

# **GEANT4 / GAMOS Tissue Optics Package User Guide**

## Introduction

The tissue optics module is based on the GEANT4 simulation architecture and operates as a plugin to the GAMOS interface. Before using the tissue optics module, users should download, compile, and familiarize themselves with the basics of using GAMOS by visiting <http://fismed.ciemat.es/GAMOS/>.

Users may find the tissue optics module a flexible, robust, and easy-to-use alternative over alternatively available light transport Monte Carlo codes. In just a few lines of code embedded in simple script-based text files, users can execute a unique variety of simulations, output virtually any desired data quantity, and view the simulations using numerous visualization renderers.

Although GEANT4 is inherently built to handle optical simulations, the physics processes are non-ideal for biomedical optics research. The tissue optics module bridges this gap by giving the user a familiar framework with which to execute simulations.

## Installation

Installing the GEANT4/GAMOS tissue optics package is simple, and acts as a patch to the GAMOS. Currently the tissue optics package is compatible and tested for GAMOS.4.0.0. To install the package, download the compressed directory GamosCore.tar.gz from <http://www.dartmouth.edu/optmed/research-projects/monte-carlo-software/> and follow the instructions below.

1. Navigate to your compiled GAMOS.4.0.0 installation directory and into the source directory, i.e. INSTALL\_DIR/GAMOS.4.0.0/source.
2. Delete, or if you wish to, backup the current GamosCore directory.
3. Copy and uncompress the GamosCore.tar.gz file so that the modified GamosCore directory is now located in the GAMOS source directory.
4. In the terminal, navigate to your compiled GAMOS.4.0.0 installation directory and into the config directory, i.e. INSTALL\_DIR/GAMOS.4.0.0/config
5. Issue the command the following command

*source configamos.sh* **or** *source configamos.csh* depending on your OS

6. In the terminal, navigate back to the GAMOS source directory, i.e., INSTALL\_DIR/GAMOS.4.0.0/source
7. In the terminal, issue the following commands

*make clean*  
*make*

This should recompile the GamosCore directory with the patched files for the tissue optics package

**IMPORTANT NOTE:** If you are having trouble compiling GAMOS 4.0.0, while following the GAMOS compilation instructions, change the environment variable GAMOS\_NO\_ROOT to 1 (i.e., type 'export GAMOS\_NO\_ROOT=1' on Linux), to compile without ROOT (for any compiling ROOT may be an issue).

If you compile GAMOS without ROOT, you must also compile the tissue optics plug-in without ROOT, (i.e., before step 7, you must change the environment variable GAMOS\_NO\_ROOT to be equal to 1).

## Important Notes

In using the tissue optics module, there are a few basic things which users must be aware of in order to ensure that simulations execute properly.

1. As the tissue optics module operates as a plugin to GAMOS, the simulations must follow the GAMOS structure. In this context, two files are needed to execute a simulation, the simulation file (.in) and the geometry file (.geom).
2. To activate the tissue optics module, users must enable the physics by including the command:

*gamos/physics/addPhysics tissue-optics*

in the simulation (.in) file. This statement must be issued AFTER the /run/initialize command (see the provided examples).

3. In order to instantiate the various physics processes, the optical properties values (i.e., the absorption and scattering coefficients) must be defined in a material properties table in the geometry (.geom) file. The material properties tables must all be built BEFORE the definition of the geometry solids and volumes (see the provided examples).
4. Several of the tissue optics physics processes require additional settings to be defined in the simulation (.in) file (i.e., for fluorescence, the nature of the fluorescence time profile must be defined as a delta or exponential function). These statements must be issued BEFORE the *gamos/physics/addPhysics tissue-optics* command (see the provided examples).
5. When using externally read .txt files, as in the user-defined phase function or user-defined source wavelength distribution, the file MUST end with the tag :ENDFILE to ensure that the last row is read and not skipped.

## GEANT4/GAMOS Tissue Optics Package

Included in the tissue optics module are several physics processes, which the user can activate in any combination. These include:

- Absorption
- Scattering
  - Rayleigh
  - Modified Rayleigh
  - Mie Henyey-Greenstein
  - Modified Henyey-Greenstein
  - User Defined Phase Function
- Fluorescence

In addition, refraction and reflection at mismatched interfaces is handled using the standard GEANT4 optical boundary process physics. *Please see the last section on how to specify the GEANT4/GAMOS optical boundary processes.*

Optical photons may be generated directly as the primary simulation particle, or induced by radiation, as is the case with the Cerenkov and scintillation processes. Inherently in GEANT4, both processes are sampled continuously over a broadband waveband. For many simulations, it is desirable for statistical reasons to confine a white light spectrum to a discrete number of wavelengths. To facilitate this, both radiation induced processes have been modified to allow for discrete sampling, see the sections on the Cerenkov and scintillation processes.

In addition to the physics processes, the following plugins have been added to GAMOS to provide the user with additional simulation flexibility

- Uniform Wavelength Source Distribution
- User Defined Wavelength Source Distribution
- Tracklength Fluence Scorer
- CSV-format Scoring Printer

**Example and validation files are provided which demonstrate the use of all of these processes.**

## Unit Definitions

By convention, GEANT4 operates on the CLHEP unit definition database. Quantities are defined as a string which contains the numerical quantity, followed by a \*, and then the desired unit definition. This system is extremely flexible and allows the user to define quantities in any desired unit (i.e., for a length 1.0\*cm would be equivalent to 10.0\*mm). However, the system is rigid and options for defining inverse length units, as well as photon energy in terms of wavelength is not provided.

With the tissue optics module we have added these features by introducing the following new unit definitions. Photon energy can be defined by a wavelength by using the unit definition \*wv followed by the desired length (i.e, \*wvnm or \*wvum), and inverse length units can be defined by using the unit definition \*/ followed by the desired length unit (i.e., \*/mm or \*/cm).

## Material Property Tables

The optical physics processes rely on material property tables defined in the geometry (.geom) file to access the necessary physical quantities. A material property table is created and then attached to a given material, and any subsequent geometry solid or volume defined by the given material will inherit the defined material properties.

The material property tables can contain any number of quantities to instantiate the processes (i.e., absorption, scattering fluorescence). However, each material property table MUST contain a definition for the refractive index of that material using the property identified RINDEX. Failure to do so will lead to optical photons terminating within that material, as in GEANT4 optical photons cannot exist in a medium for which no refractive index is defined.

In addition, each property can be defined spectrally (i.e., in a discrete nature at definite photon wavelengths). The resolution and waveband of these definitions can be anything, which the user desires, although ALL properties in a given table must be defined at the same discrete wavelengths. An example is shown below for defining the refractive index of the G4\_WATER material.

However, any number of materials can be used in a simulation (see the list of materials at the end of this guide). The specific material does not actually matter, as the user manually defines the optical properties. However, if radiation interactions coupled to optical transport are being considered, then the materials should be carefully chosen as the GEANT4 predefined materials have inherently loaded radiation interaction properties.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wvnm 600.0*wvnm 800.0*wvnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

Depending on the spectral resolution of the desired material property, it can be cumbersome to manually create the table. Therefore automation is desirable. A MATLAB file (mpt\_maker.m) capable of producing the material property table text is available on the website at <http://www.dartmouth.edu/optmed/research-projects/monte-carlo-software/>.

## Absorption

The absorption physics process operates on an all or none basis, unlike alternative Monte Carlo codes which use a photon packet weight. To activate the absorption physics process, users must add the material property ABSCOE. An example is shown below for defining the absorption coefficient of the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wnm 600.0*wnm 800.0*wnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table ABSCOE 1.2*/mm 1.1*/mm 1.0*/mm  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```



## Rayleigh Scattering

The Rayleigh scattering process samples the polar angle phase function based upon the following relationship

$$\cos(\theta) = (2R - 1)$$

where R is a random number between 0-1. This generates a uniform distribution in  $\cos(\theta)$ .

To activate the Rayleigh scattering physics process, users must add the material property RAYLEIGH\_SCATCOEF. An example is shown below for defining the Rayleigh scattering coefficient of the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wnnm 600.0*wnnm 800.0*wnnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table RAYLEIGH_SCATCOEF 90.0*/cm 85.0*/cm  
84.0*/cm  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

## Modified Rayleigh Scattering

The Rayleigh scattering process samples the polar angle phase function based upon the following relationship

$$\cos(\theta) = R^{1/3}$$

where R is a random number between 0-1. This generates a phase function proportional to  $\cos^2(\theta)$ .

To activate the modified Rayleigh scattering physics process, users must add the material property RAYLEIGH\_MHG\_SCATCOEF. An example is shown below for defining the Rayleigh scattering coefficient of the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wnnm 600.0*wnnm 800.0*wnnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table RAYLEIGH_MHG_SCATCOEF 90.0*/cm 85.0*/cm  
84.0*/cm  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

## Mie Henyey-Greenstein Scattering

The Mie Henyey-Greenstein scattering process samples the polar angle phase function based upon the following relationship

$$\cos(\theta) = \frac{(2R)(1 + g)^2(1 - g^2R)}{(1 - g + 2gR)^2 - 1}$$

where R is a random number between 0-1 for a scattering anisotropy  $g > 0$ . In the event that  $g = 0$  the phase function is sampled as

$$\cos(\theta) = (2R - 1)$$

analogous to Rayleigh scattering.

To activate the Mie scattering physics process, users must add the material properties MIE\_SCATCOEF and MIE\_GVALUE. An example is shown below for defining Mie scattering in the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wnnm 600.0*wnnm 800.0*wnnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table MIE_SCATCOEF 90.0*/cm 85.0*/cm 84.0*/cm  
:MATEPT_ADD_PROPERTY example_table MIE_GVALUE 0.91 0.87 0.85  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

## Modified Henyey-Greenstein Scattering

The modified Henyey-Greenstein scattering process samples the polar angle phase function as a proportional summation of Rayleigh and Mie Henyey-Greenstein scattering. The phase function is designed such that

$$P_{MHG}(\theta) = \alpha P_{HG} + (1 - \alpha) P_R$$

where  $P_{HG}$  is sampled as

$$\cos(\theta) = \frac{(2R)(1 + g)^2(1 - g^2R)}{(1 - g + 2gR)^2 - 1}$$

and  $P_R$  is sampled as

$$\cos(\theta) = R^{1/3}$$

where  $R$  is a random number between 0-1,  $g$  is the scattering anisotropy, and  $\alpha$  dictates the proportional relationship between the two scattering mechanisms.

To activate the modified Mie scattering physics process, users must add the material properties MHG\_SCATCOEF, MHG\_GVALUE, and MHG\_ALPHAVALUE. An example is shown below for defining Mie scattering in the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wnnm 600.0*wnnm 800.0*wnnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table MIE_SCATCOEF 90.0*/cm 85.0*/cm 84.0*/cm  
:MATEPT_ADD_PROPERTY example_table MIE_GVALUE 0.91 0.87 0.85  
:MATEPT_ADD_PROPERTY example_table MIE_ALPHAVALUE 0.9 0.9 0.9  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

## User Defined Scattering

The user defined scattering physics process utilizes any user defined scattering phase function. The phase function must be provided in a text (.txt) file in the same directory as the simulation (.in) and geometry (.geom) files. The text file should contain the phase function in the following format

```
:COSTHETA cos( $\theta$ )1 cos( $\theta$ )2 cos( $\theta$ )3 ... cos( $\theta$ )N-2 cos( $\theta$ )N-1 cos( $\theta$ )N
:WAVELENGTH  $\lambda_1$   $\lambda_2$   $\lambda_3$  ...  $\lambda_{M-2}$   $\lambda_{M-1}$   $\lambda_M$ 

P[ $\lambda_1$ , cos( $\theta$ )1] P[ $\lambda_1$ , cos( $\theta$ )2] P[ $\lambda_1$ , cos( $\theta$ )3] ... P[ $\lambda_1$ , cos( $\theta$ )N-2] P[ $\lambda_1$ , cos( $\theta$ )N-1] P[ $\lambda_1$ , cos( $\theta$ )N]

P[ $\lambda_2$ , cos( $\theta$ )1] P[ $\lambda_2$ , cos( $\theta$ )2] P[ $\lambda_2$ , cos( $\theta$ )3] ... P[ $\lambda_2$ , cos( $\theta$ )N-2] P[ $\lambda_2$ , cos( $\theta$ )N-1] P[ $\lambda_2$ , cos( $\theta$ )N]

P[ $\lambda_3$ , cos( $\theta$ )1] P[ $\lambda_3$ , cos( $\theta$ )2] P[ $\lambda_3$ , cos( $\theta$ )3] ... P[ $\lambda_3$ , cos( $\theta$ )N-2] P[ $\lambda_3$ , cos( $\theta$ )N-1] P[ $\lambda_3$ , cos( $\theta$ )N]

⋮ ⋮ ⋮

P[ $\lambda_{M-2}$ , cos( $\theta$ )1] P[ $\lambda_{M-2}$ , cos( $\theta$ )2] P[ $\lambda_{M-2}$ , cos( $\theta$ )3] ... P[ $\lambda_{M-2}$ , cos( $\theta$ )N-2] P[ $\lambda_{M-2}$ , cos( $\theta$ )N-1] P[ $\lambda_{M-2}$ , cos( $\theta$ )N]

P[ $\lambda_{M-1}$ , cos( $\theta$ )1] P[ $\lambda_{M-1}$ , cos( $\theta$ )2] P[ $\lambda_{M-1}$ , cos( $\theta$ )3] ... P[ $\lambda_{M-1}$ , cos( $\theta$ )N-2] P[ $\lambda_{M-1}$ , cos( $\theta$ )N-1] P[ $\lambda_{M-1}$ , cos( $\theta$ )N]

P[ $\lambda_M$ , cos( $\theta$ )1] P[ $\lambda_M$ , cos( $\theta$ )2] P[ $\lambda_M$ , cos( $\theta$ )3] ... P[ $\lambda_M$ , cos( $\theta$ )N-2] P[ $\lambda_M$ , cos( $\theta$ )N-1] P[ $\lambda_M$ , cos( $\theta$ )N]

:ENDFILE
```

where the first row defines the values of  $\cos(\theta)$ , the second row defines the wavelength values, and the following 2D distribution corresponds to the probability value for each wavelength,  $\cos(\theta)$  pair. The file ends with the :ENDFILE tag.

To activate the user defined scattering physics process, users must add the material property USER\_SCATCOEF in the geometry (.geom) file. The phase function can be defined per material, and must be named

*phase\_function.MATERIAL\_NAME.txt*

i.e., for G4\_WATER, the phase function must be saved in a file named phase\_function.G4\_WATER.txt.

An example is shown below for defining the user defined scattering coefficient of the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wvnm 600.0*wvnm 800.0*wvnm
```

*:MATEPT\_ADD\_PROPERTY example\_table RINDEX 1.334 1.333 1.331*

*:MATEPT\_ADD\_PROPERTY example\_table USER\_SCATCOEF 90.0\*/cm 85.0\*/cm 84.0\*/cm*

*:MATEPT\_ATTACH\_TO\_MATERIAL example\_table G4\_WATER*

## Fluorescence

To activate the fluorescence process, users must add the material properties FLUOR\_ABSCOEF, FLUOR\_LIFETIME, and FLUOR\_QUANTUMYIELD in the geometry (.geom) file, and provide the time profile using the following commands in the simulation (.in) file.

```
/gamos/setParam G4OpTissueFluor:TimeProfile exponential
```

The time profile options are delta, and exponential, and the sampling space options are wavelength and energy. The emission spectrum must be defined in the material properties table as FLUOR\_EMISSION, defined as a probability of fluorescent emission at each wavelength. The cumulative probability does not need to sum to 1.0 and will be auto scaled within the physics process. One parameter must be set for the emission spectrum filename and sampling method using

```
/gamos/setParam G4OpTissueFluor:Method interpolate
```

An example is shown below for defining the absorption coefficient of the G4\_WATER material.

```
:MATE_PROPERTIES_TABLE example_table  
:MATEPT_ADD_WAVELENGTHS example_table 400.0*wvnm 600.0*wvnm 800.0*wvnm  
:MATEPT_ADD_PROPERTY example_table RINDEX 1.334 1.333 1.331  
:MATEPT_ADD_PROPERTY example_table FLUOR_ABSCOEF 9.0*/mm 8.5*/mm 8.4*/mm  
:MATEPT_ADD_PROPERTY example_table FLUOR_EMISSION 0.5 1.0 0.25  
:MATEPT_ADD_CONST_PROPERTY example_table FLUOR_LIFETIME 100*ns  
:MATEPT_ADD_CONST_PROPERTY example_table FLUOR_QUANTUMYIELD 0.5  
:MATEPT_ATTACH_TO_MATERIAL example_table G4_WATER
```

Note that the FLUOR\_LIFETIME and FLUOR\_QUANTUMYIELD properties are constant properties and are instantiated with the command :MATEPT\_ADD\_CONST\_PROPERTY.

## The Cerenkov Process

Optical photons may be induced by radiation, as in the case of the Cerenkov process. To instantiate the process, the user must include the following lines in the simulation (.in) file

```
/gamos/physics/addPhysics cerenkov
```

The number of optical photons generated within a given step can also be limited to a maximum by setting the following parameter

```
/gamos/setParam GmPhysicsCerenkov:MaxNumPhotonsPerStep N
```

where N is the maximum number of photons per step. In addition, rather than first tracking an electron and building a stack of emitted optical photons to be tracked afterwards, the optical photons generated at each step can be tracked first for efficiency reasons. This can be controlled through the parameter

```
/gamos/setParam GmPhysicsCerenkov:TrackSecondariesFirst VALUE
```

where value is 1 for yes, and 0 for no. Finally, the emission of optical photons can be interpolated continuously or set to discrete wavelengths only through the parameter

```
/gamos/setParam G4OpCerenkov:Method NAME
```

where NAME is either fixed, for discrete sampling, or interpolate for continuous sampling.

In either case, for the Cerenkov process the limits of the waveband are the limits of the defined wavelength range for the given material property table (see Material Property Table section). For discrete sampling, optical photons are only generated at the discrete wavelength points specified in the given material property table.



## The Scintillation Process

Optical photons may also be induced by the scintillation process, which can be instantiated with the following command

```
/gamos/physics/addPhysics scintillation
```

In order to have scintillation in a material, the first parameter that has to be specified is the SCINTILLATIONYIELD (1/Mev, 1/keV), which gives the number of photons that is emitted per amount of energy absorbed, or, more precisely, it gives the expectation value of this number, since the real number of emitted photons follows a normal distribution. The variance of this normal distribution is RESOLUTIONSCALE times this expectation value. Thus, for example, when a gamma photon deposits E amount of energy in the scintillator, N optical photons are emitted with an expectation value of

$$\mu(N) = SCINTILLATIONYIELD$$

and a standard deviation

$$\sigma(N) = RESOLUTIONSCALE \sqrt{E \times SCINTILLATIONYIELD}$$

The scintillation follows an exponential decay with two time constants, a fast and a slow one. The ratio between the fast decay and the total decay is given by YELDRATIO and the two time constants by FASTTIMECONSTANT and SLOWTIMECONSTANT. The property vectors FASTCOMPONENT and SLOWCOMPONENT give the emission spectra of both decays respectively. These vectors specify the probability that a photon with the given energy is emitted. The emission over these two components can be either continuous or discretely sampled through the parameter

```
/gamos/setParam G4OpScintillation:Method NAME
```

where NAME is either fixed, for discrete sampling, or interpolate for continuous sampling. An example material property definition for the scintillation process is given below.

```
:MATE_PROPERTIES_TABLE mpt1  
:MATEPT_ADD_WAVELENGTHS mpt1 400.0*wnm 500.0*wnm 600.0*wnm  
:MATEPT_ADD_PROPERTY mpt1 RINDEX 1.33 1.33 1.33  
:MATEPT_ADD_CONST_PROPERTY mpt1 SCINTILLATIONYIELD 6000.0/MeV  
:MATEPT_ADD_CONST_PROPERTY mpt1 RESOLUTIONSCALE 100.0  
:MATEPT_ADD_CONST_PROPERTY mpt1 YELDRATIO 0.4  
:MATEPT_ADD_PROPERTY mpt1 SLOWCOMPONENT 1.0 2.0 1.0  
:MATEPT_ADD_PROPERTY mpt1 FASTCOMPONENT 2. 1.0 2.0  
:MATEPT_ADD_CONST_PROPERTY mpt1 SLOWTIMECONSTANT 10.0*us
```

```
:MATEPT_ADD_CONST_PROPERTY mpt1 FASTTIMECONSTANT 1.0*ns  
:MATEPT_ATTACH_TO_MATERIAL mpt1 G4_WATER
```

## Uniform Wavelength Source Distribution

Although GAMOS inherently has the ability to provide a uniform energy source distribution, this is not adequate for optical simulations, i.e.,

$$d\lambda \neq d\epsilon$$

and the conversion between bin widths in wavelength and energy space are not equivalent. Therefore, a new source plugin has been added to provide this functionality, and can be instantiated with the command

*/gamos/generator/energyDist SRCNAME GmGenerDistWavelengthRandomFlat*

where SRCNAME is the name of the source instantiated in the simulation (.in) file.

## User Defined Wavelength Source Distribution

If a user wishes to define a source wavelength distribution of an arbitrary spectrum, a plugin has been designed to facilitate this. The source spectrum must be provided in a text (.txt) file in the same directory as the simulation (.in) and geometry (.geom) files. The text file should contain the emission spectrum in the following format

```
400*wnm 0.1  
500*wnm 0.2  
600*wnm 0.5  
700*wnm 0.2  
:ENDFILE
```

The plugin can be instantiated as the source using the following command

```
/gamos/generator/energyDist SRCNAME GmGenerDistWavelengthFromFile a1 a2
```

where SRCNAME is the name of the source instantiated in the simulation (.in) file, a1 is the argument specifying the source spectrum filename, and a2 is the sampling method, i.e.,

```
/gamos/generator/energyDist SRCNAME GmGenerDistWavelengthFromFile spectrum.txt  
interpolate
```

would sample a wavelength distribution from a file (spectrum.txt) using linear interpolation.

## Tracklength Fluence Scorer

Scoring in a homogenous medium can be adequately performed using the existing GAMOS tracklength scorer. However, for inhomogenous media, the tracklength scorer will not adequately represent the inhomogenous boundary, and results must be normalized by the absorption coefficient in each voxel. To handle this, a new scorer has been designed which scores the tracklength in each voxel by the local absorption coefficient. The scorer can be activated as a normal scorer (see GAMOS user guide section on scoring) with the name GmPSTrackLengthFluence.

## CSV-format Scoring Printer

The default GAMOS text file printer outputs the data in a way, which is difficult to read into a post-editing program (i.e., MATLAB). Therefore, a new printer plugin has been designed to give the user the ability to output scored data in CSV format. The printer is instantiated as a normal GAMOS printer (see GAMOS user guide printer section). In addition, three parameters must be set for the printer to determine how the CSV file will be generated. These include

```
/gamos/setParam PRINTER_NAME:PrintHeader a1  
/gamos/scoring/scoreErrors PRINTER_NAME a2  
/gamos/scoring/printByEvent PRINTER_NAME a3
```

where PRINTER\_NAME is the name of the instantiated printer, a1 is TRUE or FALSE for printing header information in the CSV file, a2 is TRUE or FALSE for scoring the projected error for each scored quantity, and a3 is TRUE or FALSE for normalizing the scored quantity by the number of simulated particles.

## Boundary Processes

The majority of Monte Carlo codes handle the optical boundary processes with only simplified reflection (specular only) and refraction. GEANT4/GAMOS has the inherent capability of modeling much more complex reflection processes. There are two models available, the GLISUR and UNIFIED model, both of which are dependent on the type of surface specified.

The GLISUR model was developed in GEANT3, and the UNIFIED model a newer model for handling optical boundary processes at either a dielectric-metal or dielectric-dielectric boundary. By default, the optical boundary processes will default to the UNIFIED model for a perfectly polished surface, which simplifies to the typical Fresnel equations used in most optical Monte Carlo codes. The UNIFIED model should be used although the GLISUR model is available. Information on the models is available in the following GEANT4 documentation

<http://geant4.slac.stanford.edu/UsersWorkshop/PDF/Peter/OpticalPhoton.pdf>.

To enable a more complex reflection model, an optical surface must be defined in the geometry (.geom) file with the following command

*:OPTICAL\_SURFACE name model surface type*

Where name is the optical surface name, model is UNIFIED, surface is the type of surface (see list of available types on next page), and type is dielectric\_dielectric or dielectric\_metal. After an optical surface has been defined, it must be attached to a logical border between two logical volumes in the geometry using the following command

*:LOGICAL\_BORDER\_SURFACE name volume1 volume2 opticalsurface*

Where name is the name of the logical border surface, volume1 and volume2 are the two volumes of interest, optical surface is the name of the optical surface.

When using the UNIFIED model, an additional material property table must be defined for the optical surface itself. This material property table MUST contain a definition of refractive index, as well as a wavelength dependent definition of the specular lobe constant, specular spike constant, backscatter constant, reflectivity, efficiency, and transmittance. By default the reflectivity is 0, and the transmittance is calculated based upon the refractive indices of the two volumes of interest.

The values can be set using the following commands in the (.geom) file. An example is given below.

*:MATE\_PROPERTIES\_TABLE mpt1*  
*:MATEPT\_ADD\_WAVELENGTHS mpt1 600\*wvnm*  
*:MATEPT\_ADD\_PROPERTY mpt1 RINDEX 1.5*  
*:MATEPT\_ADD\_PROPERTY mpt1 SPECULARLOBECONSTANT 0.7*  
*:MATEPT\_ADD\_PROPERTY mpt1 SPECULARSPIKECONSTANT 0.2*  
*:MATEPT\_ADD\_PROPERTY mpt1 BACKSCATTERCONSTANT 0.1*  
*:MATEPT\_ATTACH\_TO\_MATERIAL mpt1 G4\_WATER*

*:MATE\_PROPERTIES\_TABLE mpt2*  
*:MATEPT\_ADD\_WAVELENGTHS mpt2 600\*wvnm*  
*:MATEPT\_ADD\_PROPERTY mpt2 RINDEX 1.0*  
*:MATEPT\_ATTACH\_TO\_MATERIAL mpt2 G4\_AIR*

*:OPTICAL\_SURFACE os1 UNIFIED ground dielectric\_dielectric*  
*:LOGICAL\_BORDER\_SURFACE lbs1 medium world os1*  
*:LOGICAL\_BORDER\_SURFACE lbs2 world medium os1*  
*:MATEPT\_ATTACH\_TO\_OPTICAL\_SURFACE mpt1 os1*



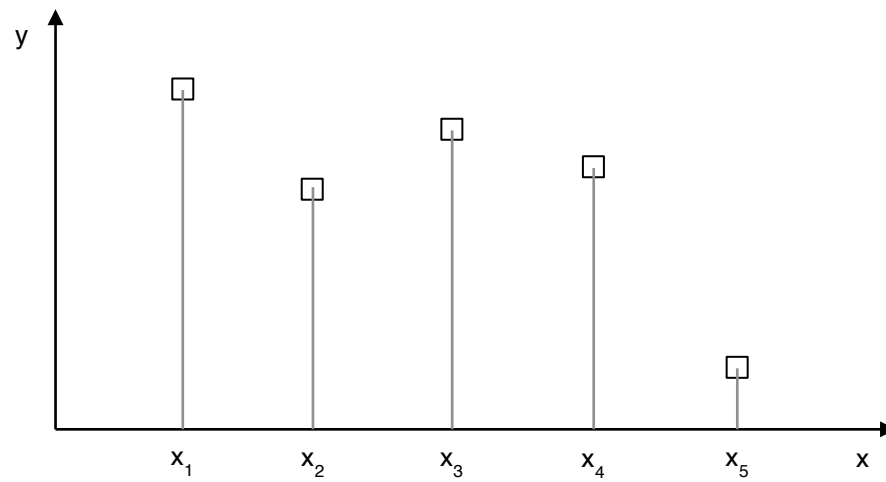
## Surface types

polishedfrontpainted  
polishedbackpainted  
ground  
groundfrontpainted  
groundbackpainted  
polishedlumirrorair  
polishedlumirrorglue  
polishedair  
polishedteflonair  
polishedtioair  
polishedtyvekair  
polishedvm2000air  
polishedvm2000glue  
etchedlumirrorair  
etchedlumirrorglue  
etchedair  
etchedteflonair  
etchedtioair  
etchedtyvekair  
etchedvm2000air  
etchedvm2000glue  
groundlumirrorair  
groundlumirrorglue  
groundair  
groundteflonair  
groundtioair  
groundtyvekair  
groundvm2000air  
groundvm2000glue

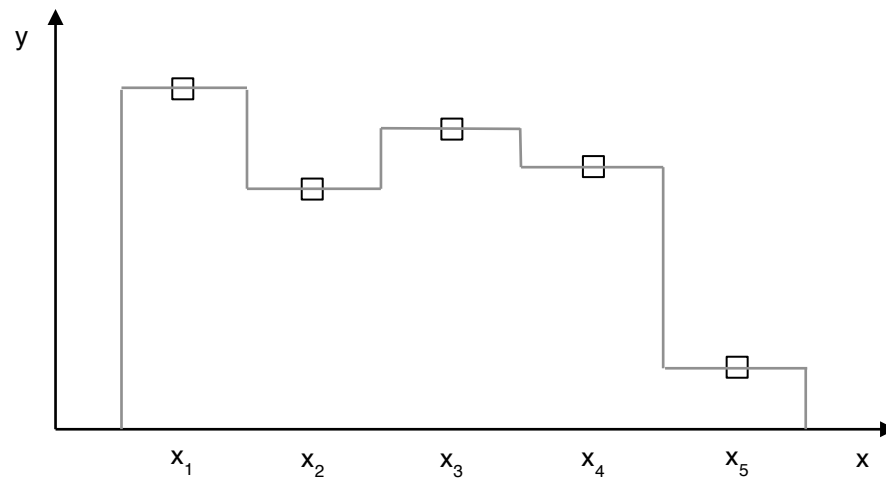
## Sampling

If the type is fixed the energies used are only those listed. For example if you want half of your primary particles with energy 0.5 MeV and half with energy 1. MeV, you can write the following file:

```
0.5 0.5  
1. 0.5
```



If the type is histogram (the default value if the second argument is not provided) the data read will be interpreted as that of a constant-bin histogram: the energies are the values of the centre of each histogram bin and the energies will be randomly distributed (with the corresponding probability) in the histogram bin. In this case if the difference between data points is not constant, an exception will be thrown.



For example if you want a quarter of your primary particles uniformly distributed between 0 and 1 MeV and three quarters between 1 and 2 MeV, you can write the following file:

```
0.5 0.25
```

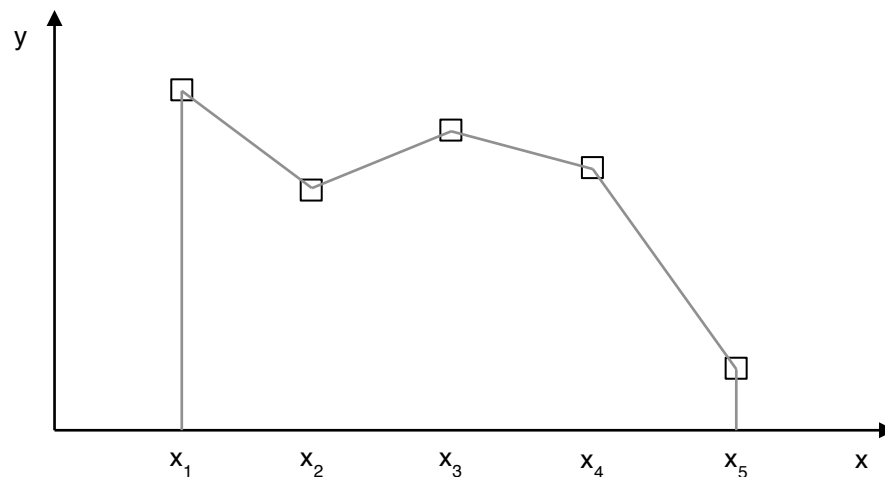
```
1.5 0.75
```

If type is interpolate the data read will be interpreted as that of an histogram, with constant or non-constant bin. As the bins may be not equal, the behaviour has to be different than for the 'histogram' case above: one cannot use the bin centres and calculate the bin limits, but the bin limits have to be explicitly provided. In other words, the energies given will be the limits of the bins and the probability read together with an energy is the probability between the energy and the next energy. We recommend then that the last energy has probability 0. For example if you want a quarter of your primary particles uniformly distributed between 0 and 1 MeV and three quarters between 1 and 2 MeV, you can write the following file:

```
0. 0.25
```

```
1. 0.75
```

```
2. 0.
```



## Materials List

G4\_A-150\_TISSUE,  
G4\_ACETONE,  
G4\_ACETYLENE,  
G4\_ADENINE,  
G4\_ADIPOSE\_TISSUE\_ICRP,  
G4\_AIR,  
G4\_ALANINE,  
G4\_ALUMINUM\_OXIDE,  
G4\_AMBER,  
G4\_AMMONIA,  
G4\_ANILINE,  
G4\_ANTHRACENE,  
G4\_B-100\_BONE,  
G4\_BAKELITE,  
G4\_BARIUM\_FLUORIDE,  
G4\_BARIUM\_SULFATE,  
G4\_BENZENE,  
G4\_BERYLLIUM\_OXIDE,  
G4\_BGO,  
G4\_BLOOD\_ICRP,  
G4\_BONE\_COMPACT\_ICRU,  
G4\_BONE\_CORTICAL\_ICRP,  
G4\_BORON\_CARBIDE,  
G4\_BORON\_OXIDE,  
G4\_BRAIN\_ICRP,  
G4\_BUTANE,  
G4\_N-BUTYL\_ALCOHOL,  
G4\_C-552,  
G4\_CADMIUM\_TELLURIDE,  
G4\_CADMIUM\_TUNGSTATE,  
G4\_CALCIUM\_CARBONATE,  
G4\_CALCIUM\_FLUORIDE,  
G4\_CALCIUM\_OXIDE,  
G4\_CALCIUM\_SULFATE,  
G4\_CALCIUM\_TUNGSTATE,  
G4\_CARBON\_DIOXIDE,  
G4\_CARBON\_TETRACHLORIDE,  
G4\_CELLULOSE\_CELLOPHANE,  
G4\_CELLULOSE\_BUTYRATE,  
G4\_CELLULOSE\_NITRATE,  
G4\_CERIC\_SULFATE,  
G4\_CESIUM\_FLUORIDE,

G4\_CESIUM\_IODIDE,  
G4\_CHLOROBENZENE,  
G4\_CHLOROFORM,  
G4\_CONCRETE,  
G4\_CYCLOHEXANE,  
G4\_1, 2-DICHLOROBENZENE,  
G4\_DICHLORODIETHYL\_ETHER,  
G4\_1,2-DICHLOROETHANE,  
G4\_DIETHYL\_ETHER,  
G4\_N, N-DIMETHYL\_FORMAMIDE,  
G4\_DIMETHYL\_SULFOXIDE,  
G4\_ETHANE,  
G4\_ETHYL\_ALCOHOL,  
G4\_ETHYL\_CELLULOSE,  
G4\_ETHYLENE,  
G4\_EYE\_LENS\_ICRP,  
G4\_FERRIC\_OXIDE,  
G4\_FERROBORIDE,  
G4\_FERROUS\_OXIDE,  
G4\_FERROUS\_SULFATE,  
G4\_FREON-12,  
G4\_FREON-12B2,  
G4\_FREON-13,  
G4\_FREON-13B1,  
G4\_FREON-13I1,  
G4\_GADOLINIUM\_OXYSULFIDE,  
G4\_GALLIUM\_ARSENIDE,  
G4\_GEL\_PHOTO\_EMULSION,  
G4\_Pyrex\_Glass,  
G4\_GLASS\_LEAD,  
G4\_GLASS\_PLATE,  
G4\_GLUCOSE,  
G4 GLUTAMINE,  
G4 GLYCEROL,  
G4\_GUANINE,  
G4\_GYPSUM,  
G4\_N-HEPTANE,  
G4\_N-HEXANE,  
G4\_KAPTON,  
G4\_LANTHANUM\_OXYBROMIDE,  
G4\_LANTHANUM\_OXYSULFIDE,  
G4\_LEAD\_OXIDE,  
G4\_LITHIUM\_AMIDE,  
G4\_LITHIUM CARBONATE,

G4\_LITHIUM\_FLUORIDE,  
G4\_LITHIUM\_HYDRIDE,  
G4\_LITHIUM\_IODIDE,  
G4\_LITHIUM\_OXIDE,  
G4\_LITHIUM\_TETRABORATE,  
G4\_LUNG\_ICRP,  
G4\_M3\_WAX,  
G4\_MAGNESIUM\_CARBONATE,  
G4\_MAGNESIUM\_FLUORIDE,  
G4\_MAGNESIUM\_OXIDE,  
G4\_MAGNESIUM\_TETRABORATE,  
G4\_MERCURIC\_IODIDE,  
G4\_METHANE,  
G4\_METHANOL,  
G4\_MIX\_D\_WAX,  
G4\_MS20\_TISSUE,  
G4\_MUSCLE\_SKELETAL\_ICRP,  
G4\_MUSCLE\_STRIATED\_ICRU,  
G4\_MUSCLE\_WITH\_SUCROSE,  
G4\_MUSCLE\_WITHOUT\_SUCROSE,  
G4\_NAPHTHALENE,  
G4\_NITROBENZENE,  
G4\_NITROUS\_OXIDE,  
G4\_NYLON-8062,  
G4\_NYLON-6/6,  
G4\_NYLON-6/10,  
G4\_NYLON-11\_RILSAN,  
G4\_OCTANE,  
G4\_PARAFFIN,  
G4\_N-PENTANE,  
G4\_PHOTO\_EMULSION,  
G4\_PLASTIC\_SC\_VINYLTOLUENE,  
G4\_PLUTONIUM\_DIOXIDE,  
G4\_POLYACRYLONITRILE,  
G4\_POLYCARBONATE,  
G4\_POLYCHLOROSTYRENE,  
G4\_PLYETHYLENE,  
G4\_MYLAR,  
G4\_PLEXIGLASS,  
G4\_PLYOXYMETHYLENE,  
G4\_PLYPROPYLENE,  
G4\_PLYSTYRENE,  
G4\_TEFロン,  
G4\_PLYTRIFLUOROCHLOROETHYLENE,

G4\_POLYVINYL\_ACETATE,  
G4\_POLYVINYL\_ALCOHOL,  
G4\_POLYVINYL\_BUTYRAL,  
G4\_POLYVINYL\_CHLORIDE,  
G4\_POLYVINYLIDENE\_CHLORIDE,  
G4\_POLYVINYLIDENE\_FLUORIDE,  
G4\_POLYVINYL\_PYRROLIDONE,  
G4\_POTASSIUM\_IODIDE,  
G4\_POTASSIUM\_OXIDE,  
G4\_PROPANE,  
G4\_IPROPANE,  
G4\_N-PROPYL\_ALCOHOL,  
G4\_PYRIDINE,  
G4\_RUBBER\_BUTYL,  
G4\_RUBBER\_NATURAL,  
G4\_RUBBER\_NEOPRENE,  
G4\_SILICON\_DIOXIDE,  
G4\_SILVER\_BROMIDE,  
G4\_SILVER\_CHLORIDE,  
G4\_SILVER\_HALIDES,  
G4\_SILVER\_IODIDE,  
G4\_SKIN\_ICRP,  
G4\_SODIUM\_CARBONATE,  
G4\_SODIUM\_IODIDE,  
G4\_SODIUM\_MONOXIDE,  
G4\_SODIUM\_NITRATE,  
G4\_STILBENE,  
G4\_SUCROSE,  
G4\_TERPHENYL,  
G4\_TESTES\_ICRP,  
G4\_TETRACHLOROETHYLENE,  
G4\_THALLIUM\_CHLORIDE,  
G4\_TISSUE\_SOFT\_ICRP,  
G4\_TISSUE\_SOFT\_ICRU-4,  
G4\_TISSUE-METHANE,  
G4\_TISSUE-PROPANE,  
G4\_TITANIUM\_DIOXIDE,  
G4\_TOLUENE,  
G4\_TRICHLOROETHYLENE,  
G4\_TRIETHYL\_PHOSPHATE,  
G4\_TUNGSTEN\_HEXAFLUORIDE,  
G4\_URANIUM\_DICARBIDE,  
G4\_URANIUM\_MONOCARBIDE,  
G4\_URANIUM\_OXIDE,

G4\_UREA,  
G4\_VALINE,  
G4\_VITON,  
G4\_WATER,  
G4\_WATER\_VAPOR,  
G4\_XYLENE,  
G4\_GRAPHITE,  
G4\_IH2,  
G4\_IN2,  
G4\_IO2,  
G4\_IAr,  
G4\_IKr,  
G4\_IXe,  
G4\_PbWO4,  
G4\_Galactic