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MCNP6 Elevation Scaling of Cosmic Ray Backgrounds

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INTRODUCTION

The galactic cosmic-ray (GCR) source option[1] was implemented in the all-energy, all-particle transport code MCNP6[2] in 2010. This source option along with other newly added features to MCNP6 have been used to produce increasingly accurate global cosmic and terrestrial background flux data files (background.dat).[3] This data file is produced on a grid and is read and sampled by MCNP6 whenever a user invokes the background source option. The most recent adaptation of this data file, Version 4, will be completed in 2014. This paper reports on current progress toward enhancements that have been made to the modeling and simulation of these background spectra, in particular the elevation scaling used to produce more accurate spectra at off-grid locations.

Cosmic radiation continuously bombards Earth with various particles, such as protons, alpha particles, and heavier nuclei, some of which are deflected by the Earth's shielding magnetic field. Particles that carry sufficient momentum can overcome the deflection and penetrate into the atmosphere. The sufficient momentum is dependent on the terrestrial coordinates due to the shape of the Earth's magnetic field and the Lorentz force's proportionality to the sine of the angle between the velocity vector of the incoming particle and the magnetic field direction.

As the particles propagate through the atmosphere, collisions with atmospheric molecules generate secondary particles such as neutrons, protons, photons, muons, pions, and other exotic particles. These secondary particles often have sufficient energy to undergo additional nuclear interactions, and so on, forming what is known as a cascade shower.

The particles in the cascade shower are constantly undergoing energy losses due to interactions, especially charged particles whose paths are bent into helical trajectories around magnetic field lines. These energy losses make the integral flux of the cosmic background at the ground level highly dependent on the atmospheric depth traveled by the incident particle and its progeny, and therefore dependent on the elevation of the ground where the cascade deposits its energy. For relatively small depth changes of approximately 100 g/cm^2 or less, the ground-level cosmic flux follows an exponential model.[3,4]

The tabulation of background particle fluxes on the surface of the earth is important for a variety of reasons, one of which is the design of nuclear material detection systems. This method is also useful in producing user-specified effective attenuation lengths for particles. Attenuation lengths are an essential parameter used to compare particle spectra from different locations, elevations, and energy ranges. Traditionally these attenuation lengths are inferred from measured data. Now with the ability to simulate an accurate galactic cosmic ray source and transport it and its shower through a modeled atmosphere, these attenuation lengths can be calculated for any set of conditions.

DESCRIPTION OF ACTUAL WORK

The simulations reported here used various models and data sources to represent atmospheric and terrestrial conditions as accurately as possible. These conditions were used to model the propagation of the initial light- and heavy-ion GCR particles as well as all subsequently produced shower particles through the atmosphere and into the earth's surface. The atmospheric model is based on the U.S. Standard Atmosphere, 1976.[5] The terrestrial model was derived from the nominal soil composition presented in Shue, 2006[6] as well as location-specific USGS data.[7] GCR particles were transported from 65 km above sea level to ground level utilizing periodic boundary conditions to account for the asymmetry introduced by the location-specific magnetic field vector. The specifics of the models and data used can be found in *MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 4*.[8] The fluxes produced by MCNP6 on the 2054 point grid provided the necessary data to calculate an elevation scaling factor that will be used to scale background neutron fluxes from the grid-point elevation in the background.dat file to a user-specified elevation.

RESULTS

Due to the homeland-security focus of this work, the data used for the background.dat elevation scaling was taken entirely from US terrestrial locations. The resulting 39 grid points that lay within the contiguous United States span 16^{o} in latitude from 30^{o} N to 46^{o} N. Because the entire energy spectrum is normalized by the total integral flux, those values were used to compute the scaling factors instead of using energy ranges with more constant attenuation lengths. The integral flux values at each location were renormalized by the lowest elevation's value to calculate scaling factors. The scaling factors for

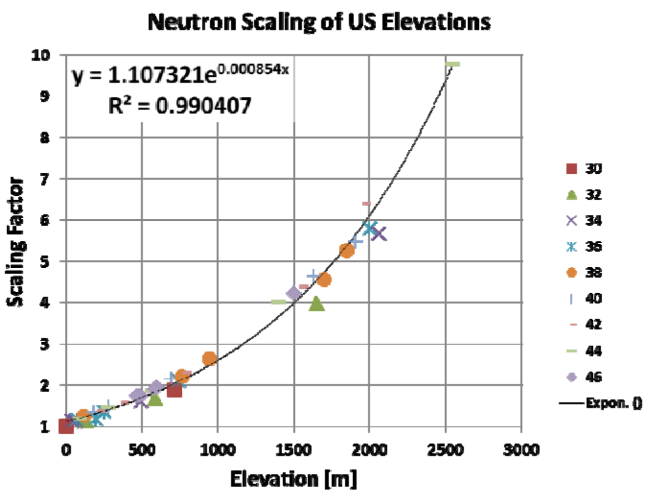

Fig. 1. Integral neutron fluxes from terrestrial US grid-point locations along with the corresponding exponential fit used to scale grid elevations to user's input. Scaling factors are demarked by latitude.

$$F_{scaling} = \frac{e^{BZ_{user}}}{e^{BZ_{grid}}} = e^{B(Z_{user}-Z_{grid})} \qquad (1)$$

$F_{scaling}$ = Flux elevation scaling function.
B = Exp.fit parameter for US grid points (8.54e-4).
Z_{user} = User defined elevation (3rd entry on LOC).
Z_{grid} = Elevation of nearest grid point.

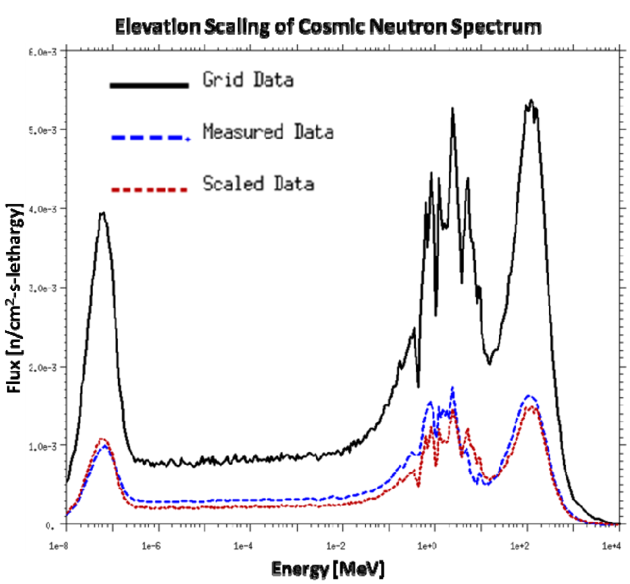

Fig. 2. Spectrum from background.dat at 38° N, 120° W, 1,695 m grid point (black) and scaled to SNLL location 37.7° N, 122.7° W, 196 m (red) where measured data was taken (blue). The scaling function value of 0.2779 was applied to scale from 1,695 m to 196 m.

each grid-point location, as well as the exponential fit to the data, can be seen in Fig. 1. The function used by MCNP6 to scale the integral flux utilizing the fit parameter from Fig. 1 is shown in Eqn. 1. As shown in Fig. 2, the scaling of the flux to off-grid elevations vastly improves the accuracy of the spectrum being sampled by MCNP. The next release of MCNP6 will include this feature along with additional warnings when a user attempts to scale an ocean water grid point spectrum to a terrestrial location. MCNP users will also have the option of specifying a -1 on the 3rd entry of the LOC keyword to omit any elevation scaling and default to using the nearest grid point's elevation that is in the background.dat file.

The background data file also includes photon spectra on the same grid for both cosmically induced photons as well as terrestrially produced from naturally occurring radionuclides. An initial attempt was made to scale the photon spectra for elevation, but it was found that the terrestrially produced photons, which account for the majority of the integral flux, did not have a strong enough correlation with elevation, see Fig. 3. However, the cosmic photons show a similar exponential decrease with elevation as the neutrons. Fig. 4 shows the integral photon data converted to scaling factors along with an exponential fit. This may be incorporated into a future release of MCNP as an energy dependent scaling factor but will not be included in the next release.

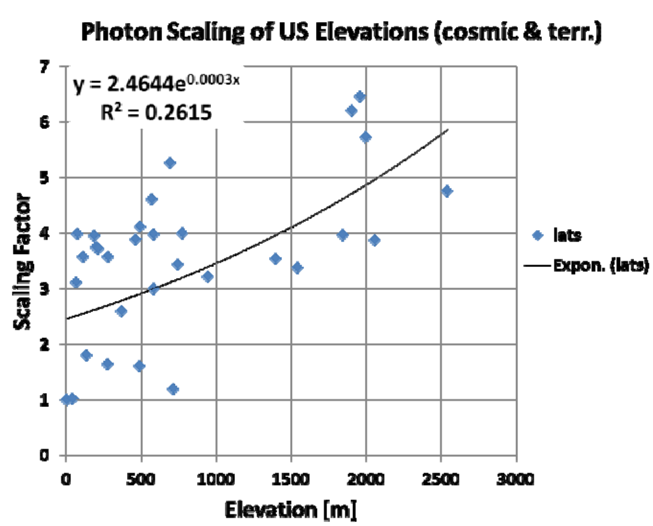

Fig. 3. Integral photon fluxes from terrestrial US grid-point locations, along with the corresponding exponential fit for terrestrially and cosmically produced photons.

This capability can be expanded to a variety of other particles of interest to obtain effective attenuation lengths. As an example, Table 1 lists the effective attenuation lengths for neutrons interpolated from the same U.S. data for energies greater than 10 MeV. This provides latitude and elevation dependent attenuation lengths for any

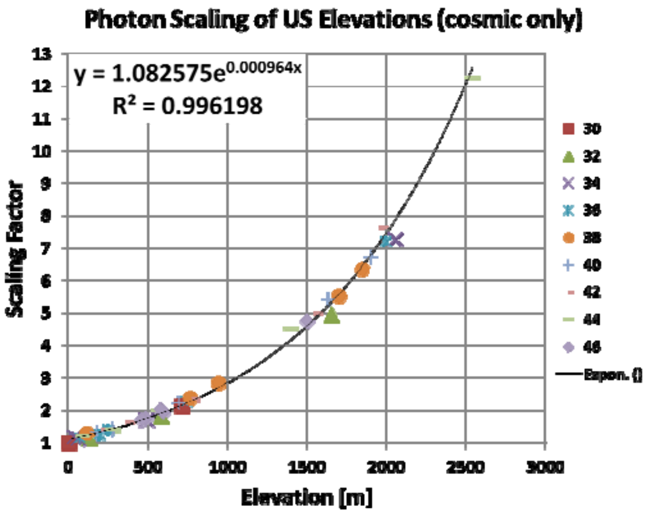

Fig. 4. Integral photon fluxes from terrestrial US grid-point locations along with the corresponding exponential fit for cosmically produced photons only.

cosmically produced particle of interest. This is used frequently in the area of studying terrestrial cosmogenic nuclides (TCN). The current data for this field is widely varying being dependent on field measurements taken for a constraining set of conditions thereby reducing its usability, see Gosse and Phillips, 2001,[9] Desilets, 2001,[3] and Gordon, 2004.[4]

TABLE I. Eff. Neutron Attenuation Lengths (> 10 MeV)

Latitude [°]	Λ_f [g cm^{-2}]	Elev. Range [m]
30	133.4991	3 < Z < 715
32	134.2104	133 < Z < 1652
34	134.8565	41 < Z < 2060
36	127.3388	74 < Z < 1999
38	133.8514	115 < Z < 1848
40	131.5849	185 < Z < 1906
42	124.1478	213 < Z < 1960
44	121.9333	92 < Z < 2542
46	125.3033	464 < Z < 1500
30-46	126.8095	3 < Z < 2552

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