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New Radiation Dose Model for Geostationary Orbit

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Active semiconductor components in satellites are sensitive to accumulated space radiation doses. Radiation dose and additional shield thickness estimations for electronic components are usually carried out using the NASA models of space radiation particle flux and dose. Accurate dose versus shield thickness data are essential for optimizing radiation shielding design. Dosimeters designed using radiation-sensitive field-effect transistors as sensors measured the accumulated dose at geostationary orbit. Radiation dose measured by the dosimeters with spherical aluminum shields of different thicknesses, are presented and compared with NASA and Combined Release and Radiation Effects Satellite model doses. The NASA AE-8 model electron doses are a few times higher than the measured dose, and the Combined Release and Radiation Effects Satellite model electron doses are much smaller than the measured dose. A new radiation dose model has been developed for geostationary orbit using the measured data. Doses estimated at a point inside the satellite, using software based on a ray-tracing technique, was verified by direct measurement.

I. Introduction

LIFE of active semiconductor components in space is limited by the total ionizing dose due to space radiation, which mainly consists of electrons, protons trapped in the geomagnetic field, and solar flare protons. Total radiation dose analysis for satellites are commonly carried out using NASA models AP-8 and AE-8 for protons and electron flux, respectively. The accuracy of dose vs shield thickness data for geostationary orbit derived from NASA models is not known exactly. Radiation dose at geostationary orbit was first measured in 1988, in the satellite METEOSAT-3 using a radiation-sensitive field-effect transistor (RADFET) as sensor [1]. RADFET is a radiation-sensitive P-channel metal oxide semiconductor field-effect transistor specially designed to measure accumulated ionizing dose. The Combined Release and Radiation Effects Satellite (CRRES) (1990) satellite in geostationary transfer orbit [2,3] and KITSAT-1 (1992) at 1330 km elliptic orbit [4] also used RADFET as a sensor to measure accumulated ionizing dose. Now geostationary orbit satellites (GSAT) are designed for a life of 15 years, hence more accurate dose vs shield thickness data should be used for designing radiation shielding for electronic components. Because space radiation electron and proton fluxes are dynamic, dose should be measured over a long period of time to arrive at accurate average dose, which can be used for designing radiation shielding on electronic components. Dosimeters were designed by the Indian Space Research Organisation team using RADFETs manufactured by National Microelectronics Research Center, Ireland. The GSAT-2 satellite carried five dosimeters, which were launched to geostationary orbit on 8 May 2003. The design and calibration of the dosimeters are described in [5]. Preliminary data received from those dosimeters are also given in [5]. Data received during the period from May 2003 to May 2008 are presented in this paper. The main objective of this experiment is to generate dose vs shield thickness data for spherical aluminum shields and compare the result with model doses which are derived from electron and proton flux models. A new radiation dose model has been developed using the measured data over a period of five years. The second objective of the experiment is to check the accuracy of the dose estimated by the software DOSEMAP in satellite. DOSEMAP is inhouse-developed software which can estimate the dose at the chip of a semiconductor component in the satellite, considering the exact configuration of the satellite. For checking the accuracy of software, radiation dose was measured at a location inside the satellite and compared with the estimated dose.

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II. Description of Dosimeters

Total Radiation Dose Monitor (TRDM) is an experimental payload in GSAT-2 satellite at geostationary orbit. It consists of five dosimeters, the details of which are in Table 1. Four GSAT radiation dosimeters (GRD) with hemispherical domes GRD-10, GRD-20, GRD-30, and GRD-40 are mounted on the outer surface of the west panel of the satellite. These four dosimeters have base plates of thickness 10 mm aluminum to reduce the uncertainties in dose received from the backside. The thicknesses of the hemispherical domes are approximately 1, 3, 6, and 9 mm. There is only one card containing the dosimeter circuit inside the dome. The RADFET sensor is on the dome side and all other electronic components are mounted on the backside facing the base plate. Therefore, the RADFET is shielded by a spherical aluminum dome and rectangular Kovar top cover of thickness $0.24\ \mathrm{gm/cm^2}$ on the front side. On the backside, it is shielded by a 10-mm-thick aluminum base plate, satellite structure, electronic card, and the substrate of the RADFET package. All the four dosimeters are covered by the multilayer insulation blanket which limits the maximum temperature to 45°C in space. The response of RADFET to radiation is lower in the power-off condition than when power is on. Ground calibration was carried out in the power-on condition. In the satellite, RADFETs are continuously in the power-on condition from the day of launch. Telemetry continuously sends the readings of the five dosimeters and the package temperatures. Temperatures of the dosimeters are measured at the base plate. Temperature coefficients of the output of the dosimeters given in Table 1 were used to apply corrections for variation with temperature. Readings of the dosimeters are in counts and each count is 40 mV.

There is one electronic package that interfaces dosimeters to power, telecommand, and telemetry. This electronic package also contains one dosimeter circuit GRD-50. GRD-50 is used to check the accuracy of dose estimated by the inhouse-developed software DOSEMAP. In this circuit, RADFET does not have any shielding. This electronic package is mounted on the inner surface of the north deck. It is surrounded by various other electronic packages in the satellite. RADFET in GRD-50 is mounted on the backside of

Table 1 TRDM dosimeter details

Dosimeter	Spherical dome thickness[a]		Correction factor for backside dose[b]	Temperature coefficient, mV/°C
	gm/cm^2	mm		
GRD-10	0.51	1.89	1.00	−3.75
GRD-20	1.06	3.90	0.97	−3.10
GRD-30	1.88	6.96	0.76	−8.75
GRD-40	2.75	10.19	0.60	−11.25
GRD-50	——	——	——	−1.60

[a]Dome thickness includes the thickness of Kovar top lid.
[b]Total dose measured by the dosimeters should be multiplied by this factor to get dose through the spherical dome.

the card. On the front side, RADFET is shielded by its top cover ($0.24\ gm/cm^2$), base plate of the electronic package, and the honeycomb panel of the satellite. On the backside, it is shielded by the card, box cover, satellite structure, and all other systems in the satellite. The accumulated dose in the RADFET chip was estimated using the software DOSEMAP and dose vs shield thickness data for a spherical aluminum shield.

The inhouse-developed software DOSEMAP can estimate the dose at the chip of a semiconductor component, considering the exact configuration of the satellite. Because GRD-50 is shielded by the satellite structure and various electronic packages, the amount of radiation shielding seen by the RADFET chip is different in different directions. To take into account the variation in dose from different directions, DOSEMAP uses a ray-tracing technique. In ray-tracing, the point where dose is to be estimated is at the center of an imaginary cube whose surface is divided into several thousand sectors. The satellite structure and all equipment are defined using planar, spherical, and cylindrical objects. A ray is drawn from the center of the cube to the center of a sector. The software DOSEMAP calculates the solid angle subtended by a sector at the center of the cube and the thickness intercepted by the ray with various objects in the satellite. The dose received at the center of the cube, in the direction of the ray, is then calculated using the dose vs shield thickness data for the spherical aluminum shield. The ray is then scanned through all the sectors and dose from each ray is summed to get 4π dose at the center of the cube. The accuracy of the ray-tracing technique is proportional to the number of sectors on the cube. To estimate dose at the chip of RADFET in GRD-50, we used 10,000 sectors on each surface of the cube. DOSEMAP can calculate the dose at the chip of a semiconductor component, considering the component wall thicknesses, printed circuit boards, equipment box wall thicknesses, satellite structure, and all other systems.

The accuracy of measured data depends on 1) calibration, 2) annealing of accumulated dose, 3) sensitivity of RADFET to dose rate, and 4) variation of data with temperature. Calibration of RADFET was carried out using Co-60 gamma ray. It was confirmed by test that the responses of RADFET to electron and gamma ray are the same. Ideally, RADFET should not anneal over a long period of time in space. In general, annealing of metal oxide semiconductor field-effect transistor is insignificant below 100°C. The dosimeters temperatures were maintained below 45°C all the time. During calibration in the year 2002, several RADFETs were irradiated and kept at room temperature. After six years, no measurable annealing was observed. When calibration was carried out, the output voltage stabilized in a few hours and thereafter no significant annealing was observed. Enhanced low dose rate sensitivity is not applicable to RADFETs manufactured by National Microelectronics Research Center, Ireland. Corrections were applied on the data for the variations with temperature. Temperature coefficients of dosimeter outputs are given in the Table 1.

III. On-Orbit Measured Dose

GSAT-2 was injected into the transfer orbit on 8 May 2003 at 17 h, 17 m Indian Standard Time and switched on at 20 h, 6 m. Initial readings of the dosimeters were taken at the launching pad. The satellite reached the geostationary orbit after the second apogee motor firing on 10 May 2003 at 16 h, 53 m. Parking longitude of GSAT-2 is 48° east. Dosimeter readings were available continuously and recorded every week. During solar flare events, the dose rate was high, hence the observed jumps in readings. Measured doses are given in Tables 2 and 3. Using the measured doses, the dose at the center of the spherical shield was calculated as follows:

1) Subtract transfer orbit dose from the accumulated dose.
2) Subtract solar flare dose.
3) Multiply by correction factor given in Table 1 to get 2π dose.
4) Multiply by two to get 4π dose.

The calculated dose at the center of the spherical aluminum shield due to electrons at geostationary orbit is given in Table 4.

Table 3 Transfer orbit and solar flare dose measured by dosimeters

	Dose in kilorads			
	GRD-10	GRD-20	GRD-30	GRD-40
Transfer orbit 8–10 May 2003	4.432	0.378	0.027	0.013
Solar flare 28 Oct. 2003 to 3 Nov. 2003	2.790	0.256	0.061	0.060
27 July 2004 to 1 Aug. 2004	8.000	0.250	0.040	0.026
18 Jan. 2005 to 23 Jan. 2005	3.470	0.108	0.042	0.035
12 Sept. 2005 to 22 Sept. 2005	14.000	0.290	0.050	0.032

Table 2 Total dose measured by dosimeters

Period of measurement	Dose in kilorads, excluding transfer orbit, including flare				
	GRD-10	GRD-20	GRD-30	GRD-40	GRD-50
First yr 8 May 2003 to 8 May 2004	42.130	1.534	0.376	0.381	——
Second yr 8 May 2004 to 8 May 2005	45.640	1.138	0.334	0.365	——
Third yr 8 May 2005 to 8 May 2006	63.800	1.390	0.353	0.411	——
Fourth yr 8 May 2006 to 8 May 2007	64.000	1.140	0.370	0.430	——
Fifth yr 8 May 2007 to 8 May 2008	58.000	1.490	0.390	0.500	——
Total	273.570	6.692	1.823	2.087	6.16

Table 4 Electron dose at the center of spherical aluminum shield

Dosimeter → Dome thickness →	4π dose in kilorads			
	GRD-10, 1.89 mm	GRD-20, 3.90 mm	GRD-30, 6.96 mm	GRD-40, 10.19 mm
First yr 8 May 2003 to 8 May 2004	78.68	2.479	0.479	0.385
Second yr 8 May 2004 to 8 May 2005	68.40	1.513	0.383	0.365
Third yr 8 May 2005 to 8 May 2006	99.60	2.134	0.460	0.455
Fourth yr 8 May 2006 to 8 May 2007	128.00	2.212	0.562	0.516
Fifth yr 8 May 2007 to 8 May 2008	116.00	2.890	0.593	0.600
Average kilorads/yr	98.14	2.25	0.495	0.464

Table 5 Ratio of AE-8 model dose to measured electron dose

Shield thickness, mm (Al)	Measured data, rads (read from Fig. 1)	AE-8 model data, rads	Ratio, AE-8 model/measured
2.0	1.0 E 6	2.7 E 6	2.7
3.0	1.0 E 5	6.8 E 5	6.8
4.0	3.0 E 4	2.0 E 5	6.7
5.5	1.0 E 4	4.5 E 4	4.5
6.0	9.0 E 3	3.1 E 4	3.4
7.0	7.0 E 3	1.7 E 4	2.5
10.0	6.0 E 3	7.5 E 3	1.25

Table 6 GSAT-2 model dose at geostationary orbit

Spherical aluminum shield thickness, mm	AE-8 model electron dose, rads/15 yrs	GSAT-2 model electron dose, rads/15 yrs	JPL model solar flare proton dose, rads/2 cycles	GSAT-2 model total dose, rads/15 yrs (col. 3 + col. 4)
0.05	8.581 E 8	3.081 E 8	1.325 E 6	3.094 E 8
0.10	4.984 E 8	2.505 E 8	7.306 E 5	2.512 E 8
0.20	2.446 E 8	1.674 E 8	4.002 E 5	1.678 E 8
0.30	1.426 E 8	1.136 E 8	2.798 E 5	1.139 E 8
0.40	9.197 E 7	7.818 E 7	2.066 E 5	7.839 E 7
0.50	6.272 E 7	5.456 E 7	1.583 E 5	5.472 E 7
1.0	1.586 E 7	1.092 E 7	7.428 E 4	1.099 E 7
1.5	6.077 E 6	2.879 E 6	5.462 E 4	2.933 E 6
2.0	2.700 E 6	9.542 E 5	4.238 E 4	9.966 E 5
2.5	1.305 E 6	3.823 E 5	3.456 E 4	4.168 E 5
3.0	6.803 E 5	1.792 E 5	2.874 E 4	2.079 E 5
4.0	1.988 E 5	5.685 E 4	2.076 E 4	7.761 E 4
5.0	6.767 E 4	2.586 E 4	1.607 E 4	4.193 E 4
6.0	3.081 E 4	1.506 E 4	1.359 E 4	2.865 E 4
7.0	1.718 E 4	1.039 E 4	1.181 E 4	2.220 E 4
8.0	1.126 E 4	8.056 E 3	1.043 E 4	1.848 E 4
9.0	8.669 E 3	6.764 E 3	9.372 E 3	1.614 E 4
10.0	7.508 E 3	6.000 E 3	8.408 E 3	1.441 E 4
12.0	6.425 E 3	5.222 E 3	7.026 E 3	1.225 E 4
14.0	5.733 E 3	4.892 E 3	5.926 E 3	1.082 E 4
16.0	5.187 E 3	4.744 E 3	5.114 E 3	9.858 E 3
18.0	4.741 E 3	4.675 E 3	4.506 E 3	9.181 E 3
20.0	4.321 E 3	4.644 E 3	3.936 E 3	8.580 E 3

Contribution of protons trapped in the geomagnetic field at geostationary orbit is negligible. Total dose measured by GRD-50 during five years is 6160 rads. Dose estimation was carried out using the software DOSEMAP in the RADFET of GRD-50, considering the exact location of the RADFET in the satellite. The estimated doses from the NASA electron model and the GSAT-2 electron model developed in this paper are 18.65 Krads/5 years and 6.5 Krads/5 years, respectively. The estimated dose from GSAT-2 model is nearly equal to the measured dose 6.16 Krads/5 years. Therefore, we can conclude that the software DOSEMAP, based on the ray-tracing technique, estimates dose very accurately.

IV. Comparison of Measured Dose with Models

The measured electron doses at the center of the spherical aluminum shield are plotted in Fig. 1. AE-8 and CRRES model dose data from ESA's Space Environment Information System† (SPENVIS) are also plotted in Fig. 1. The CRRES satellite was in the geosynchronous transfer orbit at 18.2 deg inclination. The average CRRES model used data taken over the entire 14 months of the CRRES mission from July 1990 to October 1991 [2]. The NASA model AE-8

†Data available at http://www.spenvis.oma.be.

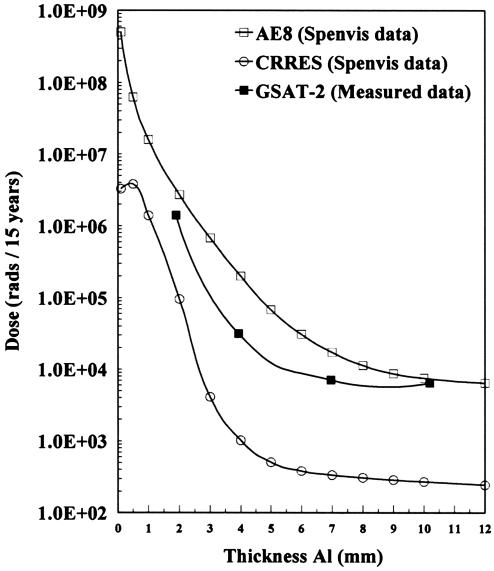

Fig. 1 Comparison of measured and model electron doses.

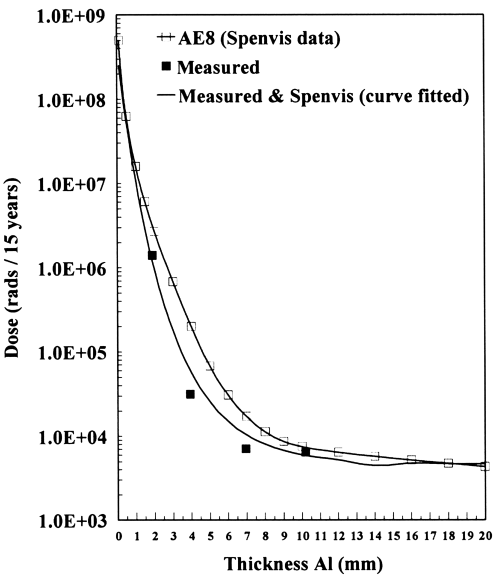

Fig. 2 Comparison of GSAT-2 and AE-8 model electron doses.

was constructed from particle measurements made from 1958 to 1970. The AE-8 model doses are a few times higher than the measured doses (Table 5). The CRRES model doses are small compared with the AE-8 model and measured doses. We can optimize the dose vs shield thickness data for geostationary orbit using the measured data on GSAT-2 and AE-8 data. The AE-8 model dose data in the thickness range of 2.0–10.0 mm in column 2 of Table 6 was replaced by the measured data and fitted to the exponential Eq. (1):

$$\log_{10}(\text{dose}) = \mathbf{a}\exp(-\mathbf{b}t) + \mathbf{c} \tag{1}$$

where $\mathbf{a} = 4.916$, $\mathbf{b} = 0.3765$, and $\mathbf{c} = 3.664$. Dose is in rads/15 years and t is shield thickness in millimeters of aluminum

The calculated doses from Eq. (1) are given in column 3 of Table 6 and plotted in Fig. 2. The error between fitted and measured data for the dosimeters GRD-10, 20, 30, and 40 are −18, +86, +42, and −15%, respectively.

V. Conclusions

The main objective of the experiment is to check the accuracy of the dose vs shield thickness data for geostationary orbit given by models. Total electron doses measured by four dosimeters on GSAT-2 are smaller than the AE-8 model doses in the shield thickness range of 1.89–10.19 mm aluminum. The CRRES model dose is much lower than the dose measured on the GSAT-2 and AE-8 model dose, hence should not be used for satellite applications. The GSAT-2 model electron dose was derived using the measured doses in the shield thickness range 1.89–10.19 mm Al and AE-8 model doses at lower and higher thicknesses. The GSAT-2 model total dose at geostationary orbit includes Jet Propulsion Laboratory (JPL) model solar flare proton dose for two solar cycles. Using the GSAT-2 model total dose for the estimation of shield thickness for electronic components in geostationary orbit satellites, shield weight can be saved considerably. The second objective of the experiment is to check the accuracy of the dose estimated by the software DOSEMAP. The estimated dose for the RADFET inside the satellite, using the GSAT-2 model dose, is nearly equal to the measured dose. Therefore, we can conclude that the software DOSEMAP, based on the ray-tracing technique, estimates dose very accurately.

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