Analysis distribution of galactic cosmic rays particle energy with polar orbit satellite for Geant4 application

W Suparta1,* and W S Putro1

1Institute of Space Science (ANGKASA), Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia.

Email: wayan@ukm.my

Abstract. Galactic Cosmic Rays (GCR) are photon waves originating from astrophysical sources which traverse through the interstellar/interplanetary medium and reaching the terrestrial atmosphere. The energies of Galactic Cosmic Ray particles up to and exceeding 10^{12} eV, and this spectrum are peaked around 1 GeV. The National Aeronautics and Space Administration (NASA) provide satellite mission for monitoring the energy GCR particles in polar orbit, so-called the ACE and OMNI. In this paper, we analyze results from measurement error of GCR sensor. The error result is obtained by comparing the measurements from GCR sensor with ground-based neutron monitors at Bartol University. The measurements were taken for two periods during a Solar Particle Event (SPE) maximum on 14 July 2000 and 28 October 2003. The largest value of measurement error from GCR sensor in this study is OMNI satellites. After the error results were obtained, they were applied into Geant4 simulation. This simulation shows the shape of particle energy distribution of GCR sensors. The simulation has been tested and can be operated very well under Linux based platform.

Keywords: Galactic Cosmic Rays, Measurement error, Geant4, Polar orbit, Simulation

1. Introduction

The radiation of space radiation environment is composed different particles (neutron, electron, protons and heavier charged particle), with large energy range up to 10^{20} eV. Among the crucial components are ionizing charged particles, i.e. the particle trapped in the radiation belts, the solar particle event (SPE) and galactic cosmic ray (GCR) radiation [1]. GCRs are high energy charged particle that originated from the outside of solar system, which strongly causes Single Event Effect (SEE) in microelectronics and photonics [2]. The phenomena of GCR radiation will be peaked at SPE activity. GCRs dominated the effect in terms of linear energy transfer (LET) in satellite application. These effects on spacecraft system and instruments near Earth orbit are difficult quantified due to highly energetic particles in the heavy ion component compared to polar orbiting satellites [3].

Boscherini et al [4] discussed more details about the radiation damage of electronic in space, and Tajima [5] also discussed a detector for cosmic rays measurement on ground and in space, whereas in his study emphasizes error result of GCR sensor on satellite based by comparing this sensor with detector from ground-based. Our work progress is to analyze the energetic particles for developing a GCR sensor for equatorial inclination satellite that later can be operated in Low-Earth Orbit (LEO).

In this paper, we started first to study the distribution of galactic cosmic rays particle energy during a SPE maximum occurred on 14 July 2000 and 28 October 2003. This study is very important because satellite is a complex device with electronic components. If the satellite is attached by maximum radiation then the electronic component would be damage by LET from space, then the sensor accuracy will be affected seriously. In line with above purpose, Geant4 (GEometry ANd Tracking) is proposed to simulate the passage of particle through matter.
2. Methodology

2.1 Data Collection

Data used in this study were taken from ACE and OMNI satellites that can be accessed through http://cdaweb.gsfc.nasa.gov/cgi-bin/eval2.cgi, and ground-based neutron monitors at Bartol University is downloaded from http://neutronm.bartol.udel.edu/~pyler/bri_table.html. ACE satellite is placed at an altitude of 1.5 million km with an inclination of (i~29°). ACE satellite equipped with a sensor called CRIS (Cosmic Ray Isotope Spectrometer) recorded isotopes of galactic cosmic ray nuclei from He to Zn over the energy range from ~100 to 600 MeV/nucleon [6]. For OMNI satellite, it is placed at an altitude of 600 km with an inclination of (i~90°) equipped with Energy Proton Fluxes and Electron Detector sensor [6]. ACE and OMNI satellites record data every 1 hour, and recording of ground-based neutron monitors is also similar interval, which is every 1 hour. In this study, we are comparing the distribution of GCR’s particle for 2 periods (14 July 2000 and 28 October 2003) from satellites and ground-based neutron monitors (see Table 1).

Table 1. Ground-based neutron monitors data from Bartol University at four selected stations

| Date   | McMurdo Corr | McMurdo Uncorr | Newark Press | South Pole Corr | South Pole Uncorr | Thule Press |
|--------|--------------|----------------|--------------|-----------------|--------------------|-------------|
| 2000/1 | 8462         | 8029           | 735.3        | 3056            | 3033               | 760.8       |
|        |              |                |              | 8589            | 9331               | 504.8       |
|        |              |                |              | 504.8           | 3822               | 756.5       |
| 2000/2 | 8485         | 8043           | 735.4        | 3030            | 3005               | 760.9       |
|        |              |                |              | 8892            | 9358               | 504.9       |
|        |              |                |              | 3927            | 3817               | 756.9       |
| 2000/3 | 8458         | 8010           | 735.5        | 3038            | 3010               | 761.0       |
|        |              |                |              | 8894            | 9350               | 505.0       |
|        |              |                |              | 3938            | 3813               | 757.2       |

2.2 Error Analysis

Error analysis is one of the analysis techniques that used in statistic and mathematics. Nowadays, it has been widely used in every case study of measurement. Some errors can be divided into two classes: systematic and random. Systematic errors are those which tend to shift all the measurements in a systematic way, so their mean value is displaced, and random errors are those which fluctuate from one measurement to another. In this paper, we choose this method for error analysis of each sensor satellite. Some data set of repetitive measurements is often expressed as a single representative number called the mean or average. Below is the formulas that commonly used in the analysis of measurements errors, as described in detail by Hongchem [7]. The mean ($\bar{x}$) is the sum of individual measurements ($x_i$) divided by the number of measurements ($n$).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

The average deviation, $\Delta \bar{x}$ is used when a data set contains less than 5 repetitive measurements. A small value of average deviation indicates data points clustered is closely around the mean and good precision.

$$\Delta \bar{x} = \pm \sum_{i=1}^{n} \frac{|x_i - \bar{x}|}{n} \quad (\Delta \bar{x}, N \leq 4)$$

The absolute value is taken of the deviation from the mean $|x_i - \bar{x}|$ and no information is gained about the direction of the error. The relative value of average deviation is the average deviation divided by the average and then expressed as a percentage:

$$|x_i - \bar{x}| = \frac{\Delta \bar{x}}{\bar{x}} \times 100 \%$$
The estimated standard deviation ($S$) is used to express the precision of the measurements with the number of degrees of freedom ($N−1$) expressed as

$$S = \pm \sqrt{\sum_{N=1}^{(x_i-x̄)^2}(N−1)}$$

(4)

The accuracy of a result can be quantified by calculating the percentage of error. The percentage of error can only be found if the true value is known. Although the percentage error is usually written as an absolute value, it can be expressed as a negative or positive sign to indicate the direction of error from true value.

$$\% \text{ Error} = \frac{(x_T-x_E)}{x_T} \times 100 \%$$

(5)

where $x_T$ and $x_E$ are true and experimental values, respectively.

3. Results and Discussion

Figures 1 and 2 show the comparison distribution particle of GCR, simulated with Geant4 on 14 July 2000 and 28 October 2003 from ground-based neutron monitors at Bartol University for the station of McMurdo, Newark, South Pole, and Thule. As shown in the figure, the distribution of particle was most effectively influenced by SPE phenomena, where GCR’s energy can peak to around 1 GeV during the increased of SPE. GCR’s activities on 28 October 2003 is super active than those of SPE on 14 July 2000, which produce solar eruption maximum, as indicated by a sudden burst of solar particles. Based on these phenomena, our next task is to create a suitable simulation of GCR’s particles energy activity of SPE on 14 July 2000 and 28 October 2003 for ACE satellite with Geant4.

Figure 1. Flux distribution of GCR’s energy particle for SPE max on 14 July 2000

Figure 2. Flux distribution of GCR’s energy article for SPE max on 28 Oct 2003

Figures 3 and 4 show the ACE satellite passing through ground-based neutron monitors, recorded at Bartol University region on 28 October 2003. Figure 4 shows the distributions of GCR’s energy at Thule area of 287 MeV during SPE maximum on 28 October 2003 from ACE satellite that has a CRIS
sensor. Although, ACE satellite is placed at an altitude of 1.5 million km (i~29°), it has an accurate measurement of GCR’s. The sensor capable to detect distribution energy for Ni, Ne, Proton, Electron and Neutron fluxes. The error values of CRIS for Thule area are 1.39 % during SPE maximum on 28 October 2003. Table 2 and Table 3 show that OMNI satellite has bigger error compared to ACE satellite. OMNI satellites are placed at an altitude of 600 km (i~90°), which possibly limited to detect the particle distribution. The different orbit between ACE and OMNI is more than 1 million km.

Table 2. Error analysis of SPE maximum for 14 July 2000.

| Station   | ACE Satellite deviation (S) | Mean | Error (%) | OMNI Satellite deviation (S) | Mean | Error (%) |
|-----------|-----------------------------|------|-----------|-------------------------------|------|-----------|
| McMurdo   | ± 0.35                      | 16.37| 1.32%     | ± 0.41                        | 24.42| 2.29%     |
| Newark    | ± 0.28                      | 15.81| 1.23%     | ± 0.55                        | 21.53| 2.12%     |
| South Pole| ± 0.67                      | 25.43| 1.63%     | ± 0.72                        | 37.86| 2.53%     |
| Thule     | ± 0.34                      | 16.34| 1.31%     | ± 0.48                        | 24.23| 2.38%     |

Table 3. Error analysis of SPE maximum for 28 October 2003.

| Station   | ACE Satellite deviation (S) | Mean | Error (%) | OMNI Satellite deviation (S) | Mean | Error (%) |
|-----------|-----------------------------|------|-----------|-------------------------------|------|-----------|
| McMurdo   | ± 0.42                      | 32.36| 1.24%     | ± 0.56                        | 43.39| 2.38%     |
| Newark    | ± 0.36                      | 25.21| 1.36%     | ± 0.50                        | 35.32| 2.24%     |
| South Pole| ± 0.77                      | 38.48| 1.67%     | ± 0.87                        | 45.15| 2.68%     |
| Thule     | ± 0.49                      | 26.24| 1.39%     | ± 0.58                        | 36.28| 2.33%     |

Table 4 and Table 5 show ACE satellite has a good resolution of area measurement compared to OMNI satellite, which indicated that orbiting area is very important to detect radiation. ACE is a complex satellite that can detect distribution energy of GCR particle; not only Proton and Electron fluxes, but all component particles of GCR. With Geant4 simulation, we can detect that the radiation area has been affected by GCR’s. From the table, maximum radiation occurred on 14 July 2000 and 28 October 2003 is at South Pole area, which is located in highly latitude. This location is very dangerous area during SPE because the particle energy deposited by GCR’s was more than 200 MeV, and this radiation could be a cancer risk for human [9].
4. Conclusion
We have successfully to do an analysis of error measurement of GCRs particle for polar orbit satellite. A simulation of GCR’s energy particle during a SPE maximum was also performed with Geant4 software on major solar events occurred at 14 July 2000 and 28 October 2003. OMNI satellite found an error of 2.86% with energy particle is 307 MeV for South Pole station, and for 14 July 2000, the error values are 2.53% with energy particle is 298 MeV. During SPE maximum, a small area of Antarctica (South Pole and McMurdo) has high deposit energy from GCR of 280 MeV for 28 October 2003 and more than 260 MeV for 14 July 2000. The maximum area during distribution of GCR’s energy particles are 16, 17, and 50 km on 28 October 2003 for South Pole station. Then 14, 16, and 43 km for 14 July 2000, which indicated that the event on 28 October 2003 is stronger than those of 14 July 2000. The largest value of measurement error from GCR sensor in this study is OMNI satellites.

Our next study is to do a modeling of GCR radiation for a satellite application in equatorial region like Near Equatorial Orbit (NEqO). This is in order to generate a real-time fluxes radiation of GCR prediction, as a part of an early warning system development.

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Table 4. Simulation of Geant4 for radiation area of GCR’s and deposit energy on 14 July 2000

| Station   | ACE Satellite | OMNI Satellite |
|-----------|---------------|----------------|
|           | Area (X, Y, Z) | Energy (MeV)   | Area (X, Y, Z) | Energy (MeV) |
| McMurdoo  | 15, 17, 40    | 270            | 11, 12, 35    | 296          |
| Newark    | 16, 16, 42    | 258            | 10, 13, 32    | 262          |
| South Pole| 14, 16, 43    | 273            | 12, 15, 36    | 298          |
| Thule     | 15, 13, 41    | 268            | 13, 14, 34    | 277          |

Table 5. Simulation of Geant4 for radiation area of GCR’s and deposit energy on 28 October 2003

| Station   | ACE Satellite | OMNI Satellite |
|-----------|---------------|----------------|
|           | Area (X, Y, Z) | Energy (MeV)   | Area (X, Y, Z) | Energy (MeV) |
| McMurdoo  | 18, 17, 48    | 290            | 14, 13, 33    | 296          |
| Newark    | 17, 18, 44    | 271            | 13, 11, 37    | 285          |
| South Pole| 16, 17, 50    | 293            | 12, 14, 38    | 307          |
| Thule     | 15, 18, 49    | 287            | 11, 13, 36    | 291          |
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