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A comparison of radiation shielding effectiveness of materials for highly elliptical orbits

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Abstract

The Canadian Space Agency (CSA) has proposed a Polar Communications and Weather (PCW) satellite mission, in conjunction with other partners. The PCW will provide essential communications and meteorological services to the Canadian Arctic, as well as space weather observations of in situ ionizing radiation along the orbit. The CSA has identified three potential Highly Elliptical Orbits (HEOs) for a PCW satellite constellation, Molniya, Modified Tundra and Triple Apogee (TAP), each having specific merits, which would directly benefit the performance/longevity of a PCW spacecraft. Radiation shielding effectiveness of various materials was studied for the three PCW orbit options to determine the feasibility of employing materials other than conventional aluminium to achieve a specified spacecraft shielding level with weight savings over aluminium. It was found that, depending on the orbit-specific radiation environment characteristics, the benefits of using polyethylene based materials is significant enough (e.g., 22% in Molniya for PE at 50 krad TID) to merit further investigation.

Keywords: Radiation shielding; Simulation; Highly elliptical orbit; Satellite; Shielding material

1. Introduction

A Canadian Polar and Communication (PCW) satellite mission has been proposed by the Canadian Space Agency (CSA) in conjunction with the Department of Defence (DND), the Environment Canada (EC) and other government and industrial partners. The objectives of the mission includes provision of continuous satellite communication services throughout the Canadian Arctic region, weather monitoring and meteorological Earth observation, air and marine navigation, Arctic science, and support efforts to maintain the security and the territorial integrity of the Canadian border (Kroupnik, 2011). The mission plans to achieve continuous coverage of the Canadian polar region using a 2-satellite constellation in a Highly Elliptical Orbit (HEO). A HEO satellite is preferable to a geo-synchronous satellite since the latter lacks the capacity for continuous coverage of the polar region above 60°N latitude from its orbital plane. The CSA has identified (Kroupnik, 2011; McConnell et al., 2012) three highly elliptical orbits (HEOs) for the PCW mission, namely a 12 h Molniya orbit, a 16 h Triple Apogee and a 24 h Modified Tundra, which are based on studies by Trishchenko et al. (2011a,b). The HEO satellites have the capacity to provide an imagery of high latitude regions more efficiently than several combinations of LEO satellites as reported in Trishchenko and Garand (2012). The orbital properties of the three proposed orbits are given in Table 1 (Trishchenko et al., 2011a).

A 2-satellite constellation system in the Molniya orbit enables continuous observation of the Arctic region of Canada with some unique merits. These, as explained by Trishchenko and Garand (2011) include high latitude

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Table 1
Orbital properties for the three HEOs identified for the PCW Mission (Trishchenko et al., 2011a).

	Period (h)	Perigee altitude (km)	Apogee altitude (km)	Inclination angle $\acute{\imath}$ (deg)	Eccentricity
Molniya	12	500	39850	63.4	0.74
TAP	16	8100	43493	63.4 – 70	0.55
Mod. Tundra	24	23144	48442	90	0.3

viewing and good imagery of the region of interest at lower apogee, which is desirable for Earth observation, higher eccentricity of 0.74 that provides GEO-like imagery, higher orbital stability, resulting from critical orbital inclination ($\acute{\imath} = 63.435°$) of the Molniya orbit with minimal effort for drift correction and good reception at terrestrial satellite control stations.

A major known limitation of the Molniya orbit is the hazardous radiation environment, with high-concentration of energetic trapped protons and electrons encountered during each perigee pass (Trishchenko et al., 2011), which poses a serious threat to the spacecraft bus and its payload. Alternate HEO orbits such as TAP and Modified Tundra have been developed, by varying the perigee, to either avoid or minimize the exposure to hazardous radiation environment. Since the level of radiation is strongly dependent on the altitude and the latitude, the trajectories of the three HEO orbits expose a satellite in these orbits to various levels of trapped proton, electrons, and solar flare radiation.

In general, HEO satellites require a level of shielding higher than that of LEO and GEO satellites, to protect the on-board electronic systems from a comparatively harsher and hostile space environment. Achieving the desired level of radiation shielding without increasing the weight and the mission cost is a challenge. The three basic shielding concepts to reduce dose from external radiation (NRC, 2008) are: (i) increase the distance from the source of radiation, (ii) reduce the amount of exposure time (i.e. mission duration), and (iii) develop a suitable shielding material.

This study is focused on the development of radiation shielding materials for a pre-determined orbit and mission duration. The purpose of the shield is to attenuate the energy of the charged particles as they pass through the shield material, such that the energy deposited per unit mass (i.e., the dose absorbed by a silicon detector behind the shield) is sufficiently below the maximum dose rating for the electronic components. This attenuation is achieved through energy loss (mainly due to elastic and inelastic collision with the constituents of the shield) and through change in particle identities resulting from nuclear fragmentation (NRC, 2008; Sen et al., 2009).

In this study, radiation shielding effectiveness of various materials was simulated for the three PCW orbit options to determine the feasibility of employing materials other than conventional aluminium to achieve a specified spacecraft shielding level with weight savings over aluminium. This was accomplished through particle transport simulation of energetic radiation particles through a material.

2. Simulation details

Total Ionization Dose (TID) transmitted by a shielding material during the PCW mission for 15 years, was simulated using particle transport simulation codes and compared. The intense radiation environment in HEOs is due to Van Allen radiation belts (both proton and electron belts) as well as solar particles and cosmic rays. The latter was modelled using standardized models in European Space Agency's (ESA) SPace ENVironment Information System (SPENVIS) software (Heynderickx et al., 2004; Heynderickx et al., 1998). The trapped proton and the trapped electron fluxes were calculated, for the satellite's orbital trajectory, using NASA's AP8 and AE8 models (Sawyer and Vette 1976; Vette, 1991). "Worst case" conditions were simulated using AP8 MAX proton model and AE8 MAX electron model. The "Worst case" condition represents the highest radiation fluxes that the satellite could experience during its mission duration of 15 years.

Emission of Solar Protons (ESP) model (Xapsos et al., 1999; Xapsos et al., 2000), available within SPENVIS, was used to determine the long-term solar particle events (SPE) fluence into the shielding structure while ISO-15390 model (International Standard, 2004) was used to determine the galactic cosmic ray flux (GCR) based on 2 solar cycles during the 15 years mission duration, which included a solar maximum cycle for 9.87 years and a solar

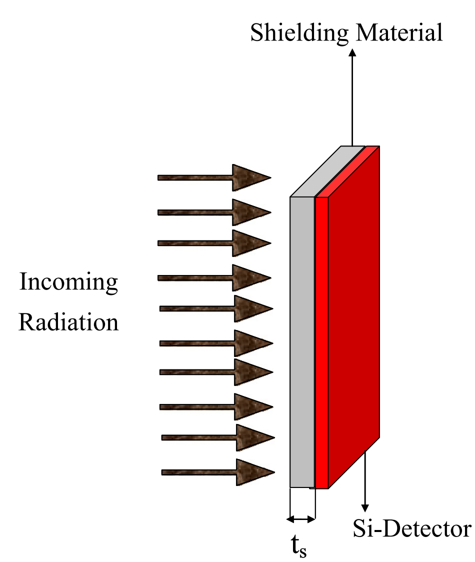

Fig. 1. A schematic of shield geometry used in simulation (t_s = shield thickness).