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A deterministic computational model for the two dimensional electron and photon transport

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ABSTRACT

A deterministic (non-statistical) two dimensional (2D) computational model describing the transport of electron and photon typical of space radiation environment in various shield media is described. The 2D formalism is casted into a code which is an extension of a previously developed one dimensional (1D) deterministic electron and photon transport code. The goal of both 1D and 2D codes is to satisfy engineering design applications (i.e. rapid analysis) while maintaining an accurate physics based representation of electron and photon transport in space environment. Both 1D and 2D transport codes have utilized established theoretical representations to describe the relevant collisional and radiative interactions and transport processes. In the 2D version, the shield material specifications are made more general as having the pertinent cross sections. In the 2D model, the specification of the computational field is in terms of a distance of traverse z along an axial direction as well as a variable distribution of deflection (i.e. polar) angles θ where $-\pi/2 < \theta < \pi/2$, and corresponding symmetry is assumed for the range of azimuth angles $(0 < \varphi < 2\pi)$. In the transport formalism, a combined mean-free-path and average trajectory approach is used. For candidate shielding materials, using the trapped electron radiation environments at low Earth orbit (LEO), geosynchronous orbit (GEO) and Jupiter moon Europa, verification of the 2D formalism vs. 1D and an existing Monte Carlo code are presented.

1. Introduction

The concept of developing a rapid analysis electron and photon transport code at NASA Langley research center (LaRC) arose from a desire to have a companion code to the LaRC deterministic heavy ion code High charge (Z) and Energy TRaNsport (HZETRN) [1–3]. The initial effort named Coupled Electron Photon TRNansport (CEPTRN) [4] resulted in a code which incorporated parameterizations of effective range of electrons. These parametric functions were derived from the experimental range data for electron beams incident on a variety of materials, and liberal use of interpolation/extrapolation methods was used in the transport process. Although numerous verifications [4] indicated that the code was reasonably accurate for the low Earth orbit (LEO) trapped electron radiation environment, it soon became clear that the limit of applicability of the code was dictated by the data range on which the code algorithms was based. Using the available deep space Voyager and Galileo missions measurements, application of the code to these gas giant outer planets, with very high energy trapped electron environments, required questionable extrapolation with regard to both energy and shield compositions. Thus, in order to properly account for the transport of very high energy electrons, work on a substantial up-grade to the CEPTRN began and resulted in essentially a new one dimensional (1D) formulation [5,6].

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In the revised 1D formalism of CEPTRN, the parametric effective range approach was abandoned in favor of a continuous slowing down approximation (CSDA), combined with an elastic multiple scattering formalism, to define an electron mean free path and a transmission function at a given target location. The pertinent cross sections relevant to CSDA and multiple scattering were calculated with established theoretical formulas, valid over a much broader energy range than in the original approach of reference [4], and the additional calculation of positron production/annihilation was incorporated as a consequence. The cross section equations were cast in terms of specific elemental atomic charges, from which cross sections applicable to any user-defined molecular system were automatically constructed.

Upon the completion of the 1D version of CEPTRN [5,6], it was decided to extend the formalism to a 2D version (henceforth referred to as CEPTRN2D), in order to have a code that can be verified against available Monte Carlo routines. Here, the transport is assumed to be axially symmetric about a specified direction (hence 2D rather than 3D computational field). That is, the specification of axially symmetric field is in terms of a distance of traverse z along an axial direction as well as a variable distribution of deflection (i.e. polar) angles θ where $-\pi/2<\theta<\pi/2$, and corresponding symmetry is assumed for the range of azimuth angles $(0<\varphi<2\pi)$.

Details of the CEPTRN2D transport formulation will be described in a subsequent section, and are based on motion related to some initial direction. Behavior of the slowing and stopping of electrons and their associated stopping radiation (bremsstrahlung) are evaluated in terms of quantities contained in the direction of the hemisphere pointing in the initial direction. The scattering and mean free path calculations permit definition of mean trajectories relative to the initial motion direction, so that axis-symmetric spatial and energy distributions may be inferred.

In the CEPTRN2D, the electron and photon cross section formulations are updated version of the 1D code [5,6]. In all other respects, in particular the transport methodologies, the computational procedures of the 2D code are completely different than the 1D code. The differential energy spectrum used as boundary condition in the 1D code is changed to a series of discrete energy bins in the 2D code. This simpler description of scattering of a monoenergetic beam about a directional axis is used as a basis for establishing the transport algorithms.

For CEPTRN2D verification, dosemetric comparisons with 1D code results and corresponding available Monte Carlo calculations are demonstrated. The Monte Carlo cases were initially utilized to verify the 1D code [5,6]. The Monte Carlo runs utilized several hours of machine time, whereas the CEPTRN2D code calculations were practically instantaneous. Despite some differences in the final magnitudes, general functional behavior is consistent in the verification results, so that use of the deterministic code in the engineering trade studies, where repeated runs are required, can be performed quickly and credibly.

A further improvement in the CEPTRN2D code is that the required inputs are greatly simplified, consisting of an atomic data base permanent file and two user-defined files specifying material composition, and environment energy spectra.

The rest of the paper is composed of the following sections. First, the relevant electron and photon cross sections are briefly described. These interactions were discussed in great detail in prior papers [5,6], and here, for the sake of completeness are presented in an abbreviated version. Second, the CEPTRN2D electron and photon transport formalisms are discussed. Third, a dosemetric evaluation of electron and photon collisions is presented. This is followed by sample calculations for LEO, geosynchronous orbit (GEO), Jovian environments and a monoenergetic electron beam for candidate shielding materials. The paper concludes by discussing the ongoing and future activities.

2. Cross sections

The theoretical description of propagation of energetic electrons and photons in condensed media requires representation of interaction of high energy radiation with constituent atoms of the medium. Application of the principles of quantum and semi-classical physics has gone far toward providing formulations for electron and photon interaction cross sections. Although many of these formulations are mathematically complicated, they are often amenable to approximation and parameterizations that greatly simplify their practical application. For the electrons and photons collisional interactions, the following sub-sections describe the cross sectional formulations used in CEPTRN2D code. These cross sections were described in great detail in prior work [5,6], and here, for the sake of completeness, are briefly discussed.

2.1. Electrons

Free energetic electrons passing through a material are slowed and eventually stopped as they interact with the fields of the nuclei and bound electrons of the material. The electron deceleration process is expressed in terms of energy loss by collisions and accompanying photon production (bremsstrahlung).

2.1.1. Collision slowing and stopping

Electron deceleration by collision processes in which energy from the projectile electron imparted to the bound electrons of the medium is usually cast in terms of the stopping power, or energy loss per unit distance parameter, $-dE/ds$, with distance parameter defined by "scaled density" in unit of g/cm^2. A commonly used derived expression, often referred to as the modified Bethe–Bloch formula [7], defines the collisional term as

$$S_{col}=2\pi r_e^2 m_e c^2 (N_0 Z/A) G_T C^{\pm} \tag{1}$$

where N_0 is the Avogadro number, A and Z are the atomic weight and charge number, r_e is the classical electron radius and $m_e c^2$ is the electron rest mass energy. The nondimensional factors G_T and C are defined as

$$G_T=\frac{(T+m_e c^2)^2}{T(T+2m_e c^2)}$$