Preliminary detection efficiency evaluation for the Gamma-Light telescope

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Change history:

Version	Date	Notes
1.0	May 17th, 2012	
1.1	May 21st, 2012	Projected path section added.

1. Introduction

Gamma-Light is a Compton/pair production based Gamma-ray mission to be proposed to the ESA call for a small mission opportunity for a launch in 2017. Supported by a joint Italian-European high energy Astrophysics community, the telescope goal is to observe the 10 – 100 MeV energy with unprecedented sensitivity ($<2\text{-}3\times10^{-6}$ cm^{-2} s^{-1} MeV^{-1} at 10 MeV, for $\Delta T = 1$ Ms) and angular resolution (1°-2° at 10 MeV [1]), about an order of magnitude better than the COMPTEL instrument on board CGRO [2].
The BoGEMMS (Bologna Geant4 Multi-Mission Simulator, Bulgarelli et al. in prep.) architecture is exploited to develop a customizable geometry of the Gamma-Light instruments and evaluate the telescope scientific performances.
In the present document, the preliminary Gamma-Light tracker detection efficiency is presented as a first fundamental step in the mission concept development.

2. BoGEMMS configuration

A new geometry branch, designed to be applied to a wide range of mission configurations, and a new output file type have been added to the BoGEMMS architecture for the Gamma-Light simulations.

2.1 Geometry

At present, the geometry is composed by a customizable tracker (and surrounding electronic cards), a calorimeter and an anticoincidence system. The code is designed around the tracker, which is fixed: the calorimeter and the anticoincidence system can be added or removed from the environment at run time. Since the tracker detection efficiency is evaluated, only the tracker design is presented in detail.
The following parameters can be configured at run time:

- tray number;
- tray side;
- distance between trays;
- addition of a converter layer;
- addition of a glue layer;
- thickness of the tracker layers (the same for all the trays);
- tracker visualization type.

2.2 Output file type

The new output file, in FITS format, collects the hits of the activated sensitive volumes. When the particle enters the volume, the energy deposit is summed until the particle exits the volume, or it is absorbed/converted. If a secondary is produced within the sensitive volume, its energy deposit is also recorded along its path. A new feature in the sensitive detector class has been added for the analysis of tracks in Compton/pair production telescopes. When a secondary is produced, if it is generated by a Compton scattering or a gamma conversion a flag is added according to the process. In addition, both primary and secondary photons that Compton scatter in the active tracker layers are flagged in the output file. In the configuration file is possible not only to select which volumes writing in output, but also the tracker layers.
In the end, the following information is written:

- EVT_ID = event number (starting from 0)
- TRK_ID = track number (starting from 1)
- VOLUME_ID = volume number
    - Given N the number of trays, the tray ID is N×1000 (starting from the tracker bottom).

  - Given N_{layer} the layer number (from the tray bottom), the layer ID, in each tray, is the tray ID + (N_{layer} – 1).
- VOLUME_NAME = volume name string
- E_DEP = energy deposit (in keV)
- X_ENT, Y_ENT, Z_ENT = position, in mm, of the particle entrance (or generation) point in the sensitive volume
- X_EXIT, Y_EXIT, Z_EXIT = position, in mm, of the particle exit (or final) point in the sensitive volume
- E_KIN_ENT = particle kinetic energy, in keV, at the entrance (or generation) point
- E_KIN_EXIT = particle kinetic energy, in keV, at the exit (or final) point
- MDX_ENT, MDY_ENT, MDZ_ENT = particle direction cosines at the entrance (or generation) point
- MDX_EXIT, MDY_ EXIT, MDZ_ EXIT = particle direction cosines at the exit (or final) point
- GTIME_ENT = simulation global time at the particle entrance (or generation) point
- GTIME_EXIT = simulation global time at the particle exit (or final) point
- PARTICLE_ID = particle identification number according to the Particle Data Group
  - Gamma = 22
  - Electron = 11
  - Positron = -11
  - Proton = 2212
  - Neutron = 2112
- PARTICLE_NAME = particle name string
- PROCESS_FLAG = flag for Compton/pair production identification

3. Gamma-Light tracker geometry

The tracker is designed as one single column of 40 trays, 2 mm distant each, with a lateral side of 50 cm. The passive and active layers configuration is based on the AGILE tracker design [3], with the main difference being the removal of the Tungsten based converter in order to decrease the lower energy limit. Figure 1 shows a lateral zoom of the tray Geant4 geometry, with the Silicon, Kapton, Carbon fiber and Al honeycomb layers visualized in gray, black, red and yellow respectively.

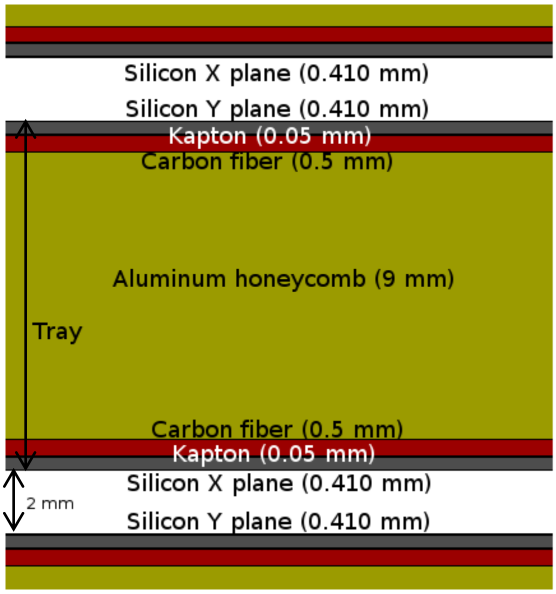

Figure 1: The lateral zoomed view of a tray, visible in the central part of the image (the white regions are the 2 mm separation between the trays). *Gray*: Silicon layer; *black*: Kapton layer; *red*: Carbon fiber layer; *yellow*: Al honeycomb layer.

Each tray, except for the first and the last, is composed by three modules:

- Lower module (from the bottom):
    - Silicon layer (X plane) = 0.410 mm
    - Kapton layer = 0.05 mm
- Central module:
    - Carbon fiber layer = 0.5 mm
    - Aluminum honeycomb layer = 9 mm
    - Carbon fiber layer = 0.5 mm
- Upper module (from the bottom):
    - Kapton layer = 0.05 mm
    - Silicon layer (Y plane) = 0.410 mm

In the trays at the bottom and top of the tracker the lower and upper modules are respectively removed, so that 40 trays translate into 39 Si X-Y couples.

The tracker is placed on the Z plane (tracker axis parallel to the Z axis), at Z = 0.46 mm. The central trays total height is 10.92 mm, which translates into an X-X planes distance of 12.92 mm. The tracker total height is 51.388 cm.

Figure 2 shows the 3D geometry (left panel) of the Silicon planes (in gray), with the calorimeter visualized in yellow, and the tracks (right panel) generated by 10 MeV monochromatic photons simulated from the tracker top and parallel to its axis. The green, red and blue lines refer to the photons, electrons and positrons respectively.

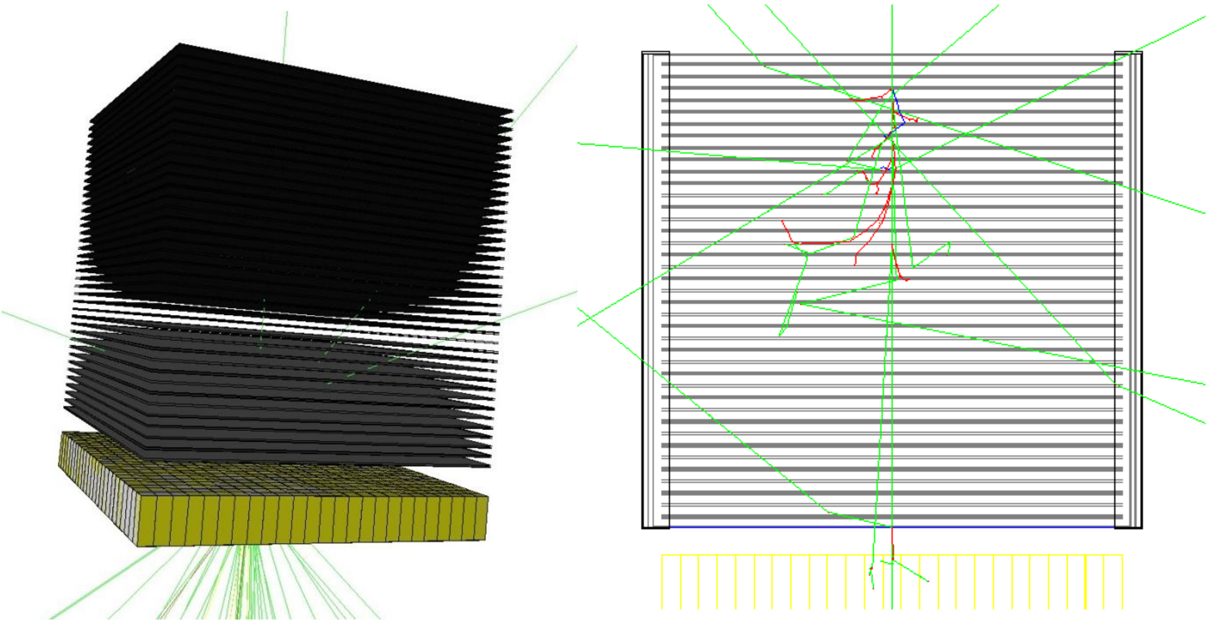

Figure 2: *Left panel*: View of the tracker Si layers (in gray) and, at the bottom, the CsI based calorimeter (in yellow) as built by BoGEMMS. *Right panel*: Lateral view of the photons (in green), electrons (in red) and positrons (in blue) generated by a 10 MeV monochromatic beam (10 summed primary photons) along the tracker. The lateral bars represent the electronics surrounding the tracker.

4. Efficiency evaluation

The efficiency is evaluated for the following energies: 1, 5, 10, 20, 30, 40, 50, 75, 100, 300, 500 MeV and 1 GeV. The photons are simulated as monochromatic beams for two inclination angles (in polar angles):

- $\theta = 0^{\circ}$ (parallel to the tracker axis);
- $\theta = 30^{\circ}$, $\varphi = 225^{\circ}$.

The detection efficiency is generally defined as:

$$\text{Efficiency} = \frac{\mathrm{N_{det}}}{\mathrm{N_{in}}} \ ,$$

where N_{det} and N_{in} are the number of detected events and input particles respectively.

Since Gamma-rays can not be directly detected, but must be observed by means of the secondary particles produced by Compton scattering and/or pair production, the detection efficiency depends not only on the instrument sensitivity but also on the accuracy of the recognition pattern.

Three different patterns are applied here in the evaluation of the Gamma-Light efficiency. The incoming photon is counted as detected (N_{det}) if:

A. it generates at least one hit (energy deposit > 0) in a Si layer (X and/or Y);
B. it is detected by at least three planes (X and Y Si layers) in the whole tracker;
C. it is detected by at least three planes (X and Y Si layers) of four contiguous planes.

Each efficiency represents a subset of the previous case, with case A being the most general approach. These patterns, especially cases A and B, are raw approximation of the complex data analysis, given the simplified geometry and the simulation level (e.g. no digitizing and noise applied). Although preliminary as the mission status itself, the results presented here are a first, fundamental indication of the potential scientific performances of Gamma-Light.

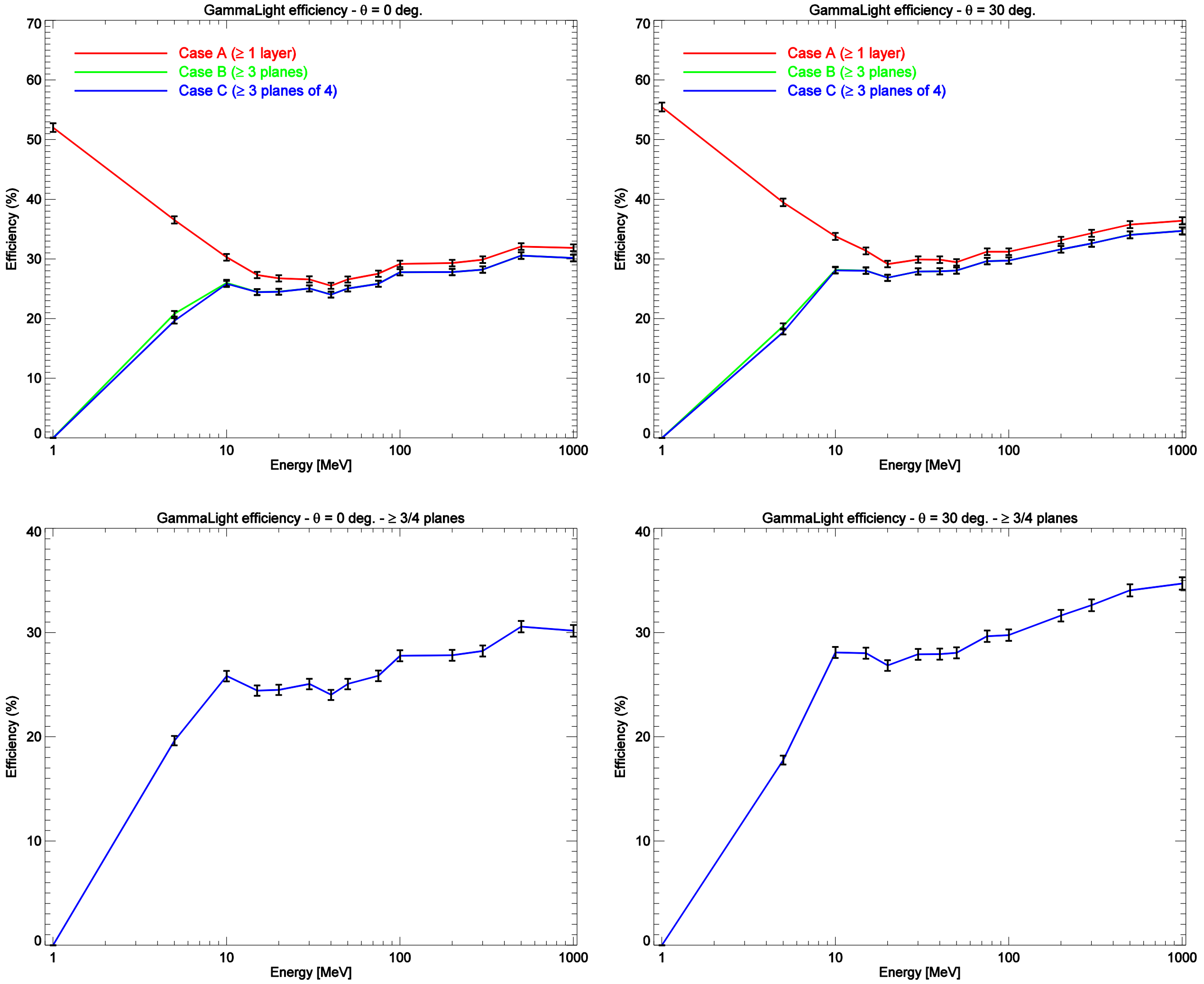

Figure 3: *Top panels*: The efficiency (in % of the simulated events) for the analysis case A (red line), B (green line) and C (blue line), for an incoming photon angle (respect to the tracker axis) of 0˚ (left panel) and 30˚ (right panel). *Bottom panels*: The detection efficiency for the case C, i.e. the percentage of photons detected by at least 3 planes of 4 contiguous X-Y couples. The error bars, for all the plots, refer to the Poisson statistical fluctuations given by the Monte Carlo simulation.

As shown in Fig. 3 (top panels), cases B and C, green and blue lines respectively, are almost coincident, meaning that, if a track is generated, the secondary particle (the electrons/positrons) loses continuously its energy in the next 3-4 planes. As expected, the detection efficiency for these cases increases from 1 MeV to 10 MeV as the pair production cross section increases (see Fig. 3, bottom panels), reaching a stable value of about 25% for θ = 0˚ and 28% for θ = 30˚. At E > 100 MeV, the detection efficiency increases again up to 30% (θ = 0˚) and 35% (θ = 30˚), as the energy of the secondary increases (longest path and lower Moliere scattering).

The efficiency behavior if single hits on single Si layers are counted (case A) is opposite: it decreases from 1 MeV (> 50%) to 10 MeV (about 30%), where the subset of cases B and C becomes the majority of the counted events. The reason is that a single hit is most probably caused by a photon Compton scattered on the Silicon layer and a recoil electron absorbed in the same layer. Since the Compton scattering cross section decreases in the simulated energy range (1 MeV – 1 GeV), the case A efficiency also decreases below 10 MeV. At E > 10 MeV, the pair production becomes the dominant interaction process and the three efficiency cases follow the same path.

If the inclination angle of the incoming photon respect to the tracker axis increases from 0 to 30 degrees (left and right panels of Fig. 3), the probability of detecting the photon increases of about 15%.

4.1 Projected particle path

As described in Section 2.2, for each particle crossing the sensitive volume, the entrance (generation) and exit (final) point is given, while the energy deposit results from the summed energy losses of each step within the volume. In the end, we know a position range where the particle loses its energy and not the effective deposit position.

In the present efficiency evaluation, we look for energy deposits in the Si planes regardless the hit position and track properties (amount of energy loss, particle angle, etc.). If we take into account the AGILE tracker configuration as design of reference, Aluminum strips, 121 µm sides, are placed on the Si layers to retrieve the deposited charge. In the real case, the charge would be distributed along several strips that cover the particle path, so that the position of the energy loss is required if, for example, the angular resolution is simulated.

It is interesting here to plot the path of the particles interacting with the tracker, to evaluate the level of approximation and plan the future steps in the BoGEMMS evolution as a powerful Compton/pair production based telescope simulator.

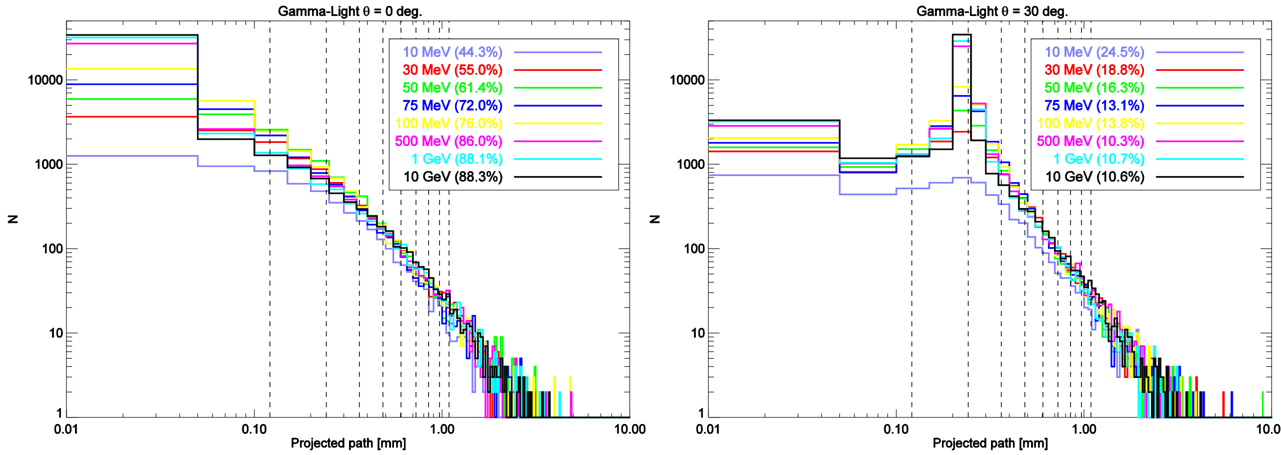

Figure 4: The projected (X-Y plane) path of the particles losing energy in the Silicon layers, for θ = 0˚ (left panel) and 30˚ (right panel). Each color refers to different incoming photon energies: 10 MeV (purple), 30 MeV (red), 50 MeV (green), 75 MeV (dark blue), 100 MeV (yellow), 500 MeV (pink), 1 GeV (light blue), 10 GeV (black). In the legend the percentage of particle paths within the strip size (121 µm) is also listed. The vertical dashed lines refer to the strip sizes up to about 1 mm.

We compute the histogram (Fig. 4) of the number of particles (depositing energy in the Si layers) that cross the sensitive volumes along a projected path (X-Y plane) in the 10 µm – 10 mm range. The simulation is run for two inclination angles of 0 and 30 degrees and the following energies: 10, 30, 50, 75, 100, 500 MeV, 1 and 10 GeV. The dashed lines represent the strip dimension up to about 1 mm.

As the incoming photon energy increases, the projected path decreases, i.e. the secondary particles are less scattered within the volume and cross a lower amount of Si, following the primary particle direction.

For $\theta = 0^\circ$ the lowest is the path, the highest is the number of particles in a smooth distribution: the single strip is crossed by the 44% of the particles at 10 MeV and the 88% of the particles at 10 GeV.

On the contrary, for $\theta = 30^\circ$ the projected path is peaked (especially at highest energies) at about 200 µm, coinciding with two strips being crossed by the interacting particle. As a consequence, only the 25% (10 MeV) and 11% (10 GeV) of particles are stopped within one single strip.

For both the angle configurations, more than 90% of the particles crosses a number of strips lower than five. If the charge sharing between the strips is applied, an uncertainty of ±2 strip in the energy loss position is given by the actual simulation configuration.

5. Summary and planned actions

The BoGEMMS architecture is exploited to build a virtual model of the Gamma-Light tracker and evaluate the detection efficiency for three analysis patterns. The probability of detecting a photon in the 10 MeV – 1 GeV energy range is about **25-30%** for a track depositing energy in at least three of four contiguous planes (Si X-Y couples).

Although preliminary, this result is a promising starting point in the definition of the Gamma-Light scientific performances such as the effective area and the sensitivity. The future Gamma-Light simulation steps will follow the increase in the geometry and analysis complexity:

- addition of the strip charge sharing;
- addition of the instrumental noise;
- increase of the energy loss position resolution along the sensitive volume;
- visualization and characterization of the tracks generated by the Compton scattering/pair production induced events;
- anticoincidence system efficiency evaluation and trigger analysis;
- background evaluation.

6. References

1. Donnarumma, I et al., “Scientific performance of a new generation of Gamma-ray detectors”, INAF/IAPS Technical Report, May 2012
2. Gehrels, N. et al., “The Compton Gamma Ray Observatory: Mission status”, 1994, AIP Conf. Proc., 304, 3
3. Tavani, M. et al., “The AGILE mission”, 2009, A&A, 552, 995