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ALGORITHM OF SEU RATE PREDICTION INSIDE SPACECRAFTS

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ABSTRACT

One of the important effects of the space environment on the satellites and spacecrafts is the single event upsets (SEUs) which are caused by the high energy particles in space. A SEU occurs when an ionizing radiation produces a burst of electron-hole pairs in a digital microelectronic circuit and causes the charge state to change. We have developed and integrated a software package which can estimate the SEU rates for any specified locations or altitudes under various geophysical conditions. We report in this paper the algorithm of the software and the results for some devices with known parameters. We also compare the results with actual observations made by Akebono.

1. INTRODUCTION

One of the harsh environments which make the operation of satellites and spacecrafts difficult is the high energy particles in space. These high energy particles may originate from the solar wind and galactic cosmic rays, but most of them are trapped in the Van Allen radiation belts. Some of the high energy particles can penetrate deep into the inner core of the magnetosphere, reaching the altitude of the low earth orbit, and cause various problems in satellite microelectronics. A Single Event Upset (SEU) is one of such phenomena that occurs when an ionizing radiation produces a burst of electron-hole pairs in a digital microelectronic circuit and causes the charge state to change. These unplanned changes of the charge state usually result from two mechanisms, by the direct ionization of cosmic heavy ions or by the products of nuclear reactions initiated by high energy particles.

SEUs are known to have caused operational difficulties of various kinds on many spacecrafts. Thus, it is natural that vulnerability to SEUs must be considered in the design of spacecrafts. In order to assess the vulnerability of any proposed design, engineers must have a reliable means of estimating the SEU rates in the radiation environments that can be expected during the mission. It not only requires the experimental measurements and circuit modeling to acquire the parameters that determine the SEU sensitivity of each device in the circuit, but it also requires a reliable model of the particle radiation environment.

We have developed and integrated a software package which can estimate the SEU rates for any specified locations or altitudes under various geophysical conditions. We report in this paper the algorithm of the software and the results for some devices with known parameters. We also compare the results with actual observations made by Akebono.

2. THEORY

2.1 Radiation Transport

In order to find the differential energy spectra at the microelectronic components inside the spacecraft, a transport calculation must be performed (Nichols *et al.* 1983, Petersen & Adams 1992, Petersen *et al.* 1992). This is best done by the method of Adams (1982, 1983). This method takes into account the effects of energy loss and particle losses through total inelastic collisions.

The differential energy spectrum $f(E)$, inside the spacecraft behind a shielding wall of thickness t (in g/cm^2 of aluminum or equivalent) is

$$f(E) = f'(E')[S(E')/S(E)]\exp(-\sigma t),$$

and

$$\sigma = [5 \times 10^{-26} n(A^{1/3} + 27^{1/3} - 0.4)^2]/27,$$

where $f'(E')$ is the differential energy spectrum at the skin of the spacecraft, E' is the energy at the skin of the spacecraft, i.e., $E' = R^{-1}[R(E) + t]$, where $R(E)$ is the residual range of an ion having an energy E and R^{-1} is the inverse function of $R(E)$, E is the particle energy inside the spacecraft, $S(E)$ is the stopping power of an ion having an energy E, A is the atomic mass of the ion, and n is the Avogadro's number. The above equations give estimates of the differential energy spectra inside spacecraft that are satisfactory for estimating SEU rates provided the shielding thickness does not exceed 50 g/cm.

2.2 Calculation of SEU Rates

2.2.1 Direct Ionization of Charged particles

A SEU occurs when a sufficiently large burst of charge is collected on a critical node in one of the digital microcircuits on a chip. The minimum charge required to produce a SEU is called the critical charge. This burst of charge can come from a segment of the ionized trail left by the passage of an intensely ionizing particle. It is assumed that each critical node is surrounded by a sensitive volume and that the charge deposited in this volume gets collected. The dimensions of the sensitive volume are related to those of the critical node. Charge is also collected from the silicon surrounding the node by diffusion. The efficiency of charge collection from beyond the node falls off with distance. Pickel & Blandford (1980) discusses how the critical charge and the dimensions of the sensitive volume can be found. In general, experimental measurements of the operational SEU cross section for the device, as well as design data supplied by the manufacturer, are required. One method of estimating soft upset rates due to the direct ionization by particles originating outside the spacecraft is given below in the form presented by Adams (1983). The upset rate, N_e, in upsets/(bit sec) is

$$N_e = 22.5\pi A Q_{\text{crit}} \int_{22.5Q_{\text{crit}}/P_{\text{max}}}^{L_{\text{max}}} D[p(L)]F(L)/L^2 dL,$$

where A is the surface area of the sensitive volume in m^2, Q_{crit} is the minimum charge required to produce an upset, in picocoulombs, $L_{\text{max}} = 1.05\text{e}5$ MeV cm^2/g, the highest LET any stopping ion can deliver, P_{max} is the largest diameter of the sensitive volume in g/cm^2, L is LET in MeV cm^2/g,

$F(L)$ is the integral LET spectrum in particles/m^2 ster-sec, and $D[p(L)]$ is the differential pathlength distribution in the sensitive volume of each memory cell in cm^2/g, where $p(L) = 22.5Q_{\text{crit}}/L$ is the pathlength over which an ion of LET, L, will produce a charge Q_{crit}.

2.2.2 Nuclear Reactions Caused by Protons

The intensely ionizing particles that cause SEUs can be the fragments of a silicon nucleus struck by a particle originating outside the spacecraft. The most common particle in space capable of causing such a nuclear reaction is the proton. At present, the most practical method for calculating proton-induced SEUs is to measure the operational SEU cross section at one proton energy and then use the method of Bendel & Petersen (1983) to find the SEU rate in any proton environment. Bendel & Petersen (1983) gives the SEU operational cross section in upsets per proton/cm^2 per bit as

$$\sigma = 1 \times 10^2 \times (24/A)^{14} \times [1 - \exp(-0.18Y^{0.5})]^4,$$

where

$$Y = [(18/A)^{0.5}](E - A),$$

where E and A are in MeV. Then the SEU rate due to nuclear reactions caused by protons is given by

$$R = (1 \times 10^{-4}) \times 4\pi \int_0^{\infty} f(E)\sigma(E)dE,$$

where $f(E)$ is in protons/(m^2 ster sec MeV) and R is in upsets per bit-sec.

3. ALGORITHM AND TEST RESULTS

3.1 Algorithm

The CREME program is a group of FORTRAN routines that calculate differential and integral energy and LET spectra of cosmic rays incident on the electronics inside any spacecraft in any earth orbit and the single event upset rates that result. Input parameters for running these programs describe the interplanetary and magnetospheric weather conditions, the spacecraft's orbit, the shielding surrounding the electronics, and the characterizations of the device under consideration. Input data files contain tabulations of stopping powers and ranges of cosmic ray nuclei in aluminum and silcon, and geomagnetic cutoffs. The output file contains energy and LET spectra, and single event upset rates.

In CREME program, LET and the corresponding cross section of a device are needed. Therefore it is important to know the cross section as a function of LET. The statistical distribution that is used to describe the cross section of the device is the Weibull distribution. This distribution is most often used for cases in which the failure probability varies as a power of the time. The integral form of the distribution, which is appropriate to describe upset cross section measurements, is

$$F(L) = 1 - \exp(-[(L - L_0)/W]^s)$$

for $L > L_0$, and

$$F(L) = 0,$$

otherwise, where L_0 is the threshold, W is the width of the distribution, and s is a shape parameter. $s = 1$ corresponds to an exponential distribution function, $s = 2$ to a Rayleigh distribution, $s = 4$ to a normal distribution, and at large s it approaches the log-normal distribution.

The CREME program consists of six main routines and subroutines. Main routines are SPEC, GEOMAG, LET, BENDEL, UPSET and STASS. Subroutines are INSIDE, CUT, CRF, DEDXSI, DEDXAL, RAL, DIFPLD, SIGMA, STORMER, and ORBIT. The functions of these routines are as follows:

< MAIN ROUTINES >
CREME: links all routines and executes specific routines according to the input
STASS: converts input data into trapped proton environment
SPEC: gives differential and integral energy spectra of cosmic rays of a specified charge
LET: provides LET spectrum for a certain range of atoms
GEOMAG: calculates the geomagnetic transmission function from the given orbit
UPSET: calculates upset rates induced by ions
BENDEL: calculates proton induced upsets

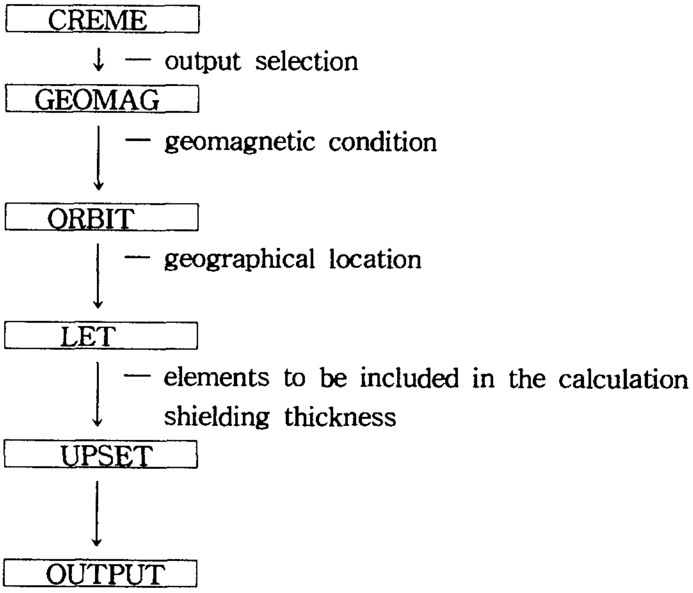

Figure 1. Flow chart of the CREME program.

Table 1. Parameters for LET distribution.

DEVICE	CS (cm^2/bit)	L_0(MeV/mg/cm^2)	W	s
93422	$3.7\times10^{-}5$	0.58	5.5	0.8
93L422	2.6^{-5}	0.60	4.4	0.7
82S212	8.7^{-6}	1.0	6.0	0.8
TCS130	5.0×10^{-8}	40.0	40.0	1.4
4042	1.25×10^{-7}	16.2	25.0	1.4
6508	4.2×10^{-6}	38.8	57.0	0.75
6516	2.2×10^{-6}	4.0	12.4	2.7
6504	4.2×10^{-6}	30.8	62.0	1.5

< SUB ROUTINES >
ORBIT: determines geographical location
SIGMA: calculates scattering cross section from BENDEL's formula
INSIDE: computes the flux inside
DEDXAL: calculates stopping power in aluminum (MeV cm^2/g)
RAL: calculates residual range (g/cm^2)
CRF: in high orbits, returns the differential flux in particles as it is found in the interplanetary medium near the earth (m^2 ster sec MeV/u)
CUT: in low orbits, obtains differential particle flux from CRF, applies geomagnetic cutoff transmission function and returns the resulting flux, modulated to the orbit average cutoff
STORMER: Stormer theory
DEDXSI: calculates stopping power in silicon
DIFPLD: determines the differential path length distribution needed in upset calculation

Figure 1 shows the execution procedure of the CREME program.

3.2 Results

We have selected several devices to test the program (Zoutendyk *et al.* 1984). Table 1 shows the parameters of the Weibull distribution for these devices. The parameter CS is the limiting cross section per bit.

In order to calculate SEU rates caused by nuclear reactions differential trapped proton flux is needed. Only proton fluxes above 10 MeV are considered in CREME program. Table 2 is the integral trapped proton flux estimated for KITSAT-1, in circular orbit at an altitude 1300 km with the orbital inclination 65 degrees.

The shielding material surrounding the device is assumed to be an aluminum of 10 mm (or equivalent). Environments used in the run of CREME program are as follows: only the galactic cosmic ray is considered for the interplanetary weather, while the effect of the shadow of the earth is included, and the magnetic weather condition used in this calculation is stormy. We have calculated the SEU rates for the devices listed in Table 1. Table 3 shows the results for KITSAT-1 orbit. Since the result depends on the device very sensitively, it is difficult to verify the test results quantitatively, unless the same type of the device is flown in space. Fortunately, we were able to find the necessary

Table 2. Trapped proton flux in 1300 km.

ENERGY (MeV)	INTEGRAL FLUENCE (#/m^2/sr)
1.000×10^{01}	1.99036×10^{11}
1.500×10^{01}	1.68559×10^{11}
2.000×10^{01}	1.51430×10^{11}
3.000×10^{01}	1.31965×10^{11}
5.000×10^{01}	1.07990×10^{11}
6.000×10^{01}	9.83184×10^{10}
8.000×10^{01}	8.07919×10^{10}
1.000×10^{02}	6.62010×10^{10}
2.000×10^{02}	3.49494×10^{10}
4.000×10^{02}	3.69772×10^{09}

Table 3. SEU rates in 1300 km.

DEVICE NUMBER	ERROR RATE (upsets/bit sec)	ERROR RATE (upsets/bit day)
93422	1.236×10^{-07}	1.067×10^{-02}
93L422	1.073×10^{-07}	9.273×10^{-03}
82S212	8.358×10^{-09}	7.221×10^{-04}
TCS130	1.672×10^{-16}	1.444×10^{-11}
4042	1.483×10^{-14}	1.281×10^{-09}
6508	2.387×10^{-13}	2.069×10^{-08}
6516	8.175×10^{-12}	7.063×10^{-07}
6504	2.508×10^{-13}	2.167×10^{-08}

parameters for M5M5164 in the literature (Shiono 1986) which was tested in space on board the satellite Akebono. Akbono is in the elliptical orbit with the apogee 10000 km and the perigee 250 km, and with the orbital inclination angle 75 degrees. M5M5164 is a 64k RAM with a threshold LET 3.5 MEV/(mg/cm^2), and the limiting latch-up cross section 10^{-6} cm^2/particle/device. Figure 2 shows the results of the calculation plotted against the precession angle. The trend of the curve agrees well with the actual observation shown in Figure 3. The observed upset rate is about 5 times higher than the calculation result (Takagi *et al.* 1993). However, when it is taken into account that the observed proton flux is also 5 times higher than the AP 8 model, the agreement seems reasonable.

4. SUMMARY

We developed and integrated a software package which can estimate the SEU rates for any specified locations or altitudes under various geophysical conditions. We reported in this paper the algorithm of the software and the results of calculation at the KITSAT-1 altitude for some devices with known parameters. We also compared the results with actual observations made by Akebono

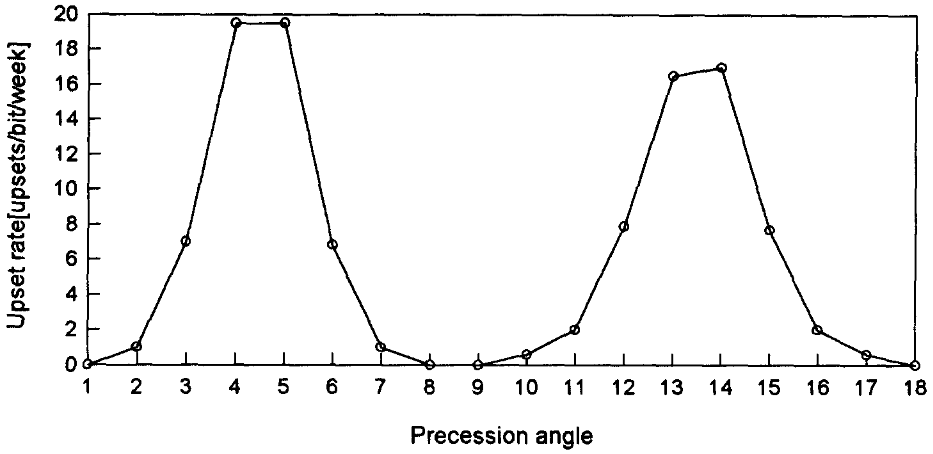

Figure 2. Trapped proton induced upset rate per week per bit. The abscissa is the angle divided by 20 degrees which represents the precession of the satellite oribital plane.

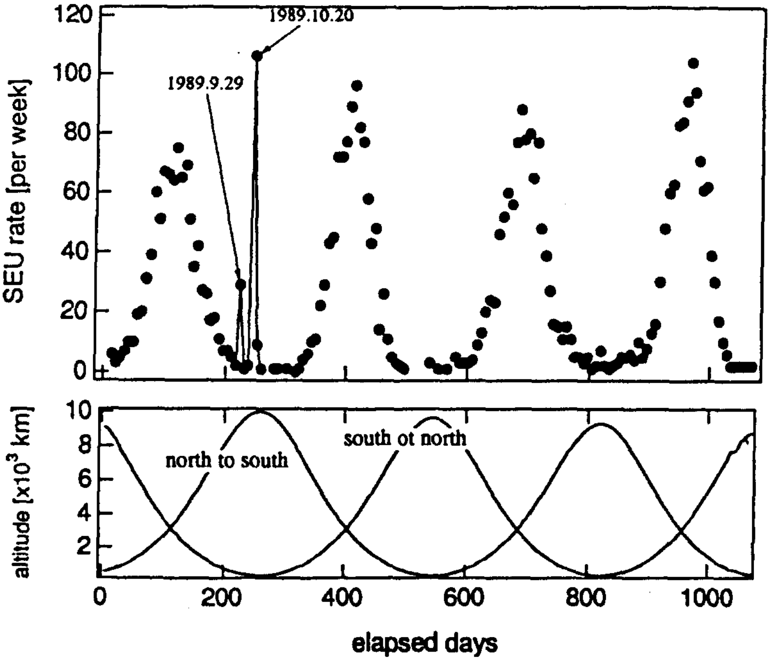

Figure 3. SEU rate observed by Akebono and the corresponding altitude of the satellite.

and obtained a reasonble agreement. The package can be readily applicable to the actual assessment of SEUs in the satellite design.

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