

ADJOINT ELECTRON-PHOTON TRANSPORT

MONTE CARLO CALCULATIONS WITH ITS

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ABSTRACT

A general adjoint coupled electron-photon Monte Carlo code for solving the Boltzmann-Fokker-Planck equation has recently been created. It is a modified version of ITS 3.0, a coupled electron-photon Monte Carlo code that has world-wide distribution. The applicability of the new code to radiation-interaction problems of the type found in space environments is demonstrated.

SUMMARY

The propagation of radiation through matter is described by the Boltzmann transport equation. An adjoint formulation of this equation exists [1]. Recently, one-dimensional calculations with the discrete ordinates method [2-3] have demonstrated that adjoint coupled electron-photon formulation is a powerful tool that can be used for a wide variety of radiation-effects applications. For some types of calculations, the adjoint transport formulation can be much more efficient than conventional or forward transport. The adjoint solution is in some sense an inverse solution of the Boltzmann transport equation. This difference between forward and adjoint transport solution can be best illustrated by a Monte Carlo problem description.

In Fig. 1, a Monte Carlo forward transport calculation of radiation into a satellite is illustrated. A region of interest or "detector" is the rectangular volume inside the satellite. The detector may be an actual detector, a sensor, or an integrated circuit board in which it is necessary to determine dose. A Monte Carlo forward history begins with a source particle at the space-satellite interface (actually any non-reentrant surface surrounding the satellite) and proceeds to follow the transport of this particle as well as secondary particles. Generally in the electron-photon cascade, particles either lose energy or scatter elastically. If the detector region is very small compared to the entire satellite, such that it subtends a small solid angle with respect to the location of the source particles which can reach the detector, then very few of those source particles or their secondaries will "score" or contribute to the dose in the detector. Since the statistical accuracy of a Monte Carlo solution depends on the number of particles that score, forward transport can be very inefficient for such small-solid-angle-type problems that arise in the shielding of satellite components. In general, forward Monte Carlo is inefficient when the "detector" occupies a small region of the phase space.

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Adjoint Monte Carlo offers a much more efficient way of performing a small-detector transport calculation like the one described. As shown in Fig. 2, all adjoint particles, or adjunctons, in an adjoint calculation originate in the region of interest. Thus the size of the detector has no effect on efficiency. Indeed, even a point-dose calculation can be performed in adjoint mode. Source adjunctons (and secondary adjunctons) are followed backwards from the detector to the space-satellite boundary. In a sense, adjoint transport is a time-reversed transport in which particles either increase in energy or scatter elastically as a result of interactions. Adjunctons score if they emerge with the same energy and at the same position as the radiation source. The direction of a scoring adjuncton is however opposite to that of an allowed source particle. Thus adjoint Monte Carlo is efficient when the source is broadly distributed in phase-space. Such is the case in space radiation environments when a mission-averaged source is incident on all sides, from all directions, and with a broad energy spectrum. In general, adjoint Monte Carlo is inefficient when the source occupies a small region of the phase space. For instance, adjoint Monte Carlo would not be efficient (i.e. a large run time would be needed for acceptable statistical uncertainty) for a mono-energetic, pencil-beam source. As will be shown, the adjoint method is still efficient if the only part of the phase-space is restricted (e.g. a mono-energetic source)

In most electron-photon Monte Carlo codes, the phase-space parameters of a particle are not discretized, but are allowed to vary continuously. Such is the case with ITS 3.0 [4], a coupled electron-photon Monte Carlo code that has world-wide distribution. In a purely continuous-energy Monte Carlo code, the adjoint coupled electron-photon algorithm is difficult to implement [5]. However, the multigroup approximation [1], an energy approximation conventionally employed in discrete ordinates codes, can be used to make the adjoint formulation amenable. In a Monte Carlo context, the multigroup approximation need only be used to format the cross sections. The phase space of the particles in the Monte Carlo algorithm can remain continuous. This is important, since a continuous energy is needed to properly treat the slowing down of charged particles. Thus, our method is a hybrid multigroup/continuous-energy algorithm [6]. In order to exploit the efficiencies of the adjoint approach, we have recently created a version of the ITS 3.0 which implements this algorithm.

The applicability of adjoint electron Monte Carlo to space-radiation dose predictions has been previously demonstrated with the NOVICE code package [7]. Our work differs from this earlier work in several respects. Most significantly, our work is based on a technique for solving the Boltzmann-Fokker-Planck (BFP) equation, a special form of the Boltzmann transport equation for charged particles. No attempt is made to recast the angular-straggling and energy-straggling algorithms of the continuous-energy ITS code into an adjoint formulation. Rather, such effects are modeled by other means in the adjoint solution of the BFP equation. Our modified version of ITS also models all of the coupled electron-photon processes that are currently modeled in ITS 3.0. In particular, fluorescence radiation, which can be difficult to model in adjoint fashion [5], is explicitly modeled. The multigroup-formatted cross sections generated by the CEPXS code [2] are used. This code produces multigroup cross sections for all electron-photon interactions above 1.0 keV. It has recently been amended to utilize the latest cross section data bases [4] developed at the National Institute of Science and Technology.

To demonstrate the small detector calculation, a simple problem that incorporates many features of a space-radiation dose problem was constructed. The detector was a small cube embedded off-

center in an aluminum shield in the shape of a canonical (1x2x4) brick. The ratio of the volume of the detector to the shield was about 10^{-4} . The shortest dimension of the shield corresponded to a fifth range of five MeV electrons. The shield was exposed to an isotropic flux of electrons on all faces. A single adjoint and five forward Monte Carlo calculations were carried out. The forward calculations had comparable, but no better, statistical uncertainty estimates. As shown in Fig. 3, the results were in excellent agreement, but the single adjoint calculation was 50-100 times faster than any one of the forward runs. In addition to overcoming the "small detector" problem in Monte Carlo calculations, the adjoint approach offers another advantage. Note that Fig. 3 represents the dose from an ensemble of mono-energetic sources (approximately fifty). Since this data was obtained in single adjoint calculation, the effective efficiency of the adjoint method for this example is very large relative to an ensemble of forward calculations. Indeed, Fig. 3 can be used to obtain the response for any source that spans the energy range over which the adjoint calculation was performed. This ability to calculate a response function for any general source is another advantage of the adjoint approach.

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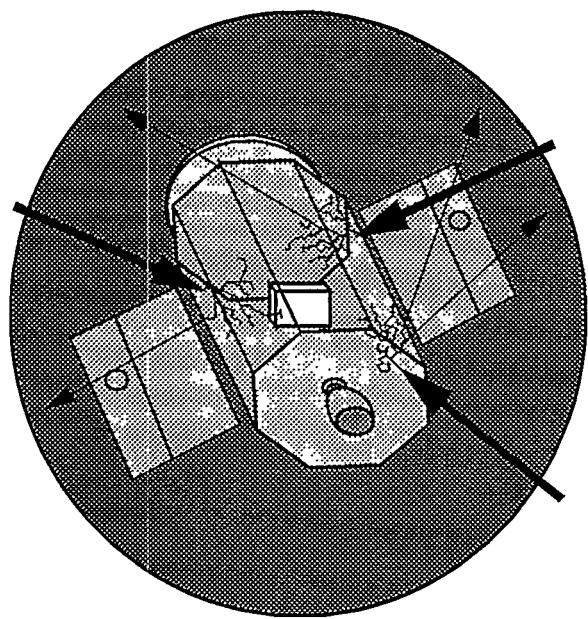


Fig. 1. Forward Monte Carlo

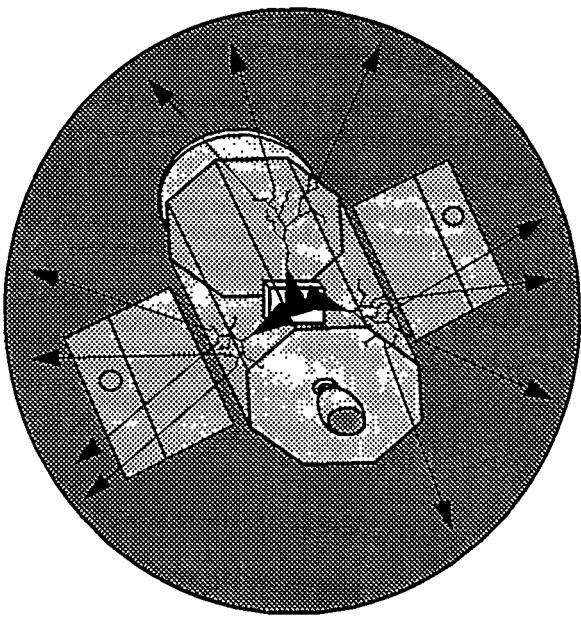


Fig. 2. Adjoint Monte Carlo

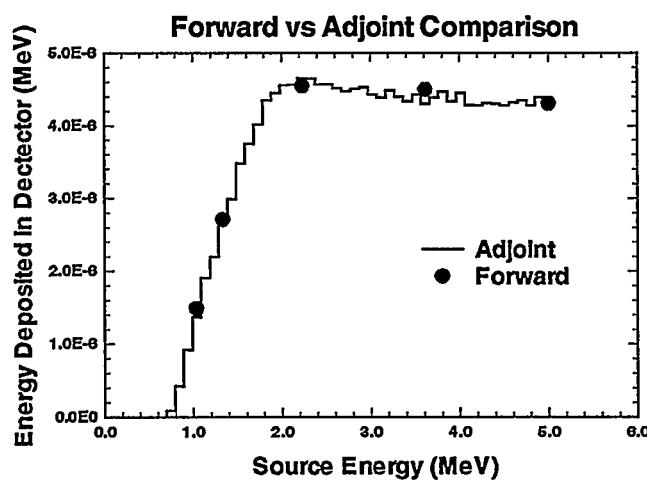


Fig. 3. Comparison of Forward and Adjoint Calculations