Prediction of the Space Radiation Environment of PakSat, a Geostationary Communication Satellite

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Abstract— This paper presents the prediction of various space radiation parameters for PakSat. The measurement of the parameters includes the measurement of trapped particles, solar energetic protons and Galactic Cosmic Rays. The outcome of this paper is the radiation dose prediction that the satellite will have to encounter while in orbit. The necessary space radiation effects are pointed out and some design mitigation techniques are also proposed based upon the existing standards and flight history. The ECSS standard for Space Environment is taken as a guideline for radiation predictions.

Index Terms— Galactic Cosmic Rays, Radiation Dose-Depth Curve, SEP, SEU, Space Radiation

1 INTRODUCTION

Geostationary orbit (GEO) is a circular orbit at an altitude of 35786 km. The spacecraft placed in this orbit moves with the same speed as that of earth hence appearing stationary with respect to earth. Solar flares and solar wind have unobstructed access to this specific orbit and the solar particles emitted by the sun affect the space systems in terms of total radiation dose and Single Event Phenomena (SEP). The spacecraft orbit drives the space environment effects encountering the space system.

The space radiation environment in GEO is very dynamic; it varies spatially (longitudinally) and temporally (solar cycle and diurnal). These variations have their corresponding impacts on the satellite. Therefore, it is very important to analyze the space radiation environment of the satellite in the mission planning stage. PakSat is a geostationary communication satellite which is going to be launched in 2011 at 38^0 E longitude. In this analysis, SPENVIS (Space Environment Information System) online software is used because almost all of the radiation environment models can be simulated in SPENVIS. The predictions include the trapped radiation environment, solar energetic protons, dose-depth curve, the solar cell degradation rate and single event upsets. Simulation of the PakSat radiation environment

2 TRAPPED RADIATION ENVIRONMENT

The trapped radiation environment in GEO is mostly due to the trapped electrons which have severe effects on the spacecraft. The trapped electrons and protons are estimated for PakSat. Electron environment is simulated with IGE 2006 Average Model (S. BOURDARIE, et al. 2008) and proton environment is simulated with AP-8 MIN (Sawyer and Vette, 1976) and AP-8 MAX model (Sawyer and Vette, 1976). AP-8 model uses GSFC 12/66 120 Term updated to 1970 model (Cain et al. 1967) for internal magnetic field. AP-8MIN model (Sawyer and Vette, 1976) results are shown in Figure 1 and AP-8MAX model (Sawyer and Vette, 1976) results are shown in Figure 2. The Proton particles graphs show that at geostationary orbit altitude, there are no energetic protons present. The maximum energy of the protons is 1.5 MeV and total protons of this energy are 8 for the whole 15 years period. This ratio of the protons is not sufficient to cause a severe effect on a satellite.

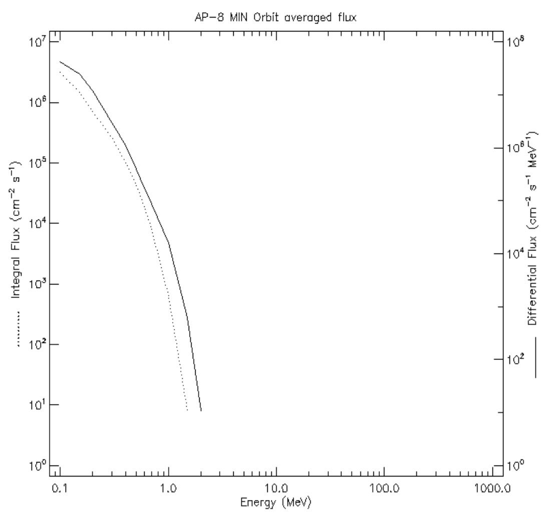

Figure 1 - Energy spectra of trapped protons for PakSat using AP-8 MIN model

The electron spectra graph in Figure 3 shows the energies of the electrons in trapped radiation belts along with their fluence level. This plot is obtained by using IGE-2006 (S.Bourdarie, et al. 2008) average flux model which has its maximum energy limit of 5.2 MeV. But the graph shows that the maximum energy level of the trapped electrons at 38^0 E longitude is 3.97 MeV and there are 1117 electrons having this energy in 15 years of mission duration. It shows that the electron environment at this altitude is very severe and can cause spacecraft internal charging due to the higher penetrating power of the electrons. So the necessary internal charging mitigation techniques will have to be applied in the PakSat design. On the basis of the electron spectra shown in Figure 3, a radiation budget is calculated which gives the estimations of the protective shielding to be applied for PakSat.

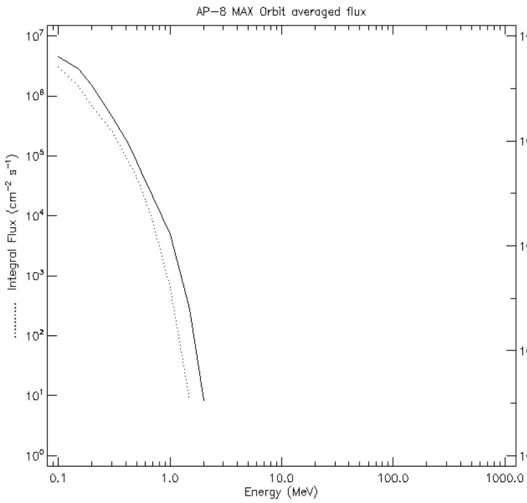

Figure 2 - Energy spectra of trapped protons for PakSat using AP-8 MAX model

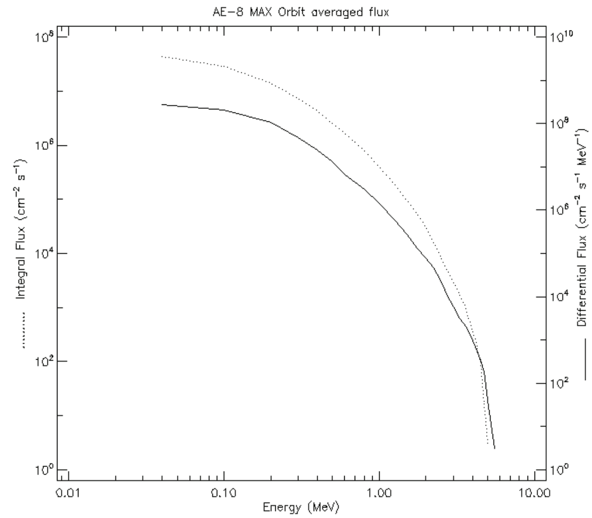

Figure 4 - Trapped electron spectra by using AE-8MAX model simulated for PakSat

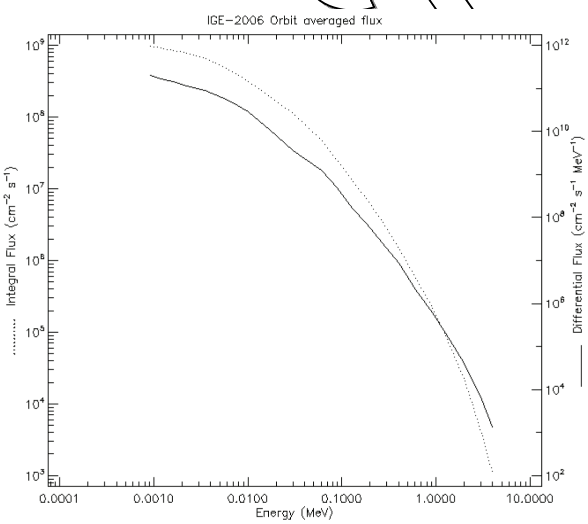

Figure 3 - The trapped electron spectra for PakSat with IGE-2006 model

On the basis of the electron spectra shown in Figure 3, a radiation budget is calculated which gives the estimations of the protective shielding to be applied for PakSat.

The AE-8 Max (Vette, 1991) model, shown in Figure 4 predicts some electrons with the energies higher than shown by IGE-2006 (S. Bourdarie, et al. 2008) average flux model. The electrons with lower energy are important for solar cell degradations and to some extent surface accumulation leading to surface charging and discharging phenomenon.

In Figure 4, the AE-8 Max (Vette, 1991) model plot shows that there are some electrons present at 38^0 E longitude with energies higher than calculated by IGE-2006 (S.Bourdarie, et al. 2008).

2.1 Simulation of Solar Energetic Protons

The SPENVIS software predicts that PakSat will spend 11 years in solar maximum and only 4 years in solar minimum. So, it will have to counter very severe and dynamic conditions of the solar flare protons. The solar flare proton environment is simulated by using ESP total fluence model (Xapsos, 1999, 2000) with 90 % confidence level and Størmer formula for quiet magnetosphere applied. The results are shown in Table 1 and the graph is shown in Figure 5.

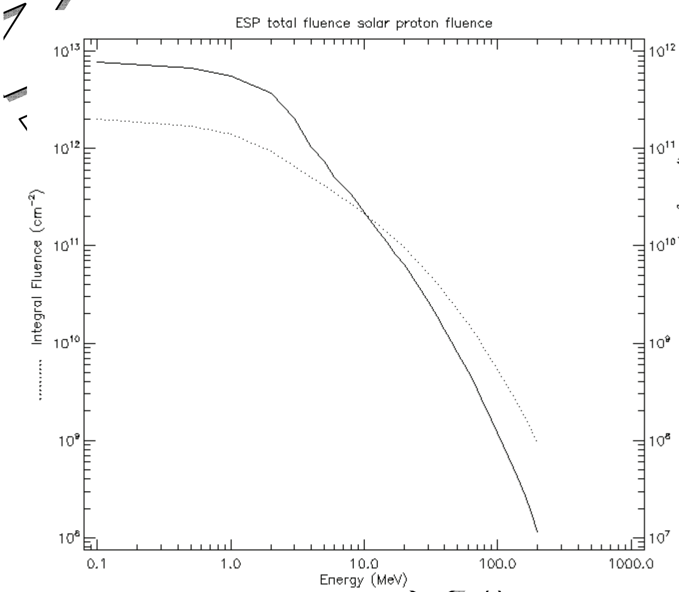

Figure 5 - Solar Proton spectra predicted for PakSat

The graph in Figure 5 is showing the expected solar protons incident on spacecraft; with logarithmic energy scale. For PakSat, the minimum energy of protons calculated is 0.10 MeV with 2.0 x 10^{12} (cm^{-2}) integral fluxes. These protons are important for solar cells degradation effect. But the actual matter of concern is the higher energy protons reaching upto 200 MeV.

Table 1 - Solar Energetic Protons Predicted for PakSat Mission

	Fluence at Spacecraft	
	Total Mission Fluence	
Energy (MeV)	Integral (cm^{-2})	Differential (cm^{-2} MeV^{-1})
0.1	2.00E+12	7.70E+11
0.5	1.70E+12	6.70E+11
1	1.40E+12	5.50E+11
2	9.50E+11	3.70E+11
3	6.60E+11	2.10E+11
4	5.00E+11	1.00E+11
5	4.20E+11	7.40E+10
6	3.50E+11	5.10E+10
8	2.70E+11	3.40E+10
10	2.10E+11	2.20E+10
12	1.80E+11	1.60E+10
15	1.40E+11	1.10E+10
17	1.20E+11	8.20E+09
20	9.50E+10	6.40E+09
25	6.90E+10	4.00E+09
30	5.30E+10	2.70E+09
35	4.10E+10	1.90E+09
40	3.30E+10	1.40E+09
45	2.70E+10	1.00E+09
50	2.20E+10	8.00E+08
60	1.60E+10	5.10E+08
70	1.20E+10	3.40E+08
80	8.70E+09	2.30E+08
90	6.80E+09	1.60E+08
100	5.40E+09	1.20E+08
120	3.50E+09	6.80E+07
140	2.40E+09	4.20E+07
160	1.70E+09	2.70E+07
180	1.30E+09	1.80E+07
200	9.60E+08	1.10E+07

These protons can cause Single Event Effects (SEE) such as Single Event Upset (SEU), Single Event Gate Rupture (SEGR) and Single Event Burnout (SEB).To avoid these effects, the necessary SEU mitigation like Hamming code should be applied and Rad-Hard components should be used in sensitive subsystems.

2.2 Dose-Thickness Curve

Dose-Thickness curve is important for the estimation of shielding level required to counter the particle dose in orbit. To a first approximation, the spacecraft is considered a spherical aluminium ball with the electronic part in the centre. Then Dose-Thickness curve is derived for the mission.

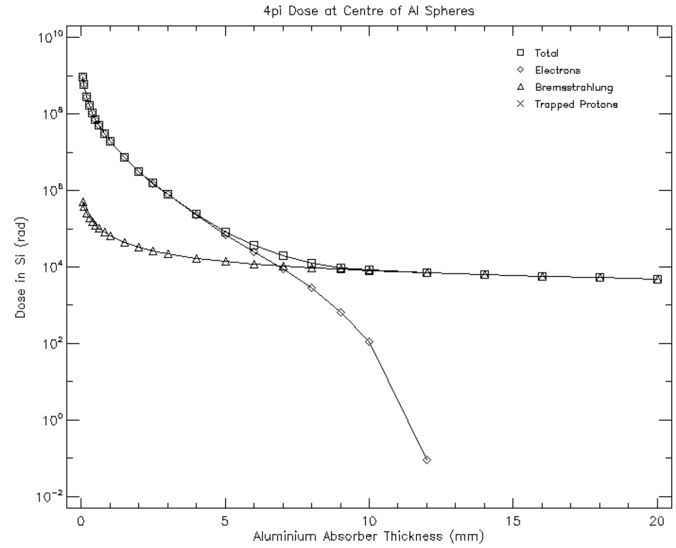

Figure 6 - Dose Vs thickness curve for Aluminium material over 15 years of satellite mission life time.

SPENVIS calculates the Dose-thickness curve for different materials. In this paper, the dose-thickness graph is simulated with SHIELDOSE model (SPENVIS help) and shield configuration is taken at the centre of Al sphere. The target material taken is Si. The plot is shown in Figure 6. Figure 6 is showing the dose (in rad (Si)) deposited by electrons, protons and Bremsstrahlung (secondary radiation) to the Al absorber. The trapped protons are very low in number, so negligible. At 7 mm thickness level, the dose deposited by electrons meets the line of dose of Bremsstrahlung particles, but after that increasing the dose does not contribute against Bremsstrahlung particles. But 7 mm thickness can not be applied on the spacecraft due to mass/volume and cost concerns. For even higher thickness, the dose-depth curve continues to flatten for Bremsstrahlung particles. Therefore, it becomes less effective (in weight) to add shielding to reduce dose to electronics if much shielding is already present. The Rad. hard components may be used with lower shielding. The dose levels at specific levels of Al thickness are shown in table 2.

Table 2 - Al Thickness Vs Dose levels

Al Thickness	Dose (rad (Si))
1 mm	1.89×10^7
2 mm	3.17×10^6
3 mm	8.19×10^5
4 mm	2.41×10^5
5 mm	8.21×10^4
6 mm	42.0×10^3

The graph shows that 6 mm Al-thickness is enough to counter the effects of trapped electrons (42 krad (Si)). But 6 mm thickness is too much to be applied due to mass/volume and cost concerns.
The results conclude that Bremsstrahlung radiation effect is very severe and this increases largely when the thickness is increased from 4 mm. The Bremsstrahlung radiation are more severe than the electrons especially after 7 mm but at this level and after that, the shielding can not prevent the material from the Bremsstrahlung particles. The thickness greater than 3.5 mm is not generally preferred for the spacecraft design.

2.3 Prediction of the displacement damage effects

It is very important to predict the displacement effects in solar cells due to the radiation environment. The total mission environment effects on the silicon and gallium arsenide solar cells by the effective 1 MeV electron flux are predicted and shown in the table 3 for Silicon and in table 4 for GaAs solar cells.

Table 3 - Coverglass thickness for Silicon solar cell

Silica cover glass (g/cm2)	Silicon		
	PMAX	VOC	ISC
0.0335	3.09E+14	3.09E+14	3.09E+14
0.0671	2.05E+14	2.05E+14	2.05E+14
0.112	1.33E+14	1.33E+14	1.33E+14

The values stated in the table are used to evaluate how the two types of solar cells perform under a specified radiation environment and then these values are coupled with the radiation test data (typically supplied by the manufacturer) for predicting the electrical performance of solar cells at mission end.

Table 4 - Coverglass thickness for Gallium Arsenide solar cell

Silica cover glass (g/cm2)	Gallium Arsenide		
	PMAX	VOC	ISC
0.0335	3.10E+14	3.10E+14	3.10E+14
0.0671	2.06E+14	2.06E+14	2.06E+14
0.112	1.33E+14	1.33E+14	1.33E+14

2.4 SEU prediction

For SEU predictions, the PakSat environment is simulated with ISO 15390 model with 3 mm of Al shielding for Fairchild 93L422s device, the bendel parameters for this device are provided in SPENVIS (Tylka, 1996). The parameters of 93L422s are set as under and the results are shown in Table 5;

Direct Ionization effects:

Device Dimensions (micron): 38.70 by 38.70 by 2.00
Critical charge: 1.13 E -02 pC

Proton nuclear interaction effects:

Bendel function parameters:
Proton Upset parameter/ threshold parameter, A= 4.88 MeV
Saturation cross section or Limiting Cross section, $Sigma_{lim}$=1.87E-10 cm^2/bit

The table 5 shows the SEU produced in the device caused by both the effects i.e. direct ionization and Proton nuclear interactions. The protons directly interacting with spacecraft systems cause direct ionization SEUs through LET (SPENVIS help). A very few devices onboard spacecraft are affected by direct ionization. The nuclear reactions occurring inside the shielding material produce recoil particles with LET high enough to cause SEUs.

Table 5 - SEU Rates Calculated for PakSat

Effect	bit-1	bit-1s-1	bit-1day-1
Direct ionization	2.50E+01	5.29E-08	4.57E-03
Proton nuclear interactions	3.58E-01	7.58E-10	6.55E-05
Total	2.54E+01	5.37E-08	4.64E-03

The SEUs produced due to the ionization effects are greater than the SEU produced due to Proton nuclear interactions (SPENVIS help). The location and number of the SEU is found out with this method and then relative shielding level or SEU mitigation technique is applied to counter these effects.
To have a more understanding about the SEU rates in devices, the PakSat radiation environment is simulated and SEU rates are calculated for more devices on the basis of bendel function parameter. The thickness of Al is kept as 3 mm. The reference data of these devices is taken from W.J. Stapor et al. 1990. The table 6 gives the summary of the calculated SEU rates produced due to proton nuclear interactions of every device under consideration.
In this analysis,

$$\text{Limiting cross section} = (24/A)^{14} \times 10^{-12}$$

And the Al thickness is 3 mm.

The table 6 presents the SEU rates for different devices. The CMOS/SOS 16KRAM can be the best choice because it is less vulnerable to the Single Event Effects as compared to the other technology. This is why CMOS/SOS devices are preferred for space missions. But generally speaking, the COTS devices are not preferable for a geostationary satellite with 15 years of life time. Even, the shielding applied for these devices can not do much for protecting the devices from SEUs because the shielding produces secondary particles that are very disastrous for the spacecraft.

Table 6 - SEU rates of various devices

Device	A(MeV)	($sigma_{lim}$ (cm^2/bit)	SEU(bit-1day-1)
4044	25.97	3.31×10^{-13}	1.08×10^{-7}
MM 5280	21.16	5.83×10^{-12}	1.92×10^{-6}
C2107B	18.27	4.56×10^{-11}	1.52×10^{-5}
MK4116J-2	23.21	1.60×10^{-12}	5.21×10^{-7}

8X350	14.85	8.29×10^{-10}	2.79×10^{-4}
93422	18.20	4.81×10^{-11}	1.60×10^{-5}
7164NMOS SRAM	29.85	4.72×10^{-14}	1.52×10^{-8}
CMOS/SOS 16KRAM	37	2.33×10^{-15}	7.4×10^{-10}

3 CONCLUSION

The radiation environment predicted for PakSat reveals that 15-years space mission in GEO is a crucial challenge to build for the spacecraft designers. Increasing the spacecraft shielding level does not contribute much against the GCR heavy ions.

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