

Gorad (version with Geant4 10.7)

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0] Preamble

Gorad (Geant4 Open-source Radiation Analysis and Design) is developed as a turn-key application for radiation analysis and spacecraft design built on top of Geant4. Simulation geometry should be provided in the form of GDML.

Gorad is controlled by UI commands, and it works both in interactive mode with Qt window and in batch mode with an input macro file. UI commands starting with */gorad/* are implemented in Gorad code and thus they are not available in Geant4 itself (or other Geant4 applications). These Gorad-specific commands are listed in Appendix A. Other commands that do not start with */gorad/* are provided in Geant4 and available with Geant4 version 10.7 that is released in December 2020. For demonstration purposes, Gorad includes a macro file *run.mac* that can be used for both interactive mode and batch mode. Tips for installing and running Gorad are given in Appendix B.

1] Initialization

Gorad has to be initialized by the following command.

```
/gorad/initialize
```

This command internally calls */run/initialize* to initialize *G4MTRunManager*, so that the user should not use */run/initialize*. Prior to this initialization command, Gorad needs the following to be defined:

- Simulation geometry (see section 2)
- Choice of Physics models (see section 3)
- Biasing geometry (optional, see section 11)

Other simulation settings, e.g. radiation source spectrum as well as scoring and histogramming should be defined after Gorad is initialized.

2] Simulation geometry

The geometry has to be provided as an input GDML file. Gorad assumes the shape of the world volume is a box.

```
/gorad/geometry/selectGDML <filename>
```

There are a few utility commands to access to the geometry information, that are listed in Appendix A.2. These utility commands are available after Gorad is initialized and the GDML file is processed. For example,

```
/gorad/geometry/listLogicalVolumes 2
```

will dump all the defined logical volumes with their names, materials, solid names, masses, etc. The mass takes into account of daughter volumes, so it might be a good idea to check the total weight of the satellite to verify the correctness of the geometry.

The user may assign a material to a volume defined in the GDML file. If the volume already has a material, it is overwritten by the new material. The assigning material can be taken from a material defined in the GDML file or a new material can be created from the *G4NistManager*. All the material-related commands are listed in Appendix A.3.

The world volume defines the default region where the global production thresholds are applied. Optionally, the user may define a region and set it to logical volumes that are placed inside the world volume. A region may take its specific values of alternative production thresholds or step limitation (both will be discussed in the following sections). The user cannot set a region to the world volume. If a region is set to a logical volume, all daughter volumes contained in this logical volume belong to the same region.

3] Choice of physics models

Geant4 as a Monte Carlo toolkit offers many physics options, with some being alternatives to others. For the convenience of the users, Geant4 has several “Physics Lists” that are pre-packaged as “educated guesses” for various use-cases. Gorad as a turn-key application for radiation analysis and spacecraft radiation design has a few limited numbers of options that are suitable for this purpose. For most of the cases, the user of Gorad should just pick electromagnetic and hadronic physics options.

```
/gorad/physics/EM <EM_option>  
/gorad/physics/Hadronic <Had_option>
```

Available options and their suitable use-cases are described in Appendices A.4 ~ A.6.

Production thresholds (a.k.a. cuts) for electron, positron, gamma and proton should also be specified. For most of the use-cases, these four thresholds should be same.

```
/gorad/physics/cuts/setCuts <length> <unit>
```

For most of the geometries with macroscopic size, 0.7~1.0 mm would be a good value. For microscopic simulation such as for single event upset simulation where the typical size of the volumes is in the order of micrometers, thresholds should be much smaller. If a region is defined, dedicated production thresholds could be assigned.

```
/gorad/geometry/createRegion <regionName> <logVolName>  
/gorad/physics/cuts/setRegionCuts <regionName> <length> <unit>
```

In general, a step of a track is limited either by a volume boundary crossing or discrete physics interaction (e.g. decay, inelastic scattering, etc.). Artificial limitation to the maximum step length to the specified particle type may be defined. Maximum step length could be assigned to a region. Artificial step limitation is useful for particles generating optical photons.

4] Radiation spectrum

The following command defines the radiation spectrum

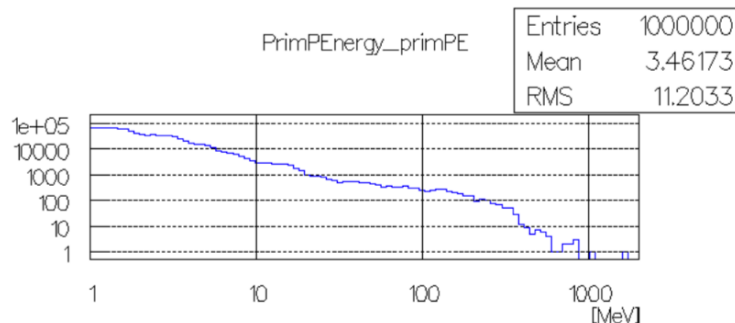
```
/gorad/source/define <pName> <fName> <srcType> <radius> <unit> <x0> <y0> <z0>
```

where *<pName>* is the primary particle name and *<fName>* is its spectrum file in ASCII text format. *<fName>* may contain directory path. Each line of the spectrum file should have energy in MeV and bin height separated by a space. A line in the spectrum file starting with “#” is ignored as a comment line. Two spectrum data files, *King.spec* and *Trap.spec*, are provided as examples. Primary particles are generated inward from the sphere of *<radius>* and *<unit>*. If *<radius>* is not specified, the size of this sphere is defined as 95% of the size of the world volume. This sphere is located at the center of the world volume by default, but can be displaced by specifying the location (*<x0>*, *<y0>*, *<z0>*). The same *<unit>* is applied to (*<x0>*, *<y0>*, *<z0>*). It is user’s responsibility to make sure the sphere is completely contained in the world volume.

<srcType> defines how the primary tracks are generated. It can be either “Arb” or “LW”. “Arb” generates primary tracks along the defined spectrum, while “LW” generates primary tracks in flat distribution with track weight representing the spectrum.

The following is the “Arb” option that generates primary tracks along with the provided *Trap.spec* energy spectrum.

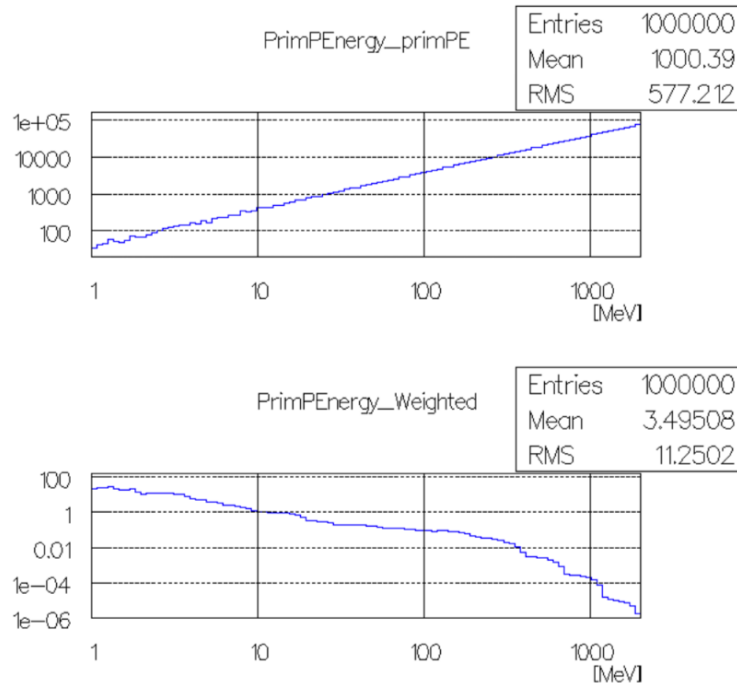
```
/gorad/source/define proton Trap.spec Arb
```



Please note that despite the *Trap.spec* spectrum file having data up to 2 GeV, this plot does not have many entries higher than 1 GeV due to insufficient statistics, i.e. 1 million events are not enough to have tracks higher than 1 GeV.

The following is the “LW” option where energy of primary tracks is in flat distribution, but each track has a weight proportional to the energy spectrum.

```
/gorad/source/define proton Trap.spec LW
```



Here, the upper plot shows the energy spectrum of the generated primary tracks without their weights, while lower plot shows the same energy spectrum of the generated primary tracks with weights. This option can statistically enhance higher energy tracks that are rare but contribute largely to the scores.

Track weight is automatically taken into account for every primitive scorer, and every plot filled by the primitive scorers. The only exception is the energy spectrum of primary tracks discussed in the next section where a flag is available for applying weight.

Please note that this `/gorad/source/define` command is not mandatory for Gorad but alternatively `granular/gps/` commands can be used for defining primary particles. As examples, two macro files, `gps_focus.mac` and `gps_point_mac` are provided. The former macro shoots primaries from the sphere inward to the center, and the latter shoots primaries from a point.

5] 1-D histogram for kinetic energy spectrum of primary tracks

The following UI command creates a 1-D histogram for the kinetic energy spectrum of primary tracks.

```
/gorad/analysis/1D/primary <plotName> <weightFlag>
```

Weight of each primary track are taken into account if `<weightFlag>` is true. This command has to be immediately followed by `/gorad/analysis/1D/config` command (discussed in section 10) to specify the histogram parameters. For example, the last plot in the previous section was created with the following commands.

```
/gorad/analysis/1D/primary Weighted true
/gorad/analysis/1D/config 100 1.0 2.0e3 MeV log
/gorad/analysis/1D/yaxisLog true
```

6] Scoring probe

This functionality allows the user to locate scoring “probes” at arbitrary locations. A “probe” is a virtual cube, to which any Geant4 primitive scorers could be assigned. This is a concept alternative to a scoring mesh, where cells of three-dimensional mesh are touching each other.

```
/score/create/probe <probeName> <halfWidth> <unit>  
/score/probe/locate <x> <y> <z> <unit>
```

The user can locate an arbitrary number of probes by repeating `/score/probe/locate` commands, but all of these probes are the same shape. Given these probes are located in an artificial “parallel world”, probes may overlap to the volumes defined in the mass geometry, as long as probes themselves are not overlapping to each other or protruding from the world volume.

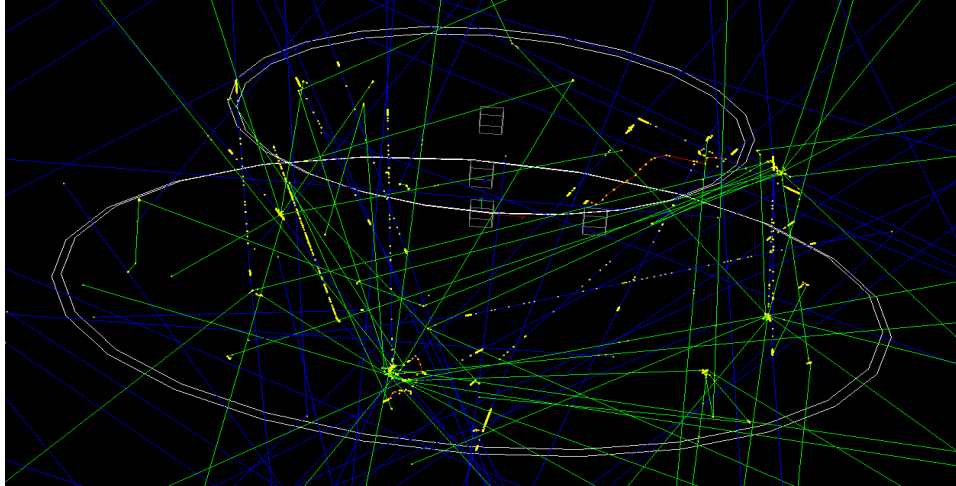
In addition, the user may optionally set a material to the probe. Once a material is set to the probe, it overwrites the material(s) defined in the mass geometry when a track enters the probe cube. Because of this overwriting, physics quantities that depend on material or density, e.g. energy deposition or dose, would be measured accordingly to the specified material. The material to be set has to be pre-defined in the input GDML file or in *G4NISTManager*. To use a material defined in the *G4NISTManager*, it has to be created before setting to the probe. Please note that this overwriting material obviously affects to the simulation results, so the size and number of probes should be reasonably small to avoid significant side effects.

Once a probe is defined, the user can associate arbitrary number of primitive scorers and filters like the ordinary scoring mesh. All probes have the same scorers but score individually. The following is a sample macro to locate 4 probes and score energy deposition, dose in water, flux and proton flux for each of these probes.

```
/score/create/probe Probes 5 cm  
/score/probe/material G4_WATER  
/score/probe/locate 0 0 0 cm  
/score/probe/locate 25 0 0 cm  
/score/probe/locate 0 25 0 cm  
/score/probe/locate 0 0 25 cm  
/score/quantity/energyDeposit eDep MeV  
/score/quantity/doseDeposit dose mGy  
/score/quantity/volumeFlux volFlx  
/score/quantity/volumeFlux protonFlux  
/score/filter/particle protonFilter proton  
/score/close
```

Please note that the size of the probe is specified by **half width**. In the above sample, the actual size of the probe is $10 \times 10 \times 10 \text{ cm}^3$. After the simulation run, scored data can be dumped into a file by usual Geant4 `/score/dump` commands. The file format of `/score/dump` commands are common for all kinds of scorers, so that first three columns of each row are indices along x, y and z axes. For one-dimensional scorers including probes and real-world volume scorer (to be discussed in the next section), indices of y and z axes are always zero. If probes are placed more than once, scores are dumped separately for each probe, with the order of the `/score/probe/locate` command.

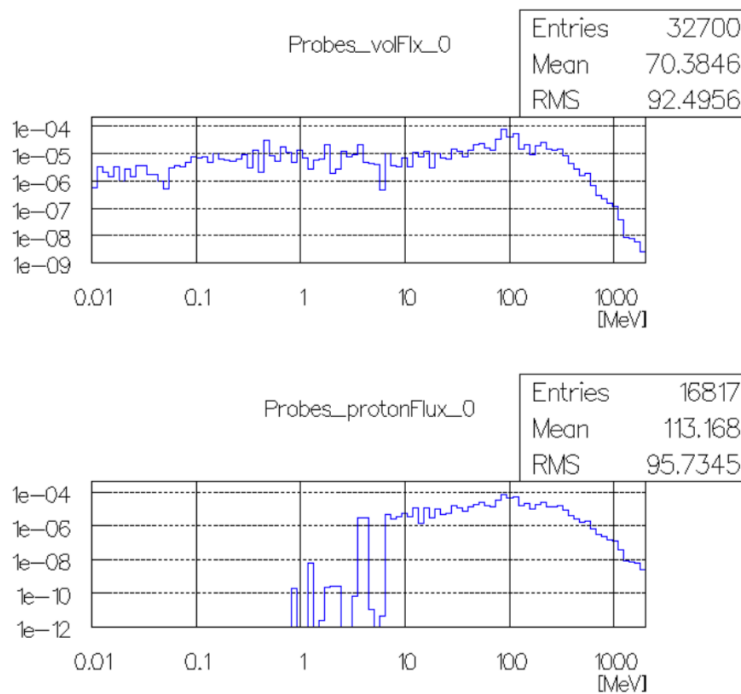
```
/run/beamOn 100000  
/score/dumpAllQuantitiesWithFactor Probes Probes.csv
```



In this event display, four probe cubes are drawn in gray. To visualize the probes defined in a parallel world, the following command is required.

```
/vis/drawVolume worlds
```

Also, probes are created at the beginning of an event loop. Thus, they are not drawn before the first event loop (a.k.a. `/run/beamOn`).



These plots are the energy spectrum measured with a $10 \times 10 \times 10 \text{ cm}^3$ probe cube placed at the origin. The above is for all particle types and the bottom is proton only. The following are the UI commands to create these plots (`/gorad/analysis/` commands will be discussed in sections 8 and 10).

```

/score/create/probe Probes 5 cm
/score/probe/locate 0 0 0 cm
/score/quantity/volumeFlux volFlx
/score/quantity/volumeFlux protonFlux
/score/filter/particle protonFilter proton
/score/close
/gorad/analysis/1D/spectrum Probes volFlx
/gorad/analysis/1D/config 100 1.0e-2 2.0e3 MeV log
/gorad/analysis/1D/yaxisLog true
/gorad/analysis/1D/spectrum Probes protonFlux
/gorad/analysis/1D/config 100 1.0e-2 2.0e3 MeV log
/gorad/analysis/1D/yaxisLog true
/gorad/analysis/plot -1

```

7] Real-world volume scorer

Alternative to the scoring probe discussed in the previous section, the user may define primitive scorers to a logical volume in the mass geometry. This real-world volume scorer behaves like a probe and thus any `/score/quantity/` commands can be associated with it.

```

/score/create/realWorldLogVol <logVolName> <level>

```

where `<logVolName>` is the name of the logical volume that appears in the mass geometry, and it is also used as the name of the probe. If more than one physical volumes share the same logical volume, scores are filled individually with the copy number of the physical volume as the index. If `<level>` is set, the copy number of the `<level>`-th higher ancestor in the geometrical hierarchy is used as the index.

8] 1-D energy spectrum histogram directly filled by a primitive scorer

The following UI command creates a 1-D energy spectrum histogram that is directly filled by the associated primitive scorer.

```

/gorad/analysis/1D/spectrum <probeName> <scorerName>

```

`<probeName>` may be either the name of the probe defined by `/score/create/probe` command or the name of the Logical Volume defined by `/score/create/realWorldLogicalVol` command described in the previous sections. The x-axis of the histogram defined by this command is the kinetic energy of the track. This “*spectrum*” command is not available for scoring mesh due to memory consumption concerns. This command has to be immediately followed by `/gorad/analysis/1D/config` command (discussed in section 10) to specify the histogram parameters. If more than one probes are located, histograms are created and filled separately to each probe with their sequential order of `/score/probe/locate` command or with copy numbers of the real-world volumes.

This command is different from `/gorad/analysis/1D/create` command discussed in the next section that is filled indirectly through `G4Event` class. The histogram created by the “*spectrum*” command is for track-by-track energy spectrum, while the histogram created by the “*create*” command is for cumulative quantities such as dose or energy deposition.

Currently (with Geant4 version 10.7) `/gorad/analysis/1D/spectrum` is available only for “*volumeFlux*” primitive scorer.

9] 1-D histogram indirectly filled through *G4Event*

The following UI command creates a 1-D histogram that is associated with a primitive scorer but filled indirectly through *G4Event* object at the end of each event.

```
/gorad/analysis/1D/create <probeName> <scorerName> <idx>
```

<probeName> may be either the name of the scoring mesh defined by */score/create/boxMesh* or */score/create/cylinderMesh* command, the name of the probe defined by */score/create/probe* command, or the name of the Logical Volume defined by */score/create/realWorldLogicalVol* command. This command has to be immediately followed by */gorad/analysis/1D/config* command (discussed in section 10) to specify the histogram parameters. If <idx> is set to -1, scores of all mesh cells or probes are merged. If it is set to 0 or positive number, the histogram is filled only for the volume of specified copy number. If it is used for a scorer defined for 3-dimensional mesh, <idx> is given as $ix*ny*nz + iy*nz + iz$, where *ix*, *iy* and *iz* are the indices of each axis and *ny* and *nz* are number of cells in each axis.

10] Gorad analysis commands

Gorad offers three different kinds of one-dimensional histograms, distinguished by how it is filled.

- */gorad/analysis/1D/primary* command creates an energy spectrum histogram that is filled with individual primary tracks (discussed in section 5).
- */gorad/analysis/1D/spectrum* command creates an energy spectrum histogram that is filled directly by the associated primitive scorer in track-by-track basis (discussed in section 8).
- */gorad/analysis/1D/create* command creates a histogram that is filled indirectly through *G4Event* class for the quantity accumulated for an event such as energy deposition or dose (discussed in section 9).

Once a histogram is defined by either of these commands, it has to be configured by the following command.

```
/gorad/analysis/1D/config <nBin> <minVal> <maxVal> <unit> <scale> <logVal>
```

Details of each parameters are given in Appendix A.11. <scale> is for the x-axis and it can be either “linear” or “log”. Binning of the histogram is determined by this parameter so that scale cannot be changed once configured. For the y-axis, linear-/log-scale can be chosen with the following command.

```
/gorad/analysis/1D/yaxisLog <flag>
```

Please note that the y-axis scale is used for plotting this histogram to a PostScript file and does not affect the dumped data.

At the end of a run, each histogram is dumped to a separate file. File name should be specified by this command

```
/gorad/analysis/file <fileName>
```

but the actual file name will be appended by the histogram type and scorer name, and also by copy number if it is filled for the specified copy number of the volume. Gorad dumps histograms in CSV

format. The file format of the histogram file is described in [the *g4tools* section of Geant4 Application Developers Guide](#). If another format (Root or xml) is preferred, *GRAnalysis.hh* has to be modified accordingly and Gorad has to be recompiled. In addition to dumping to CSV files, histograms can be plotted to a PostScript file if */gorad/analysis/plot* command is set. *<fileName>* is also used for this PostScript file.

In addition to histograms, Gorad can also create an n-tuple output file, where each row has columns of scores of each individual event. Each column has to be defined by the following command

```
/gorad/analysis/addColumn <probeName> <primName> <unit> <idx>
```

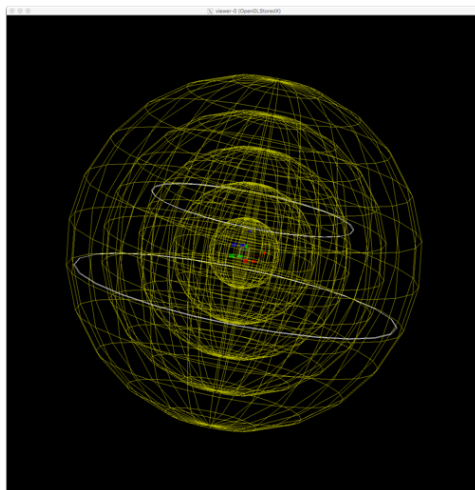
and the scores are columned in the order of this command. *<probeName>* may be either the name of the scoring mesh defined by */score/create/boxMesh* or */score/create/cylinderMesh* command, the name of the probe defined by */score/create/probe* command, or the name of the Logical Volume defined by */score/create/realWorldLogicalVol* command described in the previous sections. If *<idx>* is set to -1, scores of all mesh cells or probes are merged. If it is set to 0 or positive number, histogram is filled only by the volume of specified copy number. In multithreaded mode, n-tuple files created by individual threads are merged into one file at the end of run without sorting, so that the order of rows are not sequential to the event number.

11] Geometry-based importance biasing

This functionality allows the user to define spheres in an artificial parallel world and assign geometrical importance to each sphere. The following UI command enables this functionality and defines the number of spheres and the radius of the outermost sphere.

```
/gorad/bias/geomImportance <nLayer> <radius> <unit>
```

There must be at least two layers. This command has to precede to all other */gorad/bias* commands. If *radius* is not specified, it is set to 80% of the size of the world volume.



When a track passes through a boundary of biasing spheres from the outer and less important sphere to the inner and more important sphere, the track is duplicated (cloned) and each of them has half weight.

When a track passes to the opposite direction, it is Russian-rouletted with 50% probability, and has the doubled weight if it survives.

By default, the center of the outermost sphere is placed at the center of the world volume, but could be placed elsewhere by the following UI command.

```
/gorad/bias/geomImpLocate <x0> <y0> <z0> <unit>
```

It is user's responsibility to make sure the sphere is located completely within the world volume. To visualize the biasing spheres defined in a parallel world, the following command is required.

```
/vis/drawVolume worlds
```

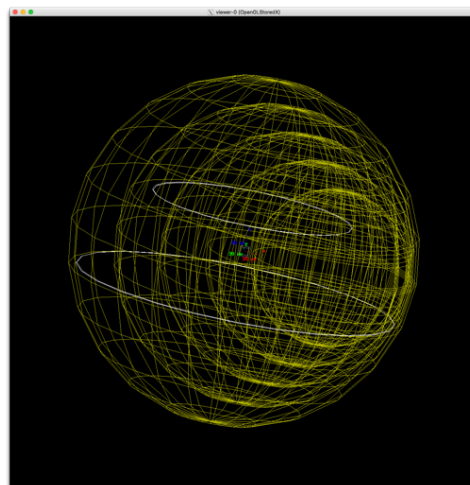
Also, spheres are created at the beginning of an event loop. Thus, they are not drawn before the first event loop.

By default, the radius of the innermost sphere is $1/n_{Layer}$ of the radius of the outermost sphere, but could be altered. In addition, the center of the innermost sphere could be dislocated from the center of the outermost sphere. It is the user's responsibility to make sure the innermost sphere is fully contained by the outermost sphere. Intermediate layers are sized and placed proportionally.

```
/gorad/bias/geomImpInnerRadius <rT> <unit>  
/gorad/bias/geomImpLocTgt <xT> <yT> <zT> <unit>
```

The biasing spheres shown in the following figure are created by these commands.

```
/gorad/bias/geomImportance 5 2. m  
/gorad/bias/geomImpInnerRadius 0.9 m  
/gorad/bias/geomImpLocTgt 1. 0. 0. m
```



The more biasing layers the user has, the stronger enhancement toward the center tracks will have. Please note that over-biasing would cause distorted results. So, we do not recommend having too many layers. Biasing factor (by default it is set to 2) can be increased by the following UI command.

```
/gorad/bias/geomImpFactor <factor>
```

For example, if *<factor>* is set to 3, a track passing to the more important sphere is duplicated (cloned) to three tracks and each of them has one-third weight. When a track passes to the opposite direction, it is Russian-rouletted with two-thirds probability, and has the tripled weight if it survives. It is not recommended to use a biasing factor much larger than 2 as that may cause distorted results, too.

One of the typical symptoms of over-biasing is unphysical spikes in the resulting plots despite of the enough statistics. If the user sees the default factor 2 is still too large, he may reduce the number of layers. Also, he may use the following UI command.

```
/gorad/bias/geomImpProbability <prob>
```

For example, if this *<prob>* is set to 0.8, biasing will take place only for 80% of the boundary crossing, so that the effective biasing factor is 1.8 in the case where the biasing factor is 2.

12] Acknowledgements

Gorad is developed under the NASA JSC contract NNJ15HK11B.

Appendix A. /gorad/ UI commands

Note:

- Commands available only for *PreInit* state should be applied prior to */gorad/initialize* command, while commands available only for *Idle* state should be applied after */gorad/initialize* command. Commands available for both states may be used at any time.

A.1. Command directory path /gorad/

- */gorad/initialize*
 - Initialize Gorad and G4RunManager.
 - This command internally calls */run/initialize* so that the user does not need to call it.
 - Available Geant4 state(s) : PreInit

A.2. Command directory path /gorad/geometry/

- */gorad/geometry/selectGDML <filename>*
 - Select GDML file
 - Available Geant4 state(s) : PreInit

parameter name	type	omittable	
filename	s	false	GDML file name (may contain Linux-style directory path)

- */gorad/geometry/listSolids <level>*
 - List all the defined solids
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
level	i	true	0	$0 \leq \text{level} \leq 2$	0: solid name 1: 0 + cubic volume and surface area 2: 1 + shape parameters

- */gorad/geometry/listLogicalVolumes <level>*
 - List all the defined logical volumes
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
level	i	true	0	$0 \leq \text{level} \leq 2$	0: name, solid name and material 1: 0 + sensitive detector and number of daughter volumes 2: 1 + weight

- */gorad/geometry/listPhysicalVolumes <level>*
 - List all the defined physical volumes
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
level	i	true	0	$0 \leq \text{level} \leq 2$	0: name

					1: 0 + logical volume and mother logical volume 2: 1 + type of physical volume
--	--	--	--	--	---

- `/gorad/geometry/listRegions <level>`

- List all the defined regions
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
level	i	true	0	$0 \leq \text{level} \leq 2$	0: name, world volume 1: 0 + root logical volume and associated pointers 2: 1 + production cuts

- `/gorad/geometry/createRegion <regionName> <logVolName>`

- Create a region and set the root logical volume to it.
- Region propagates to the daughter volumes. So, only the root logical volume (i.e. top of the hierarchy) should be defined.
- If two isolated root logical volumes should share the same region, the same region name can be used.
- Region must not be set to the world volume.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	
regionName	s	false	region name
logVolName	s	false	root logical volume name

A.3. Command directory path `/gorad/material/`

- `/gorad/material/list <matName>`

- Dump the information of the specified material, i.e. name, density, radiation length, interaction length, etc., as well as its composition.
- If material name is not specified or ****ALL**** is used, names of all created materials are listed.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
matName	s	true	**ALL**	Material name

- `/gorad/material/dumpNistMaterials`

- List all pre-defined material names in G4NistManager.
- Note : a material has to be instantiated with `/gorad/material/create` command before setting it to a logical volume.
- Available Geant4 state(s) : Idle

- `/gorad/material/create <matName>`

- Instantiate a material pre-defined in G4NistManager.
- If the material has already been instantiated, this command does nothing.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	
matName	s	false	Material name

- /gorad/material/show <logVol>

- Show the current material of the specified logical volume.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	
logVol	s	false	Logical volume name

- /gorad/material/set <logVol> <matName>

- Set the material to the logical volume. The material has to be instantiated in advance.
- If the logical volume has already had a material, it is overwritten by the new material.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	
logVol	s	false	Logical volume name
matName	s	false	Material name

A.4. Command directory path /gorad/physics/

- /gorad/physics/EM <EM_option>

- Select EM physics option.
 - Op_0 (default) : Suitable to medium and high energy applications
 - Op_1 : Faster than Op_0 because of less accurate MSC step limitation
 - Op_3 : Suitable for medical applications - more accurate MSC for all particle types
 - Op_4 : Most accurate (Goudsmit-Saunderson MSC model with Mott correction and error-free stepping for e+/-)
 - LIV : Livermore models for e-/gamma below 1 GeV, otherwise Op_0
 - LIV_Pol : Polarized extension of Livermore models (to be added)
- For most of the space-related applications, Op_0 is good. For applications of single event effects, Op_4 is recommended.
- Available Geant4 state(s) : PreInit

parameter name	type	omittable	default value	
EM_option	s	true	Op_0	EM option name

- /gorad/physics/Hadronic <Had_option>

- Select hadronic physics option.
 - FTFP_BERT (default) : Fritiof string + Bertini cascade + Precompound de-excitation - suitable to most of medium and high energy applications
 - QGSP_BIC : Quark-Gluon-String + Fritiof string + Binary cascade + Precompound de-excitation - suitable for lower energy applications such as medical
 - Shielding : Similar to FTFP_BERT with better ion-ion interactions. High-Precision neutron and Radioactive Decay models are included by default. - suitable for some space applications with more accurate treatment for low-energy neutron and heavy ions
- Available Geant4 state(s) : PreInit

parameter name	type	omittable	default value	
Had_option	s	true	FTFP_BERT	Hadronic physics option name

- /gorad/physics/addHP

- /gorad/physics/addRDM

- Add High-precision neutron and radioactive decay, respectively.
- These commands do not make effect for Shielding option, as it already includes them.

- Available Geant4 state(s) : PreInit
- /gorad/physics/addRMC
 - Add reverse Monte Carlo to EM particles.
 - This option makes sense only if simulation is limited to electron/positron/gamma.
 - Available Geant4 state(s) : PreInit
- /gorad/physics/addOptical
 - Add optical physics.
 - Gorad currently does not support handling of optical properties of material or surface. This option makes sense only if the input GDML file already has such properties.
 - Available Geant4 state(s) : PreInit
- /gorad/physics/addStepLimit <particle>
 - Add artificial step limitation to the specified particle types.
 - In addition to this command, you need to specify the limitation value by /gorad/physics/limit/stepLimit or /gorad/physics/limit/localStepLimit command. If a region does not have any specified limit defined by either /gorad/physics/limit/stepLimit or /gorad/physics/limit/regionStepLimit, step limitation is not applied for that region.
 - Artificial step limitation is useful for particles generating optical photons.
 - Available Geant4 state(s) : PreInit

parameter name	type	omittable	default value	
particle	s	true	charged	charged (default) : applied only to the charged particles neutral : applied only to the neutral particles all : applied to all particle types e+/- : applied only to e+/e-

A.5. Command directory path /gorad/physics/limit/

- /gorad/physics/limit/stepLimit <length> <unit>
 - Define the step length limitation if /gorad/physics/addStepLimit is set.
 - This limit is applied to the entire geometry except the region that has its own limit defined by the following /gorad/physics/limit/regionStepLimit command.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
length	d	false		maximum step length
unit	s	true	mm	unit

- /gorad/physics/limit/regionStepLimit <regionName> <length> <unit>
 - Define the step length limitation for a region.
 - This limit is applied only to the specified region. If new region is necessary, create it by /gorad/geometry/createRegion command in advance.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
regionName	s	false		region name
length	d	false		maximum step length
unit	s	true	mm	unit

A.6. Command directory path /gorad/physics/cuts/

- `/gorad/physics/cuts/setCuts <length> <unit>`
 - Specify production thresholds (a.k.a. cuts) that is applied to the entire geometry
 - This threshold is applied to all of e-, e+, gamma and proton.
 - Threshold of each particle can be overwritten by `/gorad/physics/cuts/setParticleCut` command.
 - Available Geant4 state(s) : Prelinit, Idle

parameter name	type	omittable	default value	
length	d	false		production threshold
unit	s	true	mm	unit

- `/gorad/physics/cuts/setParticleCut <particle> <length> <unit>`
 - Specify production threshold (a.k.a. cut) for the specified particle type that is applied to the entire geometry
 - Available Geant4 state(s) : Prelinit, Idle

parameter name	type	omittable	default value	
particle	s	false		e-, e+, gamma or proton
length	d	false		production threshold
unit	s	true	mm	unit

- `/gorad/physics/cuts/setRegionCut <region> <length> <unit>`
 - Specify production thresholds (a.k.a. cuts) that is applied to the specified region.
 - This threshold is applied to all of e-, e+, gamma and proton.
 - Threshold of each particle can be overwritten by `/gorad/physics/cuts/setRegionParticleCut` command.
 - Region has to be defined in advance to this command. If new region is necessary, use `/gorad/geometry/createRegion` to create it.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
region	s	false		region name
length	d	false		production threshold
unit	s	true	mm	unit

- `/gorad/physics/cuts/setRegionParticleCut <region> <particle> <length> <unit>`
 - Specify production threshold (a.k.a. cut) for the specified particle type that is applied to the specified region.
 - Region has to be defined in advance to this command. If new region is necessary, use `/gorad/geometry/createRegion` to create it.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
region	s	false		region name
particle	s	false		e-, e+, gamma or proton
length	d	false		production threshold
unit	s	true	mm	unit

A.7. Command directory path `/gorad/generator/`

By default, Geant4 general particle source is used. Following commands may be used to change the generator.

- `/gorad/generator/useParticleSource <flag>`
 - Use Geant4 general particle source.
 - Geant4's `/gps/` commands are available only if this option is chosen.

- Available Geant4 state(s) : Preinit

parameter name	type	omittable
flag	b	true

- /gorad/generator/useParticleGun <flag>

- Use Geant4 particle gun.
- Geant4's /gun/ commands are available only if this option is chosen.
- Available Geant4 state(s) : Preinit

parameter name	type	omittable
flag	b	false

A.8. Command directory path /gorad/source/

- /gorad/source/define <pName> <fName> <srcType> <radius> <unit> <x0> <y0> <z0>

- This command defines the primary particle spectrum.
- If radius is not specified, it is calculated as 98% of the size of the world volume (if the world is cuboid, it is 98% of the shortest side).
- If the user sets the radius or defines the position, it's the user's responsibility to make sure the entire source sphere to be fully contained in the world volume.
- Each line of the spectrum file should have energy in MeV and bin height separated by a space. A line in the spectrum file starting with "#" is ignored as a comment line.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
pName	s	false		particle name
fName	s	false		spectrum file name
srcType	s	false		"Arb" or "LW"
radius	d	true		radius of sphere
unit	s	true	m	unit
x0, y0, z0	d	true	0., 0., 0.	Position of the sphere (optional)

A.9. Command directory path /gorad/bias/

- /gorad/bias/geomImpImportance <nLayer> <radius> <unit>

- This command turns on the geometry importance biasing, and defines the number of biasing spherical layers and optionally the radius of the outermost sphere.
- If radius is not specified, it is calculated as 80% of the size of the world volume (if the world is cuboid, it is 80% of the shortest side).
- This command has to precede to all other related commands of geometry importance biasing.
- It is user's responsibility to make sure the biasing sphere is fully contained inside the world volume.
- Available Geant4 state(s) : Preinit

parameter name	type	omittable	default value	range	
nLayer	i	false		nLayer > 1	Number of layers. There must be at least two layers.
radius	d	false		radius > 0.	radius of the outermost biasing sphere
unit	s	true	mm		unit

- /gorad/bias/geomImpLocate <x0> <y0> <z0> <unit>

- Define the position of the center of the outermost sphere.
- By default, the center of the sphere is located at the origin of the master coordinate system (i.e. the center of the world volume). This command changes the location. It is user's responsibility to make sure the biasing sphere is fully contained inside the world volume.
- Available Geant4 state(s) : Prelnit

parameter name	type	omittable	default value	
x0	d	false		position of the center of the sphere
y0	d	false		
z0	d	false		
unit	s	true	mm	unit

- /gorad/bias/geomImpInnerRadius <rT> <unit>
 - Define the radius of the innermost sphere.
 - By default, the radius of the innermost sphere is 1/nLayer of the radius of outermost sphere. This command changes it. It is user's responsibility to make sure the biasing sphere is fully contained inside the outer sphere.
 - Available Geant4 state(s) : Prelnit

parameter name	type	omittable	default value	range	
rT	d	false		rT > 0.	radius of the innermost biasing sphere
unit	s	true	mm		unit

- /gorad/bias/geomImpLocTgt <xT> <yT> <zT> <unit>
 - Define the position of the center of the innermost sphere.
 - By default, the center of the sphere is located at the same position as the outermost sphere. This command changes the location.
 - It is user's responsibility to make sure the biasing sphere is fully contained inside the outer sphere. Distance between (x0,y0,z0) and (xT,yT,zT) must be smaller than r0*(nLayer-1)/nLayer (smaller than r0-rT if radius of innermost sphere is set).
 - Available Geant4 state(s) : Prelnit

parameter name	type	omittable	default value	
x0	d	false		position of the center of the innermost sphere
y0	d	false		
z0	d	false		
unit	s	true	mm	unit

- /gorad/bias/geomImpFactor <factor>
 - Alternate the geometry importance biasing factor.
 - By default, the factor is set to 2. We do not recommend the factor to be much larger than 2.
 - Available Geant4 state(s) : Prelnit, Idle

parameter name	type	omittable	default value	range
factor	i	true	taken from the current value	factor > 0

- /gorad/bias/geomImpProbability <prob>
 - Reduce the probability of geometry importance biasing to avoid over biasing.
 - By default, the probability is set to 1.0 (i.e. 100%).
 - Available Geant4 state(s) : Prelnit, Idle

parameter name	type	omittable	default value	range

prob	d	true	taken from the current value	$0. < \text{prob} \leq 1.$
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A.10. Command directory path /gorad/analysis/

- /gorad/analysis/verbose <level>

- Set verbosity level.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range
level	i	true	0	level ≥ 0

- /gorad/analysis/file <file>

- Define the output file name. Actual file name will be appended by the histogram type and histogram name.
- Available Geant4 state(s) : Idle

parameter name	type	omittable
file	s	false

- /gorad/analysis/list

- List currently defined histograms.
- Available Geant4 state(s) : Idle

- /gorad/analysis/open <id>

- Open a histogram that has already been closed.
- “create” command automatically opens the new histogram, so the user does not need to open it. A histogram is closed when another histogram is created. This “open” command is required only for reopening the closed histogram.
- Available Geant4 state(s) : Idle

parameter name	type	omittable
id	i	false

- /gorad/analysis/plot <id>

- Create an additional postscript plot for specified histogram/profile.
- Regardless of this command, histogram is anyway dumped to the output file.
- If *id* is not specified, currently open histogram/profile is plotted.
- If *id* = -1, all currently defined histograms/profiles are plotted.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value
id	i	true	taken from the current opened histogram/profile

- /gorad/analysis/carry <carry>

- Carry histograms over more than one runs.
- Once this is set, histograms won't be output until /gorad/analysis/flush is explicitly issued.
- This command has to be issued before starting the run to be carried over.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value
carry	b	true	true

- /gorad/analysis/flush

- Make output. This command is necessary if /gorad/analysis/carry is set.
- Available Geant4 state(s) : Idle

- `/gorad/analysis/reset`
 - Reset histograms without making output. This command should be used as an alternative to `/gorad/analysis/flush` command. This command does not make effect without `/gorad/analysis/carry` command applied before the beginning of the run.
 - Available Geant4 state(s) : Idle
- `/gorad/analysis/idOffset <offset> <factor>`
 - Define offset numbers of the histogram ID.
 - Histogram ID is set as $(\text{scorer_id} + \text{<offset>}) * \text{<factor>} + \text{copy_number} - 1$.
 - This command is necessary only if the user needs to define immense number of histograms.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range
offset	i	true	0	offset ≥ 0
factor	i	true	1000	factor > 0

A.11. Command directory path `/gorad/analysis/1D/`

- `/gorad/analysis/1D/create <meshName> <primName> <idx>`
 - Create a 1D histogram and fill it with event-by-event score.
 - Scoring mesh, scoring probe, or logical volume for real-world volume scoring have to be defined and primitive scorers must be assigned prior to this command.
 - If `idx` is specified, histogram is filled only for the volume of specified copy number. If is it -1, scores of all cells are merged.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
meshName	s	false		name of scoring mesh or scoring probe (logical volume name for real-world volume scoring)
primName	s	false		scorer name
idx	i	true	-1	index (i.e. copy number) of the cell to be scored.

- `/gorad/analysis/1D/primary <histName> <weightFlag>`
 - Create a 1D energy spectrum histogram and fill it with kinetic energy of each primary particle.
 - Weight of each primary track is taken into account if `weightFlag` is set.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
histName	s	false		histogram name
weightFlag	b	true	true	flag to take track weight

- `/gorad/analysis/1D/spectrum <meshName> <primName>`
 - Create a 1D energy spectrum histogram and fill it with each individual track that gets into the volume.
 - Histogram is created for each physical volume separately. So, this command should not be used for Box or Cylinder mesh type due to memory consumption concern.
 - Currently, this is supported only for volume flux scorer.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	

meshName	s	false		name of scoring mesh or scoring probe (logical volume name for real-world volume scoring)
primName	s	false		scorer name

- `/gorad/analysis/1D/config <nBin> <minVal> <maxVal> <unit> <scale> <logVal>`
 - Define binning parameters of the current 1D histogram.
 - Histogram has to be created prior to this command.
 - If `scale` is "log" and `logVal` is true, labels of x-axis is given as log10(x).
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
nBin	i	false		nBin > 0	number of bins
minVal	d	false			low edge of the histogram
maxVal	d	false			high edge of the histogram
unit	s	true	none		unit of minVal and maxVal
scale	s	true	linear	linear, log	binning scale
logVal	b	true	false		x-axis label is given as log10(x)

- `/gorad/analysis/1D/title <title> <x_axis> <y_axis>`
 - Define histogram titles.
 - Histogram has to be created prior to this command.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable
title	s	false
x_axis	s	false
y_axis	s	false

- `/gorad/analysis/1D/yaxisLog <flag>`
 - Set y-axis in log scale.
 - Histogram has to be created prior to this command.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value
flag	b	true	true

A.12. Command directory path `/gorad/analysis/1P/`

- `/gorad/analysis/1P/create <meshName> <primName> <idx>`
 - Create a 1D profile plot and fill it with event-by-event score.
 - Scoring mesh (logical volume for real-world volume scoring) and primitive scorers must be defined prior to this command.
 - Copy number of the scoring cell is used as the x-axis value.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	
meshName	s	false	name of scoring mesh or scoring probe (logical volume name for real-world volume scoring)
primName	s	false	scorer name
idx	i	false	maximum index (i.e. copy number) of the cell to be scored

- `/gorad/analysis/1P/set <minYVal> <maxYVal> <unit> <func-x> <func-y> <scale>`

- Define binning parameters of the current 1D profile plot.
- The plot has to be created prior to this command.
- Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	range	
minYVal	d	false			low edge of the y value
maxYVal	d	false			high edge of the y value
unit	s	true	none		unit of minYVal and maxYVal
func-x	s	true	none	log, log10, exp, none	function applied to the input x value
func-y	s	true	none	log, log10, exp, none	function applied to the input y value
scale	s	true	linear	linear, log	binning scale

- `/gorad/analysis/1P/title <title> <x_axis> <y_axis>`
 - Define histogram titles.
 - Histogram has to be created prior to this command.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable
title	s	false
x_axis	s	false
y_axis	s	false

A.13. Command directory path `/gorad/analysis/ntuple/`

- `/gorad/analysis/ntuple/addColumn <meshName> <primName> <unit> <idx>`
 - Define a column for ntuple output and fill it with event-by-event score.
 - Scoring mesh (logical volume for real-world volume scoring) and primitive scorers must be defined prior to this command.
 - If `idx` is specified, column is filled only for the volume of specified copy number. If it is -1, scores of all cells are merged and filled.
 - Available Geant4 state(s) : Idle

parameter name	type	omittable	default value	
meshName	s	false		name of scoring mesh or scoring probe (logical volume name for real-world volume scoring)
primName	s	false		scorer name
unit	s	true	none	
idx	i	true	-1	index (i.e. copy number) of the cell to be scored.

Appendix B. Tips for installing and running Gorad

B.1. Geant4 installation

The current Gorad requires Geant4 version 10.7 (release of December 2020). It does not work with earlier version of Geant4. Geant4 has to be installed with multithreading mode and GDML interface enabled. Qt is also recommended for the use of Gorad in interactive mode. Please refer to the Geant4 installation guide for enabling these options.

Geant4 GDML interface requires Xerces-C++ version 3 or higher. It has to be compiled with the same compiler Geant4 is compiled. There is a known issue in Xerces-C that causes a runtime error while reading a large GDML file. If the following error message appears

```
G4GDML: VALIDATION ERROR! NodeIDMap exceeds largest available size at line: <lineNumber>
```

line 33 of `xerces-c/src/xercesc/dom/impl/DOMNodeIDMap.cpp` should be replaced by the following line

```
static const XMLSize_t gPrimes[] = {997, 9973, 99991, 999983, 9999991, 99999989, 0};
```

and Xerces-C library has to be rebuilt.

B.2 Gorad installation

To compile Gorad, all the Geant4 environment variables have to be set. Use the shell script in the Geant4 installation directory. Compilation of Gorad requires `cmake` and `make` same as the compilation of Geant4 itself.

```
$ source $G4INSTALL/bin/geant4.(c)sh
$ cmake .
$ make -f Makefile
```

B.3. Gorad execution

To execute Gorad, all the Geant4 environment variables have to be set. Use the shell script in the Geant4 installation directory. To run Gorad in interactive mode,

```
$ ./gorad
```

and then, in the keyboard input field, type

```
/control/execute <macroFile>
```

The user may also use any UI commands shown in the left side menu of the Qt window.

To run Gorad in batch mode,

```
$ ./gorad <macroFile>
```