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Improvement of Air Transport Data and Wall Transmission/ Reflection Data in the SKYSHINE Code
(1) Calculation of Line Beam Response Function for Gamma-Ray Skyshine Analysis

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The line-beam response functions (LBRFs) of a key component of a computationally simple gamma-ray skyshine analysis are generated using an electron-photon cascade Monte Carlo code EGS4. The LBRFs $R(E_0, \Phi, x)$ are given with the air-kerma (Gy per photon), 7 photon source energies ranging from 0.5 to 10 MeV, for source-detector distances between 10 and 2,000 meters, and at 19 emission angles from 0 ~ 170 degrees, as measured from the source-detector axis. Especially, the values of $R(E_0, \Phi=0.0$ and $0.1, x)$ are extremely larger than the ones of LBRFs produced by the point kernel model or the COHORT code. The LBRF is accurately approximated by a four-parameter formula. Values of four parameters for the approximate LBRF are described by monotonic and smooth curves with respect to the energy E_0 and the emitted angle Φ.

KEYWORDS : gamma-ray shyshine, line beam response function, EGS4, MCNP, COHORT, point kernel model, four-parameter approximation formula, distance, photon beam emitted angle, energy dependence

I. Introduction

Lynch et al.[(1)]calculated the air-scattered flux (or dose rate) for gamma rays with the Monte Carlo method. The calculations were performed at source-detector separation distances of from 5 to 100 feet, for source energies from 0.6 to 12 MeV and beam angles with respect to the source-detector axis from 1 to 180 degrees. Their results were used as the first line beam response function(LBRF). The skyshine dose rate R(d) rising from a bare, collimated point source which emits $S(E, \Omega)dEd\Omega$ photons per unit time with energies in dE about E into directions $d\Omega$ about Ω is found by integrating the LBRF over all source energies and over all photon emitting directions allowed by the source collimation. Lately, the LBRFs for distances greater than 100 feet have been calculated using COHORT Monte Carlo code[(2)] up to 3,750 feet and at 17 beam angles, and for source energies of 0.6, 1, 3 and 6.2 MeV. The values of COHORT were incorporated into the SKYSHINE III code[(3)].

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Bearnard[(4)] has suggested that single-scattered flux or dose rate with exponential attenuation and without buildup factor is a good approximation for evaluating the scattered flux or dose rate in air. Trubey[(5)] proposed an elementary single scattering approximation ignored both the contribution of the exponential attenuation and buildup of photons in the air, and compared his technique with the results of Lynch et al.. Kitazume approximation[(6)] was based on the single-scattering formula by incorporating exponential attenuation and a Taylor-type buildup factor for the energy of scattered gamma rays. His approximation represented the results of Lynch et al. better than those by Trubey at large distances for all source energies. The success of their works had led to a further development of the single-scattering method for applications to more complicated skyshine geometries[(7)]. Specific applications of this point kernel(single scattering) model to the skyshine have been exemplified by the work of Roseberry and Shultis[(8)], Chou et al.[(9)] and George[(10)]. Shultis et al.[(11-13)] calculated the LBRFs by the point-kernel model, and they later fitted the three parameter RRA formula to the above LBRFs. A set of fitting parameters made the LBRFs continuous in energy and emission direction. The values of the point kernel LBRFs represented by three parameter approximation were incorporated in the SKYSHINE III code.

The values of four parameter fitting function to the LBRFs proposed by one of the authors [(14)] were shown for the 280 fits to their reference data for energies of 10 MeV or less. It was

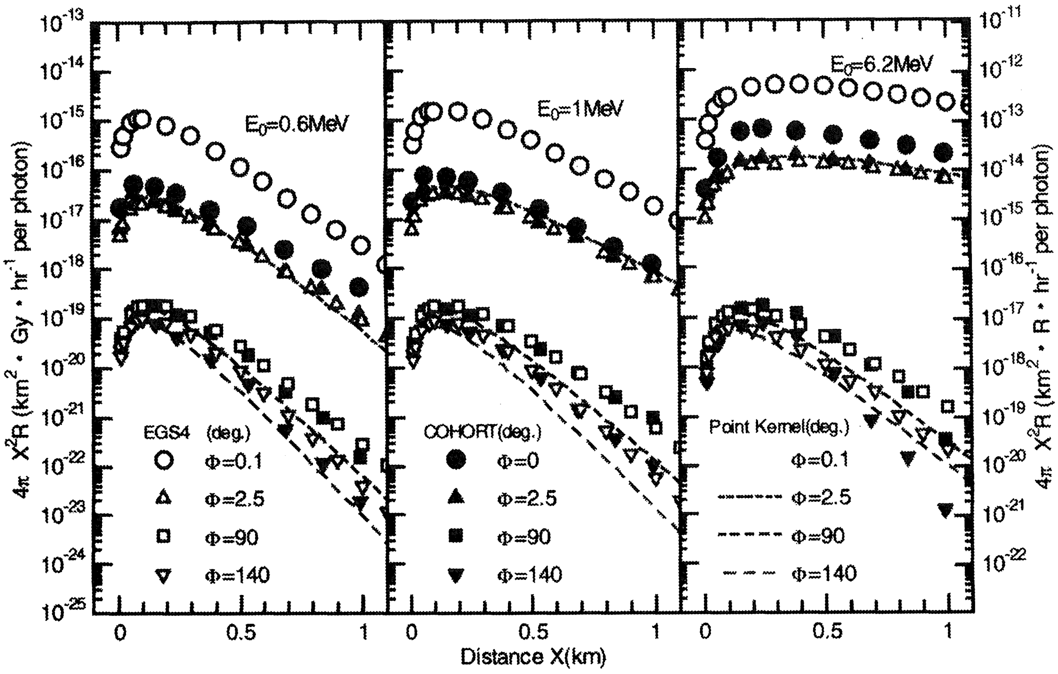

Fig. 1 Comparison of the LBRFs obtained by EGS4, COHORT and the point kernel model for source energies of 0.6, 1 and 6.2 MeV and Φ of 0.1(Φ=0 for COHORT), 2.5, 90 and 140 degrees.

shown in Ref(13). that the four parameter approximation represented their LBRF data much better than did the three parameter approximation. The authors made clear that the LBRFs obtained by the point kernel model were slightly larger at small emitted angle Φ from the source-detector axis, and are smaller at large angle Φ than the Monte Carlo calculations[15, 16] as the distance from the point source increases, especially for higher energy[17].

II. EGS4 Calculation for the Line-Beam Response Function

In previous LBRF study used skyshine analysis[17], it was shown that the results of COHORT for the source energies of 0.6 and 6.2 MeV were smaller than the ones of EGS4 [15] for far-field skyshine calculations. Furthermore, the results with the point kernel model were smaller than the ones of EGS4 for far-field calculations as the emitted angle Φ increases. **Figure 1** shows comparison between the LBRFs obtained by the EGS4, the point kernel model, and the COHORT, for source energies of 0.6, 1, and 6.2 MeV and for emitted angles Φ of 0.1(or 0), 2.5, 90 and 140 degrees. The values of LBRFs for Φ=0.1 degree calculated by the EGS4 are extremely larger than those of the other methods. The air attenuation coefficients used in the EGS4 were taken from PHOTX[18]. The value of the point kernel model is extrapolated from the LBRF values of 0.5 and 1.5 degrees obtained by four-parameter empirical formula [13]. The value of Φ=0.0 degree of COHORT is given in their table. The values of three LBRFs are calculated under the geometry that a point source and a point detector are located in an infinite air medium. The values of EGS4's LBRF for 0.1, 2.5 and 5 degrees multiplied by angle Φ are almost the same. Furthermore, those of LBRF are calculated for some angles between 0.1 and 2.5 degrees, and the values multiplied by Φ get on the same line, too. This suggests the fact that the values of LBRF for angle within 2.5 degree are larger than those for other method. Hereafter, the results of LBRF for small angle require further examination.

In the present study, the accurate values of LBRFs for very small angle Φ are offered with the EGS4 calculations. The results are verified by the MCNP code[16] in the same calculated condition. The new reference LBRF data were calculated at 19 emitted angles of 0.0, 0.1, 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160 and 170 degrees, at distances of 24 points between 10 and 2,000 meters, and for 7 source energies of 0.5, 1, 2, 3, 5, 7 and 10 MeV. Where, the value of for angle Φ=0 degree is the average value between 0 to 0.1 degrees.

The dose rate at the detector is measured by the average dose rate of photons reached on the circular disk of radius 0.1x, where x is a distance between a source and a detector for unit of meter. The dose rate reached on the disk adopted as the value of the point detector. It is made sure that both dose rates reached on a circular disk and a point detector from photons emitted to the angle of Φ=2.5 and 5 degrees are the same for the source energy of 1 MeV. In the case of Φ=2.5 and 5 degrees, the radius of the detector of the circular disk makes smaller than 0.1x, like directly emitted photons from a source do not reach at the detector.

In the process of production of reference values R of the LBRF used the EGS4 code, the values of the LBRF for 1 MeV

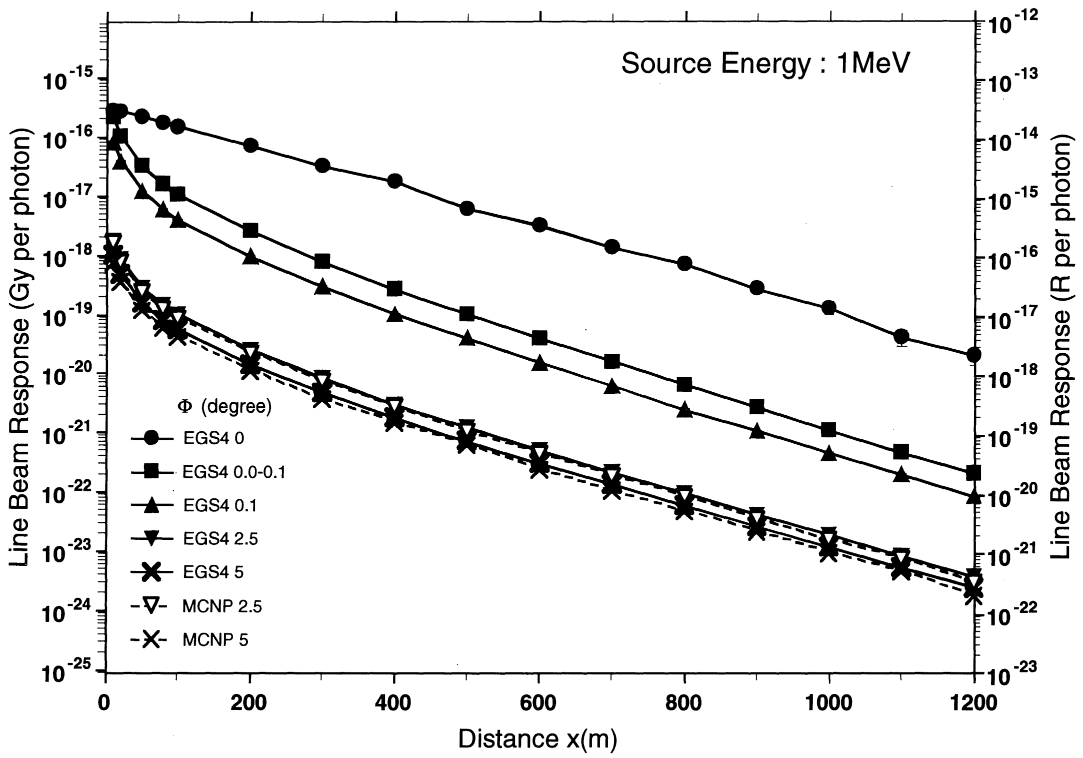

Fig. 2 Comparison of the LBRFs obtained by EGS4, MCNP for 1 MeV beam emitted at Φ=0, 0.1, 2.5 and 5 degrees.

beam emitted at 0 degree from the source-detector axis behave like exponential attenuation as seen in **Fig. 2**, where the contribution of direct beam is not included. This is different tendency from curves for the emitted angle of 0.1, 2.5 and 5 degrees for near-field skyshine. It was confirmed that the scattering point locates at the nearest place of the detector, and that the contribution to large value of LBRF for Φ=0 degree decreases rapidly as the distance from the detector increases . Therefore, the large dose rate due to contribution of gamma-ray entered at the detector does not appear for the angle except 0 degree, as seen in Fig.2.

From the above result, the value of LBRF at Φ=0 degree should treat unlike the other angles. The value of LBRF at Φ=0 degree is almost due to direct photon. In practice, the value of LBRF between Φ=0 and 0.1 degrees is adopted as the average value of LBRF by beams emitted at the area within Φ=0 and 0.1 degrees. The values of LBRFs for a fixed angle steeply decrease up to about 100 m, after that loosely decrease, and their lines for a fixed distance from the source decrease with increasing emitted angle.

The results of LBRFs for source energies 0.5 - 10 MeV are similar values at the distance 10 m at fixed emitted angle. However, those at 2,000 m separate each other dependent on the source energy at fixed emitted angle, because the differences of attenuation coefficients and of scattering angles distribution.

III. A Four-Parameter Approximation of the LBRF

An approximate LBRF was obtained by fitting the following four-parameter empirical formula[14] to the LBRF values calculated with the EGS4 code.

$$R(x', E, \Phi) = \kappa E(\rho / \rho_0)^2 (x')^{b-dx'} \exp(a - cx') \qquad (1)$$

where, $x' = x\rho/\rho_0$.

Here ρ_0 is the standard air density (=0.001225g cm^{-3}), ρ is the actual air density, E is the photon energy in MeV, and for $\kappa = 1.308\times10^{-13}$, the LBRF R has units of Gray/photon.

Values for the parameters a, b, c and d, which depend on E and Φ, were obtained by fitting the above equation to values calculated with the EGS4 code. At the first, these parameters were determined by least-square fitting a four-parameter formula (1) to calculated values of the LBRF. After that, the variations of each parameter make modify to be smooth for interpolation with regard to the arbitrary source energy and emitted angle.

The values of four parameters a, b, c and d fitting to the EGS4-LBRF are plotted for emitted angle at the fixed source energy in **Fig. 3**. The values of parameter '-a' suddenly increase and become flat as the emitted angle increases. This corresponds to the fact that values of LBRF, at the first, steeply decrease after that gently do with increasing emitted angle. Also, the curve of '-a' increases monotonously with increasing source energy, at the fixed emitted angle. The parameter '-b' monotonously decrease up to emitted angle about 90 degree, and becomes flat up to the emitted angle 170 degree. The values of parameters 'c' and 'd' give complicated curves for the values of LBRF. Both parameters behave repulsively or cooperatively, in order to give good fitting.

IV. Conclusions

The accurate values of gamma-ray reference LBRFs in an infinite air medium have been produced with the EGS4 code.

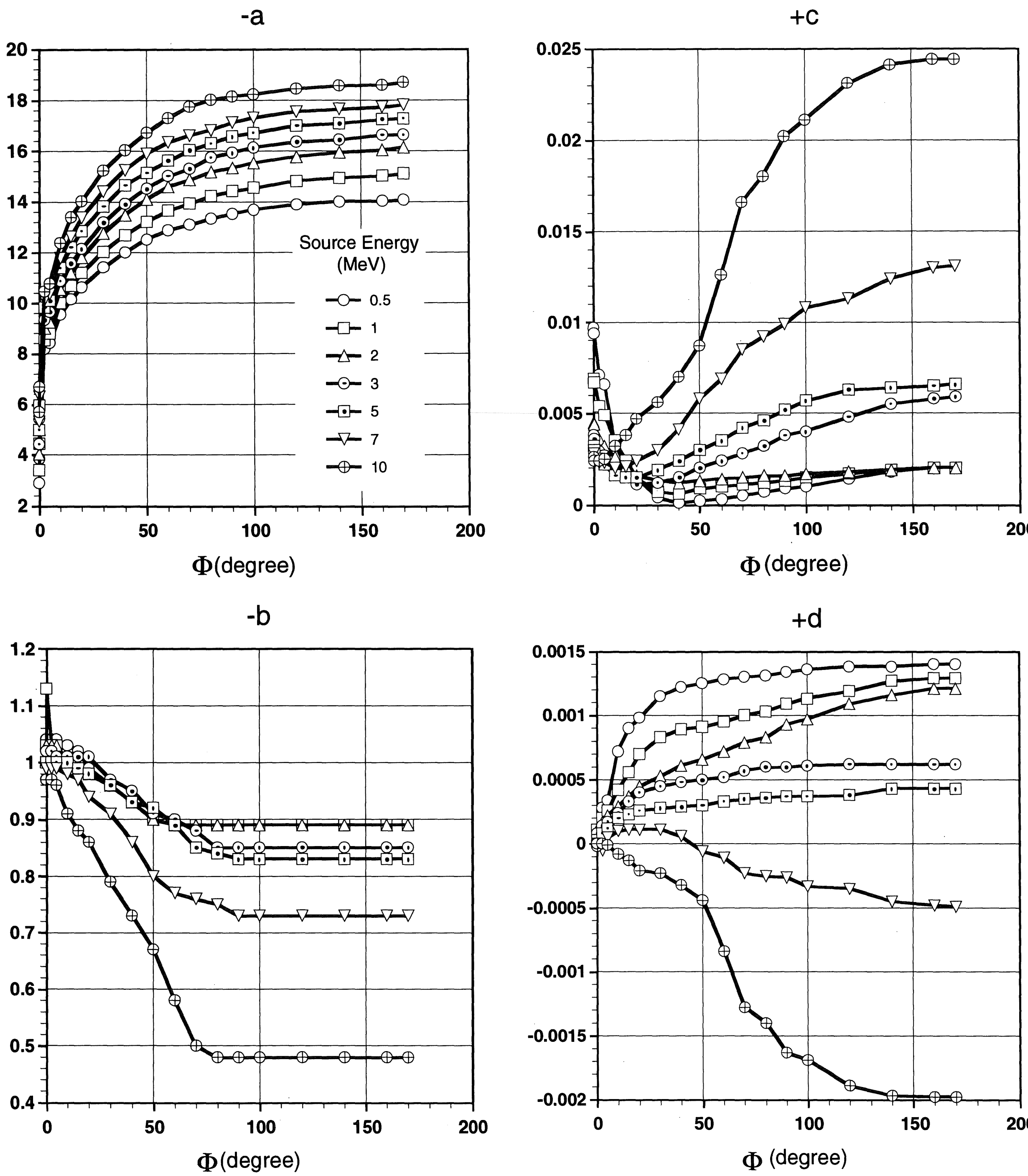

Fig. 3 Dependence of parameters a, b, c, d for the four-parameter approximate LBRF on emitted angle Φ at source energies of 0.5, 1, 2, 3, 5, 7 and 10 MeV.

A refined EGS4 calculations was able to predict the LBRF at distances up to 2,000 m from the source. Furthermore, the LBRFs for emitted angle smaller than 2.5 degree were larger than the results by the other methods. It will influence to design calculation greatly.

The reference LBRF data were used to obtain approximation for the LBRF based on a four-parameter formula. The four coefficients for the approximate LBRFs was based on minimizing the maximum absolute fractional deviation between the LBRF values and the approximation formula. After that, the values of four coefficients were sifted to be smooth for interpolation to the values in the respect to the arbitrary source energy and emitted angle. However, the values of the minimized maximum have become only larger than the ones determined by least-square fitting a four-parameter formula.

The new LBRF represented by four-parameter approximation formula will be applied to bared and shielded gamma-ray skyshine analysis and given accurate response in a short time.

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