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New method of high-energy gamma ray direction reconstruction in multilayered converters

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Abstract. A new method of high-energy gamma ray incident direction reconstruction is developed for gamma-ray detectors with multilayered converters. The method uses data from converter and, if available, from position-sensitive calorimeter to reconstruct an electromagnetic cascade axis and to determine the incident direction of a primary gamma. For the first time to find point of intersection of gamma direction line with convertor plane, median of energy deposit in sensitive plane of convertor is used. Applied, for example, to the GAMMA-400 space-based gamma-ray telescope this method allowed to achieve the angular resolution $\sim 0.01^\circ$ at gamma-ray energy of 100 GeV, being much better than accuracy of the past and present space- and ground-based experiments. In the algorithm presented, a balance between the angular resolution and the effective area can be found to meet a scientific goal of an experiment.

1. Introduction

To study fundamental problems of astrophysics, cosmophysics and particle physics detection of high energy gammas is essential. Gamma detectors are widely used both for accelerators experiments and space experiments. The task is to reconstruct direction of incident gamma as precise as possible. In many cases it is necessary to reconstruct both direction and energy of gamma.

In this paper we present a new method of high energy (more than 300 MeV) gamma-ray direction reconstruction, which enables to obtain high angular resolution. This method was primarily based on the method published in 2011 [1]. The implementation of our method is more simple than Kalman filter used in other experiments (Fermi-LAT, Agile) and at the same time achieved angular resolution much better than Kalman filter.

2. Physical scheme of imaging gamma-ray detector

As a rule, imaging gamma-ray detector is converter-tracker. Converter-tracker consists from several layers with high atomic number material for effective gamma conversion interleaved



with layers of position-sensitive charged-particles detectors. Converter-tracker enables to follow charged particles tracks, measure energy deposit in sensitive part and reconstruct direction of incident gamma.

Position measurement achieved with thin strips located parallel with pitch of the order of 0.1 mm. Usually, to have 3D picture of trajectories, layers are interleaved with perpendicular strips. Such converter-tracker can be implemented with silicon microstrip detectors or with scintillating fibers.

3. Direction reconstruction algorithm

When gamma with energy more than 300 MeV hits detector it convert to electron-positron pair and starts an electromagnetic shower. In this way signals are generated in some strips in the layers after conversion point.

The algorithm developed uses electron and positron trajectories and shower axis to reconstruct incident gamma direction. The main part of energy deposit in converter-tracker layer is located close to trajectories of particles generated by the incident gamma. At the same time it is likely to have “parasite” signals from background or from backsplash particles going in the opposite direction. Backsplash particles are generated by electromagnetic shower developed in the material after converter-tracker. In many cases this material is calorimeter. Almost all backsplash particles are gamma-quanta with energy close to 1 MeV. “Parasite” signals from backsplash have nearly uniform distribution on the layer area. Their rate increase with the incident gamma energy. Signals from background have usually also uniform distribution but their rate and distribution depend on experiment condition.

To evaluate coordinates of electron-positron pair and shower axis in layer, we analyze the distribution of energy deposit in strips of each layer. As estimation of coordinate we have chosen median of energy deposit distribution. Median coordinate depends very weakly on the coordinates and amplitude of “parasite” signals. After the first estimation we define a certain region near median and reject all signals outside this region. By means of several iterations shrinking selected region we obtain final coordinate of trajectory. Detailed description of this procedure and results of simulation are below.

Having two perpendicular directions of strips we obtain independently two angles (α_y and α_z on Fig. 2) determining direction in Cartesian coordinates. We introduce Cartesian coordinates X perpendicular to converter-tracker layers along the averaged direction of gammas and Y perpendicular to the strips. Each point of a track detected is characterized by X coordinate of layer position, Y and Z coordinates measured with two perpendicular layers of strips. In what follows we consider XY plane and the same is applicable to XZ plane. For each strip layer we obtain y_M coordinate of median of energy deposit distribution, and after that we derive a straight line on XY plane with the least square procedure. This line will be estimation of gamma direction.

As median divide layer in two parts with equal value of energy deposit in each part, the procedure of calculation of median is the following (see Fig. 3a). There are n triggered strips on the layer located along Y axis in positions from y_1 to y_n . Each strip y_i is attributed weight equal (or proportional) to energy deposit w_i (see Fig. 3b). We can attribute also cumulative weight to each strip a_i :

$$a_i = \frac{1}{2}w_i + \sum_{j=1}^{i-1} w_j.$$

Now connect each point (y_i, a_i) to point (y_{i+1}, a_{i+1}) with straight line and find on this polyline the point with ordinate equal $\frac{1}{2} \sum_{i=1}^n w_i$. Abscissa of found point is y_M gives us a coordinate of energy deposit distribution median for considered layer. So we have point on XY plane with coordinates (x_l, y_M) , where x_l is a layer position and y_M is a median position for layer number l .

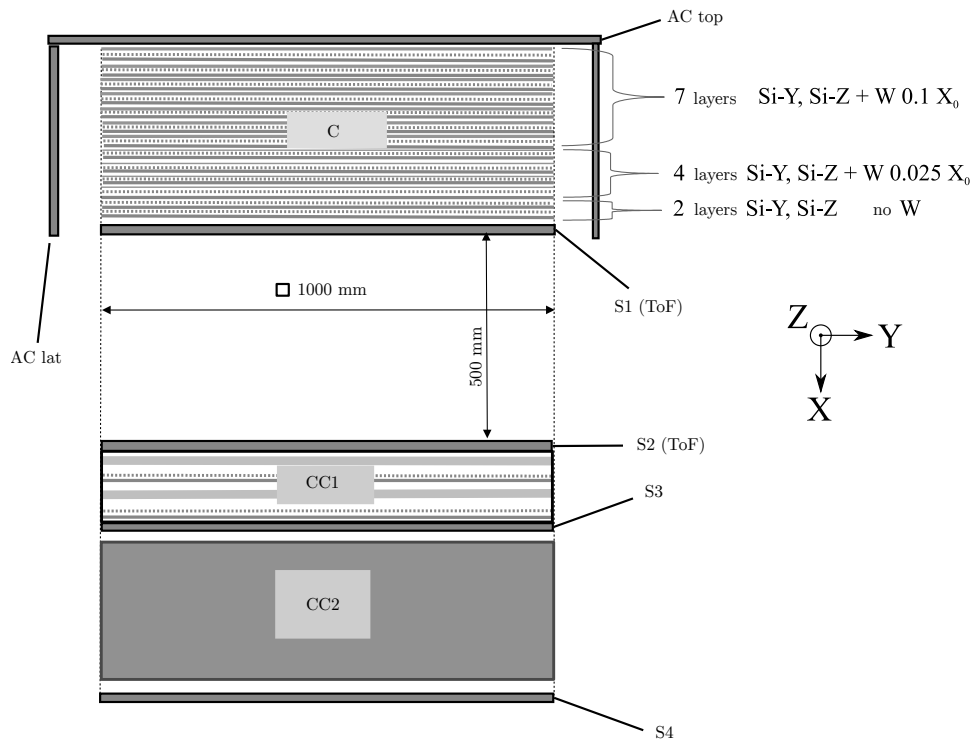


Figure 1. Physical scheme of the GAMMA-400 gamma-ray telescope. AC top and AC lat are anticoincidence system detectors; C is a converter-tracker; S1, S2 are time-of-flight detectors; CC1 is a position-sensitive calorimeter; CC2 is a thick electromagnetic calorimeter; S3, S4 are scintillator detectors of a calorimeter system.

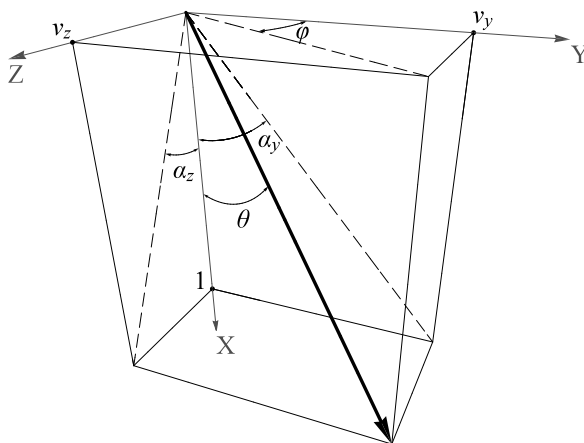


Figure 2. Angles α_y and α_z of a reconstructed direction and spherical angles θ and ϕ .

Having points for all layers traversed by trajectory (after conversion point) it is possible to set up straight line with least square procedure. This procedure again requires weight definition for each point based on median position error. More accurate are coordinates of points with high

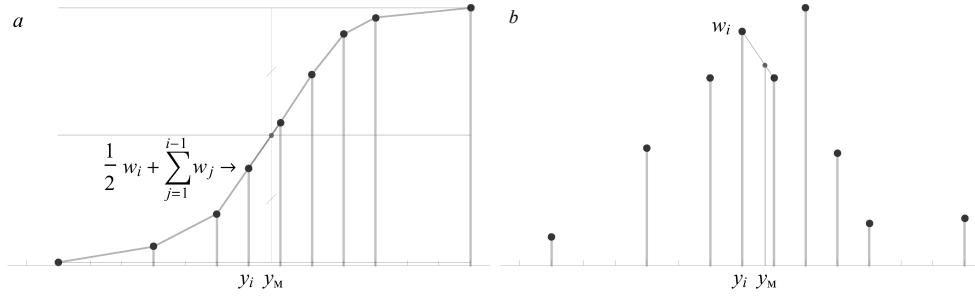


Figure 3. Procedure of finding a position y_M (a) and a weight w_M (b) of a median point in each tracker layer containing triggered strips.

energy deposit near trajectory and less accurate are coordinates of points far from conversion point due to multiple scattering in traversed material. So, nominator of weight is proportional to energy and calculated with linear interpolation procedure. For this we connect to points (y_i, w_i) and (y_{i+1}, w_{i+1}) with line segment (Fig. 3b). Ordinate of point belonging to this segment with abscissa y_M is taken as nominator of weight. Denominator of weight is sum of two terms: accuracy of position measurement and multiple scattering displacement. The simplest way to define denominator dependence from energy and traversed material is simulation of events.

Now it is possible to find straight line with least square procedure and use it as the first estimation of gamma direction. To reconstruct direction more accurately, we establish a region around this line and reject all signals out of this region. We repeat all procedure decreasing the width of region until achieve minimal value of width h_{\min} or minimal acceptable number of points for the least square procedure N_{\min} . Both h_{\min} and N_{\min} are parameters of the algorithm. By decreasing h_{\min} and increasing N_{\min} one can improve angular resolution but decrease efficiency, as more events will be rejected by this algorithm.

Straight lines found with the procedure define tangents of direction angles v_y on an XY plane and v_z on an XZ . Vector of gamma direction can be easily transformed to spherical coordinates.

4. Application to gamma-telescope GAMMA-400

The described procedure was applied to angular resolution calculation of space gamma-ray telescope GAMMA-400 [2, 3, 4]. The gamma-ray telescope includes 13 layers of the converter-tracker. The position of trajectory is measured with accuracy 0.03 mm. Layers have different thickness of tungsten converters. Algorithm was applied to simulated with GEANT4 data.

Results of direction reconstruction for 100 GeV gamma quanta are presented in Fig. 4. The incident direction angles are zenith angle $\theta_0 = 5^\circ$ and azimuth angle $\phi_0 = 15^\circ$. This direction yield projection angles on XY plane $\alpha_{y0} = 4.830^\circ$ and on XZ plane $\alpha_{z0} = 1.297^\circ$. Distributions of reconstructed angles are shown in Fig. 4a and 4b.

Distribution of angle between incident direction and reconstructed direction is presented in Fig. 4c. Gamma-ray telescope's angular resolution is obtained with a standard procedure: it is equal to the deviation angle, containing 68% of events deviated less than value of angular resolution. Dependency of GAMMA-400 angular resolution on gamma quanta energy is shown in Fig. 4d together with that of Fermi-LAT [6]. For energy >20 GeV, GAMMA-400 angular resolution is much better.

To study different astrophysical gamma-sources it is important to find balance between angular resolution and efficiency. Fig. 5a demonstrate dependence of angular resolution on energy for three values of parameter h_{\min} . Fig. 5a present dependence of efficiency on energy for the same values of h_{\min} . Recall that h_{\min} is the minimal width of region for median calculation.

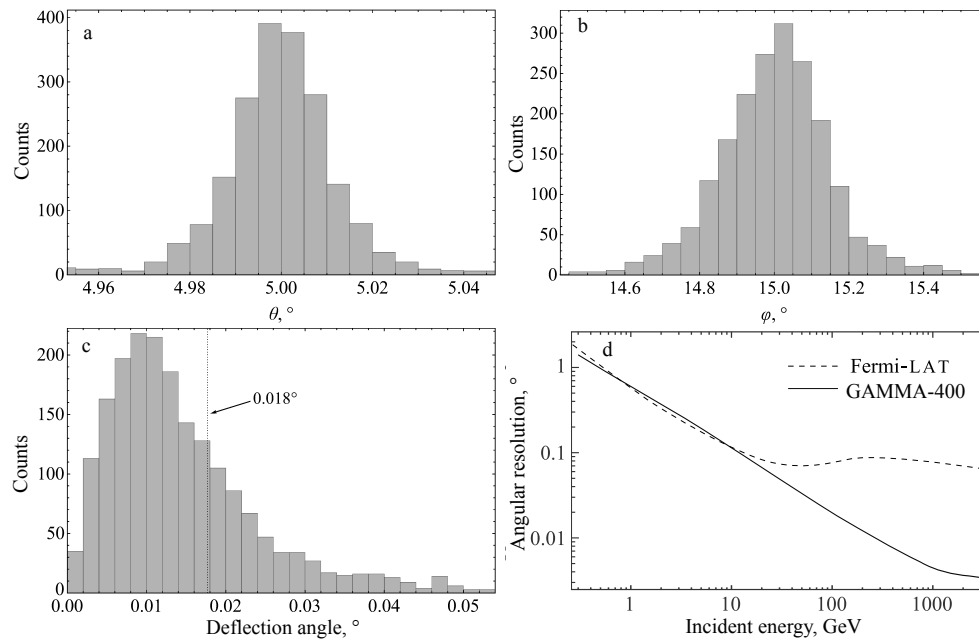


Figure 4. Histograms of distributions by reconstructed spherical angles θ (a) and ϕ (b) for gamma-ray energy 100 GeV. (c) Histogram of distribution by deflection of e reconstructed direction from a real gamma-ray direction. Vertical dashed line shows a 68th percentile. (d) GAMMA-400's angular resolution depending on energy of incident gamma rays.

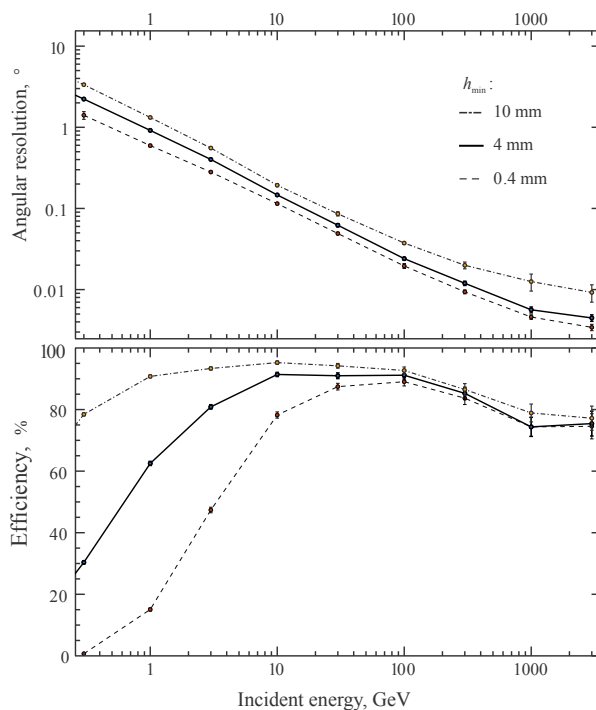


Figure 5. GAMMA-400's angular resolution and algorithm efficiency depending on energy of incident gamma rays for three values of the h_{\min} parameter.

5. Results

In this work we present a new method of gamma quanta direction reconstruction. This method enables to obtain high angular resolution. Adjustment of parameters make possible to fit

properties of instrument to physical task. The procedure is based on median calculation that made it not sensitive to backslash and background.

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