Data Analysis for the MEGA Prototype

A. Zoglauer, R. Andritschke, G. Kanbach

Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

---

Abstract

The data analysis for combined Compton and Pair telescopes like the Medium Energy Gamma-ray Astronomy telescope (MEGA) separates into 3 basic steps: The starting point is the calibration and low-level data-analysis. It is followed by the most critical part, the event reconstruction, which has to identify all event types (Pair-creation, Compton events, charged particles, etc.) while effectively suppressing different kinds of background (photons from below, chance coincidences, activation, etc.). The last stage, the high level data analysis, is dominated by image reconstruction, which in our case is performed by a technique called List-Mode Maximum-Likelihood Expectation-Maximization. The current performance of the data analysis algorithms is demonstrated by calibration measurements of the MEGA prototype.

Key words: Gamma-ray telescopes and instrumentation, Data reduction techniques, Image processing
PACS: 95.55.Ka, 95.75.-z, 95.75.Mn

---

1 Introduction

The Medium Energy Gamma-ray Astronomy telescope MEGA is a combined Compton scattering and pair creation telescope in the energy range from 400 keV up to 50 MeV and higher. The baseline design of the MEGA telescope is shown in Fig. 1. A prototype for MEGA has been built (Fig. 2). It consists of a tracker in which the primary interaction takes place and a calorimeter which absorbs the secondary particles. The tracker consists of eleven layers of double-sided Si-strip detectors (3×3 wafers of 6×6 cm^2 each, 500 μm thick with a pitch of 470 μm). It is surrounded by the calorimeter made of CsI crystals (5×5 mm^2 cross section) with lengths of 2 cm, 4 cm (side) and 8 cm (bottom). A detailed description can be found in (1).

The following sections describe the basic principles, which stand behind the data analysis. This is not intended as a complete description of the underlying

Preprint submitted to New Astronomy *27 September 2003*

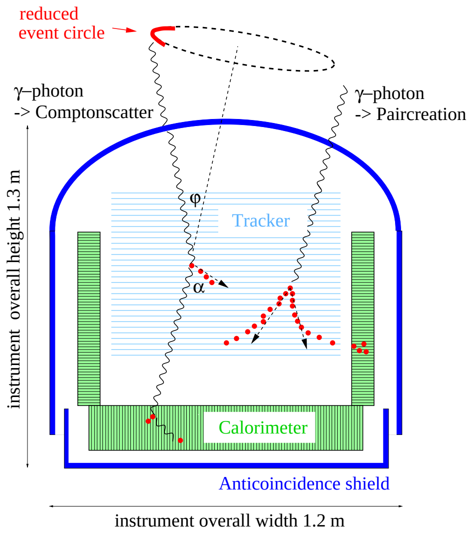

Fig. 1. Baseline design and measurement principle of the full MEGA telescope

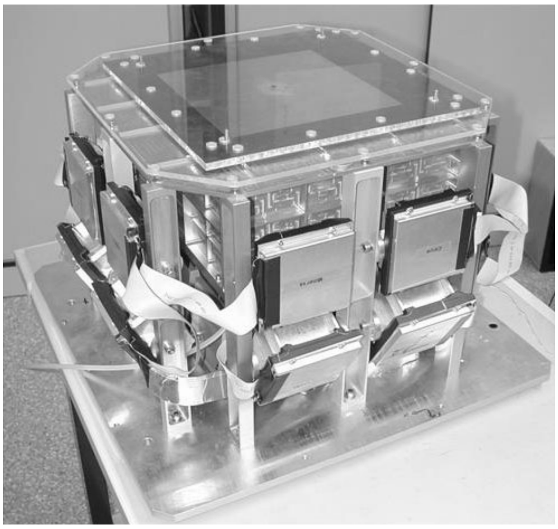

Fig. 2. MEGA prototype: the tracker (central box) is surrounded by the calorimeters

algorithms, but of the ideas behind the algorithms.

In any Compton and/or pair telescope the data analysis path splits into the following steps:

(a) Calibration and low level data analysis, like hit distribution, energy deposits, etc.
(b) Event reconstruction
(c) Image reconstruction and all other high level data analysis, like polarization, spectrum, etc.

We concentrate in this paper on steps (b) and (c), event and image reconstruction.

2 Event reconstruction

Starting from a set of "hits" in the detector, where each hit consists of a position and energy measurement, the aim of event reconstruction is to identify the interaction process, such as Compton scatter, pair creation, charged-particle track, etc., and consequently identify the origin and energy of the photon. The basic outline of this algorithm is the following:

- Search for pair events, where "Λ"-shaped structures indicate the vertex of an electron-positron pair.
- Search for high-energy charged particles like muons, protons or high-energy electrons, which appear as almost straight tracks from tracker to calorimeter

and which normally have additional hits or tracks.
- Separate Compton events from the remaining: Identify the direction of motion of the electron track, determine the overall Compton sequence and finally check, if the event can be accepted as a Compton event.

For a tracking gamma-ray telescope, the track itself is one of the most important elements to identify the event type and its direction. Three criteria enable us to identify an electron track and its direction:

- The angular scattering, due to Molière scattering, increases along the electron path.
- The energy deposit follows the Bethe-Bloch equation (Landau distribution) with minimum ionization in the beginning and increasing deposits at the end of the track.
- The first energy deposit is likely to be smaller than the average deposit, since the gamma-ray interaction takes place somewhere within the Silicon layer of the first hit.

Based on this knowledge, the basic principle of identifying the track of Compton events is the following: Firstly one searches all different possible downward *and* upward combinations (Fig. 3). Then all these combinations are checked for their compliance with the above stated criteria. The combination, whose parameters are in best compliance with those values expected from theory for a track with given energy and direction, is chosen as the correct track. The next steps are to extrapolate the track into the calorimeter and estimate the energy of missing hits caused by interactions in dead material. Calibration measurements show that at 5 MeV and for on-axis incidence 85% of the tracks with three or more hits can be correctly identified.

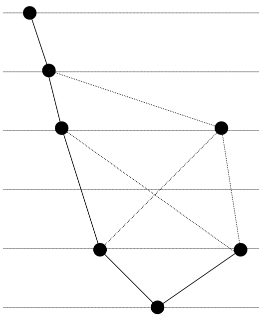

Fig. 3. **Left:** Compton tracking: the dots represent hits, and the lines represent all different analyzed downward sequences

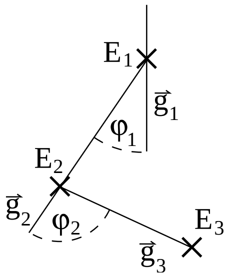

Fig. 4. **Right:** Compton sequence reconstruction (E_i: energy deposit, $\vec{g}_i$: photon flight direction, φ_i: Compton scatter angle)

If the event consists of more than two remaining elements, for example a track and several separable hits in the calorimeter, then the next step is the Compton sequence reconstruction. If an event has for example three Compton interactions (details see Fig. 4), then the second Compton scatter angle φ_2 can be computed via the energies E_2 and E_3 by applying Compton kinematics, and, geometrically, via the angles between the direction of the second ($\vec{g}_2$) and third photon ($\vec{g}_3$). This means there is redundant information, which can be used to determine the interaction sequence: Considering all different combinations of hits, which represent possible paths of the photons, one can calculate φ_2 via energy and via angle. The combination with the best fitting φ_2's has the highest probability of being the correct sequence. Since the energy and spatial resolution of the MEGA prototype is limited, additional information aids to determine the correct interaction sequence: The track normally gives the start point and absorption probabilities lead to a reduction of random coincidences. Descriptions of such algorithms can be found in the literature (e.g. in (2) or more advanced in (3)).

After this last step the event reconstruction has been completed successfully. The data is now represented by three main event types: Compton events with and without a track as well as pair events. The high level data analysis, like polarization, spectrum or image reconstruction, follows and is based on the data from the individual events.

3 Image reconstruction

The aim of image reconstruction is to reveal the original source distribution, either of radioactive material (e.g. sources) or the sky, by only using the measured events and the knowledge of detector response and background.

The accuracy to which the incoming direction of a gamma-ray can be determined is limited by different effects for the three most relevant event types in the energy regime of the telescope. Untracked Compton events lack the knowledge of the electron direction. Thus, according to the Compton equation, the origin can only be restricted to a cone section, whose width is mainly determined by the energy resolution. This results in a large ambiguity of the origin of these photons. However, with the knowledge of the electron track the full cone circle can be restricted to an arc (Fig. 1), whose length is determined by the uncertainty of the electron track due to Molière scattering. On the other hand the origin of pair events can be directly determined by the initial path vectors of the electron and positron track. Here the origin is limited by the unknown recoil of the nucleus and by the Molière scattering of electron and positron.

In addition to these considerations, the image reconstruction technique has to fulfill more requirements at the *same time*:

- Combine tracked and untracked Compton events as well as pair events into one image.
- Avoid binning of data and response, since the amount of measured parameters and the necessary fine binning makes the handling of a response matrix

impractical on normal computers.
- The detector geometry should be easily exchangeable for simulation tests.
- There should be no effort in exchanging the coordinate system, because the prototype software needs to be capable of imaging near-field 2D and 3D sources, as well as far field sources which require spherical coordinates.

One algorithm, which fulfills these requirements, is called list-mode maximum-likelihood expectation-maximization, or shorter list-mode likelihood. It has originally been developed for medical imaging (4), but with some adaptions, its principle has been proven applicable for astrophysics (5).

Since this is an unbinned likelihood method, one calculates for each event and image pixel the probability that the event came from this pixel. For example for an untracked Compton event, the probability would peak inside the cone section. Besides the detector sensitivity and the background, this is the input for the list-mode likelihood algorithm: In an iterative approach the algorithm maximizes the expectation of the likelihood function. The image obtained after the convergence of the algorithm fits the measured data best. Nevertheless the best compliance between the width of the response and the width of the reconstructed point sources is reached shortly before convergence. Thus these images are shown in the later examples. A complete description of the problems, equations and algorithms of this image reconstruction technique can be found in (5).

4 Selected calibration results

In order to demonstrate the functionality of the MEGA detector design, the prototype has been calibrated with lab sources (energies from 511 keV up to 4 MeV) and for energies up to 49 MeV at the HIγS (High Intensity Gamma-ray Source) facility of the Free Electron Laser Laboratory (FELL), Duke University, North Carolina. A detailed description of the technical aspects of the calibration can be found in (6).

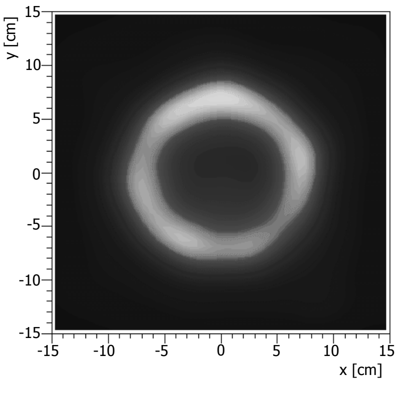

Fig. 5. Circular source distribution produced by ^{88}Y sources on a rotating propeller, which performs a circle with a radius of 7 cm. The propeller was located 27 cm above the center of the tracker. This equals a diameter of ~29° at infinity. It contains ~138000 Compton events which passed the event reconstruction, where the majority of events is not tracked. An energy selection around the 0.9 MeV line has been applied (0.8-1.0 MeV).

To demonstrate the ability to resolve extended sources in the Compton regime, two ^{88}Y sources were mounted on a rotating propeller. The reconstructed image at iteration 50 can be found in Fig. 5. The minor irregularities on the circle result from the assumption that all detectors have the same efficiency.

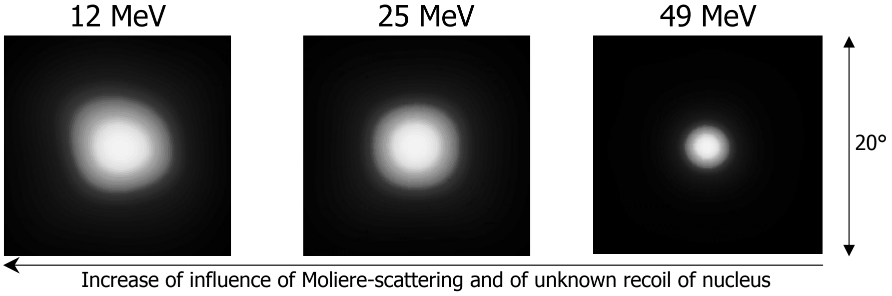

Fig. 6. Reconstructed beam images at 12, 25 and 49 MeV for on-axis incidence. Each box has a width of 20°. The images at iteration 20 contain only pair events.

Above ∼8 MeV pair creation starts to dominate. Figure 6 shows reconstructed images of the HIγS calibration beam at those energies (12 MeV, 25 MeV, 49 MeV). With increasing energy the angular resolution of the telescope improves, since at higher energies the influence of the unknown recoil of the nucleus and of the Molière scattering are reduced. At 49 MeV the angular dispersion, given as the half-angle of a cone which contains 68% of the events, is 4.3°.

The field of view of the MEGA prototype is visible in Fig. 7. It shows reconstructed images of the HIγS calibration beam at 49 MeV for incidence angles of 0°, 30°, 60° and 80°. This shows that the event reconstruction works for the complete field of view of the detector. At an incidence angle of 80°, the longer electron path through Silicon leads to stronger scattering and therefore to a broader response. Furthermore, simulations show, that there is a larger probability that these electrons leave the Silicon layer with an angle slightly tilted towards the axis compared to their incidence angle. This leads to the suppression of high incidence angles and to the slight displacement of the point source at 80° as seen in Fig. 7.

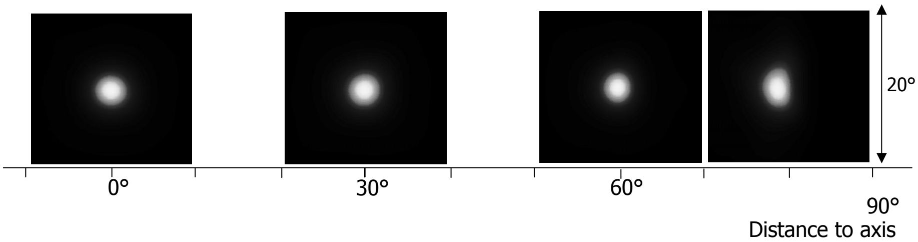

Fig. 7. Reconstructed beam images at 49 MeV for incidence angles of 0°, 30°, 60° and 80°. Each box has a width of 20°. The images at iteration 20 contain only pair events.

5 Acknowledgement

We would like to thank the colleagues at the Duke FELL, especially V. Litvinenko, for providing us with an excellent calibration beam. Also the participations in the calibration runs by P. Bloser, S. Hunter (GSFC), J. Macri, R. Miller (UNH) and the technical expertise of F. Schrey (MPE) are gratefully acknowledged.

References

[1] G. Kanbach, “The MEGA project”, *these proceedings*
[2] S.E. Boggs, “Event reconstruction in high resolution Compton telescopes”, *Astron. Astrophs. Suppl. Ser.* **145** (2000) 311-321
[3] U. Oberlack, “Reconstruction of interaction sequences and background suppression in advanced Compton telescopes”, *these proceedings*
[4] S.J. Wilderman, “List-mode Maximum Likelihood Reconstruction of Compton Scatter Camera Images in Nuclear Medicine”, *IEEE Trans. Nucl. Sci.* **45** (1998) 957
[5] A. Zoglauer, “Methods of image reconstruction for the MEGA Compton telescope” (in German), *Diploma thesis*, *Technical University Munich* (2000)
[6] R. Andritschke, “The calibration setup of the MEGA prototype at the High Intensity Gamma-ray Source”, *these proceedings*