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Low Earth orbit assessment of proton anisotropy using AP8 and AP9 trapped proton models

Francis F. Badavi*, Steven A. Walker, Lindsey M. Santos Koos

Old Dominion University, 5115 Hampton Boulevard, Norfolk, VA 23529, USA

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ABSTRACT

The completion of the International Space Station (ISS) in 2011 has provided the space research community with an ideal evaluation and testing facility for future long duration human activities in space. Ionized and secondary neutral particles radiation measurements inside ISS form the ideal tool for validation of radiation environmental models, nuclear reaction cross sections and transport codes. Studies using thermo-luminescent detectors (TLD), tissue equivalent proportional counter (TPEC), and computer aided design (CAD) models of early ISS configurations confirmed that, as input, computational dosimetry at low Earth orbit (LEO) requires an environmental model with directional (anisotropic) capability to properly describe the exposure of trapped protons within ISS.

At LEO, ISS encounters exposure from trapped electrons, protons and geomagnetically attenuated galactic cosmic rays (GCR). For short duration studies at LEO, one can ignore trapped electrons and ever present GCR exposure contributions during quiet times. However, within the trapped proton field, a challenge arises from properly estimating the amount of proton exposure acquired. There exist a number of models to define the intensity of trapped particles. Among the established trapped models are the historic AE8/AP8, dating back to the 1980s and the recently released AE9/AP9/SPM. Since at LEO electrons have minimal exposure contribution to ISS, this work ignores the AE8 and AE9 components of the models and couples a measurement derived anisotropic trapped proton formalism to omnidirectional output from the AP8 and AP9 models, allowing the assessment of the differences between the two proton models. The assessment is done at a target point within the ISS-11A configuration (circa 2003) crew quarter (CQ) of Russian Zvezda service module (SM), during its ascending and descending nodes passes through the south Atlantic anomaly (SAA).

The anisotropic formalism incorporates the contributions of proton narrow pitch angle (PA) and east–west (EW) effects. Within SAA, the EW anisotropy results in different level of exposure to each side of the ISS Zvezda SM, allowing angular evaluation of the anisotropic proton spectrum. While the combined magnitude of PA and EW effects at LEO depends on a multitude of factors such as trapped proton energy, orientation and altitude of the spacecraft along the velocity vector, this paper draws quantitative conclusions on the combined anisotropic magnitude differences within ISS SM target point between AP8 and AP9 models.

1. Introduction

At low Earth orbit (LEO), the existing trapped proton models such as the static AP8MIN/AP8MAX (Jensen and Cain, 1962; Cain et al., 1967; Sawyer and Vette, 1976; McCormack, 1988; Vette, 1991), and the new AP9 (Ginet et al., 2013) are typically used to obtain omnidirectional fluxes. In reality, the proton flux is highly directional (anisotropic) not only at LEO but at all altitudes as pitch angle anisotropies are a consequence of both source and loss mechanisms. The nature of fluxes in AP8 and AP9 models versus the directionality requirements of this work will be further discussed in Section 2 of the paper as there are distinct differences between these models.

From the physics point of view, the overall behavior of proton anisotropy in this region known as the south Atlantic anomaly (SAA), is reasonably well understood. In addition, the anisotropy of the proton field in the altitude range of 200–1800 km within SAA has been measured by a number of special purpose satellites such as the TSX5-CEASE (Ginet et al., 2007a, 2007b).

* Corresponding author at: NASA Langley Research Center, MS 188E, Hampton, VA 23681, USA. Tel.: +1 (757) 864 1410; fax: +1 (757) 864 8094.
E-mail address: francis.f.badavi@nasa.gov (F.F. Badavi).

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Inside a spacecraft, at LEO and within SAA, the trapped ionizing radiation impinging on a neutral or charged particle detector or a biological end point is mostly produced by anisotropic protons trapped within the Earth's geomagnetic field. Under the influence of Lorentz force and by the action of "cyclotron gyration", the trapped protons gyrate up and down the geomagnetic field lines, resulting in a bouncing motion between the magnetic mirrors near the north and south magnetic poles. At LEO, the radiation exposure is dominated by trapped protons within SAA, where protons reach lower altitudes. The SAA is a consequence both of the offset nature of the dipole component and of the non-dipolar higher-order field components.

The physical processes affecting proton anisotropy are due to two mechanisms. First, within SAA, protons are near their "mirror" points where their trajectories reverse direction and the pitch angle (PA, angle between geomagnetic field line and proton direction) reaches 90°. Therefore, within SAA mirroring region, proton directions become "planar" as they are confined in planes perpendicular to the magnetic field, and the PA distribution of the proton flux can best be profiled by a Gaussian. In reality, trapped proton populations at all altitudes are typically peaked near 90° pitch angle, but in LEO the distributions are particularly constrained by losses to the atmosphere. Second, at low altitudes, proton radius of gyration is comparable to the atmospheric scale height. Therefore, protons gyrating above an observation point pass through less dense atmosphere, and have a lower atmospheric collision loss rates than protons gyrating below the same observation point. This proton flux differential gives rise to the so-called east–west effect (EW), where the proton flux is asymmetric with maximum intensity in the direction of magnetic east.

The LEO anisotropic contribution to trapped proton exposure within SAA was not considered an important issue for most prior LEO missions because the random spacecraft orientation averaged out the anisotropy. Thus, in spite of the actual anisotropic exposure during SAA transits, cumulative radiation effects over multiple orbits were predicted by using the omnidirectional fluxes from models such as AP8 and AP9 under the incorrect assumption that the model fluxes were isotropic.

The omnidirectional model AP8 and the recent AP9 model were relatively successful in describing the radiation environment aboard the highly maneuverable space transportation system (STS; shuttle), wherein anisotropies were smeared out. Therefore, in prior STS related work (Badavi et al., 2009), the authors ignored the directionality of trapped proton flux, and omnidirectional averaged fluxes from AP8 were used for dosimetric calculations. Such models will not be adequate in the formation flying of the international space station (ISS), which during normal operation is oriented in the local vertical (LV) plane along the velocity vector.

Due to the very large size of ISS (356X239X66 ft.), and in order to reduce atmospheric drag, ISS travels in a LV gravity-gradient-stabilized fixed orientation, with its zenith (+Z) always pointing toward the Earth as the spacecraft travels along the velocity vector X. Due to this fixed orientation, the cumulative incident proton flux impinging on ISS is anisotropic. This anisotropy influences some of the ISS operations, such as deciding the appropriate location for sensitive electronics and biological experiments, positioning of crew work and sleep quarters, and placement of passive or active neutron and charged particle radiation detectors.

The rest of this work is organized in the following manner. First, the implemented environmental models AP8 and AP9 are briefly described. Next, the derivation of the anisotropic trapped proton formalism is presented in some detail. This is followed by the description of the particle transport algorithm, ISS-11A vehicle geometry definition, specification of the target point within ISS-11A, space boundary condition inputs into the transport code, and assessment of directionality of AP8 and AP9 within SAA.

2. Space radiation environment

The space radiation environment is constituted of three basic components; trapped radiation belts within the Earth geomagnetic field, galactic cosmic rays (GCR) and solar event particles (SEP). Prior work by the authors (Badavi, 2013, 2014; Badavi et al., 2014) have reviewed all three environments in some detail. In particular, the deficiency and omnidirectional nature of the AP8 model and new contributions of AP9 model were discussed.

An important point that requires some explanation is the difference in the distributed fields between the provided AP8 and AP9 models. Strictly, the native AP8 results and the default AP9 output are omnidirectional fluxes (i.e. integrated over all directions). The native AP8 omnidirectional fluxes are given as functions of $B/B_\circ$ and L coordinates (McIlwain, 1961), but since the distribution in $B/B_\circ$ is a consequence of distribution with equatorial pitch angle, various approaches have been used to derive directional fluxes from this, of which the works of Watts et al. (1989) and Badhwar and Konradi (1990) should be mentioned.

However, the native flux maps in AP9 are in terms of K (i.e. bounce motion) and L^* (i.e. drift motion) adiabatic invariants, with the former being directly related to equatorial pitch angle and consequently to local pitch angle. That is, AP9 fundamentally stores unidirectional fluxes (Ginet et al., 2013, Appendix B) and integrates over pitch angles to provide the default omnidirectional output, but AP9 can also directly provide these directional fluxes (AE9/AP9 user's guide, 2014). So, while AP8 model stores omnidirectional fluxes as a function of spatial location ($B/B_\circ, L$), the magnetic invariant spatial grid implemented in AP9 model effectively stores directional fluxes. These results are then integrated within the model kernel to produce omnidirectional fluxes for common engineering applications. This approach in AP9 has the added benefit of providing a more direct ability to produce unidirectional flux estimates as needed. It is worth mentioning that the unidirectional flux output of AP9 model is still subjected to some limitations. For example, EW effect and solar cycle variations on LEO protons are not yet represented in the model (Johnston et al., 2014).

Here, the authors limit the discussion of the trapped environment to the derivation of the anisotropic trapped protons within SAA as applicable to ISS.

2.1. Analytical description of anisotropic proton flux at LEO

Computing the PA distribution of protons within SAA requires making assumptions about the density of protons along a magnetic field line. Therefore, at LEO, a definition of atmospheric density scale height is needed as one of the input parameters into an anisotropic trapped model. The scale height can be obtained by using the atmospheric densities predicted by a standard atmospheric model of which a number is available (e.g. AT62, AT76). In this work, the authors follow Heckman and Nakano (1969) formalism, and at mirror point within SAA, approximate the PA distribution $f(\theta)d(\theta)$ as

$$f(\theta)d\theta \propto \rho(\theta)^{-1}d\theta, \tag{1}$$

where $\rho(\theta)$ is the atmospheric density in terms of PA, and under the assumption of constant scale height, as a function of altitude can be represented by an exponential as

$$\rho \propto \exp(-h_m/h_0). \tag{2}$$

In Eq. (2), h_m is the mirror point altitude and h_0 is the scale height in km. Within SAA, a good approximation to h_m is

$$h_m \approx h - l \sin I, \tag{3}$$