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ScienceDirect

Advances in Space Research 54 (2014) 2398–2414

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Highly Elliptical Orbits for Arctic observations: Assessment of ionizing radiation

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Received 15 April 2014; received in revised form 4 September 2014; accepted 5 September 2014
Available online 16 September 2014

Abstract

The ionizing radiation environment was analyzed for a variety of potential Highly Elliptical Orbits (HEOs) with orbital periods ranging from 6 h to 24 h suitable to continuously monitor the Arctic region. Several models available from the ESA Space Environment Information System (SPENVIS) online tool were employed, including the new-generation AE9/AP9 model for trapped radiation. Results showed that the Total Ionizing Dose (TID) has a well-pronounced local minimum for the 14-h orbit, which is nearly identical to the overall minimum observed for the longest orbital period (24 h). The thickness of slab aluminum shielding required to keep the annual TID below 10, 5 and 3.33 krad (i.e. 150, 75 and 50 krad for 15 years of mission duration) for a 14-h orbit is 2.1, 2.7 and 3.1 mm respectively. The 16-h orbit requires an additional 0.5 mm of aluminum to achieve the same results, while the 24-h orbit requires less shielding in the order of 0.2–0.3 mm. Comparison between the AE8/AP8 and AE9/AP9 models was conducted for all selected orbits. Results demonstrated that differences ranged from −70% to +170% depending on orbit geometry.

The vulnerability to the Single Event Effect (SEE) was compared for all orbits by modeling the Linear Energy Transfer (LET) for long-term conditions and for the 5 min “worst case” scenario. The analysis showed no preference among orbits with periods longer than 15 h, and in order to keep the 14-h orbit at the same level, the shielding should be increased by ∼33% or approximately by 1 mm. To keep the Single Event Upset (SEU) rate produced by the “worst case” event at the same order of magnitude as for the “statistical” long-term case, the thickness of aluminum should be as high as 22 mm. The overall conclusion from a space environment point of view is that all HEO orbits with periods equal to or longer than 14 h can be regarded as good candidates for operational missions. Therefore, selection of orbit should be based on other criteria, for example, uniformity of spatial coverage for meteorological imaging or the configuration of the ground network for data reception.

Keywords: Space environment; Arctic; Highly Elliptical Orbit; Earth radiation belts; Total Ionizing Dose

1. Introduction

The current concept of meteorological observations of the Earth from space relies on the combination of geostationary (GEO) satellites and the polar Low Earth Orbit satellites (LEO). The GEO satellites can provide continuous coverage of the tropics and mid-latitude zone up to 60°, while the imaging of regions poleward of 60° relies solely on the LEO satellite constellation.

Interest in HEO orbits has increased in the last several years due to the recognized need to have access with high temporal frequency to multi-spectral imagery of polar regions for weather and climate applications. The World

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http://dx.doi.org/10.1016/j.asr.2014.09.012
0273-1177/

Meteorological Organization (WMO) identified HEO satellite systems as a way to close the existing observational gap over the polar regions in the future satellite component of the Global Observing System (GOS) (WMO, 2013; Garand et al., 2013, 2014).

Some HEO orbits, such as the 12-h Molniya orbit and the 24-h Tundra orbit have been used for a very long time for communications and special applications such as, for example, the space-based infrared surveillance and early-warning systems (Chobotov, 2002). Chaudhary and Vishvakarma (2010) studied the feasibility of using a Molniya (12-h) orbit for solar power generation. The potential of Molniya orbit for meteorological observations over the polar and mid-latitude regions from space was first pointed out by Kidder and Vonder Haar (1990), and has been recently investigated in detail by Trishchenko and Garand (2011). The 12-h Molniya orbit combines two important features: a large eccentricity and the so-called "critical inclination" (63.4°), which results in a stable location of apogee. The continuous coverage of the entire polar region can be provided from only a pair of imagers in Molniya HEO orbit for each hemisphere, a capacity that LEO orbits cannot reach (Trishchenko and Garand, 2012a,b). In fact, a constellation consisting of several GEO satellites and two pairs of HEO satellites could observe weather patterns at any point and any time around the globe.

A few years ago the Canadian Space Agency initiated a project on HEO satellite system for continuous monitoring of the Arctic region (Garand and Morris, 2011). Based mainly on historical evidence, the 12-h Molniya orbit was initially considered as a candidate orbit for the mission. In-depth analysis of the space environment showed that the 12-h Molniya orbit exposes the spacecraft to a challenging ionizing environment due to the high energy protons of the inner radiation belt (Trichtchenko, 2012). This is perceived as a significant risk for detectors, electronics and other components of the imaging payload known to be sensitive to such conditions.

With the goal of reducing exposure to the proton radiation, a new study was conducted by Trishchenko et al. (2011). It was suggested that a 16-h orbit represents an optimal solution for HEO orbital configuration in terms of trade-offs between the proton radiation environment, and requirements for the meteorological imaging, such as spatial resolution, temporal coverage, orbit maintenance, repeatability of diurnal observational conditions, data reception, and satellite ground speed during the imaging phase. This orbit has some unique features, such as a repeating ground track over a two-day period with three apogees separated by 120° in longitude. The criteria used by Trishchenko et al. (2011) for optimization and selection of a HEO orbit for polar observations was an important step toward better understanding and shaping the future HEO satellite system for Arctic observations. However, the radiation environment analysis focused on the trapped protons only. Other types of the energetic particle radiation, such as trapped electrons, galactic cosmic rays and solar energetic protons were not considered.

The current study addresses this gap by providing a comprehensive analysis of the space radiation environment for the entire range of HEO orbits suitable for continuous Arctic monitoring. The models available via the European Space Agency's (ESA) Space Environment Information System (SPENVIS) software were employed (www.spenvis.oma.be, Heynderickx et al., 2004).

Until recently, the most popular models for estimation of the trapped radiation were AE8/AP8 (Vette, 1991; Sawyer and Vette, 1976). These models cover a wide range of spatial and energy scales and were a de facto "standard" for the satellite industry for a long time (see, for example, ECSS-E-ST-10-04A, 2008). Emmanuel et al. (2014) used these models and the SPENVIS tool to compare the effectiveness of radiation shielding for three HEO orbits described by Trishchenko et al. (2011).

It is known that the AE8/AP8 models do not always adequately represent the radiation environment, especially in HEO orbits (Blake and Cox, 1988; Blake and Mazur, 1998). The advanced AE9/AP9 models (O'Brian et al., 2009; Ginet and O'Brien, 2009; Ginet et al., 2013) have been recently completed, based on more extensive datasets, including measurements from two HEO satellites in Molniya-type orbits. The SPENVIS system was upgraded in 2012 to incorporate version 1 of the AE9/AP9 models, which is expected to improve the accuracy of the trapped radiation modeling for HEO orbits.

In the analysis presented in this paper we used the following models available through SPENVIS: (a) the new AE9/AP9 model for evaluation of the trapped radiation environment (results were also compared with the AE8/AP8 model); (b) the two most popular models for the solar energetic particles, such as Jet Propulsion Laboratory model (JPL-91) (Feynman et al., 1993) and the ESP-PSYCHIC (Emission of Solar Protons - Prediction of Solar particle Yields for CHaracterizing Integrated Circuits) model for evaluation of the impacts of the solar protons (Xapsos et al., 1999, 2000, 2007), (c) the Cosmic Ray Effects on Micro Electronics (CRÈME)-96 model for galactic cosmic rays, (d) the SHIELDOSE model for evaluation of the Total Ionizing Dose (TID) and the Single Event Effects (SEE) for standard materials and the shielding configurations (Adams, 1986; Tylka et al., 1997). Although important, the plasma and non-ionized components (meteoroids, debris, non-ionized interactions and others) were not included in this study because we do not expect they will change our conclusions.

The first part of the paper describes the criteria employed for selection of orbits used in the assessment; the second part is dedicated to the evaluation of the space environment and inter-comparison of different models. The cumulative impacts (total dose) and single-event effects are analyzed in the following section. The paper concludes with the recommendations for orbit selection from the radiation environment point of view, also taking into account imaging requirements over polar regions.