research satellite ODIN will be subjected to in a 650 km circular polar orbit, over its 2 year mission lifetime.

The Integrated Tiger Series of Monte Carlo codes for electron/photon transport and the DREO-developed PROTDOSE code were used to obtain mission dose estimates due to electrons and protons, respectively. This is a novel approach over using the industry-standard code SHIELDOSE to obtain fluence-to-dose conversion for arbitrary proton and electron energy spectra. The primary advantage to be gained from such an approach is increased simulation accuracy, due to the use of the most recent cross-section data and improved modelling of the physics of the energy deposition process. An added benefit of our methodology is that the satellite designer is afforded more analysis capability over the SHIELDOSE code (which must be treated as a "black box" code), in terms of what can be modelled and the degree of complexity.

Our mission dose estimates for ODIN, due to both protons and electron, were found to compare favourably with ESA data provided to us by Neptec Design Group Inc[16]. The simulation methodology used to obtain the ESA data was not provided, however, it is encouraging that the results agree closely, considering the complexities involved in the modelling process.

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This report summarizes the analytical approach developed to estimate the total ionizing radiation dose received by Earth-orbiting satellites. The analytical tools and methodology utilized in this work represent a departure from the more traditional, "industry standard" approaches. This has resulted in an improvement in the accuracy of the total dose estimation. The analytical approach developed was applied to the problem of determining the mission total dose for the Swedish satellite ODIN.

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