

Expected line sensitivity of the MEGA telescope

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Abstract

A new telescope for Medium Energy Gamma-Ray Astronomy, MEGA, is being developed for the energy band 0.4–50 MeV as a successor to COMPTEL and EGRET. MEGA records gamma rays by detecting and tracking Compton as well as pair creation events in a stack of double-sided Si-strip detectors and stopping them in a surrounding pixelated CsI calorimeter. It is intended to fill the sensitivity gap between scheduled or operating hard X-ray and high energy gamma-ray missions and to open the way for a future Advanced Compton Telescope (ACT).

The extensive simulation tools used for the ACT Vision Mission Concept Study are applied to estimate the performance of a potential MEGA space mission. The tools allow the detailed simulation of the different background components expected for the satellite's desired low earth orbit. We present the expected narrow line sensitivities of a MIDEX-sized telescope and show that a sensitivity 10 times better than that of COMPTEL is achievable.

Key words: Gamma-ray telescopes and instrumentation

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1. Introduction

The Medium Energy Gamma-ray Astronomy (MEGA) telescope is a combined Compton scatter and pair production telescope designed to close the “sensitivity gap” that currently exists in the energy band 0.4–50 MeV. This band contains many astrophysically important nuclear decay lines. The MEGA telescope (see (1), (2) and Fig. 1) consists of a tracker of silicon strip detectors surrounded by a calorimeter of CsI crystals. The main innovation of MEGA is that the recoil electron from a Compton interaction can be tracked, allowing the

traditional Compton event circle to be replaced by a much smaller arc (the “reduced event circle” in Fig. 1). A prototype detector has been built and calibrated.

The goal is to build a satellite instrument which exceeds in the Compton regime the sensitivity of its predecessor COMPTEL (3) by roughly a factor of 10. While it is easy to envision a Compton telescope which is 100 times better, the goal is to use only detector techniques which are currently available and allow for an immediately implementable mission.

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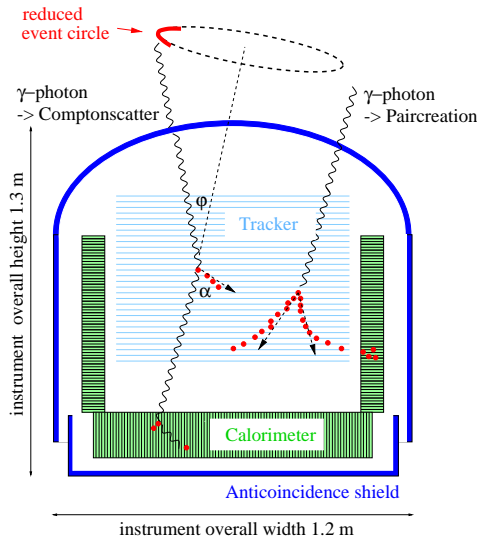


Fig. 1. Baseline design and measurement principle of the full MEGA telescope

2. Methods

The MeV regime in which MEGA will operate is characterized by high penetration power of the gamma-rays and nuclear lines. While those properties make observations at these energies particularly rewarding, they also present a challenge for observers: gamma rays are hard to completely stop and can make multiple Compton scatters, resulting in events not entirely contained in the active detector. Moreover, nuclear lines are not only observed from astrophysical sources, but also from the spacecraft itself, which gets activated by interacting protons and neutrons.

Those properties make it impossible to derive the expected performance of space-borne Compton telescopes analytically. Only detailed simulations allow performance estimates of a given instrument. Such simulations must include the exact geometry of the telescope as well as all expected background components. Furthermore, a realistic estimate may rely only on existing data analysis algorithms, because any estimate of how well a future algorithm might reject background is impossible to make. Thus we have made use of several well-tested software packages that were recently combined and enhanced to provide an end-to-end simulation framework for the ACT Vision Mission

Concept Study (4). Central to the framework are the MGGPOD (5) suite for simulations, and the MEGAlib library (6) for data analysis.

2.1. Simulation

The fluxes of all orbital background components for an equatorial low-earth orbit (525 km) have been determined using ACT-study tools (4) and are used as inputs for MEGA satellite simulations with MGGPOD. The background components include cosmic photons, albedo photons, prompt and delayed backgrounds from cosmic protons and albedo neutrons, as well as cosmic electrons and positrons. It should be noted that the Cesium and Iodine neutron cross sections currently included in MGGPOD are only estimates.

The simulation model of the satellite geometry is loosely based on the MEGA pre-phase A study (7): The 167 kg CsI calorimeter, 8 cm thick on the bottom and 4 cm thick on the sides, completely surrounds the tracker. The CsI bars (5 mm × 5 mm) are assumed to be read out by silicon drift diodes, with an energy resolution of 5% FWHM at 662 keV and a trigger threshold of 100 keV. The tracker comprises 5.3 kg silicon in 32 layers, each 0.5 mm thick. The tracker's individual wafers have the same dimensions as the prototype's, 6 cm × 6 cm, and the same pitch, 500 μm. The energy resolution is assumed to be 10 keV FWHM with a trigger threshold of 30 keV. An anticoincidence shield made of BC408 plastic scintillator surrounds the telescope. The satellite weighs 850 kg. Great care has been taken to include all materials with correct composition at the expected positions within the spacecraft.

For applying the appropriate realism (e.g. energy and position resolution) and for data analysis (event reconstruction, event selections, and sensitivity calculations) the MEGAlib package (6) was used.

2.2. Event reconstruction

The most important part of the data analysis is the event reconstruction. Its task is to determine the sequence of interactions (direction of motion

of the electrons, interaction sequence of multiple Compton scatters), as well as the event type, and to qualify the events. The probability that the given sequence of interactions is correct and corresponds to a completely absorbed event is calculated using Bayesian statistics. The necessary probability density functions have been pre-determined via extensive simulations (roughly 1.5 CPU years for a single 2.4 GHz Xeon CPU). The results of this step are the parameters of the first Compton scattering (energy and direction of the scattered gamma-ray as well as recoil electron) and a quality factor, which is essentially the probability mentioned above. This approach is described in detail in (8).

2.3. Event selections

Fig. 2 illustrates the effects of event selection (i.e. background rejection) on the on-axis effective area of the telescope. The first curve (squares) shows all kinematically possible Compton interactions which produce a track.

The second curve (diamonds) represents all events within a $\pm 1.4\sigma$ energy-resolution window around the simulated narrow-line energy, i.e. the photo-peak events. Since above ~ 1.5 MeV most events are incompletely absorbed this results in the largest reduction of events at higher energies.

The third curve shows all events which pass the background rejections. For tracked events the maximum allowed difference between the total scatter angle calculated via geometry (angle between scattered gamma ray and recoil electron) and via Compton kinematics is the key, because it eliminates most of the wrongly-reconstructed or upward-moving events. Another cut is performed using the quality factor of the event reconstruction. Events which might be reconstructed incorrectly, or occupy data space cells which are dominated by background, are suppressed. Additionally, the maximum allowed Compton scatter angle and the minimum allowed distance between interactions are restricted. Finally, for far off-axis observations an earth-horizon cut rejects events originating from the lower hemisphere of the detector (mainly photons from the Earth's albedo and from detector activation). These event selections improve the

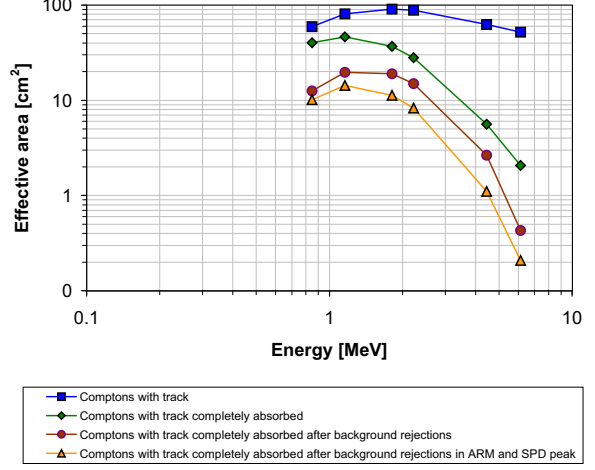


Fig. 2. Effective area after different background rejections for tracked events as a function of narrow-line energy.

instrument's sensitivity by roughly a factor 2.5.

The last curve (triangles) shows only events which are compatible with the position of the tested point source given the instrument's angular resolution. (The ARM and SPD are defined in Section 3.)

For each tested nuclear-line energy different event selections have to be used to optimize the narrow-line point-source sensitivity.

2.4. Sensitivity calculations

The final $z\text{-}\sigma$ sensitivity is calculated by using the following equation:

$$F_z \approx \frac{z\sqrt{N_S + N_B}}{A_{eff} T_{eff}} \approx \frac{z^2 + z\sqrt{z^2 + 4N_B}}{2 A_{eff} T_{eff}} \quad (1)$$

Here $A_{eff} T_{eff}$ — effective area times effective observation time — is the exposure accumulated during a given total observation time in a source element (resolution element on the sky), and N_B are the accumulated background events in the source element. To determine the sensitivity in scanning mode given a total observation time, first the effective area after event selections as a function of the incidence angle has to be determined. From an integration over the sphere and total observation time the average exposure in the source element can be retrieved. Similarly, the number of

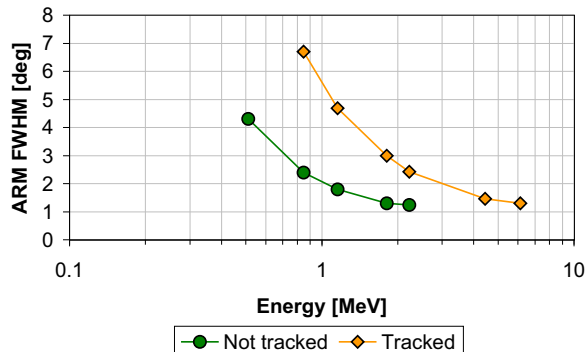


Fig. 3. FWHM angular resolution for tracked and untracked events.

background events in the source element can be obtained. Since MEGA operates in scanning mode an effective observation time of 90% is assumed.

3. Performance

Fig. 3 shows the angular resolution measure (ARM) of the telescope. The ARM is simply the angle between the reconstructed and true Compton scatter angle, and thus represents the thickness of the Compton event circle. As expected, untracked events show a better angular resolution, because for smaller scatter angles the energy resolution in the calorimeters has less influence than for large scatter angles, which are preferred for tracked events due to the larger energy transfer to the electron.

Fig. 4 shows the half width of the Compton arcs for tracked events in terms of the scatter plane deviation (SPD — the angle between the reconstructed and the true plane of the Compton scatter). It improves with higher electron energies since it is dominated by the multiple small-angle scatterings (Molière scattering) of the electron while traversing the silicon layer in which the Compton interaction occurred.

Finally, Fig. 5 shows the estimated average 3σ sensitivity of the MEGA telescope after five years observation time to narrow lines compared to COMPTEL at 1.809 MeV (9) and 2.2 MeV (10). A detailed comparison of the MEGA and COMPTEL sensitivities is beyond the scope of this paper,

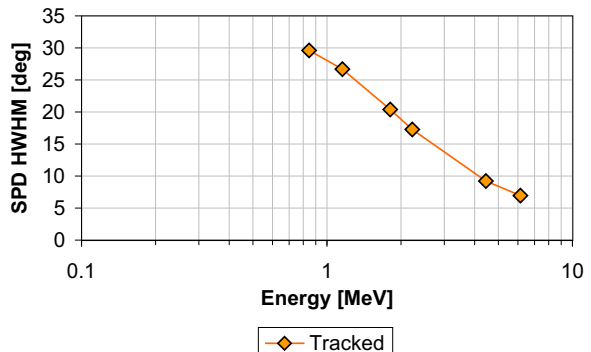


Fig. 4. Length of the Compton arc of tracked events

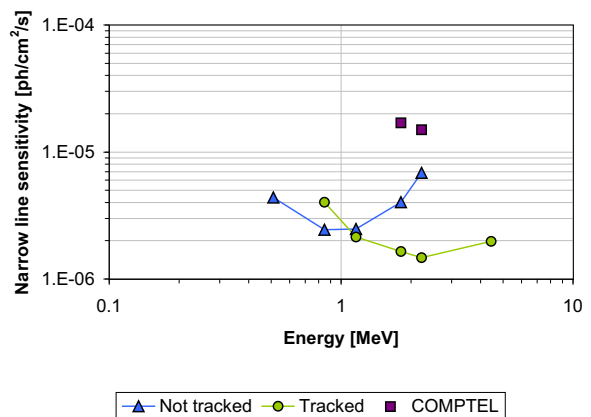


Fig. 5. Average narrow line point source sensitivity for tracked and untracked events after five years. Selected COMPTEL (5 yr) values are shown for comparison.

but we may say in general that after the same observation time (here five years) MEGA will exceed COMPTEL's narrow-line point-source sensitivity by a factor of 10. Due to the larger effective area and better angular resolution, untracked events provide a better sensitivity for MEGA below 1 MeV. However, for the current geometry and with optimized event selections, having electron tracks reduces the background counts in a given angular resolution element by roughly a factor of 8 at 1.809 MeV (averaged over the whole sky). Due to the energy resolution of the MEGA detectors, switching from narrow to broad lines does not effect the expected sensitivity significantly. For a 3% broadened 847 keV line indicating the decay of ^{56}Co produced during SN Ia, the sensitivity worsens only by $\sim 10\%$.

4. Discussion

The sensitivity improvements over COMPTEL have several reasons: First, operating in zenith-pointed scanning mode results in a significantly higher observation time compared to pointing mode (COMPTEL had roughly one third effective observation time, MEGA should have at least 90%). The second significant improvement is the orbit. While COMPTEL had a 28° orbit, passing through the South Atlantic Anomaly, MEGA is intended for an equatorial orbit. Initial tests have shown that the equatorial orbit gives at least a factor of two sensitivity improvement. Third, better angular and energy resolution yield a narrower point spread function and thus fewer background events in the resolution element used for sensitivity calculations. Moreover, MEGA has a larger field-of-view (half width $\sim 45^\circ$), leading to a significantly larger collected exposure than COMPTEL. Also, the larger amount of measured information for a single event enables better rejection of background events. For example, events with multiple Compton scatters can be resolved, and absorption probabilities can be used for background rejection. Finally, electron tracking enables a sensitivity improvement compared to untracked events in MEGA. The effect depends on the photon energy. At 1.809 MeV the effective area-corrected sensitivity improvement is a factor of 2.6.

Although the current geometry can achieve the minimum goal of improving the sky-averaged sensitivity by a factor of 10 compared to COMPTEL, the simulations have revealed some weaknesses in the geometry of the pre-phase A study. These could be easily fixed to get even better sensitivity:

(1) The total depth of the tracker represents only 17% of the radiation length of silicon. Thus the majority of the events pass through the tracker and have their first interaction in the calorimeter. More silicon would significantly improve the efficiency.

(2) The cubic shape leads to a narrow field of view. If the geometry were flatter this could be improved. Since in the nuclear-line energy regime the length of the Compton arc is dominated by Molière scattering, not the layer distance, moving the layers closer together has no negative impact on

the overall performance. Only in the high-energy pair-production regime is a deterioration expected.

(3) Current technology would allow for at least 10 cm silicon wafers instead of 6 cm. This would help to reduce the passive mass in the tracker.

(4) The geometrical limit to the instrument's angular resolution is roughly one degree. Especially for tracked Comptons at lower energies (e.g. 1.809 MeV) MEGA's angular resolution is significantly worse than this. The main reason is the energy resolution in the calorimeter, which negatively affects the ARM for events with large scatter angles. This can be resolved by using a calorimeter with improved energy resolution.

(5) Finally, many trade-off studies will be necessary to finalize the instrument concept, in particular to optimize the thickness of the side and bottom calorimeters, the height of the instrument, the depth of the silicon, the pitch in the tracker, the size of the CsI crystals, etc.

MEGA is a promising telescope which could be instantly implemented and bridge the sensitivity gap in medium energy gamma-ray astronomy.

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