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Event Reconstruction for Advanced Compton Telescopes

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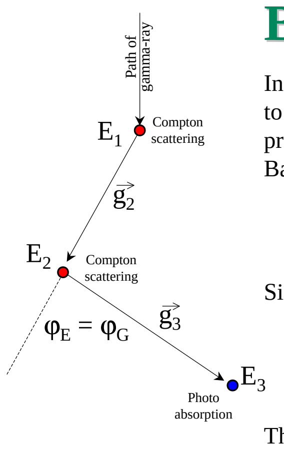
Abstract

One key issue of Advanced Compton Telescopes is the ordering of the Compton interactions and the rejection of background events. We give the current development status of a new approach to event reconstruction for Advanced Compton Telescopes, which is based on a Bayes-filter.

Compton Event Reconstruction



Advanced Compton Telescopes (ACT) intend to measure more parameters of Compton events (e.g. several Compton interactions, the recoil electron direction, etc.) with a higher accuracy than their predecessor COMPTEL. For a baseline geometry of such an ACT see poster 16.18 by S. Boggs, which describes a large area Si-Ge detector.

Most of the ACT designs have the same fundamental problems in common: Due to their compact design, the time between the interactions and their sequence cannot be measured with current semi conductor technology. In addition, space background will dominate the source signal. Thus, one crucial step in the data-analysis is to order the interactions and to identify most of the background. In the case of the Advanced Compton Telescope this ordering is mainly done via the redundant information that is provided by multiple Compton interactions.

The figure on the top right side shows an exemplary Compton event with two Compton interactions and one final photo absorption. To find the correct sequence one has to take into account all different n! sequences, in our case 6. The second Compton scatter angle φ_2 can be calculated via Compton kinematics and via geometry:

$$\cos j_E = 1 - \frac{E_0}{E_g} + \frac{E_0}{E_g + E_e} \qquad \cos j_G = \frac{\vec{g}_2 \circ \vec{g}_3}{|\vec{g}_2| \cdot |\vec{g}_3|}$$

Those angles are only identical for the correct sequence and thus are the most valuable information the correct sequence of interactions (details see e.g. [1], [2], [3]).

Bayesian Compton Tracking (BCT)

Inspired by the success of Bayes-filters in email spam detection (see [4]), a similar approach has been applied to Compton tracking. The goal is to get for each possible combination a number p, which gives the probability $p(C|\cup m_i)$ that the given sequence is correct C, based on all measurement points m_i. Applying Bayes law and assuming that all measurements are independent gives:

$$p(C|\cup m_i) = \frac{p(C) \cdot p(\cup m_i|C)}{p(\cup m_i)} = \frac{p(C) \cdot \prod_i p(m_i|C)}{p(\cup m_i)}$$

Since the denominator is not easily accessible, the following ratio is used for the actual calculations:

$$R = \frac{p(C|\cup m_i)}{p(\overline{C}|\cup m_i)} = \frac{p(C) \cdot \prod_i p(m_i|C)}{p(\overline{C}) \cdot \prod_i p(m_i|\overline{C})}$$

The necessary probabilities have to be determined in advance by simulation. All simulated event sequences are analyzed and the retrieved measurement points are stored in two data spaces: The first one contains all correct sequence points m_i, where the total energy is correct and where the previous, the current, and the next measurement point are in the correct sequence. The other data space contains all false sequences. The content of the data spaces can be considered as the „training“ data of the algorithm. Examples can be found in the next section.

Since we know that $p(C|\cup m_i) + p(\overline{C}|\cup m_i) = 1$ the final solution is the BCT factor:

$$f_{BCT} = 1 - p(C|\cup m_i) \approx \frac{R}{R-1}$$

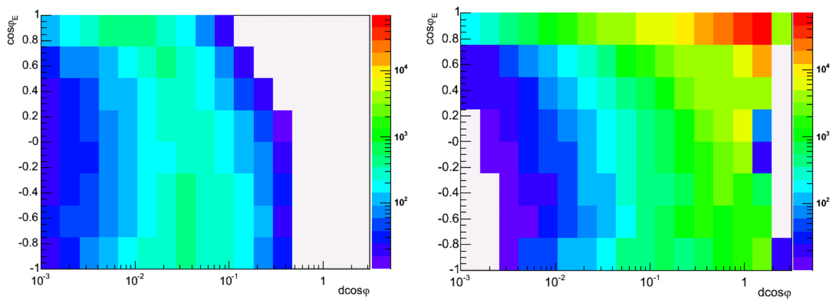
Of course we only get an approximation of the real probability, since the measurement points are not completely independent and neither data-space nor statistics are infinite.

The data space

A data space which describes the problem consists of 7 dimensions of which the first 5 are currently used:

1. The difference of the redundant Compton scatter angles: $d\cos\varphi = \cos\varphi_E - \cos\varphi_G$
2. A distance factor d, which determines the geometrical error of $d\cos\varphi$.
3. The Compton scatter angle as $\cos\varphi_E$, since larger scatter angles result in larger measurement errors and increased Doppler-broadening.
4. The total energy E_{tot}, since the distribution of $d\cos\varphi$ is given by the Klein-Nishina equation and depends on the total energy of the photon.
5. The total number of interactions, because this determines the number of combinations which have to be investigated.
6. The Compton absorption probability p_A on the photon‘s path to the current interaction point. For the last interaction point the photo absorption probability is used.
7. The material of the interaction, because this determines the Doppler-broadening.

On the right side, two aspects of such a data space are shown, which has been filled by using the ACT geometry described in poster 16.18

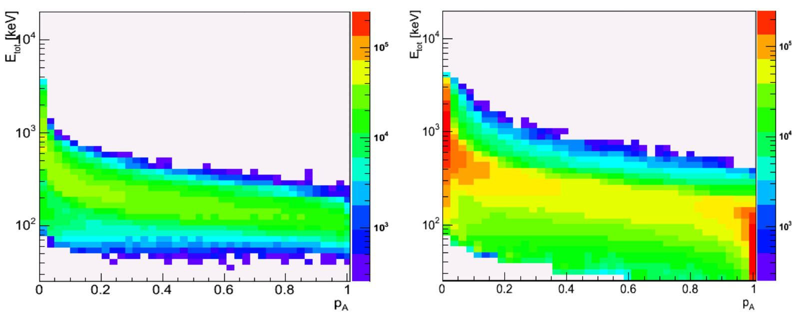


Top left: Central points of correct Compton sequences. A band is formed in the $\cos\varphi_E$-$d\cos\varphi$ data space. The other dimensions of the data space are fixed to: d = 2-5 cm, E_{tot} = 500-2000 keV, events with three hits. No other dimensions are used.

Top right: All wrong sequence points gather at larger $d\cos\varphi$ values. Nevertheless there is an overlap between good and bad sequences in the data space, which results in wrongly reconstructed events.

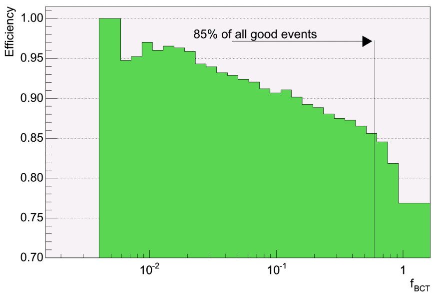
Bottom left: The data space of the final measurement point contains only the photo-absorption probability p_A and the deposited energy E_{tot}. Here, the events are roughly evenly distributed over all absorption probabilities. The small excess at low probability values originates from events, which make a Compton interaction and also a photo effect in the same voxel.

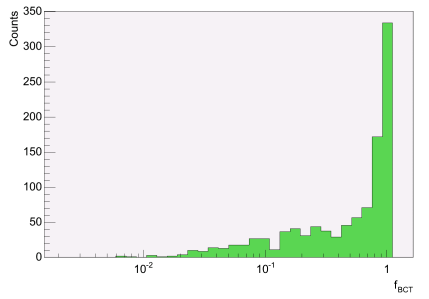
Bottom right: A significant amount of the wrong sequence points gather at large and small probability values p_A, since their energy is either too high or too small for a reasonable photo absorption.

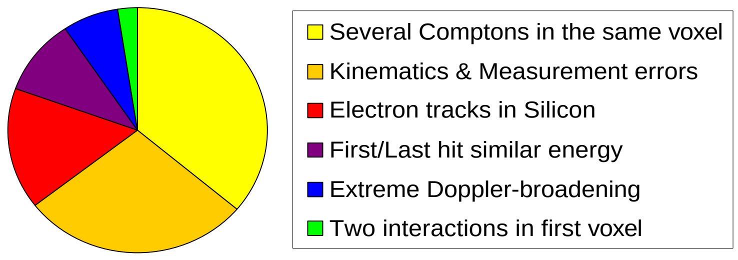


First simulation results from the 847 keV line

The left figure shows the efficiency of the reconstruction, if all photo-peak events up to a certain f_{BCT} are chosen. In addition, only those events are selected which have between 3 and 5 hits and all hits are at least 1 cm separated. If one uses the 85% best events, one gets an efficiency of 85%. With the same selection one can reduce the number of incompletely absorbed events by 76%. If one uses only the 75% best events, one can reduce the background by 82%. The figure on the right shows the distribution of all false reconstructions: As expected they accumulate at high f_{BCT} values.







The above pie chart shows the failure reasons of the reconstruction of photo-peak events. Most of them result from the bottom Germanium detector of the current ACT design, where large Doppler-broadening and small distances between the interactions result in large measurement errors. Factors like electron tracks and similar energy deposits could be resolved in a later screening of the events.

References

[1] Boggs, AA Suppl. Series 145, 2000
[2] Oberlack, SPIE 4141, 2000
[3] Zoglauer, New AR 48, 2004
[4] Graham, „A Plan for Spam“, http://www.paulgraham.com/spam.html

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