

MEGAlib - Simulation and Data Analysis for Low-to-medium-energy Gamma-ray Telescopes

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ABSTRACT

The Medium-Energy Gamma-ray Astronomy library MEGAlib is an open-source object-oriented software library designed to simulate and analyze data of low-to-medium-energy gamma-ray telescopes, especially Compton telescopes. The library comprises all necessary simulation and data analysis tools including geometry construction, Monte-Carlo simulation, response creation, event reconstruction, image reconstruction, and other high-level data-analysis tools.

Keywords: MEGAlib, gamma-ray astronomy, Monte-Carlo simulations, Compton telescope, image reconstruction

1. INTRODUCTION

Observations of the Universe in the low-to-medium-energy gamma-ray regime reveal unique information about the most powerful explosions (e.g. supernovae), and of the most dynamic sources (e.g. black holes, pulsars, etc.). However, astrophysical sources of gamma rays are usually hard to detect due to high background conditions as well as the high penetration power and scarce numbers of the emitted photons. In addition, gamma-ray detectors, especially Compton telescopes, require sophisticated data analysis tools, such as non-trivial event reconstruction in addition to iterative image reconstruction techniques. Furthermore, only accurate simulations of those instruments (source and background) enable an improved understanding of existing telescopes, and make performance estimates for future missions possible.

MEGAlib (“Medium-Energy Gamma-ray Astronomy library”) is a software library developed mainly for the analysis of Compton and low-energy pair telescopes. *MEGAlib* was originally written specifically for the MEGA Compton and pair telescope prototype,^{1–3} and to estimate the performance of different potential satellite versions based on MEGA’s technology. From the beginning, however, *MEGAlib* was designed in a very flexible way to allow for easy accommodation of different geometries and detector technologies into the simulation and analysis pipeline. As consequence it was possible to adapt, expand, and apply *MEGAlib* to different hard X-ray and gamma-ray telescopes, such as GRI, ACT, NCT, GRIPS, etc., whose performance has been successfully estimated with *MEGAlib*.^{4–6}

2. THE SIMULATION AND DATA ANALYSIS PIPELINE

MEGAlib is a completely object-oriented software library which is completely written in C++. It utilizes the ROOT⁷ software library for its graphical user interface and its data display. Its installation requirements* are an up-to-date Linux or Mac operating system, ROOT, and Geant4.⁸ The source code of the latest version of *MEGAlib*[†] can be found at <http://www.mpe.mpg.de/MEGA/megalib.html> (tar-ball or cvs).

MEGAlib encompasses the complete data analysis pipeline from simulations to high-level data analysis, which includes:

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*For more details and the required versions check the installation instructions of *MEGAlib*

[†]At the time this document was written, the latest version of *MEGAlib* was 2.18.

1. The construction of a geometry and detector setup with *Geomega*
2. The generation of data by simulations with *Cosima* and the emulation of corresponding real detector output (e.g. add detector noise, apply thresholds)
3. The generation of response matrices with *Responsecreator* for event and image reconstruction
4. The reconstruction of the events with *Revan*, i.e. the determination of photon energy, interaction sequence, and main interaction mechanism of the measured particle such as photo effect, Compton scattering, pair creation, (high-energy) charged particle interaction
5. The high-level data analysis with *Mimrec* including optimized event selections, list-mode image reconstruction, polarization analysis, sensitivity calculation, etc.

While data analysis steps 3–5 contain mostly algorithms optimized for Compton and low-energy pair telescopes, steps 1 and 2 can be used universally for all low-to-medium-energy gamma-ray telescopes. Step 4 is the usual entry point for the analysis of measured data from real detectors such as MEGA^{1–3‡}, NCT,¹⁰ or COMPTEL.¹¹ Figure 1 gives a general overview of the main features of the *MEGAlib* simulation and data-analysis pipeline.

All major *MEGAlib* programs are designed as libraries, i.e. as a set of classes providing the base functionality, which then can be accessed from outside programs. For all main programs an interface class accesses these base functionalities. The interface class is in turn accessed by a graphical user interface (*Geomega*, *Sivan*, *Revan*, and *Mimrec*) and/or by command line.

The following sections give overviews of the most important programs of *MEGAlib*. They are not intended as a detailed description of the underlying algorithms. The latter can be found in the references mentioned in the text.

2.1 Geomega — Geometry and Detector Description

An integral part of *MEGAlib* is the *Geomega* library (“Geometry for *MEGAlib*”), a tool for geometry and detector description, which provides volume, material, detector, and trigger information for the various *MEGAlib* programs. In addition, it offers visualizations of the detector as well as of the detected and reconstructed events (via the program *Eview* — “event viewer”). It also contains an instrumental effects engine for simulated data, and serves as geometry foundation for all other tools of *MEGAlib*.

2.1.1 Geometry Description

Geomega provides several of the geometry features which MGGPOD, ROOT, and Geant4 have in common, plus some enhancements:

- A set of volumes: boxes, spheres, tubes, various trapezoids, polygons, polycones, etc., which can be positioned, rotated, etc. *Geomega* does not allow divisions of volumes or overlapping volumes (MANY keyword in Geant3).
- Virtual volumes, i.e. container volumes which enable easy packaging of logical volume groups and are allowed to overlap. They are removed from the final geometry before actual display and simulation.
- A complete material description
- Geometry scaling, i.e. enlarging or shrinking a volume including all daughter volumes
- Including geometries from different files. This allows to structure the geometry into independent parts (i.e. a file containing the geometric setup of the detector, one for the instrumental characteristics of the detector, one for the satellite body, etc.) and thus allows to easily reuse parts of the geometry for different setups.

[‡]Also software exists which allows to acquire and calibrate data from the MEGA prototype,^{3,9} but this software is not included in the public *MEGAlib* release.

- Global definition of numerical constants, which can be used as place-holders for positions, rotations, etc.
- Handling of for-loops and all mathematical operations known by ROOT

All these features enable the construction of a completely flexible, scalable geometry controlled by a small set of constants. The input file, called “setup”-file, is an object-oriented, keyword-based (e.g. volume, material,

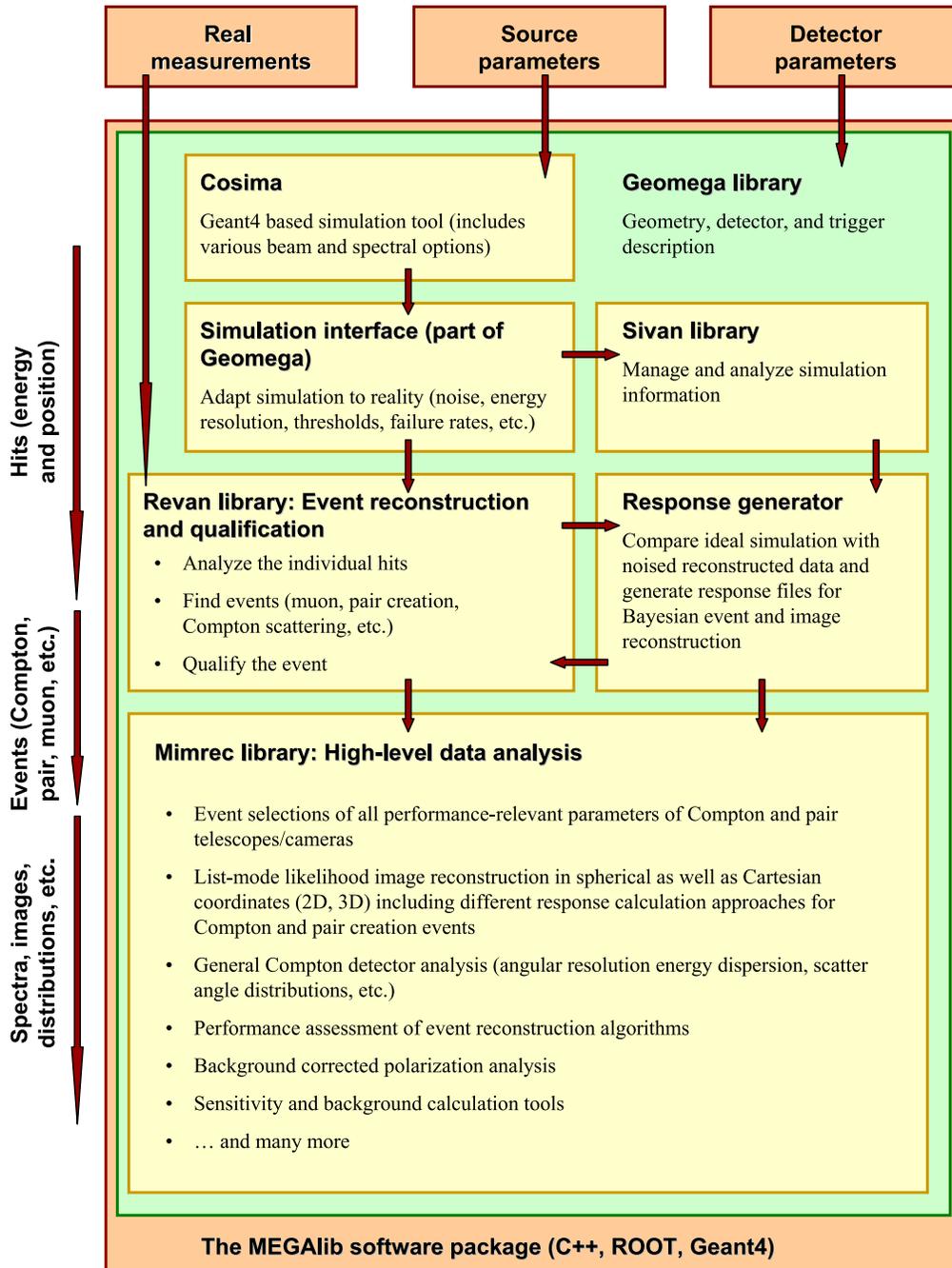


Figure 1. Basic layout of the MEGAlib software package. See the text for a detailed description.

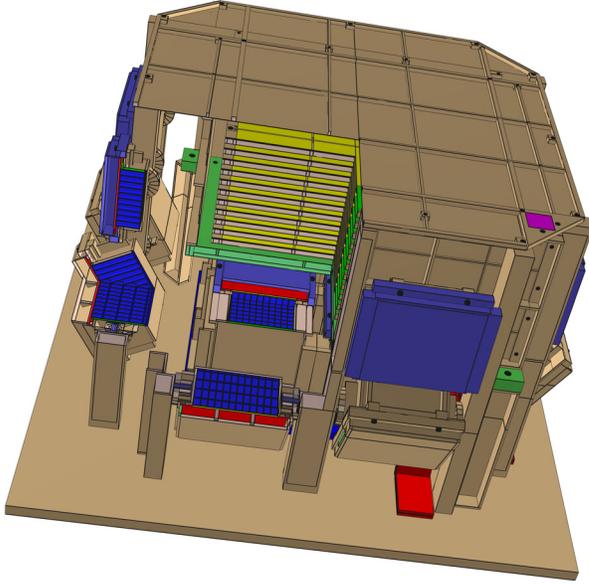


Figure 2. Cutaway-view of the MEGA prototype as seen with *Geomega* (utilizing ROOT's OpenGL viewer).

detector, trigger, etc.) ASCII file[§].

Finally, *Geomega*'s user interface contains several tools to verify the geometry during its construction phase, such as:

- Zoomable geometry display with axes (inherited from ROOT)
- Display of the whole geometry or a subset in a common mother volume
- Total mass calculations for main volume or a subset (including sum of different materials)
- Overlap detection (based on Geant4's detection capability)
- Conversion to Geant4 (via *Cosima*) and MGGPOD, as well as a limited import from MGGPOD and Geant4

2.1.2 Detector and Trigger description

In *Geomega* a set of typical gamma-ray detectors is defined such as scintillators (single detector volume, Anger camera, MEGA-type calorimeters) and strip/pixel detectors[¶] (with and without depth resolution). For all those detectors energy resolutions, position resolutions, trigger thresholds, noise threshold, overflows, defective pixels, guard-ring size, number of strips/pixels, etc. can be defined. In addition *Geomega* allows to define complex trigger and veto criteria. The user can decide if a hit above the trigger threshold results in a trigger or a veto event, how many hits in the same detector type are required to raise a trigger, or if a coincidence between several detectors is required to raise a trigger.

2.1.3 Instrumental effects engine

An important step to reproduce measurements with simulations is to adapt the ideal simulated data to the measurements by applying detrimental detector effects:

- Gaussian/Lorentzian noise for energy measurements (as a function of energy and for 3D strip/voxel detectors of depth) as well as the depth measurement in calorimeters and 3D strip/pixel detectors

[§]Examples can be found in the appropriate *MEGAlib* example directory.

[¶]In the current version for strip detectors the charge deposit is measured in voxels only.

- Noise and/or trigger thresholds (the later as a function of the interaction depth of the 3D strip/voxel detectors)
- Overflows: Energy deposits exceeding the dynamic range of an ADC are accumulated at a certain energy
- Defective channels: A given percentage of measured channels can be deactivated

The discretization (summation and centering) of the simulated energy deposits into the voxels of the detector is usually performed during simulations to minimize the required disk space.

2.2 Cosima — Geant4 Simulation

One of the key tools for understanding the complex interactions of gamma rays and high energy particles (e.g. cosmic rays) in gamma-ray telescopes are Monte-Carlo simulations. Their main goal is to accurately predict the response of the detector to external stimuli, such as cosmic sources or lab measurements, and to predict and verify the performance of the detector — both on ground and in space. For the given telescopes, incidence energies from several keV up to TeV are relevant, and the incident (cosmic) particle spectrum comprises photons, electrons, positrons, protons, neutrons, and heavier nuclei. More exotic particles might be generated during collisions. As a consequence, the most suited and also widely available simulation tools are the Geant Monte-Carlo software packages. *MEGALib* contains interface tools for Geant3¹² with its MGGPOD¹³ extension (designed for simulations of orbital background environments) as well as for its object-oriented successor Geant4.⁸ *MEGALib*'s Geant4 simulation tool is called *Cosima* (“Cosmic Simulator for *MEGALib*”). It is controlled by a keyword based input file. The user can select between the following options:

- Select between different output modes (store all information, store the information discretized, define the accuracy of the stored information, store information about entering and leaving certain volumes, etc.)
- Choose between various physics lists, e.g. Livermore with and without G4LECS¹⁴ or Penelope, and “QGSP-BIC-HP” for hadron interactions, and turn on or off fluorescence
- Define geometry regions with different simulation accuracy
- Choose from a set of typical beam geometries (celestial point and extended sources, isotropic emission, near-field point, and various extended and user defined sources^{||})
- Select from different spectral options ranging from mono-energetic, power-law, broken power-law to user defined spectra
- Various stop criteria for the simulation including time, triggered events, or simulated events
- Define a single source or multiple sources during the same run — the latter can be set to be emitted in coincidence
- Set the geometry, output-file name, polarization of the source, particle type, etc.

Cosima utilizes the *Geometa* library to internally convert the *Geometa* geometry into Geant4 logical and physical volumes as well as materials and sensitive detectors. Therefore *Cosima* has knowledge of all the different detector types (scintillators, strip detectors) and their characteristics. However, *Cosima* does not apply any detector noise, depth resolutions, thresholds, etc. It only discretizes the deposited energies into the voxels of the detector (if set by the user). The remaining adaptation to reality has to be performed in a post-simulations step, since the user should be able change/optimize those parameters without redoing the simulations that usually require significant CPU resources. Only the discretization is performed because otherwise the data size would be a factor 10–100 larger.

^{||}For a complete list of options please see the *Cosima* documentation in the “doc”-directory in the main *MEGALib* directory

The standard output file format (“*.sim”-file) is an ASCII format based on keywords such as “HTsim” for a hit in a sensitive detector, which is followed by detector type, position, and energy. The file can contain either only the individual detector hits (i.e. all the measurable data), or also information about all the ideal interactions in the detector (in passive as well as active material). The latter is necessary to retrace the simulation steps and to generate response matrices.

An alternative path to perform simulations is to use the external simulation tool MGGPOD.¹³ MGGPOD has been proven to be capable of reproducing orbital background measurements including activation for various telescopes, and is therefore an important tool to predict and verify telescope performance. *Geomega* is capable of converting its geometry information into the MGGPOD material and geometry format. In addition, if the MGGPOD simulation are performed using the ACT/INIT extensions, the fits output format can be converted into the *Cosima* output format via the tool *ConvertMGGPOD***.

2.3 Sivan — Interpreting simulations

A special library of *MEGALib* is *Sivan* (“Simulated event analysis”), which is specialized on interpreting the (ideal) interaction information section in the simulation output. The main tasks of *sivan* are:

- Provide diagnostics for the simulation, e.g. plot initial spectra, incidence angles, initial Compton scatter angles, etc.
- Identify positions of first interactions, where photons escape from the detector, where photons are stopped, etc.
- Perform an ideal event reconstruction, and thus provide a benchmark for the various event reconstruction algorithms (see 2.4).
- Provide a link between simulation and response generation (see 2.6).

2.4 Revan — Event Reconstruction

For Compton and pair telescopes the first big data analysis step is the event reconstruction with *Revan* (“Real event analyzer”). Its task is to identify the original interaction process such as photo effect (= single hit), Compton scattering, pair creation, (high-energy) charged particle interaction, radioactive decay, etc. For this task only the detector characteristics and individual hits, consisting only of energy and position information (for some special detectors also of time), can be utilized.

The event reconstruction as implemented in *Revan* consists of four main steps (for details see references 1,15–17):

1. Clusterizing: In strip and pixel detectors, a single passing particle, such as a Compton recoil electron, might interact in two or more adjacent voxels, which have to be combined into one hit. The clusterization can either be performed by distance or just for adjacent voxels.
2. Charged particle tracking: Some detectors (such as stacks of thin Si-strip detectors) are capable of identifying the tracks of electrons, positrons, and other charged particles. The following analysis steps can be applied to those:
 - Search for pair creation events: Pair creation results in a characteristic “V”-shaped pattern in the detector. If it is found, assume it is a pair and track the electron and positron.
 - Search for high-energy charged particle events: High-energy charged particle events mostly pass through the detector in one straight line. Identify those events.
 - Search for Compton electron tracks: For the electron tracking algorithm several sub-types of algorithms exist, which distinguish on how the identified tracks are evaluated: Either correlations (e.g. Pearson, Spearman-Rank) or Bayesian algorithms.

**A specialized version of MGGPOD, capable of directly writing a *MEGALib* “*.sim”-file and thus eliminating the additional *ConvertMGGPOD*-step, is available on request from the corresponding authors.

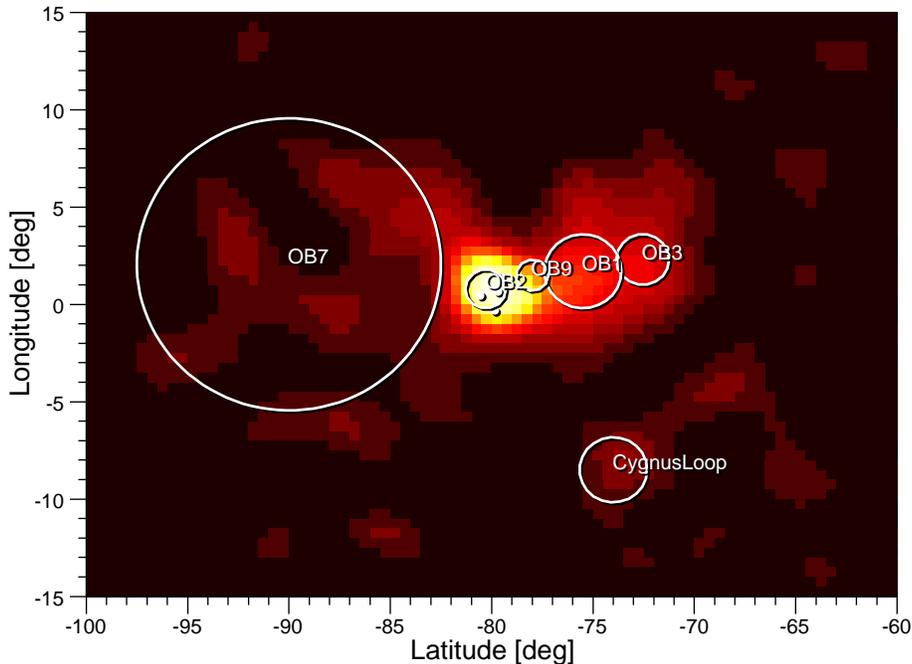


Figure 3. Image obtained from simulations (source and background) of the Cygnus region in the light of radioactive ^{26}Al after 2 years observation with a (small) MEGA satellite version: The diffuse emission of OB-associations (circles), supernova remnant (Cygnus loop), and Wolf-Rayet stars (dots) are clearly visible. For more details see reference 1.

The user can choose for which interaction types he wants to search, as well as the evaluation method.

3. Compton sequence reconstruction: The following different algorithms are currently implemented:

- A “classic” event reconstruction algorithm only utilizing the redundant Compton scatter angle ($d\varphi$ -criterion) as well as the redundant total scatter angle if an electron track is present.
- A “classic” event reconstruction algorithm with energy recovery
- A “classic” event reconstruction algorithm utilizing the $d\varphi$ -criterion and timing information (for e.g. a modern-day COMPTEL telescope)
- A Bayesian event reconstruction algorithm capable of directly calculating the probability that a given sequence originated from a completely absorbed and correctly sequenced photon

4. Decay detection: For some detectors with excellent energy and position resolution it is possible to search for certain beta-decay structures (e.g. one 511 keV hit plus an additional deposit) and reject them.

At the end of the event reconstruction step the events no longer consist of individual hits but of the parameters (positions, directions, energies) of the primary interactions such as photo effect, Compton scattering, and pair creation. In addition a quality factor has been generated for the event, describing the probability of the measured data to originate from a good event. All those information is written into a “*.tra”-file, where tra stands for “tracked”. It is again a keyword based ASCII file.

2.5 Mimrec — High Level Data Analysis and Image Reconstruction

The final step of data processing is the high-level data analysis, whose task is to invert the measurement process (e.g. Compton scattering) and to determine the properties of the sources of the measured gamma rays. The library which accomplishes this task is called *Mimrec* (“*MEGALib* image reconstruction”) named after its main task.

The first step in this process is to find optimized selections for the given scientific task. In general those will differ, for instance if one searches for extended line emission as opposed to polarization from a point source with continuum spectrum. The main task of event selections is to exclude those bins of the data space that contain most of the background events — either instrumental background or incompletely absorbed events. *Mimrec*

allows event selections on all performance-relevant parameters for both Compton and pair events. These include event type, initial detector, energies, scatter angles (Compton scatter angle, total scatter angle), distance between interactions, event quality factors, earth horizon cut, number of interactions, opening angle and initial energy deposit of the pair events, and many more.

Mimrec also contains various diagnostics tools to visualize angular resolution for Compton and pair telescopes, energy dispersion, Compton scatter angle distributions, etc. It can be helpful in assessing the performance of the detector as well as that of the event reconstruction algorithms and the quality of the chosen event selections. Moreover, automated tools are provided to determine, e.g., the set of event selection parameters that optimize an instrument’s sensitivity given raw source and background data by calculating achievable sensitivities on a grid of performance parameter values, or to assess the background-corrected polarization sensitivity of a detector.

The most challenging task for *Mimrec* is the reconstruction of images, since the origin of e.g. Compton scattered photons can only be restricted to a cone — or to an arc on this cone, if the direction of the electron is roughly known. The implemented (multi-threaded) list-mode likelihood image reconstruction algorithm (LM-ML-EM) is an event-by-event approach which avoids large data-space matrices. Several imaging response representations are possible, from a simple 1D representation which only defines a Gaussian width of the imaged Compton cones, to complex multi-dimensional response matrices. With *Mimrec* it is possible to reconstruct sources in spherical, galactic, and Cartesian coordinates (2D as well as 3D) from data consisting of a combination of tracked and not tracked Compton as well as pair events.^{1,18} It can handle point and extended sources as well as measurements during high background conditions as expected from space-borne telescopes. An example of a simulated image can be found in figure 3.

2.6 Responsecreator — Creating responses for event and image reconstruction

Another key tool of *MEGAlib* is its response creator. Many high-level data analysis methods need detector response files such as the Bayesian event reconstruction, some response representations of the list-mode imaging reconstruction, the Earth horizon cuts calculator, etc. Those describe the relation between the measured information and some parameters of the original photon or the original interaction in the detector. To generate those response files, both the interaction and the hit information from the simulation file is necessary. For example to generate an imaging response, first the hit information is processed by the event reconstruction and event selection to determine the reconstructed parameters of the original photon. Those can then be compared with the original parameters of the photon as known from the interaction information. An example for an imaging response for the NCT detector can be found in figure 4.

3. SUMMARY

MEGAlib has proven to be a versatile tool to simulate and analyze data of low-to-medium-energy gamma-ray telescopes, especially Compton and pair telescopes. For those telescopes several methods are implemented to perform event reconstruction, diagnostics, imaging, and performance assessments. *MEGAlib* has been successfully applied to the performance estimation of several existing and envisioned telescopes such as MEGA, NCT, GRIPS, ACT, GRI.

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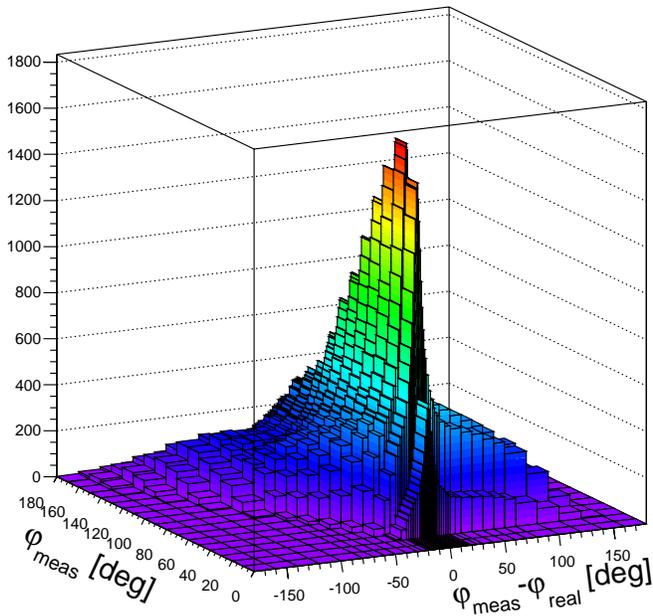


Figure 4. Example of a *MEGAlib* response: Imaging response of the NCT telescope for a continuum source in the energy range from 200 to 350 keV. Plotted is the difference between the simulated and the reconstructed Compton scatter angle φ as a function of the reconstructed scatter angle.

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