Analysis of the passage of a spacecraft between the Van Allen belts considering a low and high solar activity

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Abstract. The radiation in the Van Allen belts, produced by electrically charged particles, can cause damages to the electrical equipments of a satellite in orbit of Earth. In this paper, the Van Allen belts are modeled using the data from the space mission Van Allen Probes Mission. With this model, a study was made taking into account the passage of a spacecraft through the Van Allen belts estimating the absorbed radiation dose and the time that spacecraft remained in the radiation zones, considering the effects of a low and high solar activity.

1. Introduction

In 1958, the satellites Explorer I and Explorer III were launched with the goal to collect data about space environment around the Earth and both confirmed the existence of a charged particles ring [1, 2]. The existence of a ring of particles was accept and included the idea that these particles would be trapped in this ring. However, the main attention these experiments was to the nature this radiation belt. According to [3], there are two radiation belts and they are formed by protons and electrons trapped in the geomagnetic field but their formation differ each other. The inner belt contains more protons than the outer belt, which contains more electrons. Furthermore, between the belts, there is a region where the intensity of radiation is weak but it can to vary during a time as the outer belt owing to solar activity [4].

Nevertheless, a new structure of radiation was discovered. In 2012, NASA launched to the space the twins spacecrafts, named Radiation Belt Storm Probes (RBSP), which are part of Van Allen Probes Mission [5]. In a experiment realized in the period of September to October in 2012, the probes discovered a third structure of radiation or a third belt between the inner and outer belts [6]. The appearance of third radiation zone is associated with the passage of solar winds, which formed waves of ultra-low frequency with large amplitudes, responsible for the loss of low energy electrons in the external radiation belt [7].

The importance in studying these belts is because the electronic components on board are sensitive to space radiation dose. In this paper, the main objective is modeling the Van Allen belts using the data provided by Van Allen Probes Mission during the months of September to November 2012 and January to March 2015. From this model, will be simulated the impulsive and low-thrust orbital maneuvers and the combination between them in the periods mentioned previously. For each of these maneuvers, will be determined the time of passage of the spacecraft.
through the regions of radiation and the radiation dose accumulated in the spacecraft considering silicon, aluminum, lead, tantalum and tungsten as shielding materials.

2. Modeling the Radiation Belts
In the work of [8], the radiation belts were modeled, as a first approach, considering just the geographical latitude angle and the distance that separate the radiation zones. However, it is known that the radiation belts are not stable and vary in its sizes owing to solar activity. In this paper, the Van Allen radiation belts were modeled using the data provided by the Van Allen Probes Mission. This mission began at the end of August 2012 and is currently active with the objective of studying the dynamics of radiation belts using the twins probes, RBSP-A and RBSP-B, whose orbits are geocentric, elliptical and with an inclination of 10° [5].

However, during Van Allen Probes Mission data analysis, it was found that space probes cannot fully map the radiation belts in a single day, which leads to the appearance of failures in filling flux intensity values for these regions. In this paper, to homogenize the regions of radiation, according to their delimitation, it was applied a method of interpolation of the values of radiation flux.

This method consists in:
(i) Obtain the angles of geographical latitude and longitude from the positions of the probes, in the ECI reference;
(ii) It is considered that the Van Allen radiation belts would be modeled on the plane of the magnetic equator. So the angles of geographical latitude and longitude were transformed to the angles of magnetic latitude and longitude;
(iii) In addition, it is considered that during a period of one day, the radiation belts do not vary, that is, the Van Allen belt has the same characteristic for all values of the magnetic longitude.
(iv) Therefore, the interpolation method will only require the radiation flux values as a function of the magnetic latitude.

3. Dose of Radiation
In this work, the absorbed radiation dose equivalent rate is determined from the definitions of radiation dose and omnidirectional radiation flux, so that

\[ \hat{D}(E) = w_R \kappa \frac{\Phi(E)E^2}{\rho t} \]  

where \( w_R \) is the radiation weighting factor, such that 1 is for electron and 2 is for proton, \( \kappa \) is a constant equal to 4.80653199.10^{-11}, \( \Phi \) is the omnidirectional flux, in function of the energy \( E \), \( r_S \) is the radius of spacecraft, \( t \) is the shielding thickness and \( \rho \) is the density of shielding material. The unit of absorbed radiation dose equivalent rate is rad/s, where rad is a unit of absorbed radiation dose defined as 1 rad = 0.01J/kg [9].

4. About the Simulations
The simulations were performed in the STRS (Spacecraft Trajectory Simulator) [10, 11, 12, 13]. The Van Allen belts are delimited by McIlwain’s parameter [14], omnidirectional flux of particles (electrons and protons) and the magnetic latitude, where the inner belt is bounded between ±40° and the outer belt is bounded between ±65°.

The spacecraft will start from a low orbit around the Earth and will pass through the radiation regions. For this, we consider the low-thrust and impulsive orbital maneuvers and the combination between them, seeking for the minimum time that the spacecraft can remain
in the regions of radiation. So, the accumulated radiation dose equivalent rate will be estimated using the Eq.1, such that the spacecraft is considered as a perfect sphere with a radius of 1 m and aluminum, tungsten, lead, tantalum and silicon are the shielding materials for a layer of 1 mm of thickness. The values of densities of the shielding materials used are shown in the Tab.1.

| Materials  | Density (kg/cm³) |
|------------|------------------|
| Aluminum   | 0.002697         |
| Tungsten   | 0.019250         |
| Lead       | 0.011340         |
| Tantalum   | 0.016650         |
| Silicon    | 0.002330         |

Furthermore, it is considered the effects of external perturbations as gravitational attraction of the Sun, solar radiation pressure and the terms $J_2$, $J_3$, $J_4$, $J_5$ and $J_6$ of the Earth’s and Moon’s gravitational potentials. The control of the spacecraft’s trajectory is performed by a PID controller in a closed-loop system.

5. Results
In the period of September 2012, it was observed and expected the presence of a third structure of radiation, for the region of electrons with energy equal to 4.2 MeV, because of the high solar activity (see Fig. 1)[6]. However, during the period of January 2015, during a low solar activity, only the presence of the classical zones of radiation (outer and inner belt) was observed, as shown in the Fig. 2. In those figures, the directions $X$ and $Z$ are defined by magnetic latitude and longitude, where ER is the Earth radius.

![Figure 1. Electron radiation zones in September 2012 (E = 4.2 MeV).](image1)

![Figure 2. Electron radiation zones in January 2015 (E = 1.8 MeV).](image2)

For regions that contain only protons, no type of anomaly appeared, regardless of the variation of solar activity. Thus, in this work, we simulated the passage of a spacecraft through regions of radiation containing only electrons with energy equal to 4.2 MeV (September-November 2012)
and 1.8 MeV (January-March 2015), and for regions of radiation containing only protons with energy equal to 21.25 MeV.

The Fig.3-4 are examples of the results obtained by simulating the spacecraft passage through the Van Allen radiation belts using Hohmann maneuvers and its absorbed radiation dose equivalent rate, respectively. In the Fig. 3, the magenta color line represents the trajectory of spacecraft and the lines with hot and cold colors, forming the map of the region of radiation, represent the omnidirectional flux of electrically charged particles based on the passage of the RBSP space probes through the radiation regions, in a certain period of time that remained in the space.

![Figure 3](image)

**Figure 3.** Passage of the spacecraft through the region of electrons with energy equal to 4.2 MeV using Hohmann maneuver in September 2012.

![Figure 4](image)

**Figure 4.** Absorbed radiation dose equivalent rate for a region of electrons with energy equal to 4.2 MeV in September 2012.

The Fig.5-8 show the results of the spacecraft passage through the Van Allen radiation belts using low-thrust maneuvers and their absorbed radiation dose equivalent rate, respectively. In the Fig.5, it is observed, initially, that the spacecraft remained only in the region of the inner belt and continues further in the region as the semi-major axis of the orbit increases until the spacecraft is injected out of the region of radiation, as shown in the Fig.6.

The results of the combination of Hohmann with the low-thrust maneuver are shown in Fig.9-10. Initially, the Hohmann maneuver is applied so that the spacecraft crosses the inner belt and is then injected into the slot where it remains by means of the low thrust maneuver. Upon approaching the region of the outer radiation zone, the spacecraft again uses the Hohmann maneuver, being injected out of the radiation region where it continues, again with the low-thrust maneuver.

The Tab.2 show the time of passage and the maximum radiation dosage rate accumulated in the shielding layers of tantalum, tungsten, and lead in the period of September-November 2012 and January-March 2015.

6. Conclusions
This study aimed to determine the time in which the spacecraft remained in the regions of radiation, around the Earth. Firstly, the electron and proton radiation regions were modeled with Van Allen Probes Mission data using the interpolation method, as described in the Sec.2. Through this, it became possible to verify, in the period of high solar activity, the presence of a new radiation structure, known as the third Van Allen belt formed between the inner and
Figure 5. Passage of the spacecraft through the region of protons with energy equal to 21.25 MeV using the low-thrust maneuver in September 2012.

Figure 6. Passage of the spacecraft through the region of protons with energy equal to 21.25 MeV using the low-thrust maneuver in October 2012.

Figure 7. Absorbed radiation dose equivalent rate for a region of protons with energy equal to 21.25 MeV in September 2012.

Figure 8. Absorbed radiation dose equivalent rate for a region of protons with energy equal to 21.25 MeV in October 2012.

Table 2. Time of passage of the spacecraft through the radiation zones (days) and absorbed radiation dose equivalent rate (rad/s) between parentheses.

|         | 2012          | 2015          |
|---------|---------------|---------------|
| Electron| Proton        | Electron      | Proton        |
| H       | $< 1 - (1.10^{-5})$ | $< 1 - (5.10^{-6})$ | $< 1 - (5.10^{-3})$ | $< 1 - (5.10^{-6})$ |
| L-T     | $50 - (1.10^{-4})$ | $35 - (5.10^{-6})$ | $58 - (5.10^{-3})$ | $34 - (5.10^{-6})$ |
| H + L-T | $14 - (3.10^{-5})$ |             | $2 - (2.10^{-3})$ |               |

outer belts. This new structure was observed for a region of electrons with energy equal to 4.2 MeV in the period of September 2012. In the region of radiation that contains only protons,
it did not observe any type of anomaly. In January 2015, only the presence of the classical radiation structures (inner and outer belts), during the low solar activity, was verified for a region of electrons with energy equal to 1.8 MeV. Thus, Hohmann maneuver, low-thrust and the combination between them were simulated for regions containing only electrons and protons. For all the cases studied, it was observed that the Hohmann maneuver was the only one that managed to keep the spacecraft in minimum time in the radiation belts, while that the low-thrust maneuver maintained it in the longest time, as expected. The absorbed radiation dose equivalent rate was calculated and it was found that lead, tantalum and tungsten were the materials that received least radiation in their shielding layers, regardless of periods of solar activity. For the proton regions, the absorbed radiation dose equivalent rate were the same during Hohmann and low-thrust maneuvers. However, for the electron regions, the Hohmann maneuver was the only one that obtained the lowest rate in the period of high solar activity, whereas the combination between the Hohmann maneuvers and low-thrust obtained the lowest rate in the period of low solar activity.

References
[1] Van Allen J A, Ludwig G H, Ray E C and Mcilwain C E 1958 J. Jet Prop. 28 9 588–92
[2] Rohrlich F and Van Allen J A 1960 First Public Lecture on the Discovery of the Geomagnetically Trapped Radiation (Department of Physics and Astronomy: State University of Iowa) p 60
[3] Van Allen J A 1959 J. Geophys. Res. 64 1683–89
[4] Parker N E 1960 J. Geophys. Res. 67 10 3117–30
[5] Kessel R L, Fox N J and Weiss M 2012 Space Sci. Rev. J. 179 1 531–43
[6] Baker D N et al. 2013 Science 340 186 186–90
[7] Mann I R et al 2016 Nat. Phys. 12 978–83
[8] Oliveira T C, Rocco E M, Prado A F B and Ferreira J L A 2013 J. Phys.: Conf. Series 465
[9] Haffner J W 1967 Radiation and shielding in space (New York and London: Academic Press) chapter IV p 112
[10] Rocco E M 2008 XIV Coloquio Brasileiro de Dinamica Orbital (Aguas de Lindoia) 17–21
[11] Rocco E M 2012 Congresso Nacional de Engenharia Mecancia (Maranhao)
[12] Rocco E M 2013 J. Phys.: Conf. Series 465
[13] Rocco E M 2015 J. Phys.: Conf. Series 641
[14] Mcilwain C E 1961 J. Geophys. Res. 66 11 3681–91