SKYDOSE: A Code for Gamma Skyshine Calculations Using the Integral Line-Beam Method

(version 2.3)

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1 Summary

SKYDOSE evaluates the gamma-ray skyshine dose from a point, isotropic, polyenergetic, gamma-photon source collimated by three simple geometries: (1) a source in a silo, (2) a source behind an infinitely long, vertical, black wall, and (3) a source in a rectangular building. In all three geometries an optional overhead slab shield may be specified. This code is based on the integral line-beam method using an improved 3-parameter approximation for the line-beam response function. For shielded sources, an approximate method is used based on exponential attenuation with buildup in the shield. The source energies E must be between 0.02 and 100 MeV, except for sources with an overhead shield, for which case $0.02 \leq E \leq 10$ MeV. The maximum source-to-detector distance is 3000 m for $E \leq 10$ MeV and 1500 m for higher energies.

For more complex geometries and a more accurate treatment of the overhead source shield, a companion code MCSKY is available [1]. This code, which is much more computationally intensive, is based on a hybrid Monte Carlo and line-beam method.

2 Theory and Methods

The theory and validation for the methods used by SKYDOSE are described in detail in other references [2, 3, 4]. In this section a brief overview of the integral line-beam method used by SKYDOSE is presented.

2.1 The Integral Line-Beam Method: Unshielded Source

The integral line-beam method for skyshine analyses is based on the availability of a line-beam response function (LBRF) $\Re(x, E, \phi)$ which is the air kerma (centigray per photon = rad per photon) at a distance x from a point source that emits a photon of energy E into an infinite air medium at an angle ϕ relative to the source-detector axis. The skyshine dose $R(x)$ arising from a bare, collimated, point source which emits $S(E,\mathbf{\Omega})\,dE\,d\Omega$ photons with energies in dE about E into directions $d\Omega$ about $\mathbf{\Omega}$ is found by integrating the LBRF over all source energies and over all photon emission directions allowed by the source collimation, namely [2]

$$R(x) = \int_0^\infty dE' \int_{\mathbf{\Omega}_s} d\Omega\, S(E',\mathbf{\Omega})\, \Re(x, E', \phi(\mathbf{\Omega})). \tag{1}$$

Here $\mathbf{\Omega}_s$ represents those directions in which radiation can stream directly from the source into the atmosphere. Implicit in this approach is the assumption that the ground can be treated as an infinite air medium. This assumption has proven to be quite reasonable for most gamma skyshine problems [5].

When the source energy spectrum is represented by a multigroup approximation, Eq. (1) is written as

$$R(x) = \sum_{g=1}^{G} \int_{\mathbf{\Omega}_s} d\Omega\, S(E_g,\mathbf{\Omega})\, \Re(x, E_g, \phi(\mathbf{\Omega})). \tag{2}$$

The above results are based on two implicit approximations. First, the walls of the source collimation are assumed to be "black", i.e., any photons that hit the walls are assumed to be absorbed. This assumption allows one to neglect the dose contribution at the detector of photons that penetrate the source containment walls or that scattered from the walls before escaping into the atmosphere. Second, the source containment structure is assumed to have a negligible perturbation on the skyshine radiation field; i.e., once photons enter the atmosphere, they do not interact again with the source structure. With this assumption, the calculation of the energy and angular distribution of source photons penetrating any overhead source shield or escaping from the containment structure is independent of the subsequent transport of the photons through the air to the detector. In most far-field skyshine calculations, the source and its containment have a negligible effect on the transport of the photons through the air once the photons have left the source structure [6]. However, for near-field calculations, this second assumption is not always true.

If the point source is isotropic and polyenergetic, as is assumed in SKYDOSE, the energy and angular distribution of the source can be represented as

$$S(E',\mathbf{\Omega}) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi}\, \delta(E' - E_g). \tag{3}$$

Here S_p is the total number of photons of all energies emitted by the source and f_g is the photon emission probability or frequency for the g-th energy group, which has an average energy E_g. The sum of all the f_g frequencies should equal unity.

Then, in terms of a spherical-polar coordinate system with the source at the origin and the polar axis directed vertically upwards, Eq. (1) reduces to

$$R(x) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{min}}^{\omega_{max}} d\omega\, \Re(x, E_g, \phi), \tag{4}$$

where ω is the cosine of the polar angle θ, and the azimuthal angle ψ is defined with respect to the projection on the horizontal plane of the source-to-detector axis. Here ω_{min} and ω_{max} define the permissible range of the cosine of polar angles for photon emission allowed by the source collimation. Generally, these limits are functions of the azimuthal angle ψ.

The above formulation can be used to calculate the skyshine dose for any point skyshine source. Explicit expressions for the limits ω_{min} and ω_{max} can be obtained for some simple skyshine geometries such as the three geometries used in SKYDOSE. In any case, the integral in Eq. (1) or (4) can be evaluated readily using standard numerical integration techniques.

Finally, it should be noted that SKYDOSE calculates skyshine doses in terms of dose per source photon, i.e., S_p in the above formulation is set to unity.

2.2 The Integral Line-Beam Method: Shielded Source

The point gamma-ray sources considered by SKYDOSE may have an overhead horizontal slab shield through which the photons must penetrate before scattering in the atmosphere and reaching the detector outside the source containment. In the integral line-beam method, the effect of an overhead source shield is approximately accounted for by using simple exponential attenuation combined with a buildup factor for radiation passing through the shield. In this way the skyshine dose of Eq. (4) is modified as

$$R(x) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{min}}^{\omega_{max}} d\omega \, \Re(x, E_g, \phi) \, B(E_g, \lambda_g) e^{-\lambda_g}, \tag{5}$$

Here $B(E_g, \lambda_g)$ is the infinite medium exposure buildup factor for the shield material for photons of energy E_g and λ_g is the mean-free-path length a photon emitted in direction $\mathbf{\Omega}$ travels through the shield without collision. For a horizontal slab shield of thickness t and interaction coefficient μ_g, $\lambda_g = \mu_g t/\omega$.

This method for estimating the effect of an overhead source shield is only approximate. It accounts for the attenuation and buildup of radiation in the shield. However, it neglects the change in energy and direction of secondary photons that are produced in the shield and that subsequently escape the shield. Although this approximation has been found to give reasonable results for concrete shields and ^{60}Co photons [2], it has been found to produce over or underpredictions of skyshine doses by factors of 2 to 5 [6].

2.3 Approximation of the LBRF

An analytical approximation of the LBRF is used to evaluate efficiently the integral in Eq. (4) or (5). As originally proposed for the SKYSHINE code [7, 8] and later confirmed by Shultis et al. [4], the LBRF may be accurately approximated by the following three-parameter function:

$$\Re(x, E, \phi) \simeq \kappa E(\rho/\rho_o)^2 [x(\rho/\rho_o)]^b \mathrm{e}^{a-cx(\rho/\rho_o)}. \tag{6}$$

Here ρ is the air density in the same units as the reference density $\rho_o = 0.0012$ g/cm^3. When E is measured in MeV, x in meters, and the dose $\Re$ in air-rad/photon, the constant κ is equal to 1.308×10^{-11}. The parameters a, b and c depend on the photon energy E and the emission angle ϕ.

Several compilations of the approximation parameters a, b and c are available [9, 2, 3] for specific discrete energies and directions. SKYDOSE uses a new tabulation [4, 10] that extends the photon energy range from 0.02 to 100 MeV. For photon energies between 0.02 and 20 MeV, the approximated LBRF is valid for source-to-detector distances between 1 and 3000 m. For energies above 20 MeV, the approximate LBRF is valid over a source-to-detector range of 100 to 1500 m.

2.4 Geometries Used in SKYDOSE

Three skyshine geometries are available in SKYDOSE. In each the source may be bare (i.e., exposed directly to the atmosphere) or have an overhead horizontal slab shield atop the source structure. Four shield materials are available: water, concrete, iron and lead. The three basic geometries used in SKYDOSE for bare skyshine sources are summarized below.

2.4.1 Open Silo Geometry

In this geometry, a point, isotropic, monoenergetic source is placed on the axis a distance h_s below the top of a roofless cylindrical silo of inner radius r as shown in Fig. 1. A detector is located at a vertical distance h_d below the silo top and at a radial distance x from the silo axis. For this problem, a positive h_s (or h_d) denotes the source (or detector) is below the silo top while a negative h_s (or h_d) denotes the source (or detector) is above the silo top. For this geometry, the skyshine dose of Eq. (4) reduces to

$$R(d) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi} \int_0^{\pi} d\psi \int_{\omega_0}^{1} d\omega\, \Re(d, E_g, \phi). \tag{7}$$

For this geometry,

$$d = \sqrt{x^2 + (h_s - h_d)^2}, \tag{8}$$

$$\zeta = \tan^{-1}[(h_s - h_d)/x], \tag{9}$$

$$\omega_0 \equiv \cos\theta_{max} = h_s/\sqrt{r^2 + {h_s}^2}, \tag{10}$$

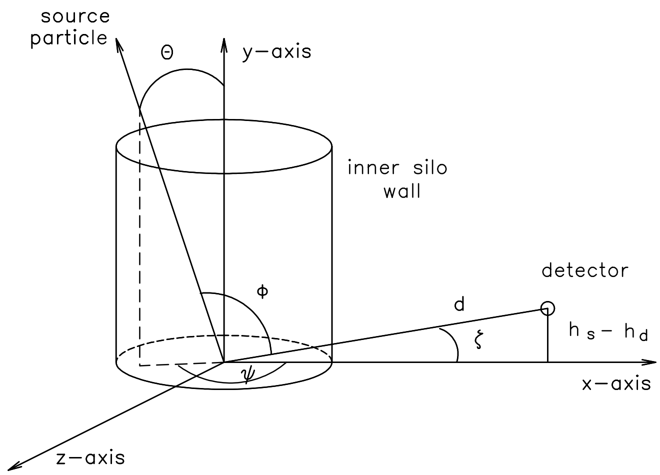

Figure 1. Geometry for the open silo skyshine problem. The point source is on the silo axis at the origin of the spherical coordinate system and at a vertical distance h_s below the silo top. A detector is located at $(x, h_s - h_d, 0)$. The silo wall is assumed to be black. In the shielded silo geometry, a slab shield is placed atop the silo.

and

$$\cos\phi = \sin\theta\cos\psi\cos\zeta + \cos\theta\sin\zeta. \tag{11}$$

2.4.2 Infinite Wall Geometry

Figure 2 depicts the geometry of the skyshine problem for a point, isotropic, monoenergetic source located at a perpendicular distance r behind an infinite black wall and at a vertical distance h_s measured from the horizontal plane touching the top of the wall. A detector, located on the opposite side of the wall, is at a horizontal distance z_d measured normally from the x-axis and at a vertical distance h_d beneath the same horizontal plane through the top of the wall.

For this geometry, Eq. (4) reduces to

$$R(d) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{min}}^{1} d\omega\, \Re(d, E_g, \phi), \tag{12}$$

where

$$d = \sqrt{x_d^2 + (h_s - h_d)^2 + z_d^2}, \tag{13}$$

$$\zeta = \tan^{-1}\left(\frac{h_s - h_d}{\sqrt{x_d^2 + z_d^2}}\right), \tag{14}$$

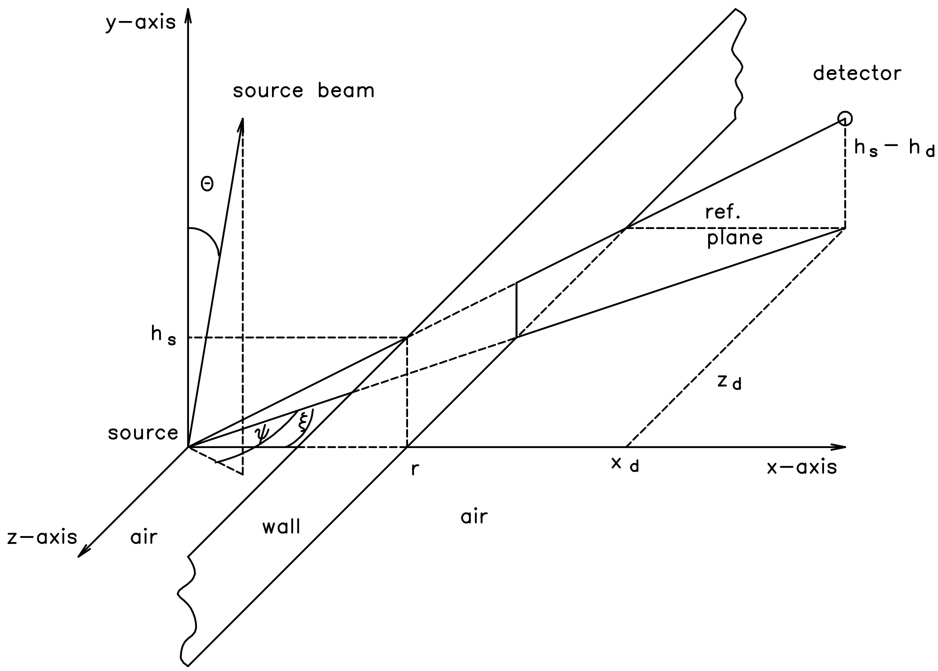

Figure 2. Geometry for the infinite black wall problem. A point isotropic source is located at a distance r behind the wall and a vertical distance h_s beneath the top of the wall. A detector is located at $(x_d, h_s - h_d, z_d)$ while the source is located at the origin of the coordinate system.

$$\xi = \tan^{-1}(z_d/x_d), \tag{15}$$

and

$$\cos\phi = \cos\psi \sin\theta \cos\zeta + \cos\theta \sin\zeta. \tag{16}$$

Since the minimum value of θ is 0^0, the upper limit of ω, $\omega_{max} = \cos\theta_{min}$, is equal to 1. The determination of $\omega_{min} = \cos\theta_{max}$ is slightly more involved. When the radiations are emitted in the direction towards the detector, that is, for the intervals $(0 \le \psi \le \pi/2+\xi)$ and $(3\pi/2+\xi \le \psi \le 2\pi)$, θ_{max} occurs when the beam just grazes the top of the wall. For these ranges, $\theta_{max} = \tan^{-1}(r/[h_s\cos(\psi-\xi)])$. When the radiations are emitted away from the detector, that is, for the range $(\pi/2+\xi \le \psi \le 3\pi/2+\xi)$, it is assumed that all radiations emitted contribute to the skyshine dose and θ_{max} is $\pi/2$ (or $\omega_{min} = 0$). Thus, the θ_{max} for the infinite wall geometry is given by

$$\theta_{max} = \begin{cases} \tan^{-1}\left(\dfrac{r}{h_s\cos(\psi-\xi)}\right), & 0 \le \psi \le \pi/2+\xi,\ 3\pi/2+\xi \le \psi \le 2\pi, \\ \pi/2, & \pi/2+\xi \le \psi \le 3\pi/2+\xi \end{cases} \tag{17}$$

The assumption that all of the photons emitted in the direction away from the wall contribute to the skyshine dose tends to overestimate the actual skyshine dose because the initial portion of these backward beams will be shielded by the infinite wall. However, since the contribution of the shielded portion of the backward beams is much smaller than the contribution from beams that are emitted towards the detector, the error due to the above assumption is usually small [3].

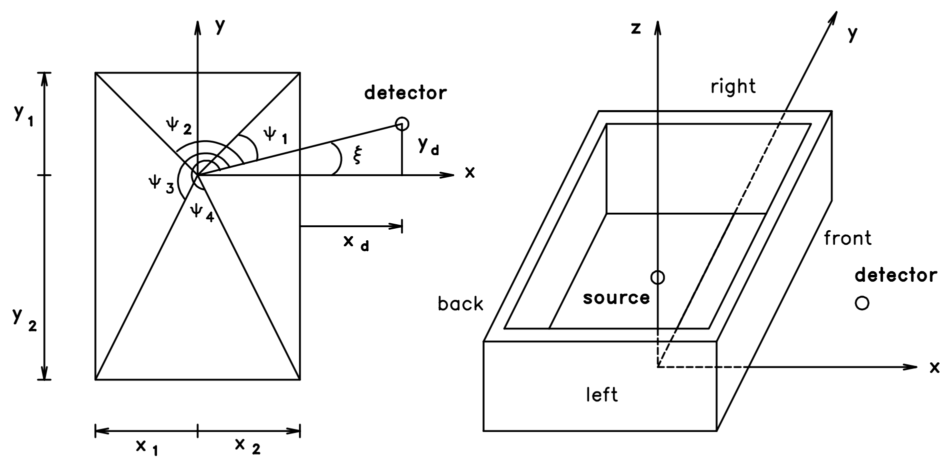

Figure 3. Geometry for roofless rectangular building. The source is on the z-axis at a vertical distance h_s below the horizontal plane through the top of the building. A detector is placed at the coordinates $(x_d, y_d, h_s - h_d)$.

2.5 Open Rectangular Building Geometry

Normally, most radiation facilities are well shielded on the sides. Much less shielding against radiations is, however, provided by the roof. Hence, the geometry analyzed here is of practical significance. The geometry of the problem is depicted in Fig. 3. A point, isotropic, and monoenergetic source is located on the z-axis at a vertical distance h_s below the horizontal plane through the top of the roof. The front and rear walls are, respectively, located at distances x_2 and x_1 from the source. The right wall of the building is located at a distance y_1 from the source along the y-axis while the left wall is located at a distance y_2 from the source. A detector is placed at the coordinate $(x_d, y_d, h_s - h_d)$. For this geometry the skyshine dose at the detector is given by

$$R(d) = \sum_{g=1}^{G} \frac{f_g S_p}{4\pi} \int_0^{2\pi} d\psi \int_{\omega_{min}(\psi)}^{1} d\omega\, \Re(d, E, \phi). \tag{18}$$

In Eq. (18), ω_{min} is a function of the azimuthal angle ψ. It can be shown that the following relations hold

$$d = \sqrt{(x_2 + x_d)^2 + (h_s - h_d)^2 + y_d^2}, \tag{19}$$

$$\xi = \tan^{-1}\left(\frac{y_d}{x_2 + x_d}\right), \tag{20}$$

and

$$\zeta = \tan^{-1}\left(\frac{h_s - h_d}{\sqrt{(x_2 + x_d)^2 + y_d^2}}\right). \tag{21}$$

The angle between the emission direction and the source-detector-axis, ϕ, is given by Eq. (16).

As for the infinite wall case, it is obvious that the minimum value of the polar angle θ is 0^0, thus $\omega_{max} = 1$. There are four possible values for θ_{max}, which occur when the source beam just clears the top corners of the rectangular room. The azimuthal angles corresponding to these four values are denoted by ψ_1, ψ_2, ψ_3, and ψ_4 which can be shown to be [3]

$$\psi_1 = \tan^{-1}(y_1/x_2) - \xi, \tag{22}$$

$$\psi_2 = \tan^{-1}(x_1/y_1) + \pi/2 - \xi, \tag{23}$$

$$\psi_3 = \tan^{-1}(y_2/x_1) + \pi - \xi, \tag{24}$$

$$\psi_4 = \tan^{-1}(x_2/y_2) + 3\pi/2 - \xi, \tag{25}$$

and the maximum polar angle is

$$\theta_{max} = \begin{cases} \tan^{-1}\left(\dfrac{x_2}{h_s \cos(\psi + \xi)}\right), & \psi_4 - 2\pi \le \psi \le \psi_1, \\ \tan^{-1}\left(\dfrac{y_1}{h_s \cos(\psi + \xi - \pi/2)}\right), & \psi_1 \le \psi \le \psi_2, \\ \tan^{-1}\left(\dfrac{x_1}{h_s \cos(\psi + \xi - \pi)}\right), & \psi_2 \le \psi \le \psi_3, \\ \tan^{-1}\left(\dfrac{y_2}{h_s \cos(\psi + \xi - 3\pi/2)}\right), & \psi_3 \le \psi \le \psi_4. \end{cases} \tag{26}$$

3 Required Input Data

Data may be entered interactively from the keyboard or from a data input file. While modest checking of input data is attempted by SKYDOSE, the program is not totally "bullet-proof" and the user must bear some responsibility to enter meaningful data.

The nature of the input data depends on which of the three geometries is to be used. The input data consist of three blocks: the first specifies geometry-independent parameters and is common to all three geometries. The second block provides information about the source energy spectrum. Finally, the third block specifies geometry variables for the geometry selected in the first block. The input parameters for each block are specified below.

3.1 Geometry-Independent Parameters:

`OUTFIL` File specification for the output file, e.g., SKYDOSE.OUT

`IPROB` Indicates the skyshine source geometry. Permissible values are
=1 source is on the axis of a circular silo (*"silo geometry"*)
=2 source is behind an infinitely long wall (*"wall geometry"*)
=3 source is in a rectangular building (*"box geometry"*)

`RHO` The air mass density in g/cm^3. The line-beam response function approximation used by SKYDOSE assumes an air density of 0.0012 g/cm^3, but the skyshine dose is corrected to the density specified by `RHO`.

`NPTS` The number of intermediate source-to-detector distances to be used for evaluation of the skyshine dose. The intermediate distances are equally spaced out to he maximum distance specified later in the input.

`MAT` Identification integer to specify the type of material in a horizontal- slab shield above the source. Permissible values are: =0 for no shield; =1 for water; =2 for concrete =3 for iron; or =4 for lead

`Z` The mass thickness (`RHO` $\times$ shield thickness) in g/cm^2 of the overhead source shield. If there is no shield (i.e., `MAT` = 0), then `Z` may be any value although 0 is more mnemonic.

`NGAU` The order of the Gaussian quadrature used for the numerical integration over the source emission directions. Permissible values are 4, 8, 16, or 32. The higher the order, the longer the calculations will take but the more precise will be the predicted skyshine doses.

`NE` The number of energy groups used to define the multigroup source spectrum (`NE` $\leq$ 100).

3.2 Source Energy Spectrum

The second data block specifies the energy spectrum of the source radiation, one energy group per line. For each of the `NE` groups, the midpoint energy and frequency of the group are entered. Thus for the ith group the following two quantities are entered with at least one space between the entries:

`E(i)` The midpoint energy (MeV) of group `i`, `i` $= 1, ...,$`NE`. Source photon energies `E(i)` must be $0.02 \leq$ `E(i)` ≤ 100 MeV, except for sources with an overhead shield. For a shielded source, $0.02 \leq$ `E(i)` ≤ 10 MeV.

`P(i)` The probability a source photon is emitted in group `i`. The sum over all `P(i)` should equal unity for the skyshine dose to be normalized to a per-source-photon basis. This normalization is assumed in the labeling of the output skyshine dose table.[1]

3.3 Geometry-Dependent Parameters

3.3.1 Silo Geometry (`IPROB` = 1)

In this geometry, a point, isotropic, monoenergetic source is on the axis of a silo with a circular cross section. The top of the silo is assumed to be in a horizontal plane and the source is below the silo top. The source location and silo radius define the effective collimation of the radiation emitted into the atmosphere. The silo walls are assumed to be impenetrable and any in-silo scattering is ignored. If a source shield is specified, it is assumed to be placed above the silo. The following input parameters are required:

`HS` Displacement or elevation of the source below the top of the silo (m). This must be positive, i.e., the source must be below the silo top.

`HD` Detector elevation with respect to the top of the silo (m). This elevation may be positive (for the detector below the silo top) or negative (for the source above the silo top).

`R` Radius of the circular silo (m). Must be positive.

`XD` The maximum horizontal distance from the source at which the skyshine dose is to be evaluated. Doses will also be estimated at NPTS intermediate points, equally distributed between the source and the maximum distance XD. XD must be greater than the silo radius R.

[1] Alternatively, the `P(i)` can be set equal to the source emission rate (number per unit time) to yield the calculated skyshine doses in units of dose per unit time. Note, however, the output table heading will still indicates a dose per source photon, and such an unconventional normalization of source frequencies should be noted on the problem title line.

3.3.2 Wall Geometry (IPROB = 2)

In this geometry a point, isotropic, monoenergetic source is placed behind and below an infinitely-long, vertical, black wall. The detector is located at some location on the other side of the wall. The following input parameters are required:

`HS` Displacement or elevation of the source below the top of the wall (m). This must be positive, i.e., the source must be below the top of the wall.

`HD` Detector elevation with respect to the top of the wall (m). This elevation may be positive (for the detector below the wall top) or negative (for the source above the wall top).

`R` The distance (m) between the source and the wall along a perpendicular from the source to the wall. This distance must be positive.

`ZD` The lateral horizontal displacement (m) of the detector from a vertical plane through the perpendicular line from the source to the wall, i.e. the perpendicular distance from the detector to this vertical plane. `Z` may be positive or negative.

`XD` The horizontal source-to-detector distance (m) along axis formed by the normal from the source to the wall. Doses will also be estimated at NPTS intermediate points, equally distributed between the source and the maximum distance `XD`. `XD` must be greater than the source to wall distance `R`.

3.3.3 Box Geometry (IPROB = 3)

In this geometry a point, isotropic, monoenergetic source is placed at an arbitrary position inside a rectangular building whose four vertical sides are assumed to be black. The detector is located outside the building. The "front" wall of the building is that wall through which a line between the source and detector passes. The following input parameters are required:

`HS` Displacement or elevation of the source below the top of the walls (m). This must be positive, i.e., the source must be below the top of the building.

`HD` Detector elevation with respect to the top of the walls (m). This elevation may be positive (for the detector below the building top) or negative (for the source above the building top).

`X1` The perpendicular distance (m) from the source to the "rear" wall, i.e., the wall opposite the "front" wall. Must be positive.

`X2` The perpendicular distance (m) from the source to the "front" wall. Must be positive.

`Y1` The perpendicular distance (m) from the source to the "left" wall as viewed from the detector position. Must be positive.

`Y2` The perpendicular distance (m) from the source to the "right" wall as viewed from the detector position. Must be positive.

`YD` Horizontal offset (m) of the detector from vertical plane through normal from the source to the front wall. Note: $-\mathtt{Y2} \leq \mathtt{YD} \leq \mathtt{Y1}$.

`XD` Maximum horizontal distance (m) from the detector along a normal to the front wall. It is required that the detector be outside the building, i.e., $\mathtt{XD} > 0$.

4 Data Files

Rather than enter input data interactively with SKYDOSE, it is often more convenient, especially if multiple cases are to be analyzed, to place the input data into a separate input file and have SKYDOSE read this file. If you indicate to SKYDOSE that the input data is to be read from a file, SKYDOSE will ask you to enter the file name (e.g., `SKYDOSE.INP`). The file will then be opened an the input data read.

The ASCII input file must contain the input data in the order specified above. The structure of an input file is thus

```
Output file name (OUTFIL)
     (blank line after first line)
Block 1: geometry-independent parameters    Problem 1
Block 2: energy spectrum data               Problem 1
Block 3: geometry-dependent parameters      Problem 1
     (blank line to separate problems)
Block 1: geometry-independent parameters    Problem 2
Block 2: energy spectrum data               Problem 2
Block 3: geometry-dependent parameters      Problem 2
     (blank line to separate problems)
Block 1: geometry-independent parameters    Problem 3
Block 2: energy spectrum data               Problem 3
Block 3: geometry-dependent parameters      Problem 3
     (blank line to separate problems)
...
```

The output file name, `OUTFIL`, is used for all problems analyzed in the same run. This name is entered left-justified on the first item of the input file. The second line must be a blank line.[2]

[2]Actually, the line preceding the first data block is ignored by SKYDOSE and can contain any annotation the user wished.

The first block for each problem specifies the geometry-independent parameters, namely IPROB, E, RHO, NPTS, MAT, Z, NGAU, NE They may appear on a single input line or occupy several lines of the input file. However, these parameters must appear in the order indicated. If optional annotations to the right of input data is used (as in the examples below), then all the parameters must appear on a single line. This is the recommended format.

The energy spectrum data block specifies the E_g and f_g pairs and are entered one group per line. Thus the second block consists of NE$\equiv G$ lines.

The geometry-dependent parameters needed in block three depend on the value of IPROB for each case.

For IPROB = 1 (silo geometry) they are: HS, HD, R, XD
For IPROB = 2 (wall geometry) they are: HS, HD, R, ZD, XD
For IPROB = 3 (box geometry) they are: HS, HD, X1, X2, Y1, Y2, YD, XD

These parameters must begin on a new line of the input file, and each can be placed several to a line, or each on its own line in the input file. However, if optional annotations to the right of input data is used (as in the examples below), then all the parameters must appear on a single line.

Multiple problems can be analyzed in a single run by separating their input data by a single blank line. A typical input file for analyzing two monoenergetic open-silo geometry problems might be

```
silotst.out                        Output filename

Problem 1: silo with E=0.66 MeV (Cs-137)
1  0.0012  5  0  0  16  1          PROBI  RHO  NPTS  MAT  Z  NGAU  NE
0.667 1.0                            E(1)  Freq(1)
1.5  2.5  2.0  1000.0              Geometry: HS  HD  R  XD(max range)

Problem 2: silo with E=1.25 MeV (Co-60)
1  0.0012  5  0  0  16  1          PROBI  RHO  NPTS  MAT  Z  NGAU  NE
1.25  1.0                            E(1)  Freq(1)
1.5  2.5  2.0  1000.0              Geometry: HS  HD  R  XD(max range)
```

5 Examples

Example output for the three different geometries are shown below. Although three different geometries are illustrated, each case is for the same problem, namely a 2π collimation of a point isotropic source covered by an overhead horizontal concrete shield of mass thickness 10 g/cm^2. The source and detector are just below the collimation structure so that the detector response is for skyshine arising from source photons collimated vertically into a hemisphere. For all three geometries, the predicted skyshine dose are thus the same. Finally, it should be noted that the annotations to the right of the lines in the following input file examples are optional; they are ignored by SKYDOSE and serve only to remind the user of the parameter names.

5.1 Silo Geometry

For the input file

```
silo.out                                Output filename
                                         -blank line followed by problem title
2pi silo-geometry test problem
1  0.0012  5  2  10.0  32  3            PROBI  RHO  NPTS  MAT  Z  NGAU  NE
0.667 0.50                                 E(i)  Freq(i)
1.17  0.25
1.33  0.25
.00001  .00001  1.0  3000.              Geometry: HS  HD  R  XD(max range)
```

the following output is obtained.

```
2pi silo-geometry test problem
****** SKYDOSE 2.3: Silo Geometry
  Air density (g/cm^3)       =   .001200
  Source elevation (m)       =       .00
  Detector elevation (m)     =       .00
  Silo radius (m)            =      1.00
  Source collimation (sr)    =    6.2831
  Source-detector dist. (m)  =    3000.0
  Overhead shield material   =  concrete
  Shield thickness (g/cm^2)  =     10.00
  Gauss quadrature order     =        32
  3-parm. approx. LBRF used

 Energy Spectrum: Emid (MeV) and Frequency:
                      .6670      .5000
                     1.1700      .2500
                     1.3300      .2500

                           SKYSHINE DOSES
  ------------------------------------------------------------------
      S-D(m)      g/cm^2      rad/photon    R/photon     R m^2/sr
  ------------------------------------------------------------------
        500.       60.00      1.9540E-22   2.2373E-22   8.9021E-18
       1000.      120.00      2.2345E-24   2.5585E-24   4.0721E-19
       1500.      180.00      5.2148E-26   5.9709E-26   2.1382E-20
       2000.      240.00      1.9406E-27   2.2220E-27   1.4146E-21
       2500.      300.00      9.4741E-29   1.0848E-28   1.0791E-22
       3000.      360.00      5.3391E-30   6.1132E-30   8.7567E-24
  ------------------------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 and 2 are the source-to-detector distances in units of meters and mass thickness, respectively. Columns 3 and 4 give the skyshine air kerma and exposure, respectively. The fifth column is a "normalized" dose formed by multiplying the exposure by the square of the source-to-detector distance and dividing by the solid angle of the conical collimation.

5.2 Wall Geometry

For the input file

```
wall.out                                Output filename
                                         -blank line followed by problem title
2pi wall-geometry test problem
2  0.0012  5  2  10.0  32  3            PROBI  RHO  NPTS  MAT  Z  NGAU  NE
0.667 0.50                                 E(i)  Freq(i)
1.17  0.25
1.33  0.25
.00001 .00001 1.0 0.0 3000.             Geometry: HS HD X1 X2 Y1 Y2 YD XD
```

the following output is obtained.

```
2pi wall-geometry test problem
****** SKYDOSE 2.3: Wall Geometry
  Air density (g/cm^3)       =   .001200
  Source elevation (m)       =       .00
  Detector elevation (m)     =       .00
  Source-to-wall distance(m) =      1.00
  Detector horiz. offset (m) =       .00
  Source-detector dist. (m)  =    3000.0
  Overhead shield material   =  concrete
  Shield thickness (g/cm^2)  =     10.00
  Gauss quadrature order     =        32
  3-parm. approx. LBRF used

 Energy Spectrum: Emid (MeV) and Frequency:
                      .6670      .5000
                     1.1700      .2500
                     1.3300      .2500

                     SKYSHINE DOSES
  -----------------------------------------------------
       X(m)       S-D(m)      rad/photon    R/photon
  -----------------------------------------------------
      500.0        500.0      1.9456E-22   2.2277E-22
     1000.0       1000.0      2.2327E-24   2.5564E-24
     1500.0       1500.0      5.2143E-26   5.9704E-26
     2000.0       2000.0      1.9406E-27   2.2220E-27
     2500.0       2500.0      9.4740E-29   1.0848E-28
     3000.0       3000.0      5.3389E-30   6.1131E-30
  -----------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 is the *horizontal* source-to-detector distance. Column 2 is the straight-line source-to-detector distance which will be slightly different from that of column 1 if the source and detector are at different elevations. Columns 3 and 4 give the skyshine air kerma and exposure, respectively.

5.3 Box Geometry

For the input file

```
box.out                                 Output filename
                                         -blank line followed by problem title

2pi box-geometry test problem
3  0.0012  5  2  10.0  32  3            PROBI  RHO  NPTS  MAT  Z  NGAU  NE
0.667 0.50                                 E(i)  Freq(i)
1.17  0.25
1.33  0.25
.00001 .00001 1. 1. 1. 1. 0. 3000.      Geometry: HS HD X1 X2 Y1 Y2 YD XD
```

the following output is obtained.

```
2pi box-geometry test problem
****** SKYDOSE 2.3: Rectangular Building Geometry
  Air density (g/cm^3)              =   .001200
  Source elevation (m)              =       .00
  Detector elevation (m)            =       .00
  Source-rear wall distance (m)     =      1.00
  Source-front wall distance (m)    =      1.00
  Source-left wall distance (m)     =      1.00
  Source-right wall distance (m)    =      1.00
  Detector offset from normal (m)   =       .00
  Detector-front wall distance(m)   =   2999.00
  Overhead shield material          =  concrete
  Shield mass thickness (g/cm^2)    =     10.00
  Gauss quadrature order            =        32
  3-parm. approx. LBRF used

 Energy Spectrum: Emid (MeV) and Frequency:
                     .6670      .5000
                    1.1700      .2500
                    1.3300      .2500

                   SKYSHINE DOSES
  -----------------------------------------------------
        X(m)      S-D(m)     rad/photon    R/photon
  -----------------------------------------------------
       500.8       500.8     1.9378E-22   2.2188E-22
      1000.7      1000.7     2.2224E-24   2.5447E-24
      1500.5      1500.5     5.1967E-26   5.9502E-26
      2000.3      2000.3     1.9366E-27   2.2174E-27
      2500.2      2500.2     9.4650E-29   1.0837E-28
      3000.0      3000.0     5.3391E-30   6.1133E-30
  -----------------------------------------------------
```

In the above table of calculated skyshine doses, columns 1 is the *horizontal* source-to-detector distance. Column 2 is the straight-line source-to-detector distance which will be slightly different from that of column 1 if the source and detector are at different elevations. Columns 3 and 4 give the skyshine air kerma and exposure, respectively.

6 Auxiliary Files

SKYDOSE requires two auxiliary files, `HIGHGAM.DAT` and `LOWGAM.DAT`, to be present in the same directory as SKYDOSE. These files contain the parameters a, b, and c for the approximate line-beam response function of Eq. (6). The file `HIGHGAM.DAT` contains the parameters for gamma energies above 10 MeV, while the other file contains the parameters for gamma energies below 10 MeV. For example, the file `LOWGAM.DAT` begins as follows:

```
! E=    .02
     .5     -3.2260   -1.010082    .0827326
    1.5     -4.3262   -1.025872    .0829719
    2.5     -4.8423   -1.037587    .0831220
    4.0     -5.3226   -1.051969    .0832978
    .... (lines omitted)
  110.0     -8.8880   -1.413125    .0963958
  130.0     -8.9319   -1.398953    .0991899
  150.0     -8.9420   -1.382705    .1012927
  170.0     -8.9415   -1.373270    .1024275
! E=    .03
     .5     -4.4477    -.992174    .0366235
    1.5     -5.5594    -.986039    .0364442
    2.5     -6.0823    -.981497    .0363890
    4.0     -6.5680    -.977617    .0363724
    6.0     -6.9910    -.976051    .0363954
    ....
```

The line beginning with "`!   E=` " gives the photon energy and is followed by 20 lines giving the values of a, b, and c for 20 ϕ angles at that energy. The first column is the angle ϕ (in degrees), and columns 2 through 4 give the value of a, b, and c, respectively.

From the data in these files, SKYDOSE uses interpolation procedures to evaluate the line-beam response function at any energy between 0.02 and 100 MeV and for any emission direction between 0 and 180 degrees.

References

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