Atmospheric Gamma-Ray Transport from a Radioactive Cloud to a Low Earth Orbit Satellite using MCNP[1]

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INTRODUCTION

Satellite remote detection of gamma rays from nuclear events has been an area of interest since 1963 with the launch of the Vela satellites. The Vela satellites were installed to detect atmospheric nuclear testing to help ensure compliance with the Partial Nuclear Test Ban Treaty. The Vela satellites were only the beginning: over the proceeding years, several satellites with gamma-ray detectors installed on them have been placed into different orbits to detect atmospheric testing of nuclear weapons and to track associated fallout clouds. In this paper, we model the gamma-ray transport from a radioactive cloud to a Defense Meteorological Satellite Program (DMSP) satellite [1] at 850 km altitude using MCNP; though the majority of relevant test-detecting satellites have been launched to orbits above low earth orbit, the altitude of a DMSP satellite was chosen as an initial altitude to show the work described here. In addition to modeling the gamma flux at the satellite, we also modeled the detector response using MCNP's pulse-height (F8) tally. Long-range gamma-ray transport through air is a computationally difficult problem that struggles to reach convergence using stochastic methods without the use of variance reduction methods. The small angle aspect of the problem combined with the long distance and the exponential atmosphere for the gamma rays to travel through are just a few of the challenges present in this problem that may be alleviated using variance reduction. In this paper, we will analyze two types of variance reduction techniques, weight windows and DXTRAN spheres, and identify the technique that works better for solving this problem.

DESCRIPTION OF THE ACTUAL WORK

Modeling the gamma-ray transport from a cloud to a satellite is problematic from the beginning because of the spherical divergence of the gamma-ray flux. In addition to the large distance, absorption and scattering within the atmosphere must be considered in the attenuation of the gamma-ray flux. This problem has been analyzed in the past by various teams at Los Alamos National Laboratory, with the conclusion that using point detector estimators (MCNP's F5 tally) is the most efficient solution to the issue [2, 3]. A point detector tally is adequate in estimating the gamma-ray flux at the satellite location, but this technique cannot provide a reasonable approximation of the detector response associated with this gamma-ray flux; rather, simulation of the pulses produced in a detector via MCNP's pulse-height tally is necessary. For this work, the point detector tally and a simple ray tracing method were used as a baseline comparison for the different variance reduction techniques that were used to converge the pulse-height tally.

The ray tracing calculation was performed using a Python script that used the average mass densities within atmospheric layers of increasing height, as well as linear attenuation coefficients defined at sea level in the familiar attenuation equation

$$I(x) = \frac{I_0}{4\pi x^2} e^{-\left(\frac{\mu}{\rho}\right)_0 \sum_i^N \rho_i x_i}, \tag{1}$$

where I is the attenuated gamma-ray flux, I_0 is the gamma-ray flux at the radioactive cloud, x is the distance between the radioactive cloud and the satellite, $(\frac{\mu}{\rho})_0$ is the mass attenuation coefficient for air defined at sea level, and ρ_i is the density of air in the ith atmospheric layer, located a distance x_i from the radioactive cloud.

The Earth and its atmosphere were modeled in MCNP (a Visual Editor graphic of the model can be seen in Figures 1 and 2). The model consisted of a spherical Earth and an atmosphere represented by discrete spherical shells of varying density. The density and molecular consistency of the different layers of the atmosphere were retrieved from the Naval Research Laboratory atmospheric database (NRLMSISE [4]). The atmosphere was modeled to an altitude of 1000 km. The atmosphere was discretized into 1 km sections up to an altitude of 100 km, then into 100 km sections from 100 to 1000 km. The radioactive cloud was modeled as a sphere with a 5 km radius. The cloud was placed at an altitude of 20 km above the Earth. The cloud was assumed to have an evenly distributed source of 1 MeV photons throughout its volume. The satellite was modeled simply as the detector crystal, a 3 in. × 3 in. cylindrical NaI detector with one of its faces aimed directly at Earth. The satellite was placed at an orbital altitude of 850 km and centered directly above the radioactive cloud. The detector was assumed to have perfect energy resolution and an energy range between 0 and 1 MeV with energy bin widths of 0.01 MeV.

Modeling this problem in MCNP without any variance reduction techniques (an "analog" approach) to a statistical uncertainty of less than 5% would be intractable due to the CPU time required. To speed up this calculation, we investigated two different variance reduction techniques: weight-windows using the ADVANTG program and next-event estimation using DXTRAN spheres.

ADVANTG is an automated variance reduction parameter generator for fixed-source MCNP problems [5]. Using the deterministic transport solver DENOVO, ADVANTG produces a space- and energy-dependent mesh-based weight-window

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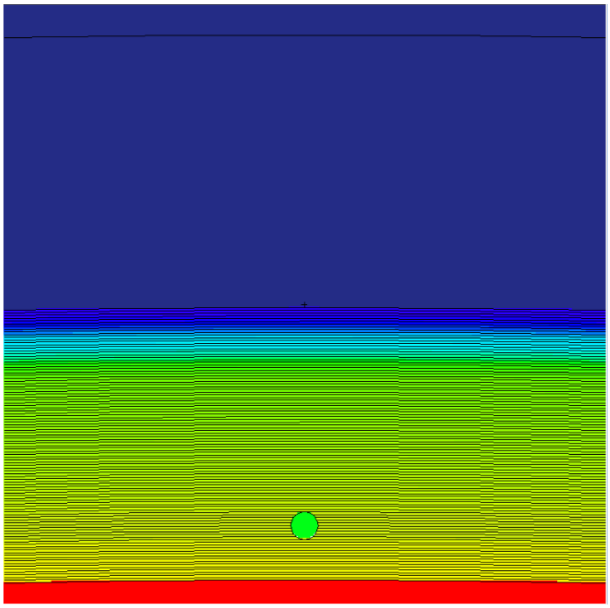

Fig. 1. Visual Editor graphic of the MCNP model showing the radioactive cloud (green sphere) among the discretized layers of atmosphere.

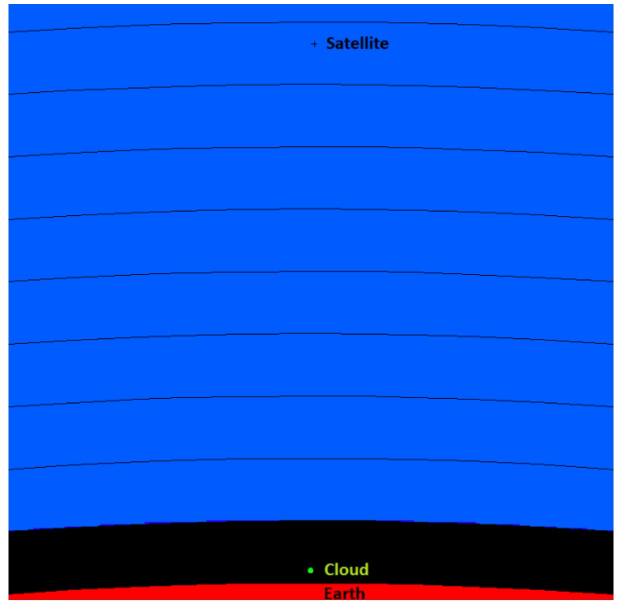

Fig. 2. Visual Editor graphic of the MCNP model showing the relative locations of Earth, the atmosphere, and the satellite detector. The atmospheric layers are indicated by the black lines.

input file based on user specifications, as well as a modified version of the user's input file containing corresponding source biasing parameters. Including these ADVANTG-generated variance reduction parameters has been shown to significantly increase the MCNP figure of merit compared to analog MCNP simulations in a diverse array of problem types [6, 7]. MCNP's figure of merit is defined as [8]

$$FOM \equiv \frac{1}{R^2 T} \tag{2}$$

where R is the relative statistical uncertainty of the desired quantity (i.e., the MCNP tally in question) and T is the computation time in minutes. Because of the large distances involved in radiation transport to a satellite's detector, ADVANTG was implemented in our model to increase the efficiency of tallied quantities (by reducing the number of particle histories that do not contribute to a tally's score).

DXTRAN spheres are an angle-biasing variance reduction technique in which the source and postcollision scattering angles are biased in the direction of the DXTRAN sphere [9]. When a particle undergoes a collision, weighted pseudo-particles are created and transported deterministically along the optical path to the DXTRAN sphere (a method referred to as "next-event estimation"). The DXTRAN sphere is similar to a point detector, but the DXTRAN sphere permits additional sampling of the original particle unlike that of the point detector. A DXTRAN sphere was implemented into our model surrounding the satellite detector to increase the number of particles scattered to the satellite.

RESULTS

To get a baseline answer for this problem, we first ran the model with a point detector tally and compared the results to the ray tracing calculation. The point detector tally was placed inside of a voided-out detector on the satellite and simulated until the answer had a relative statistical uncertainty of less than 5%. The MCNP point detector tally and ray tracing calculation results are compared in Table I.

The uncollided portion of the point detector tally (approximately 2.55% of its total) and the ray tracing calculation agree to within 2.91% error. Though the ray tracing technique only required 5% of the point detector tally's run time to reach a result, the point detector tally will be considered the baseline for pulse-height tally results because of its inclusion of both uncollided and collided gamma flux.

The first variance reduction technique to be implemented was the use of particle weight windows using the ADVANTG program. The spatial mesh was defined with 124×124 voxels in the latitudinal and longitudinal (x and y) directions and 33 voxels at increasing altitudes (the z direction). These meshes were defined coarsely in areas far from the straight-line path between the cloud and the satellite (i.e., regions far from zero in x and y, outside of the region surrounding the cloud-satellite path in z) and more finely in regions proximate to this path. The deterministic calculation was performed using a quadrature of order S_{10} with a third-order Legendre scattering-angle expansion. The step characteristics scheme was used in spatially discretizing the geometry. These options were chosen to minimize run times and maximize the potential for parallel execution of the deterministic solver; thus, weight windows could be produced for 492,000 voxels in less than 29 minutes of CPU time (the remaining voxels lying just outside the problem boundaries to ensure meshing of the entire geometry.).

The second variance reduction program we implemented was a DXTRAN sphere around the detector volume. A single DXTRAN sphere of 200 cm was placed around the detector

TABLE I. Computational efficiency of ray tracing and MCNP point detector methods for long-range radiation transport to satellites 830 km from the radioactive cloud.

	Computation time (seconds)	Particle histories	Figure of merit	Result ($10^{-18}\frac{\gamma}{cm^2}$)
Point detector (Total)	9.600	4,000	6,700	5.17 ± 5%
Point detector (Uncollided)	9.600	4,000	6,700	0.13 ± 5%
Ray tracing	0.446	—	—	0.14 ± 5%

TABLE II. Computational efficiency of analog MCNP point detector results compared to those obtained using DXTRAN spheres and ADVANTG-generated weight windows for long-range radiation transport to satellites 830 km from the radioactive cloud.

	Computation time	Particle histories	Figure of merit	Result ($10^{-18}\frac{\gamma}{cm^2}$)
Point detector	9.60 seconds	4,000	6,700	5.17 ± 5%
DXTRAN	31.2 minutes	3.07 million	21	5.03 ± 5%
ADVANTG*	30.7 hours	11.5 billion	0.22	5.01 ± 5%

* ADVANTG results were obtained at a cloud-to-satellite distance of 0.1 km rather than 830 km.

volume on the satellite. Traditionally, DXTRAN spheres are nested to prevent high-weight particles from skewing the results, but since the likelihood of high-weight particles making it to the DXTRAN sphere on their own is low, one sphere was sufficient. The results from the DXTRAN sphere and weight-windowing methods can be seen in Table II (the simulations were stopped when the statistical uncertainty for the tallies was less than 5%).

The difference in computational time between the DXTRAN sphere and the weight-windowing methods is significant, particularly when ADVANTG results are extrapolated to 830 km. At this distance, the weight-windowing method would require decades of computational time to reach a statistical uncertainty below 5%. Weight windows are an excellent tool for deep shielding problems, but in this case, spherical divergence dominates and makes the model inefficient. In addition, the lack of atmosphere at higher altitudes means that the particles rarely scatter, so weight windowing provides decreasing benefit with increasing altitude. The deterministic transport aspect of the DXTRAN sphere helps with getting particles to the satellite and overcoming spherical divergence that slows down the random walk of the normal Monte Carlo process. The difference between point detector results and those obtained using the DXTRAN sphere is 2.63%, which is expected because they both apply deterministic methods to transport particles to a specific region. The results of the pulse-height tally using the DXTRAN sphere can be seen in Figure 3.

The DXTRAN sphere decreased the computer time needed for the calculation of the pulse-height tally, but the accuracy of the implementation required evaluation. The simulated long-range energy spectrum in Figure 3 lacks many of the features typical of gamma-ray pulse-height spectra, most notably a clear Compton continuum. At large distances such as those involved in this problem, almost all gamma rays reaching the detector from the radioactive cloud will have been scattered at least once before reaching the detector (as mentioned previously, the uncollided flux makes up only 2.55% of the total). This results in a much softer gamma spectrum

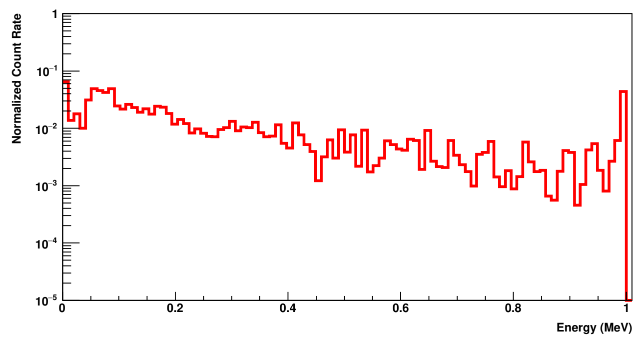

Fig. 3. Pulse-height tally results of the satellite detector using the DXTRAN variance reduction method in MCNP; results have a statistical uncertainty of 5%.

as the distance between the cloud and the satellite increases. To determine the validity of this conclusion, we benchmarked these results to a model using no variance reduction alongside a pulse-height tally with the detector at various altitudes within 0.1 km of the cloud (an altitude of 25.1 km or less). Observing the analog detector response can indicate whether the pulse-height data from the DXTRAN sphere adequately approximates the physical detector response. The pulse-height data from analog models of the detector crystal (at close range) can be seen in Figure 4 next to the DXTRAN sphere-modified pulse-height spectrum from Figure 3.

At distances closest to the source, the pulse-height tally will provide a clear Compton edge and a prominent photopeak, similar to what would be expected in a physical detector response. However, as the detector distance increases, a greater proportion of gamma rays reaching the detector will have undergone single or multiple scattering events, softening the overall spectrum and obscuring the Compton edge. This leftward skew continues to grow as the distance increases to 0.1 km, where the Compton edge is almost completely obscured because almost no unscattered gamma rays reach the detector. Although this effect is most obvious in the DXTRAN-

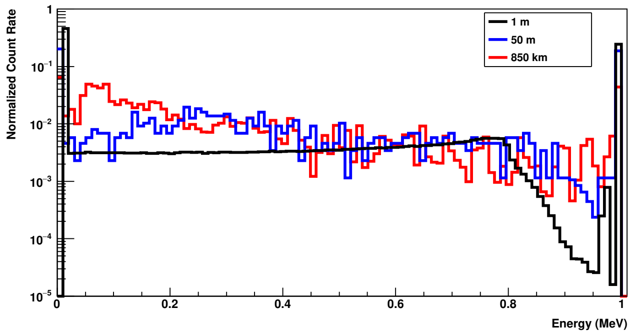

Fig. 4. Normalized pulse-height tally results for MCNP simulations of detectors placed at various distances from a monoenergetic 1 MeV gamma-ray source; results have a statistical uncertainty of 5%.

modified pulse-height results, the pattern among analog simulations indicates that this variance reduction parameter did not significantly affect detector response results.

CONCLUSIONS

Modeling the gamma-ray transport from a radioactive cloud to a satellite in orbit requires variance reduction techniques for MCNP to achieve low uncertainty in a reasonable amount of computer time. Using point detector tallies can compute a gamma flux at a satellite location in under 1 minute of computer time. To estimate the detector response at the satellite using MCNP's pulse-height tally, weight-windowing techniques are far less computationally efficient than using DXTRAN spheres. The spectrum obtained by the pulse-height tally using a DXTRAN sphere has a valid physical detector response compared to non-variance reduction pulse-height tallies at closer distances. In conclusion, using DXTRAN spheres is the better method in MCNP for converging the gamma-ray flux from a cloud to a satellite detector.

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