Integration of ESAF and Geant4 for simulation of space based telescopes

Svetlana Biktemerova, Maxim Gonchar and Dmitry Naumov
for JEM-EUSO Collaboration

Joint Institute for Nuclear Research, Russia

***Abstract*. We report about further development of ESAF — a dedicated software created within EUSO Collaboration for simulation, reconstruction and analysis of various phenomena relevant for detection of light produced by an extensive air shower (EAS). ESAF is a robust simulation code which includes simulation of EAS, production of fluorescent and Cerenkov light, its propagation in the atmosphere and the detector response. In this work we focus on implementation of a new package inside ESAF — simulation of optics response with help of Geant4. This new option allows us to quickly test different options, optimize the detector design and make the software universal and relevant for any kind of detector. We consider an implementation of two detectors: a Fresnel lenses of JEM-EUSO and a Fresnel mirror of TUS detectors. Some preliminary results on the detector performances are presented.**

***Keywords*: cosmic rays; JEM-EUSO; ESAF; Geant4;**

I. Introduction

The Extreme Universe Space Observatory (JEM-EUSO) [1] is an international project which is aimed at measuring the flux and investigating the nature of the particles of the Extreme Energy Cosmic Rays ($E > 5 \cdot 10^{19} eV$).

The JEM-EUSO detection method is based on the space observation of the fluorescent and Cerenkov photons produced by the Extensive Air Shower (EAS) caused by the interaction of the primary EECR with atmosphere. It uses a special optical system which consists of a combination of Fresnel lenses with large field of view and focal surface with fast and high-granular photodetectors. JEM-EUSO records the evolution of the EAS in time and allows to reconstruct energy of the primary particle, its direction and type.

For the analysis of the JEM-EUSO performance, special simulation package ESAF (EUSO Simulation and Analysis Framework) [2] is used. Main capabilities of ESAF are:

- EAS generation for different primary particle types and for different atmosphere states.
- Generation and transportation of the photons from EAS through the atmosphere to the optical system.
- Optical system simulation.
- Simulation of the detector electronics response.
- Reconstruction and analysis of the events.

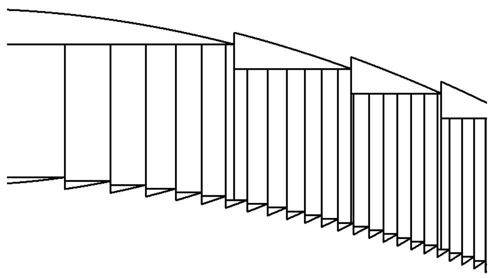


Fig. 1. Fresnel lens profile.

As an upgrade of ESAF in 2009, we reworked a detector simulation chain adding a possibility to trace particles through the detector with help of Geant4 [3] and keeping the original way of ray-tracing for checks and compatibility. This upgrade makes ESAF much flexible for a simulation of any detector and not necessarily an JEM-EUSO-like detector. We have implemented two detectors: an JEM-EUSO-like detector with three Fresnel lenses and TUS [4] detector with a Fresnel mirror.

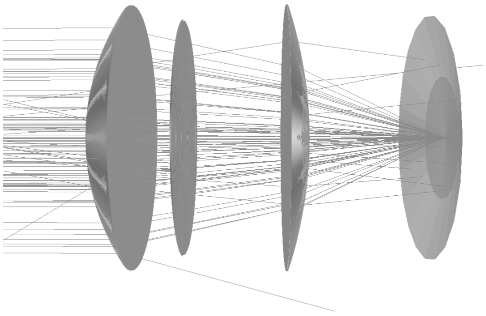
II. Using Geant4 in ESAF

Geant4 is a toolkit for the Monte-Carlo simulation of the elementary particles interaction with the matter. It allows to describe the detector geometry, define materials and physical processes and trace the particles through the detector. Geant4 has ability to define the optical parameters of the materials and can transport the optical photons, taking into account all relevant processes: Fresnel refraction and reflection on the boundary, total internal reflection, absorption, Relay scattering and some others.

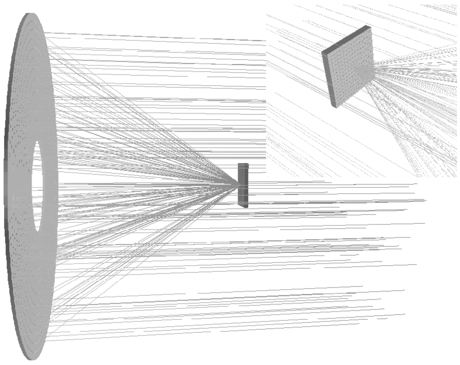
We have created an interface to use Geant4 in the ESAF simulation. Geant4 receives optical photons after the transportation from the EAS to the detector, transports them through the optical system to the matrix of PMT which is situated on the focal plane. Then ESAF handles the PMT and electronics simulation.

Use of Geant4 gives us convenient way of defining geometries and switching between them.

This new option allows us to quickly test different options, optimize the detector design and make the



(a) JEM-EUSO



(b) TUS

Fig. 2. 3D view of the two optical systems: three Fresnel lenses of the JEM-EUSO optical system (a) and TUS Fresnel mirror (b).

software universal and relevant for any kind of detector. Right now, the optical system simulation has two implementations: ESAF with Geant4 and standard ESAF approach. Using of the Geant4 gives us a lot of advantages:

- Simple geometry definition;
- Possibility of the geometry 3D visualisation (native Geant4 visualisation or via VGM and ROOT packages);
- Geant4 handles all tracking;
- Other particles (like $e^{\pm}$, p etc.) can be simulated as well to test various backgrounds, aging etc.
- The extra optical processes can be defined as required (specific diffraction on the second lens for the JEM-EUSO optical system);
- Geant4 supports definition and using of rough surfaces.

It is essential that use of more general package for tracking affects the speed of the simulation. This is mainly due to the high granularity of the geometry, because every tooth for the Fresnel lens should be defined and handled separately. Geant4 provides tools for optimizing simulation performance. The performance can be improved in future by defining Fresnel lenses via "surfaces". Using the surfaces, one can greatly decrease the number of the objects in the geometry and increase the simulation performance.

III. Geometry description

Geometry objects are described in terms of Geant4. Almost all segments have parabolic surface (as for the mirror, as for the lenses). Every segment is done with boolean operations on the basic shapes (G4Tubs and G4Paraboloid). More complex surface shapes are approximated by cones. Approximation precision can be chosen on demand. For the current simulation, it is $0.1 \mu m$.

On a Fig. 1 the profile of the first JEM-EUSO Fresnel lens is shown, solid lines indicate separate solids as defined for the Geant4.

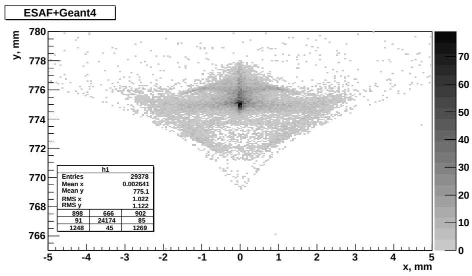


Fig. 3. The distribution of the hits on a focal plane for the JEM-EUSO simulation: GEANT4 implementation (a). The photons incident angle is 20°, wavelength is 350 nm.

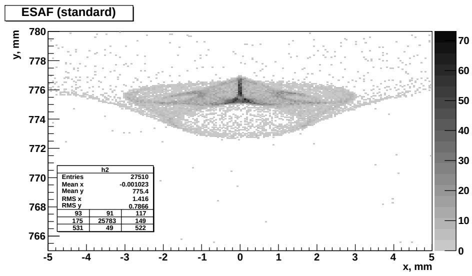


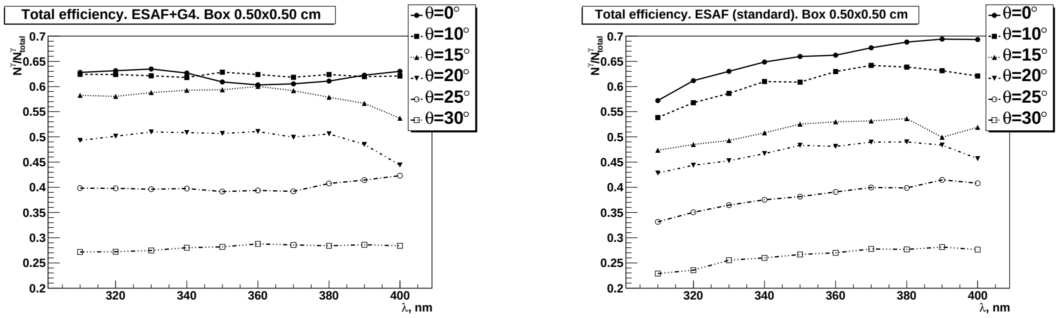
Fig. 4. The distribution of the hits on a focal plane for the JEM-EUSO simulation: standard ESAF approach. The photons incident angle is 20°, wavelength is 350 nm.

IV. JEM-EUSO implementation

The optical system of the JEM-EUSO detector consists of the three Fresnel lenses. The second surface of the second Fresnel lens is flat and covered with the special diffractive material. The diffraction on this surface is parameterised as a separate process for the Geant4.

On a Fig. 2a the 3-dimensional view of the JEM-EUSO optical system is shown (ROOT OpenGL viewer is used, the geometry is converted to the ROOT format via VGM).

As an example, the comparison between old and new simulation approach is shown (Fig. 3, 4). One can see that distributions are similar. The difference between statistics and shapes of the distributions are still to be



(a) ESAF+GEANT4

(b) ESAF (standard)

Fig. 5. Total efficiency of the optical system for the photon detection in a box with a side of 0.5 cm.

understood. The total efficiencies for the both simulation approaches for the different incident angles are shown in Fig. 5. Total efficiency defined as ratio of number of photons focused on a focal plane within a certain box $X \times X$ cm^2 to the number of photons at the entrance pupil. One can see that for the current phase of work efficiencies are quite similar. The weak dependence on a wavelength for the Geant4 is caused by use of the simplified reflectivity model and will be improved in future.

V. TUS IMPLEMENTATION

TUS experiment is the space-based experiment for the detection of the EECR. It uses the method which is similar to the one used in the JEM-EUSO experiment. The main difference is that its optical system consists of the Fresnel mirror.

On a Fig. 2b the 3-dimensional view of the TUS optical system is shown.

VI. CONCLUSION

We find that Geant4 is very powerful, efficient and flexible toolkit for the optics simulation and it can significantly broaden ESAF simulation capabilities.

VII. FURTHER WORK

- Carry out complete comparison between standard and new simulation approach;
- Define rough optical surfaces for all lenses;
- Implement another way of the geometry description using ”surfaces“ in order to improve performance;
- Implement a focal plane with pmt’s with help of Geant4;
- Provide a tool for improving the optics design.

REFERENCES

[1] Y. Takahashi [JEM-EUSO Collaboration], “JEM EUSO mission on the International Space Station,” J. Phys. Conf. Ser. **120**, 062013 (2008).

[2] EUSO Simulation and Analysis Framework, http://www.ge.infn.it/∼euso/main/Software/index_esaf.html

[3] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, and G. et al. Barrand. G4 — a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A*, 506:250–303, July 2003.

[4] V. Abrashkin *et al.*, “Space detector TUS for extreme energy cosmic ray study,” Nucl. Phys. Proc. Suppl. **166**, 68 (2007).