Radiation Dose Analysis of Galactic Cosmic Ray in Low Earth Orbit/Near Equatorial Orbit

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Abstract. Space environment contained harmful radiation that posed risk to spacecraft orbiting the Earth. In this paper, we looked into radiation doses caused by galactic cosmic ray (GCR) towards satellites orbiting in low earth orbit (LEO) near Earth’s equator (NEqO) and compared them with doses caused by solar energetic particles (SEP) and trapped particles to determine the damage level of GCR. The radiation doses included linear energy transfer (LET) and non-ionizing energy loss (NIEL) through a 1mm gallium arsenide (GaAs) planar geometry by using Space Environment Information System (SPENVIS) method. The orbital data followed Malaysian Razaksat satellite at 685km altitude and 9° inclination during selected solar minimum and solar maximum from solar cycles 21 to 24. We found that trapped particles gave the highest LET and no SEP was detected in SPENVIS. The LET values tend to be higher during solar minimum for trapped particles and GCR, corresponding to their anti-correlated fluxes with the solar activity. However, the NIEL values for GCR in solar cycle 23 did not follow the anti-correlation pattern.

1. Introduction
Many spacecraft located in low earth orbit (LEO) have lower radiation risks but there is still no guarantee that they are safe from space hazards when space conditions can be unpredictable. At altitudes starting from LEO and beyond, the highly energized space particles could affect microelectronics and photonics as a result from secondary productions [1].

Based on our previous study on spatial analysis of galactic cosmic ray (GCR) [2], we discovered that orbit located at low earth near the equator (LEO/NEqO) is dominated by high energy GCR of more than 1 GeV while trapped particles dominated the lower energy range with protons less than 400 MeV and electrons less than 1 MeV, at the same time, no solar energetic particles (SEP) was found. With the exception of SEP, it is without a doubt that GCR and trapped particles played a significant role in LEO/NEqO orbit. Therefore, in this study, we decided to look into the effects of these highly charged particles by considering ionizing and non-ionizing radiation doses caused. The doses included linear energy transfer (LET) and non-ionizing energy loss (NIEL) towards gallium arsenide (GaAs) material which is one of the materials that made up the Malaysian Razaksat satellite to determine its displacement damage. This is an important aspect because atomic displacement reduced efficiency in solar cells, degrading resolution in solid-state detectors and demeaning charge transfer in charge coupled devices, all of which are crucial in a satellite [3].
LET is the energy loss by an ionizing particle over its path length within a sensitive volume and is a quantity to best define heavier nuclei and mono-energetic ions such as proton [4]. Considering that single event upset (SEU) is an effect from direct ionization of charged particles, thus LET becomes a suitable parameter for this study.

NIEL, on the other hand, is the energy a particle conveys to a solid via mechanisms other than ionization and is the cause of atomic displacement. It accounts for Coulomb interactions as well as nuclear elastic and non-elastic reactions. Furthermore, this metric is important when SEU is produced through nuclear reactions in which by then LET metric becomes invalid [5].

2. Methodology

The tool used was Space Environment Information System (SPENVIS) as it incorporated many models to describe the space environment and its effects towards various materials [6]. To use this tool, users have to first generate orbit. Malaysian Razaksat satellite orbital data is used to represent LEO/NEqO orbit with its 685km altitude and 9° inclination. The overview of the methodology is simplified in Figure 1.

We used ISO 15390 model to obtain GCR energies and fluxes because it considers the particles with respect to variations in the solar activity and the sun’s magnetic field throughout 22-year cycles by accounting the latest solar minimum data which is May 1996 [7]. JPL model is chosen to collect SEP data based on its data set that was taken only during 7 active years of the solar cycles by assuming that no significant proton fluences occur during the quiet period [8]. Meanwhile, models selected for trapped particles were AP8 for proton and AE8 for electron due to the fact that they cover a wide range of energies for the whole region of the Earth’s radiation belt [9].

Once the orbit was generated, the data on the energetic charged particles were selected to an average of 30 days during solar minimum and solar maximum for solar cycle 21 until part of solar cycle 24 under a quiet magnetosphere. The period chosen for solar minimum and maximum for each of the solar cycle is tabulated in Table 1. The fluences obtained were then simulated into Geant4 Radiation Analysis for Space (GRAS) tool for the calculations of LET and NIEL. The geometry in this tool was set as 1mm GaAs planar.

Figure 1. Block diagram of procedures to generate radiation dose calculations in SPENVIS using 30 days average data during selected solar minimum and solar maximum from solar cycle 21 to solar cycle 24
Table 1. Period data taken to represent solar minimum and solar maximum for four recent solar cycles

| Solar Cycle | Solar Minimum       | Solar Maximum       |
|-------------|---------------------|---------------------|
| 21          | August 1986         | December 1979       |
| 22          | May 1996            | June 1989           |
| 23          | March 2007          | April 2000          |
| 24          | January 2008        | December 2013       |

3. Results and Discussion

Comparison between GCR with SEP and trapped particles are presented in terms of LET and NIEL values through a simple 1mm GaAs planar geometry. The results for LET and NIEL for four recent solar cycles are shown in Table 2 and 3 respectively.

As shown in Figure 2, LET for trapped protons were considerably higher than GCR for both solar minimum and solar maximum in all the four solar cycles. This was no surprise as trapped particles populated the Earth’s radiation belt below 20,000 km altitude so the resulting LET for trapped protons in this study were twice higher than trapped electrons. Moreover, in the Earth’s radiation belt, there is a phenomenon where it would be the closest to the surface, called South Atlantic Anomaly (SAA) in a region off the coast of Brazil. The flux of trapped protons is the highest here and this could contribute to their greater LET value.

The difference between solar activities can be seen in the figure whereby it made a significant influence towards the LET value for trapped protons. Their LET is greater during solar minimum when solar wind had the most intense speed. The population of trapped protons is believed to be resulted from Cosmic Ray Albedo Neutron Decay (CRAND) which is the product of cosmic ray interacting with the Earth’s atmosphere [10]. Hence, they followed the GCR fluxes that are anti-correlated with the solar activity. Meanwhile, the solar activity had not much effect in the case of GCR and trapped electrons.

However, it did have an impact towards the NIEL values for GCR as shown in Figure 3. Their values were higher during solar minimum for most of the solar cycles except for solar cycle 23 that showed an entirely different result. It deviated from the rest by having a higher NIEL during solar maximum. Ordinarily, GCR fluxes, which contribute to the value level of LET and NIEL, are at the greatest amount during low solar activity due to less attenuation from the solar wind [1]. Therefore, one would expect the radiation doses to also be higher during solar minimum. However, their values in solar cycle 23 showed otherwise.

While we initially assumed that there might a technical error behind this but by looking into other monthly period of the same solar maximum within solar cycle 23, we found that most of the months also showed significant higher NIEL values than the one derived during solar minimum which was taken on March 2007 (refer Figure 4). An interesting aspect to solar cycle 23 is that its maximum period had double peaks, declining from the first peak before rising again into a second peak and later on progressing into solar minimum (http://nextgrandminimum.wordpress.com/2013/02/23/a-graphical-comparison-of-solar-cycles-21-22-23-and-24-2). Based on Figure 5, the intensity of GCR in solar cycle 23 remained to be low at high solar activity and increased at low solar activity. The pattern is the same for the other three solar cycles. Hence, the GCR flux was not the main factor behind the anomaly in its NIEL values here but from some other unforeseen parameters.

Although the LET of GCR is the lowest, however, in terms of NIEL, GCR gave the same level of damage as trapped protons do. This could be said that despite its low population within LEO/NEqO orbit, GCR also had the tendency to cause damage through non-ionizing mechanisms. The NIEL values for trapped electrons, however, were too low, by the factor of 200 lower in comparison with NIEL values of GCR and trapped protons and thus, are relatively insignificant. At the same time, no LET and NIEL values produced by SEP, suggesting that there were no SEP fluxes detected within the Razaksat altitude. This could mean that the particles were effectively shielded by the Earth’s magnetosphere, particularly at the equatorial region so that none reached the low altitudes.
Table 2. LET by three radiation sources through GaAs planar geometry at 685km altitude following Razaksat orbital data during solar cycle 21 until December 2013 of solar cycle 24

| Radiation Sources | LET (MeV/cm) in 1mm GaAs planar | Solar Minimum | Solar Maximum |
|-------------------|---------------------------------|---------------|---------------|
| **Solar Cycle 21** |                                |               |               |
| GCR               | 8.445 ± 0.778                   | 8.479 ± 0.783 |               |
| SPE               | 0                               | 0             |               |
| Trapped Proton    | 35.770 ± 21.860                 | 27.810 ± 18.140 |               |
| Trapped Electron  | 10.840 ± 3.821                  | 10.030 ± 3.432 |               |
| **Solar Cycle 22** |                                |               |               |
| GCR               | 8.552 ± 1.315                   | 8.470 ± 0.773 |               |
| SPE               | 0                               | 0             |               |
| Trapped Proton    | 36.090 ± 23.110                 | 27.260 ± 16.030 |               |
| Trapped Electron  | 10.840 ± 3.821                  | 10.030 ± 3.432 |               |
| **Solar Cycle 23** |                                |               |               |
| GCR               | 8.528 ± 1.056                   | 8.408 ± 0.237 |               |
| SPE               | 0                               | 0             |               |
| Trapped Proton    | 36.890 ± 23.050                 | 29.470 ± 19.480 |               |
| Trapped Electron  | 10.840 ± 3.821                  | 10.030 ± 3.431 |               |
| **Solar Cycle 24** |                                |               |               |
| GCR               | 8.469 ± 0.817                   | 8.384 ± 0.250 |               |
| SPE               | 0                               | 0             |               |
| Trapped Proton    | 39.050 ± 21.430                 | 26.900 ± 18.010 |               |
| Trapped Electron  | 10.840 ± 3.821                  | 10.030 ± 3.432 |               |

Table 3. NIEL by three radiation sources through GaAs planar geometry at 685km altitude following Razaksat orbital data during solar cycle 21 until December 2013 of solar cycle 24

| Radiation Sources | NIEL (MeVcm²/g) in 1mm GaAs planar | Solar Minimum | Solar Maximum |
|-------------------|-----------------------------------|---------------|---------------|
| **Solar Cycle 21** |                                   |               |               |
| GCR               | 12.170 x 10⁻³ ± 47.460 x 10⁻³    | 7.256 x 10⁻³ ± 6.805 x 10⁻³ |               |
| SPE               | 0                                 | 0             |               |
| Trapped Proton    | 6.926 x 10⁻³ ± 4.051 x 10⁻³       | 6.594 x 10⁻³ ± 4.974 x 10⁻³ |               |
| Trapped Electron  | 3.012 x 10⁻⁵ ± 3.466 x 10⁻⁵       | 1.195 x 10⁻⁵ ± 1.197 x 10⁻⁵ |               |
| **Solar Cycle 22** |                                   |               |               |
| GCR               | 7.652 x 10⁻³ ± 11.430 x 10⁻³     | 7.065 x 10⁻³ ± 9.581 x 10⁻³ |               |
| SPE               | 0                                 | 0             |               |
| Trapped Proton    | 5.890 x 10⁻³ ± 2.516 x 10⁻³      | 6.208 x 10⁻³ ± 3.601 x 10⁻³ |               |
| Trapped Electron  | 3.012 x 10⁻⁵ ± 3.466 x 10⁻⁵       | 1.195 x 10⁻⁵ ± 1.197 x 10⁻⁵ |               |
| **Solar Cycle 23** |                                   |               |               |
| GCR               | 8.090 x 10⁻³ ± 11.500 x 10⁻³     | 11.270 x 10⁻³ ± 36.630 x 10⁻³ |               |
| SPE               | 0                                 | 0             |               |
| Trapped Proton    | 8.148 x 10⁻³ ± 7.142 x 10⁻³      | 6.527 x 10⁻³ ± 3.552 x 10⁻³ |               |
| Trapped Electron  | 3.012 x 10⁻⁵ ± 3.466 x 10⁻⁵       | 1.195 x 10⁻⁵ ± 1.197 x 10⁻⁵ |               |
| **Solar Cycle 24** |                                   |               |               |
| GCR               | 9.369 x 10⁻³ ± 22.830 x 10⁻³     | 9.151 x 10⁻³ ± 24.980 x 10⁻³ |               |
| SPE               | 0                                 | 0             |               |
| Trapped Proton    | 7.271 x 10⁻³ ± 5.498 x 10⁻³      | 7.506 x 10⁻³ ± 8.540 x 10⁻³ |               |
| Trapped Electron  | 3.012 x 10⁻⁵ ± 3.466 x 10⁻⁵       | 1.195 x 10⁻⁵ ± 1.197 x 10⁻⁵ |               |
Figure 2. LET values by three radiation sources in LEO/NEqO orbit through a 1mm GaAs planar during selected solar minimum and solar maximum for solar cycle 21 until December 2013 of solar cycle 24.

Figure 3. NIEL values by three radiation sources in LEO/NEqO orbit through a 1mm GaAs planar during selected solar minimum and solar maximum for solar cycle 21 until December 2013 of solar cycle 24.

Figure 4. NIEL values by GCR during double peaks solar maximum in solar cycle 23 where most are above the NIEL value of solar minimum March 2007.
4. Conclusion and Future Work
Trapped protons gave the highest LET during solar minimum, followed by GCR and trapped electrons. The LET of trapped protons was two times higher than trapped electrons due to its dominant population in the inner radiation belt and also in SAA. GCR gave the same level of displacement damage towards GaAs as trapped protons based on their NIEL values. The NIEL value of GCR was unusually high during solar maximum in solar cycle 23 indicating abnormality for non-ionizing mechanisms occurring only during solar cycle 23 at its maximum period while the other three solar cycles showed similar pattern. We also identified that flux was not the main cause behind the deviated value but from other unforeseen parameters. The NIEL values for trapped electrons were relatively insignificant by a factor of 200 with that of trapped protons. At 685km altitude and 9° inclination, no SEP was detected to give LET and NIEL values due to the effective shielding of the Earth’s magnetic field.

The abnormality of non-ionizing mechanisms by GCR during high solar activity in the 23rd cycle required further study by considering the application of other models such as CRÈME96 and to do comparison between the models so the factor behind the abnormality can be determined. Also, it would be interesting to look at the same mechanism in other materials such as silicon carbon (SiC) and indium phosphorus (InP) so more information regarding the abnormality and the effects of the space energetic particles can be acquired.

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