The Variability of Space Radiation Hazards towards LEO Spacecraft

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Abstract. The variability of space radiation hazard towards the low-Earth orbit (LEO) spacecraft is reviewed. Three major space radiations, i.e. galactic cosmic rays (GCRs), solar proton events (SPEs), and trapped particles form potential hazards for LEO spacecraft. We focused on trapped particle hazard due to its major role for LEO spacecraft anomaly. We examined the trapped particle variability distribution in solar cycle 23. The year of 2000 and 2008 were chosen to best represent solar maximum and minimum in that cycle. Monthly average particles fluxes plotted in both years showed a quite similar value for all peak values during solar maximum. We also examined events of LEO satellites anomaly for both years by using space weather and geomagnetic parameters as well as the distribution of particles fluxes during those events. Analysis showed that all parameter indicators in the year 2000 were in a critical condition, whereas for the year of 2008, the anomaly occurs was in a normal state.

1. Introduction

There are three major space radiation components in the Sun-Earth environment, i.e. Galactic Cosmic Rays (GCRs), Solar Proton Events (SEPs) and trapped particles [1]. Those three radiations form potential hazards for spacecraft operation as well as a space crew [2]. GCRs are produced in the supernova remnant by diffusive shock acceleration and distributed uniformly in the whole galaxy [3]. The energy of GCRs is in the range of 10^1 to 10^{12} MeV in the interstellar space and rises up to 1 GeV in our solar system [2]. GCRs are divided into primary and secondary cosmic ray. Primary GCRs is a result of the astrophysical process, largely consist of protons, alpha particles (99%), and a small number of heavy nuclei. Secondary GCRs is the result of the decay of primary cosmic ray when it interacts with the Earth's atmosphere. Secondary GCRs is made up of neutrons, pions, positrons, and muons. The GCRs with energy below 1 GeV are influenced by the solar cycle and are attenuated while interacting with the solar wind. The flux of GCRs reaches a minimum during the solar maximum and is maximized during a solar minimum. This occurrence is related to the intensity of solar wind. Since GCRs consist of charged particles, they are also affected by the Earth magnetic field. According to the Lorentz force law, the particle that is parallel to the magnetic field line follows the line and the particle that moves perpendicular to the line will be deflected. Hence, the GCRs are funneled toward the pole and deflected at the Equator. Related to this mechanism, an LEO satellite receives great exposure of GCRs while it flies by near the pole and face minimum GCRs exposure while in the Equator.

The Sun flare and CMEs produce electrons, protons, and heavier charged particles during their lasts. Due to its abundance and high energy, proton dominates more than the other particles. Proton that is erupted during flares, and CMEs is called a solar proton event (SPE) when their energies > 30 MeV of 10^6 up to 10^7 cm^{-2}, whereas a major SPE when their energies > 10 MeV of 10^{10} cm^{-2}. SPEs occurrences are related to solar variability and usually happened during solar maximum. The frequency of ordinary SPE during a solar cycle is ~ 50 events whereas the major SPE occurs is about 1-2 events in a cycle. There are some different characteristics of SPEs produced by flares and CMEs. SPEs produced by flares usually have short life time and release large fluxes of electron. The flare's SPE also has a small fluence (10^7 to 10^8 cm^{-2}) with restricted solar longitude angle (30-45°). On the other hand, the CME's SPE has a longer life time, high fluence (10^9 cm^{-2}), and wider solar longitude angle (from 60° to 180°). Figure 1 shows the conceptual mechanism of Earth's space radiations.

As shown in the right side of Fig. 1, trapped particles are produced by a constant solar plasma stream that flows to the Earth atmosphere and which is carried by the solar wind. These particles are trapped by the Earth's atmosphere and being deposited into two layers, the inner and the outer belts, which are well known as the Van Allen radiation belts. Trapped electron presents the inner belt as well as at the outer layer. The inner belt electron populates in the area that extends to about 2.4 Earth radii and mostly dominated by electron that has less than ~5 MeV of energy. An LEO satellite has to interact with the inner belt particles especially at the South Atlantic Anomaly (SAA) region. The SAA is a region of decreased magnetic field over southern Atlantic Ocean and South America [4]. In addition, the outer electron range is about 2.8 to 12 Earth radii with energy up to ~7 MeV. On the other hand, trapped proton only presents in the inner layer of Van Allen belt with energy ranging from several keV to several hundred of MeV. The variability of both trapped particles is influenced by the solar activity. The inner belt proton is higher during a solar minimum whereas the outer belt electron is higher during a declining phase of solar activity [5].

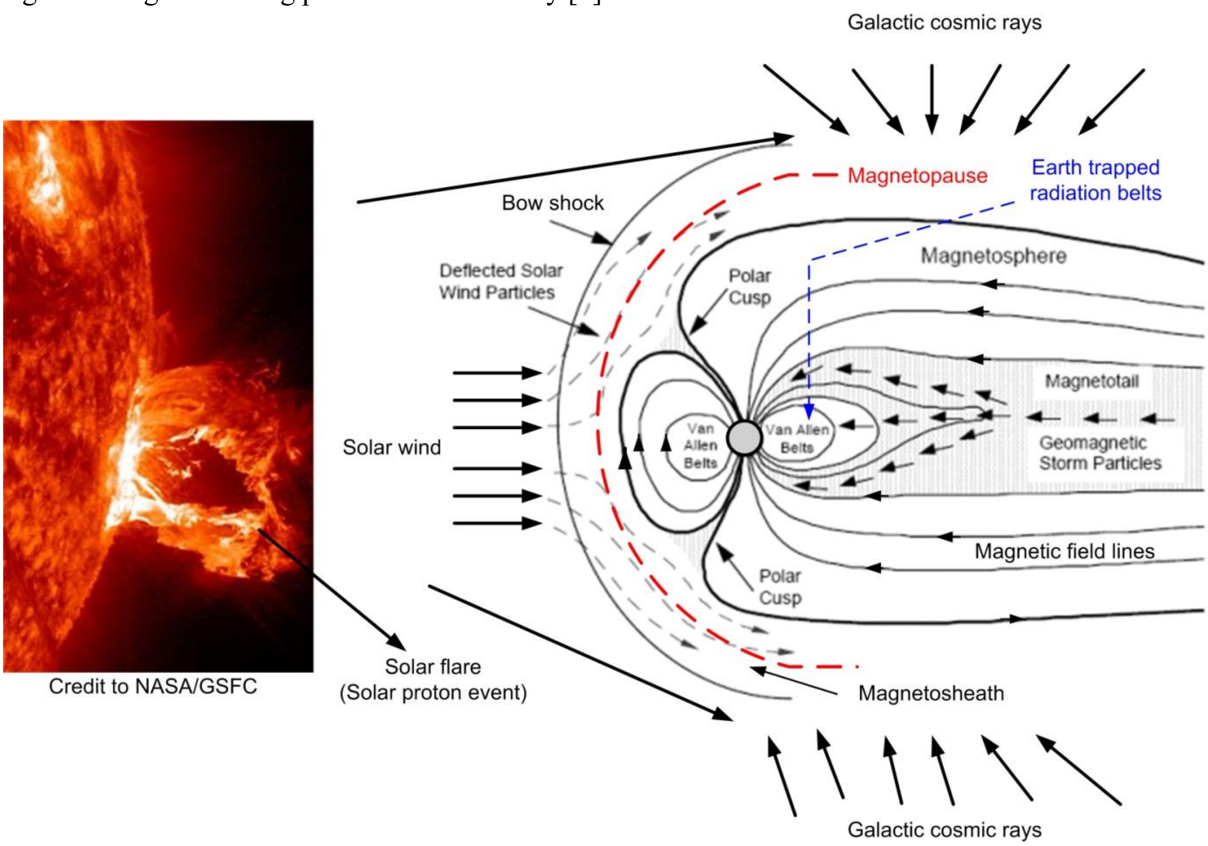

Figure 1. Space radiations conception in the Sun-Earth environment adapted from [2, 6].

The potential hazards of GCRs for the LEO spacecraft are the phenomena of single event effects (SEEs) [7]. The most dangerous component of GCRs is the abundant deposit of Fe nuclei. This heavy ion could trigger the SEEs in space electronic systems. SEEs are occurred when a charged particle is collected on spacecraft circuits such as memories, power devices, logic devices, and disrupting their operation. There are different types of SEEs such as the single even upsets (SEU), single event transients (SET), single event functional interrupts (SEFI), and multiple bit upsets (MBU). The SEU, a SEEs variant that occurred in memory, is the most known and recognized hazard from GCRs to the spacecraft. Not only trapped particles harmful to spacecraft charging, SPEs have a combination effect of GCRs and trapped particles for an LEO spacecraft. It could cause SEEs and charging effect because it triggers the particle precipitation to the Van Allen belt during solar storm. Table 1 summarizes the space radiation effects on LEO satellites [2, 8].

Table 1. The summary of space radiation hazards on LEO satellites

Radiation type	Effects on space craft	Domination in LEO
Galactic Cosmic Rays (GCRs)	Upsets in electronics, interference with sensor.	Dominate at high inclination orbit (Polar).
Solar Proton Events (SPEs)	Radiation damage in various kind, upsets in electronics, and massive interference with sensor.	More severe for high inclination orbit.
Trapped particles	Surface and interior charging, radiation damage in various kind, upsets in electronics, and considerable interference with sensor	Dominate at low inclination orbit (Equator) with high altitude.

2. Trapped Particles Distribution Variability

Considering dominant factors of trapped particles for LEO satellite anomaly summarized in Table 1, we focus our analysis on trapped particle distribution on solar activity variability. We choose solar cycle 23 as our base for analysis, and we take the year of 2000 and 2008 as the representative of solar maximum and minimum, respectively. Figure 2 presents flux variability of several electrons and protons in different energy levels, taken by National Oceanic and Atmospheric Administration (NOAA) in years mentioned. The energy levels of electron are mep0e1 (> 30 keV), mep0e2 (> 100 keV), and mep0e3 (> 300 keV). In addition, the energy levels for proton are mep0p1 (30-80 keV), mep0p2 (80-240 keV), mep0p3 (240-800 keV), mep0p4 (800-2500 keV), mep0p5 (2500-6900 keV), and mep0p6 (> 6900 keV). The NOAA 15 satellite has an altitude of 807 km with an inclination angle of 98.5°. Therefore, this satellite is measuring the flux distribution in the inner radiation belt. Details of NOAA 15 and the sensor used to measure those particles flux can be found in [9].

Figures 2a and 2b show that the fluxes of lower energy level such as mep0e1, mep0e2, and mep0p1 have higher flux values than other energy levels. It is also seen that low electron fluxes dominate the inner radiation belt, although the layer is a habitual area for trapped proton. The maximum fluxes of all particles are also quite a similar for both years. This is because the particle tends to enter the stable condition once they enter the inner layer, compared to the outer layer that is influenced directly by the sun and astrophysical processes [10].

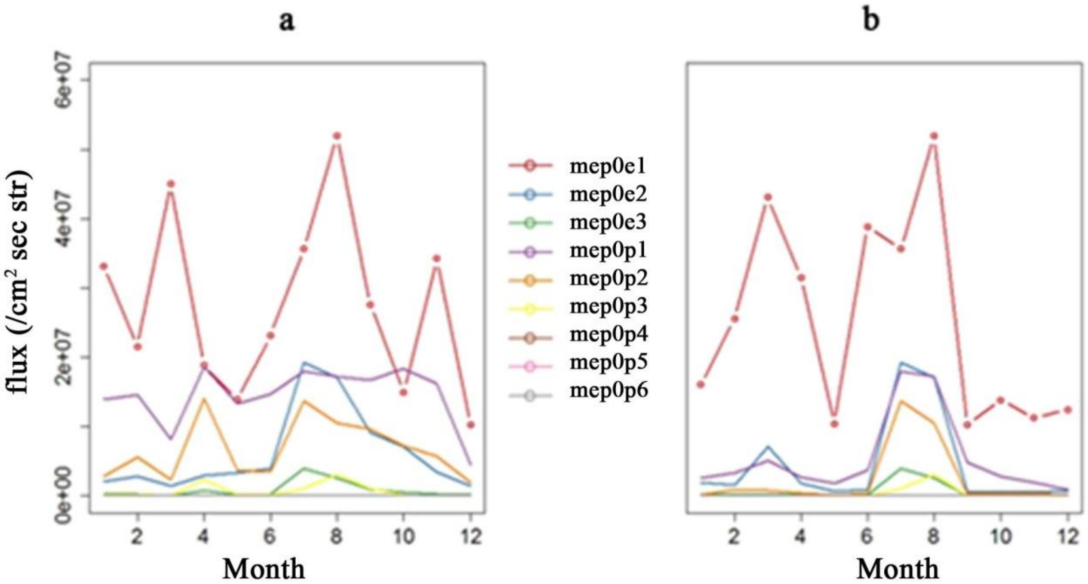

Figure 2. Trapped particles monthly average plots for the year of (a) 2000 and (b) 2008.

3. Trapped Particles and LEO Satellites anomaly

In order to examine the influence of trapped particles towards a satellite anomaly, we study the event of two satellites anomaly occurred in solar maximum and minimum phases. Two LEO satellite anomalies are chosen for this study, i.e. Astro-D and Orbcomm-1. The Astro-D, a LEO satellite with 140 km of altitude and 31° of inclination experienced an anomaly on 15 July 2000 whereas the Orbcomm-1 (altitude of 758 km and 45° of inclination) faced an anomaly on 10 November 2008 (http://sat-nd.com/failures/). We also study several space weather parameters such as solar radio wave (F10.7), solar wind flow speed (FS), and geomagnetic indexes (Ap, Dst and AE) as shown in Figs. 3a-b and 4a-b. All these parameters data can be found in http://omniweb.gsfc.nasa.gov. The particles flux distributions are also examined for those satellites anomaly event. Distribution maps from http://ngdc.noaa.gov/sem/poes/data are chosen for this purpose (as in Figs. 3c-d and 4c-d). We select date of 13-16 July 2000 for Astro-D failure and 8-11 November 2008 for the Orbcomm-1. In this study, only mep0e1 and mep0p2 distributions were selected for simplifying purpose. By this stride, we aim to study the variability distribution of trapped particles before and after the anomaly events.

From Fig. 3c-d, we find that increased radiation in the upper atmosphere occurred a few days before and after Astro-D satellite anomaly was reported. A F10.7 index reached a maximum value of about 325 sfu and accompanied by Joule heating in which the AE index reached a maximum of about 2,023 nT. Solar wind speed fluctuated during this period and reached a maximum of 1,107 km/s that allegedly caused the injection of plasma in the Earth's magnetosphere. Increased magnetic activity which triggered a large-scale extreme storm can be seen in the Dst index with minimum value of -301 nT. The magnetic storm caused changes in low orbit where the plasma electron and proton fluxes varies from 10^3 to 10^6 particles/cm^2 sec str. Magnetic storms also cause dynamic flux distribution for both electron and proton. It can be seen that along the equatorial region the particle precipitation occurred on a large scale with widespread pattern and it concentrated in the SAA area.

The date of 8-11 November 2008 was a period of the lowest solar activity in solar cycle 23 since the minimum phase in this cycle was occurred around this date. From Fig. 4, we find that solar wind speed only reaches a maximum of about 418 km/s. A F10.7 radiation index also fluctuated in an average of 67 sfu and AE index fluctuated with a maximum value of about 658 nT. There was no magnetic storm recorded during this period, although the minimum value of Dst was -29 nT. The particle dynamic was also not very significant. We also find that there was no particles precipitation toward the equatorial region.

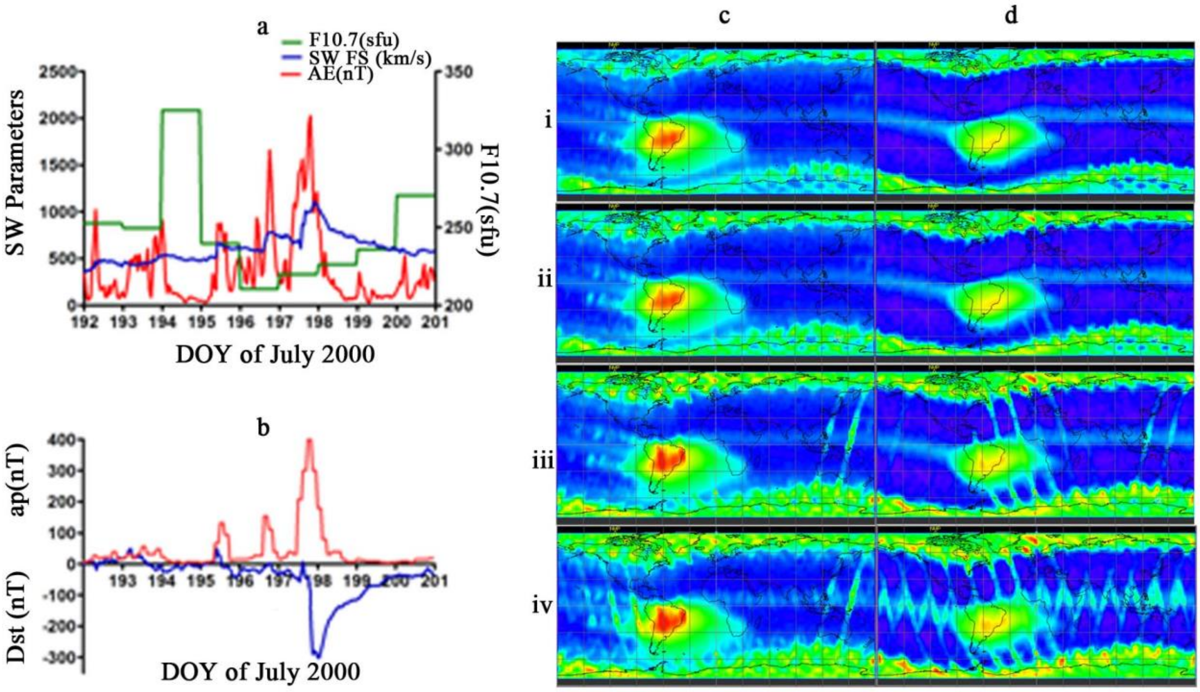

Figure 3. (a) the space weather parameters for July 2000 and (b) the geomagnetic indexes at this period, and the particle distribution for (c) mep0e1 and (d) mep0p2. The i, ii, iii, and iv are represent the mep0e1 and mep0p2 for 13, 14, 15 and 16 July 2000, respectively. The flux distribution unit in Fig. 3c-d is in particle/cm^2 sec str.

4. Summary and Future Work

From a point of view on the potential hazard of space radiation on LEO satellites, we found that three major space radiations have been identified. However, our study was focused on the trapped particle impacts because they have a major role for LEO satellite anomaly rather than other space radiation components. From Figs. 3 and 4, we found that the distributions of particles flux are quite stable at the year of solar maximum and minimum. We also examined the event of a satellite anomaly for those periods, with Astro-D and Orbcomm-1 satellites by combining the space weather and geomagnetic parameters as well as the flux distribution map of particle for analyzing those anomaly events. Our analysis found significant irregularity during the Astro-D anomaly event. This is easy to understand that when Astro-D anomaly happened, the major solar storm that accompanies with X class solar flare and halo CME was correlated with Bastille Day event on 14 July 2000. As for the incidence of Orbcomm-1 found a peculiarities factor, which must still be analyzed because the entire space weather and geomagnetic parameters as well as the distribution of particles when anomalies occur was in a normal state. We estimate that the anomaly of Orbcomm-1 is probably influenced by the length of exposure time of trapped particle in orbit. To deal with this problem in a subsequent study, we suggest calculating the radiation dose absorbed by the satellite during the mission before launch. We also intend to perform in-depth studies of all LEO satellite anomaly events by tracking the location and time of anomalies. By this step, we hope that we can provide an appropriate shielding, material, and mitigation for LEO satellites.

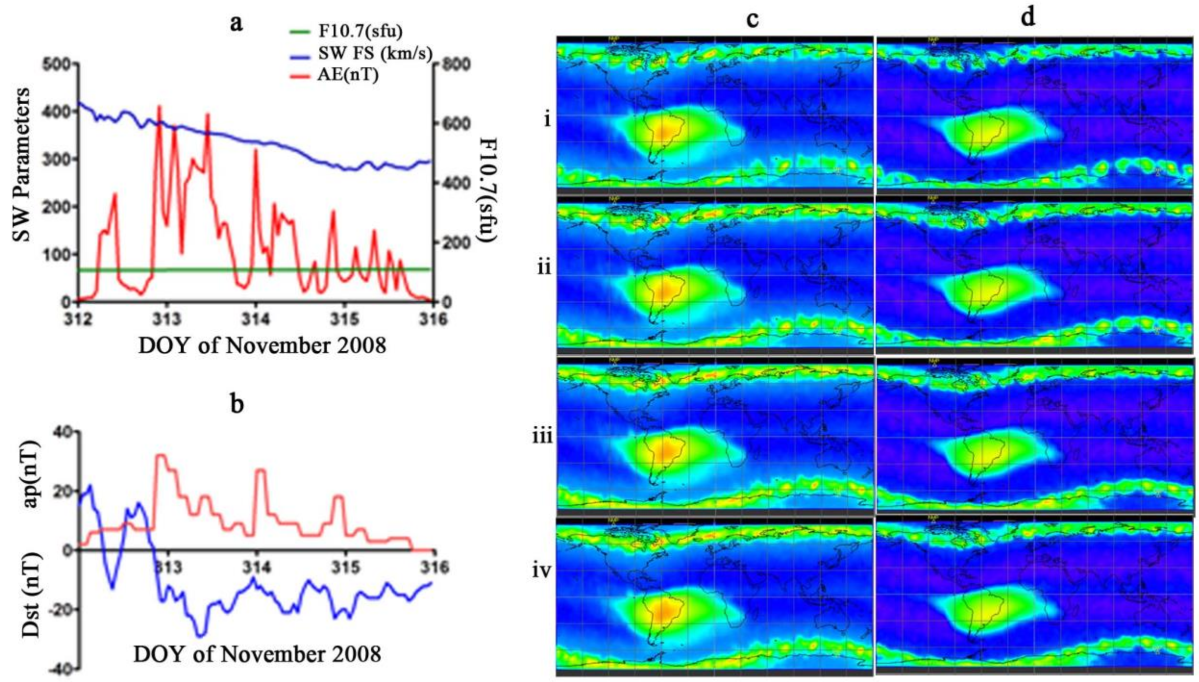

Figure 4. (a) the space weather parameters for November 2008 and (b) the geomagnetic indexes at this period, and the particle distribution for (c) mep0e1 and (d) mep0p2. The i, ii, iii, and iv are represent the mep0e1 and mep0p2 for 8, 9, 10 and 11 November 2008, respectively. The flux distribution unit in Fig. 3c-d is in particle/cm^2 sec str.

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