COMCUBE's design simulations – Part I

Mission overview and payload design

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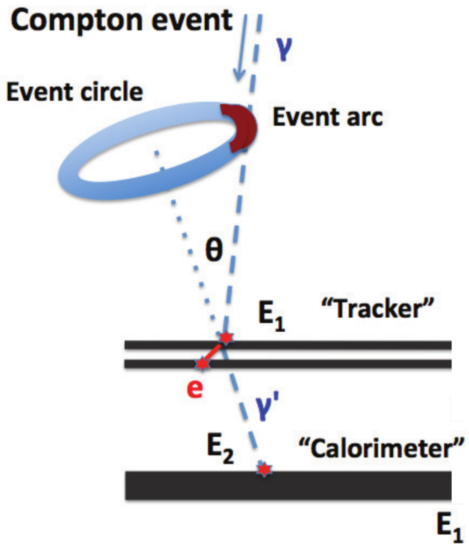
Contents

- Envisioned detectors and their measured performances
- Most investigated mass models
- Polarization measurements with several satellites

Compton instrument



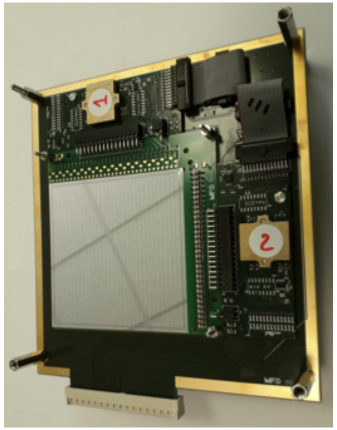
Two detectors

- Tracker or Diffuser, in which a Compton scattering occurs
- Calorimeter

Both measurements of position and energy allow the Compton scattering to be reconstructed

At the energies we consider, the electron cannot be tracked so we have event circles

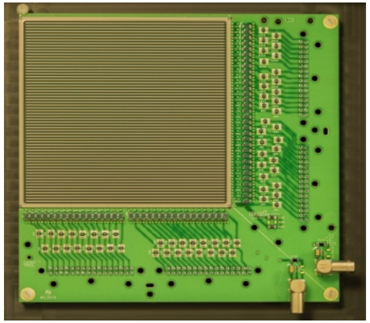
Envisioned detectors



Si DSSD (IJCLab)

DSSDs (double-sided silicon stripped detectors)

- 1.5 mm thick with a 2 mm inter-strip distance
- Good position and energy resolution (~15 keV FWHM)
- (Conservative) 30 keV trigger threshold

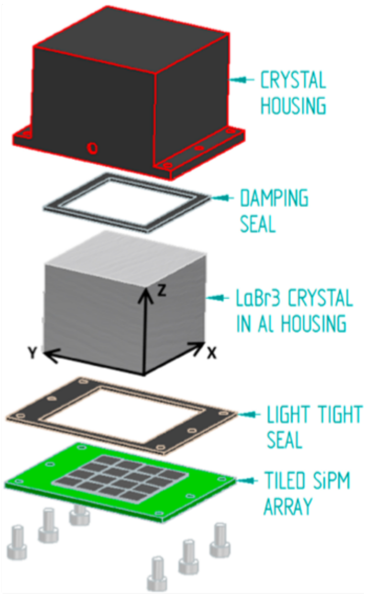


Si DSSD (CEA)

Anger Cameras

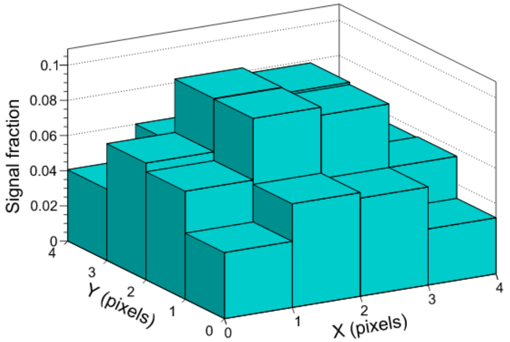
- Are made of a monolithic scintillator coupled to a multi-pixels photo-sensor
- Allow 3D position reconstruction in the sensitive volume and energy measurement

Anger camera



Calorimeter module (UCD)

1-inch module,
4x4 pixels

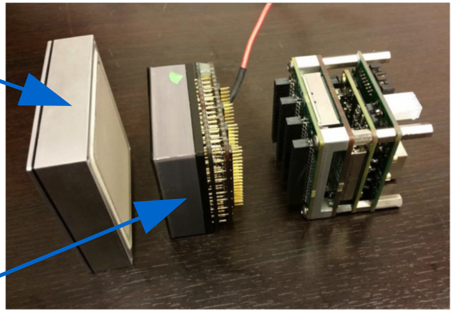


Ulyanov *et al.* 2016

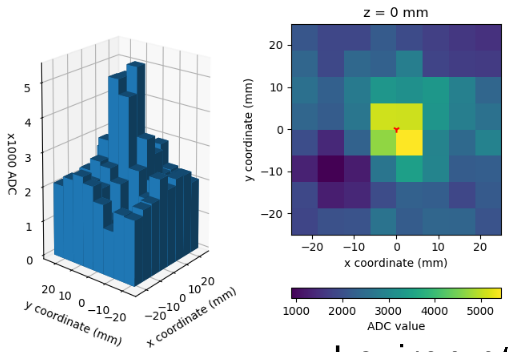
2-inch module,
8x8 pixels

2-inch $CeBr_3$ scintillator

Multi-anode PMT (will be replaced by an SiPM matrix)

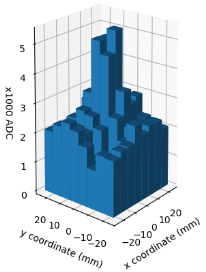


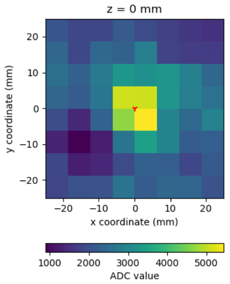
IJCLab calorimeter module

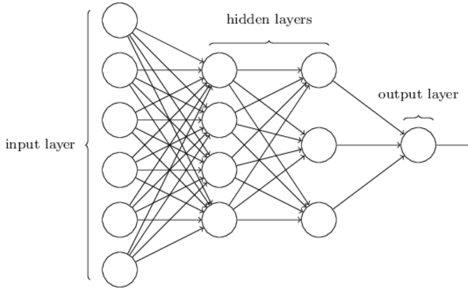


Laviron *et al.* 2020 (to be submitted)

Position reconstruction



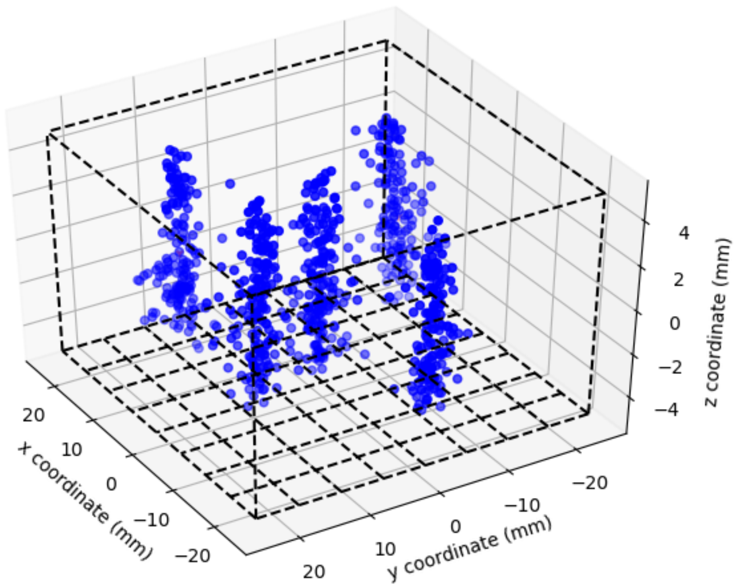




(x, y) coordinates

z coordinate

Artificial neural networks

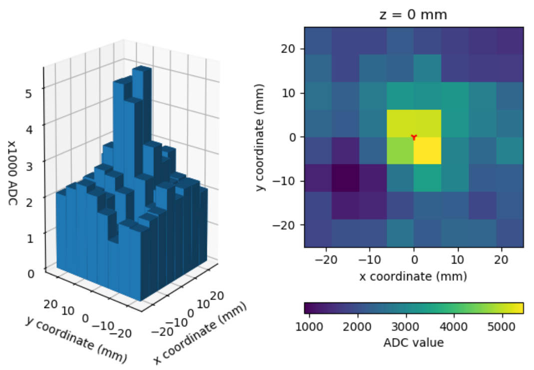


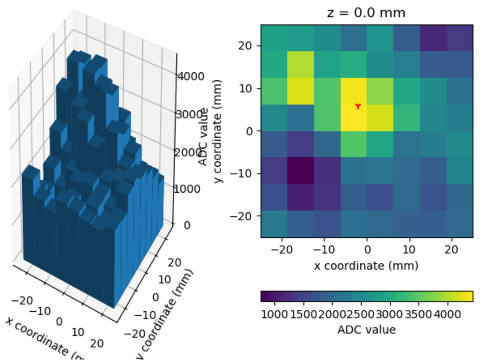
Position resolution is about **2.5 mm** at high enough energy (> 150 keV) with an optimized neural network architecture (hidden layers design)

Energy resolution of **5%** FWHM at 662 keV (after position-dependent energy correction)

Laviron *et al.* 2020 (to be submitted)

Side note on Anger cameras





Gamma rays can interact several times within the scintillating material

- If interactions occur close to each other, they are indistinguishable
- If interactions occur far from each other, the positions are hard to reconstruct and the first one hard to identify

The latter type (less than 5% of full-energy at 662 keV) can be identified automatically and discarded

Main scientific goals

- Survey the gamma-ray sky to localize GRB by timing triangulation and send alerts
  - Requires a fleet of small instruments
  - Requires enough photoelectric effective area per instrument
- Measure the polarization of several GRB per year
  - Requires enough Compton effective area

Polarization signal

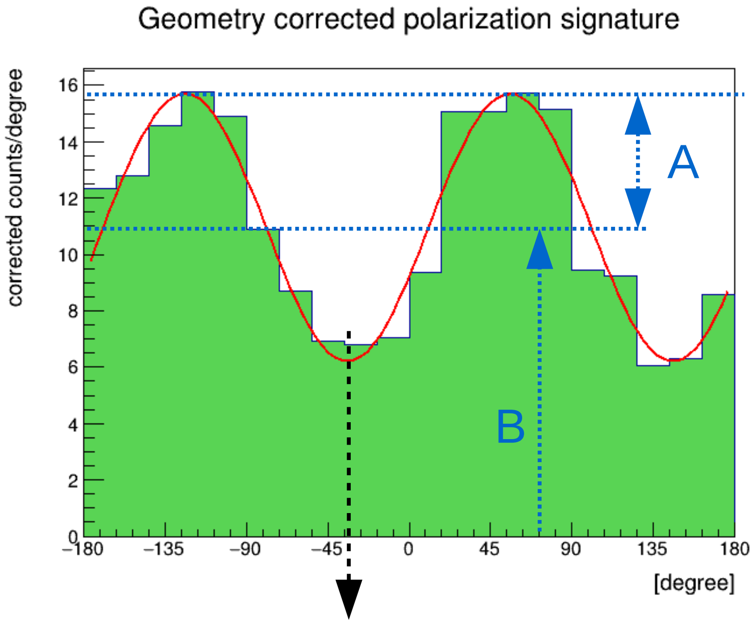
Klein-Nishina differential cross-section for polarized photons :

$$\frac{d\sigma_{KN}}{d\Omega}=\frac{1}{2}r_e^2\left(\frac{E_\gamma'}{E_\gamma}\right)^2\left[\frac{E_\gamma'}{E_\gamma}+\frac{E_\gamma}{E_\gamma'}-2\sin^2\theta\cos^2\phi\right]$$

- The polarization angle is given by a minimum of the fitted modulation
- The polarization fraction Π is given by

$$\Pi=\frac{\mu}{\mu_{100}} \text{ where } \mu=\frac{A}{B}$$

and $\mu_{100} < 1$ the modulation of a 100% polarized source seen by our instrument.

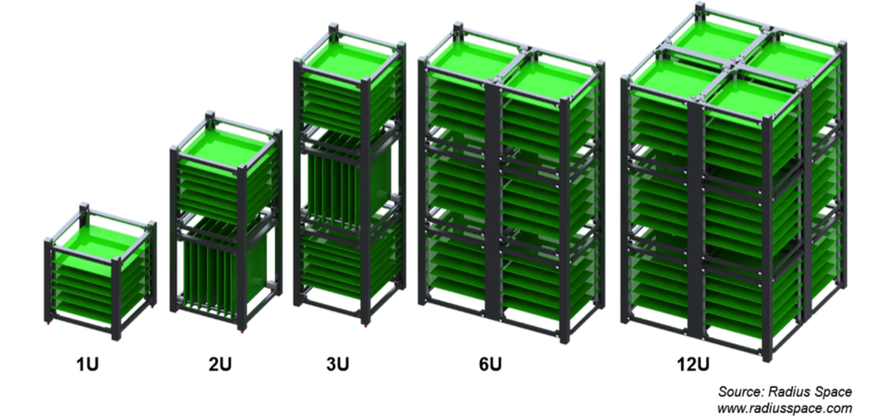


Polarization angle (PA)

Mass model constraints

Each instrument must comply with the nanosatellite constraints and standards

- 1U is one unit of satellite
  - $10x10x10\ cm^3$
  - ~1.3 kg
- Typical larger missions have size 2U, 3U, 6U, 12U …



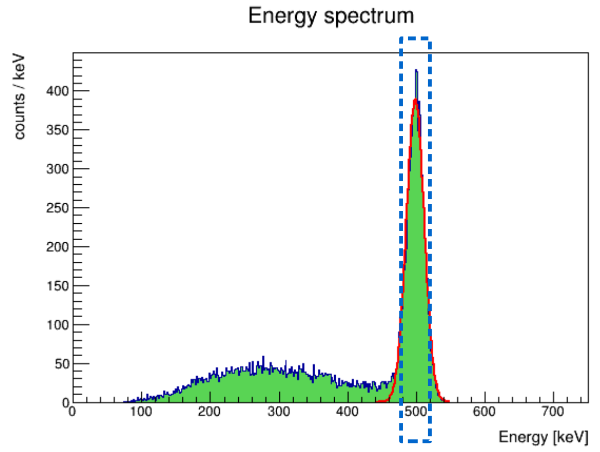
MEGAlib

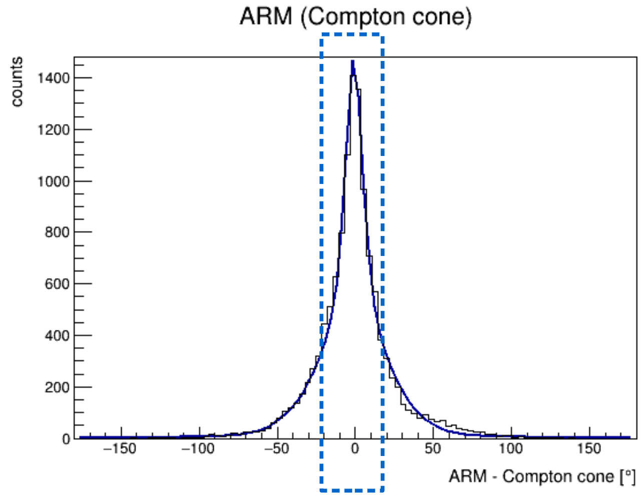
MEGAlib is a set of software tools which are designed to simulate and analyze data of gamma-ray detectors, with a specialization on Compton telescopes [Zoglauer *et al.* NewAR 50 (7-8), 2006]

Geometry definition and simulations are based on Geant4.10.02, plots are made using Root 6

We used MEGAlib 2.34 (release version) and 3.00 (master), then we updated to MEGAlib 3.01 (current master)

The simulations protocol

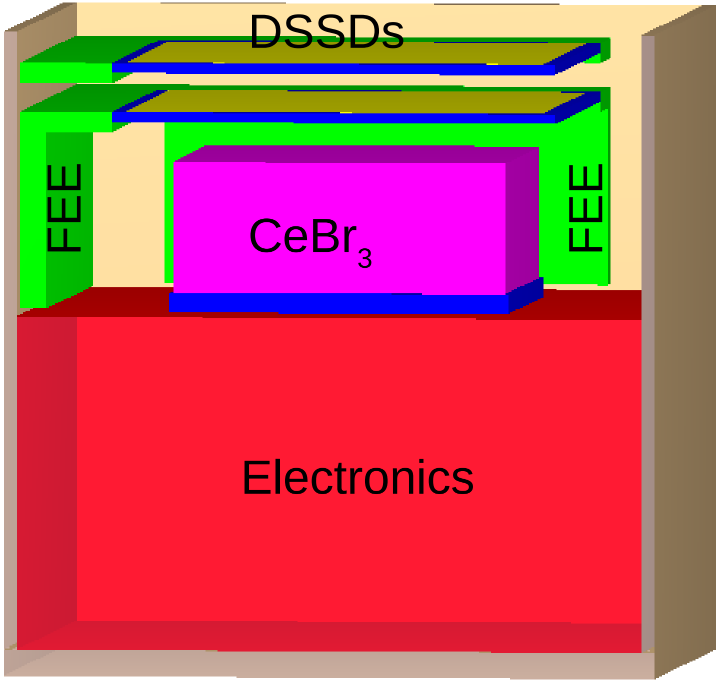




The Compton effective areas are calculated from simulated mono-energetic gamma-ray beams located at various inclination angles, after the following event selection

- Use only Compton events (at least two interactions in two different detectors)
- Energy selection : ± 1.4 σ
- ARM (reconstructed source direction) selection : ± 1 FWHM

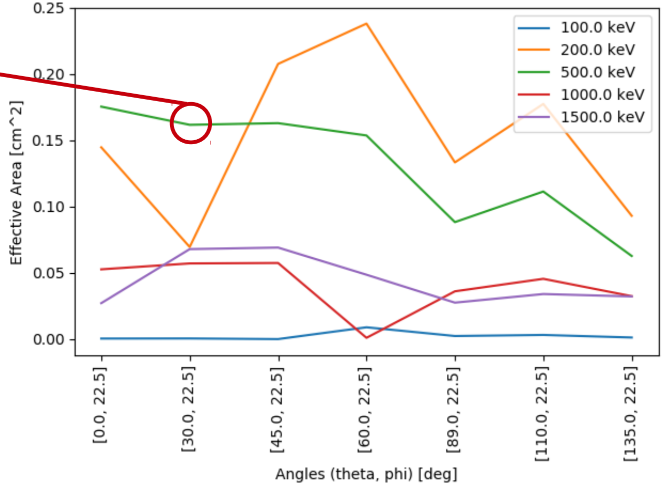
The “baseline” mass model



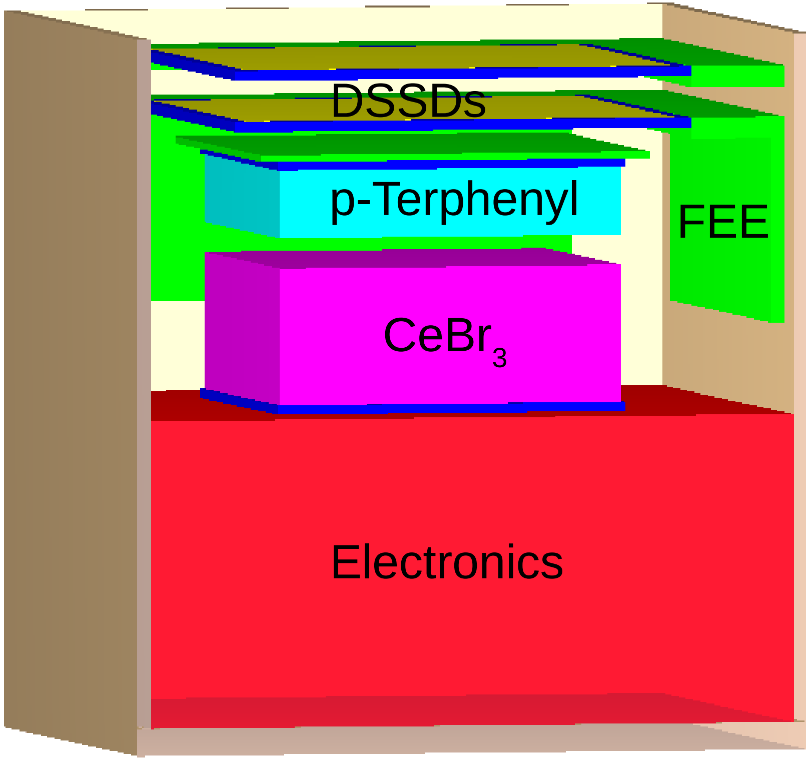
Inspired from larger Compton instrument projects :

- Two layers of DSSD
- One $CeBr_3$ calorimeter

$A_{eff} = 0.17\ cm^2$



Diffuser-enhanced baseline

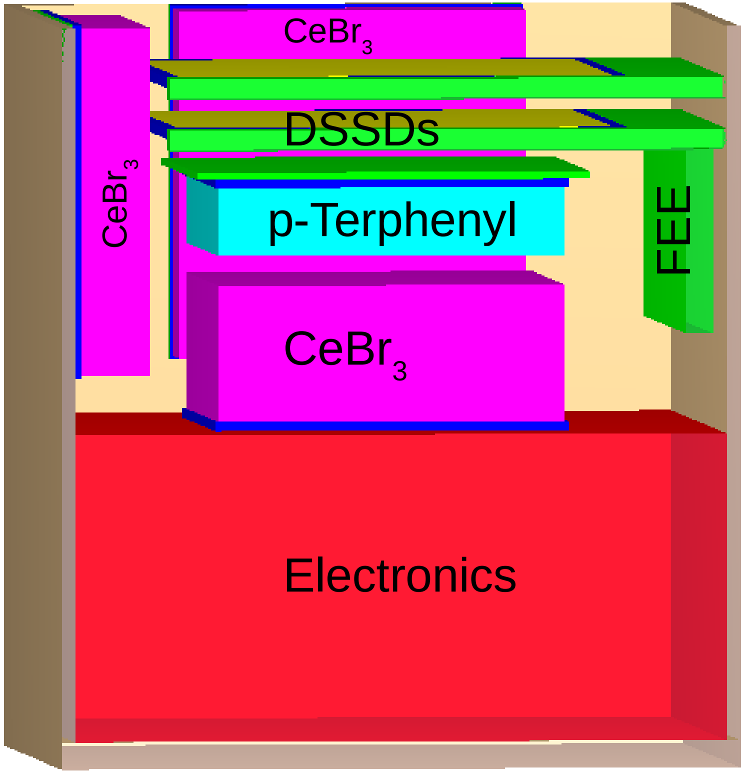


Adding a plastic (p-Terphenyl) based Anger camera increase the effective area at lesser cost than adding DSSDs

Simulated with lower position and energy resolution (resp. 6 mm and 9% FWHM at 662 keV)

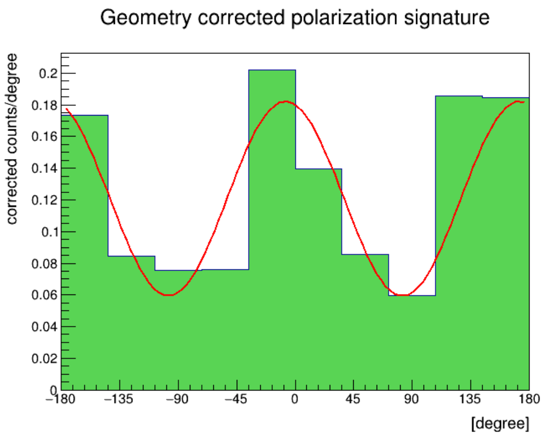
$A_{eff} = 0.27\ cm^2$

Side detectors



Adding thinner $CeBr_3$ detectors on the sides help catching scattered gamma rays

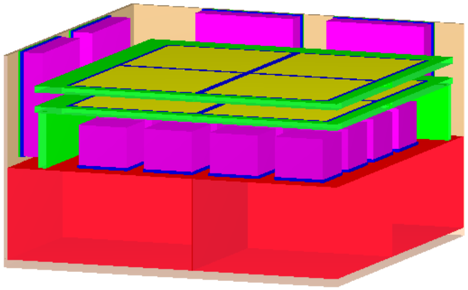
$A_{eff} = 3.5\ cm^2$

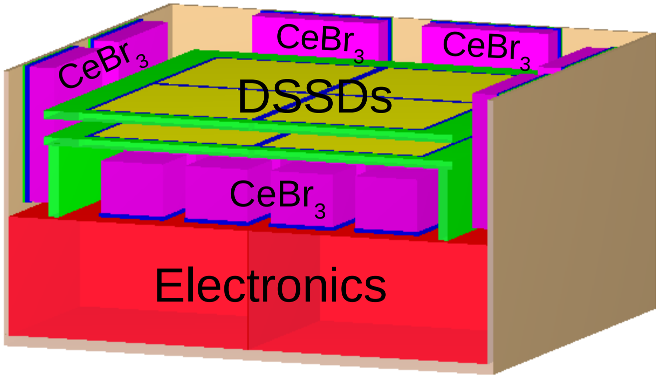


Polarized GRB simulated with typical fluence and spectrum

- 2.5×10^{-5} erg/cm²
- Band spectrum
  - E_{peak} = 300 keV
  - α = -1.1
  - β = -2.3

Towards a 4U instrument





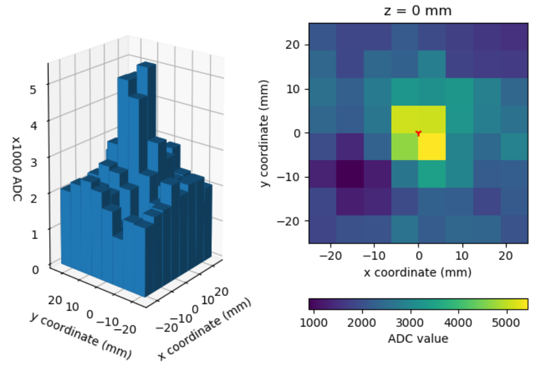
Modular design: This one is basically four times the previous one

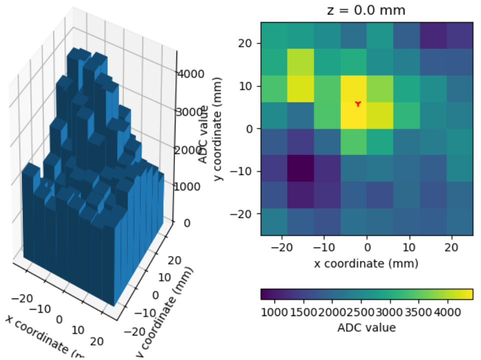
A 4U instrument can be integrated to a 6U satellite

Size and mass budget are very similar to these of BurstCube

$A_{eff} = 11\ cm^2$

Side note on Anger cameras





In MEGAlib 2.XX (release version) these detectors were simulated as depth-sensitive stripped detectors, which can separate these interactions

It led to overestimated effective areas

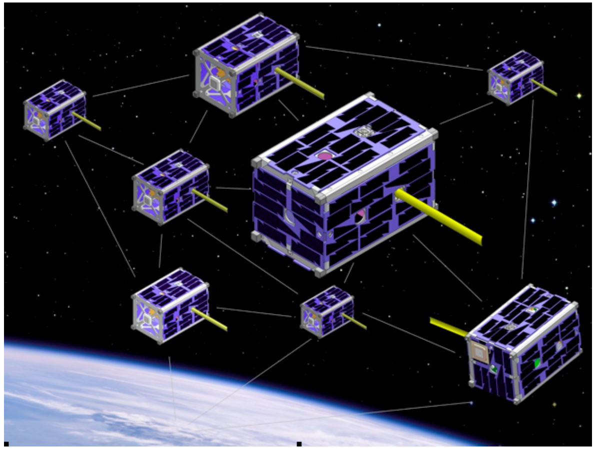
- From 11 cm^2 to 8 cm^2 for the latter mass model

Anger cameras were introduced in MEGAlib 3.XX

Multi-satellite observations

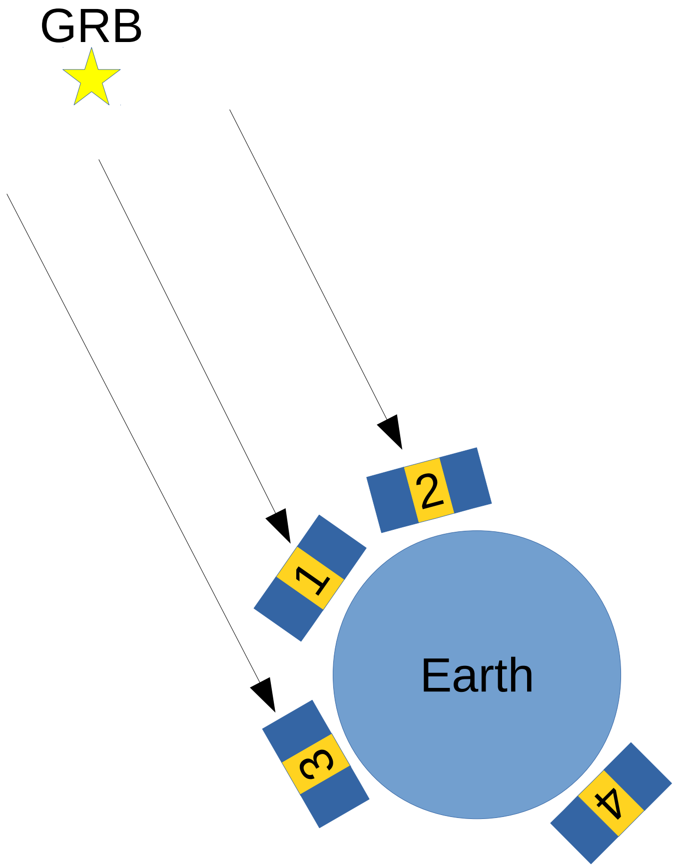
The photoelectric effective area of the current mass model is ~200 cm^2, very similar to that of CAMELOT [Werner N. *et al*, 2018]

The Compton effective area is ~8 cm^2 per instrument



Can we use data from several instruments to increase the polarization sensitivity ?

Observations with several instruments

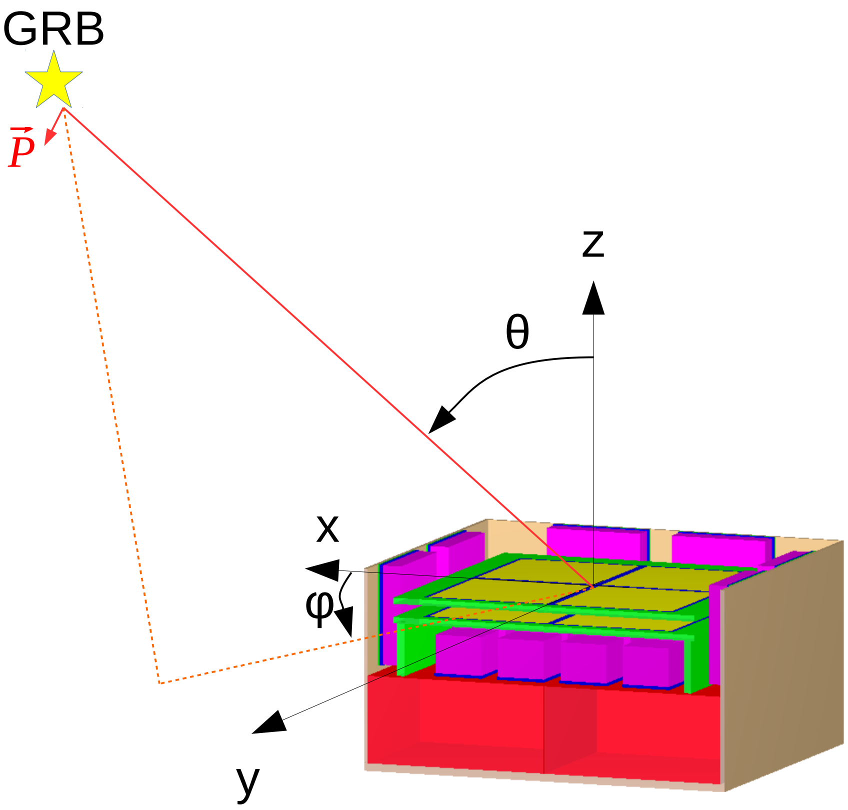


Several instruments see the same source

Each instrument sees the source at a position (θ, φ) in the sky and with a certain angle of rotation around the source direction (ψ, analogous to the polarization angle)

These **three** parameters define the satellite orientation

Observations with several instruments



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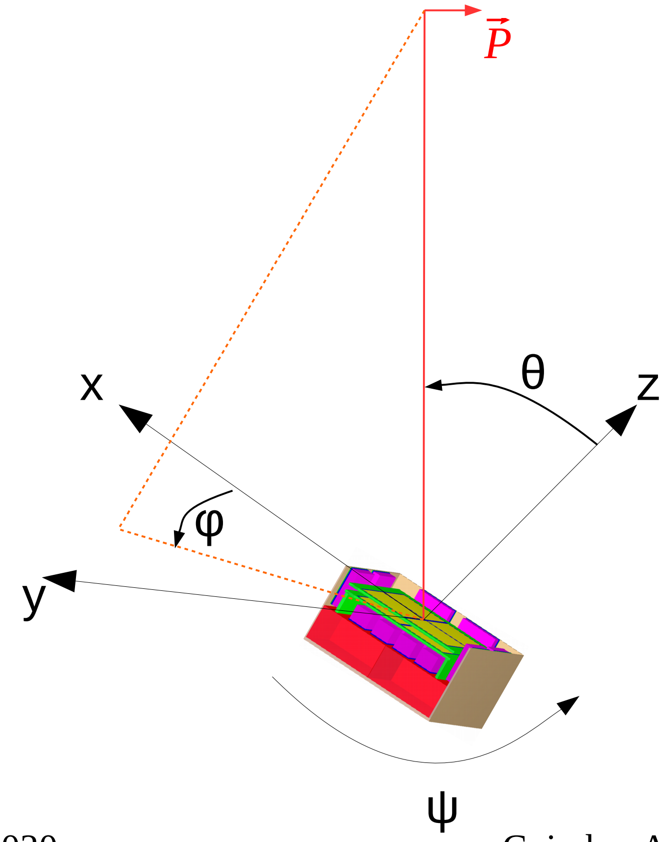
Observations with several instruments



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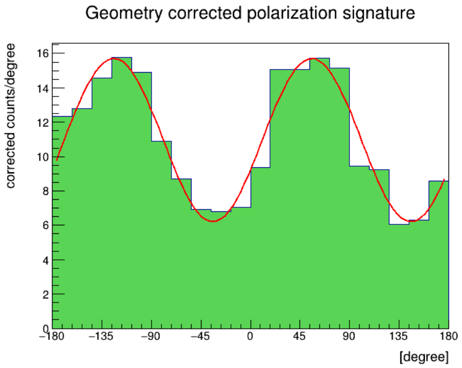
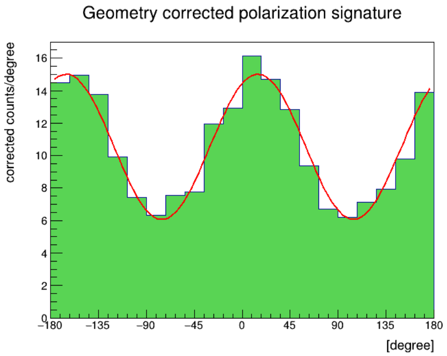
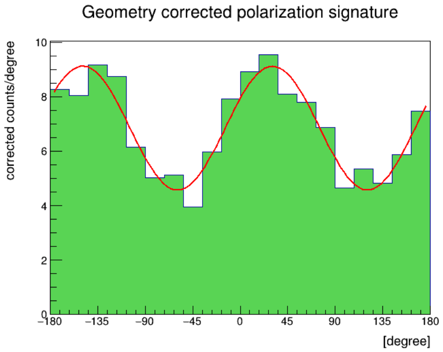
Each instrument sees the source at a position (θ, φ) in the sky and with a certain angle of rotation around the source direction (ψ, analogous to the polarization angle)

These **three** parameters define the satellite orientation

Polarigrams for different satellite orientations







Satellite	1	2	3
orientation (θ, φ, ψ)	(11°, -17°, 126°)	(35°, 51°, 147°)	(96°, 25°, 67°)
μ_{100}	0.433 ± 0.098	0.425 ± 0.100	0.333 ± 0.122
PA [°]	146 ± 6	105 ± 6	121 ± 10

Both the polarization angle and the maximum modulation factor μ_{100} vary from one satellite orientation to another.

The satellite orientation transformation

$$\vec{P} \propto \vec{z}_\gamma \times \vec{u}_y = \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix} \times \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} -\cos\theta \\ 0 \\ \sin\theta\cos\phi \end{pmatrix}$$

Reference polarization direction (from which is defined the polarization angle PA in MEGAlib)

$$\vec{P}_m \propto \vec{P} \times \underbrace{\begin{pmatrix} \cos-\phi & -\sin-\phi & 0 \\ \sin-\phi & \cos-\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{RelativeZ}(-\phi)} \times \underbrace{\begin{pmatrix} \cos-\theta & 0 & \sin-\theta \\ 0 & 1 & 0 \\ -\sin-\theta & 0 & \cos-\theta \end{pmatrix}}_{\mathrm{RelativeY}(-\theta)} = \begin{pmatrix} -\cos\phi \\ \cos\theta\sin\phi \\ 0 \end{pmatrix}$$

Measured reference polarization direction

Standard polarization analysis algorithm (MEGAlib)

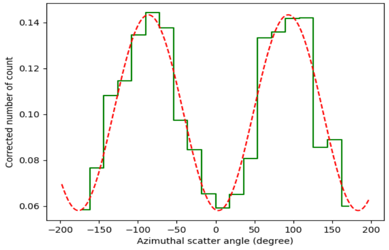
$$\Rightarrow \tan(PA_m - \psi) = -\tan\phi\cos\theta$$

The measured polarization angle can be expressed analytically from the three satellite orientation parameters

Addition of polarigrams

Orientation correction must be done for each gamma ray. For that purpose, we re-implemented MEGAlib's polarization analysis algorithm in python.

1



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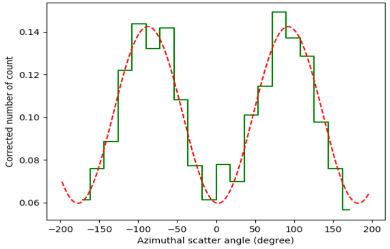

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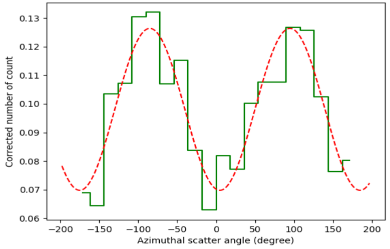
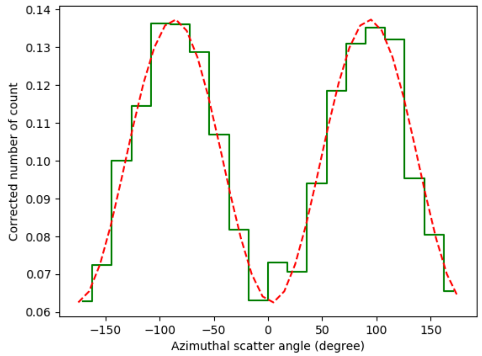


sum each bin



$\mu_{100} = 0.375 \pm 0.014$; PA = $3.5 \pm 1.1°$

The number of photons used is the sum of that of the summed distributions

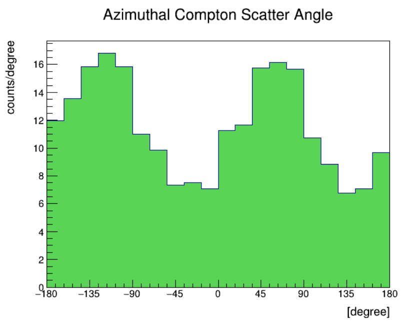
The modulation factor is the weighted mean of the modulation factors of the distributions summed

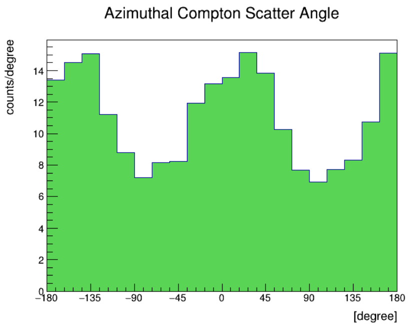
Conclusions

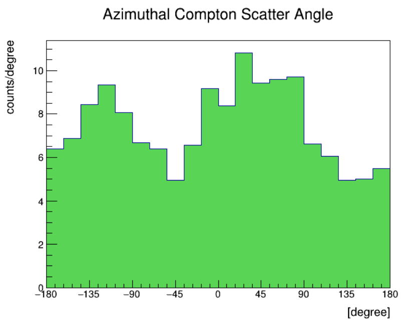
- Detectors have been developed with performances that match our needs
- Several COMCUBE mass models have been investigated, and a 4U instrument appear to show sufficient performances
- A constellation of such instruments will provide precise localization of bursts and increase the sensitivity to polarization

Backup: Raw azimuthal angle distributions

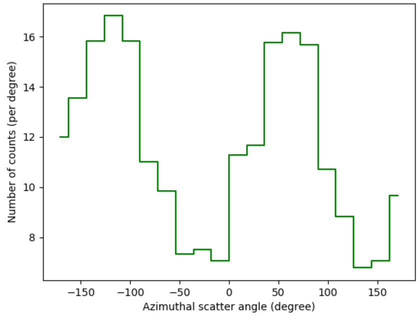
MEGAlib

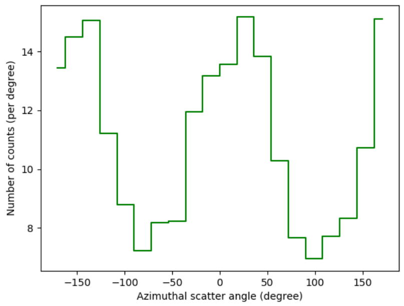


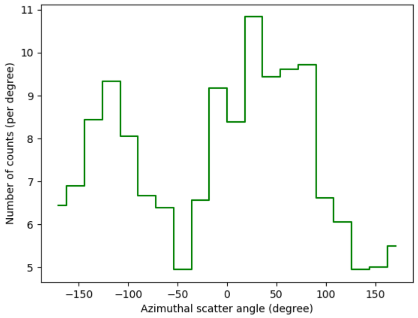




python





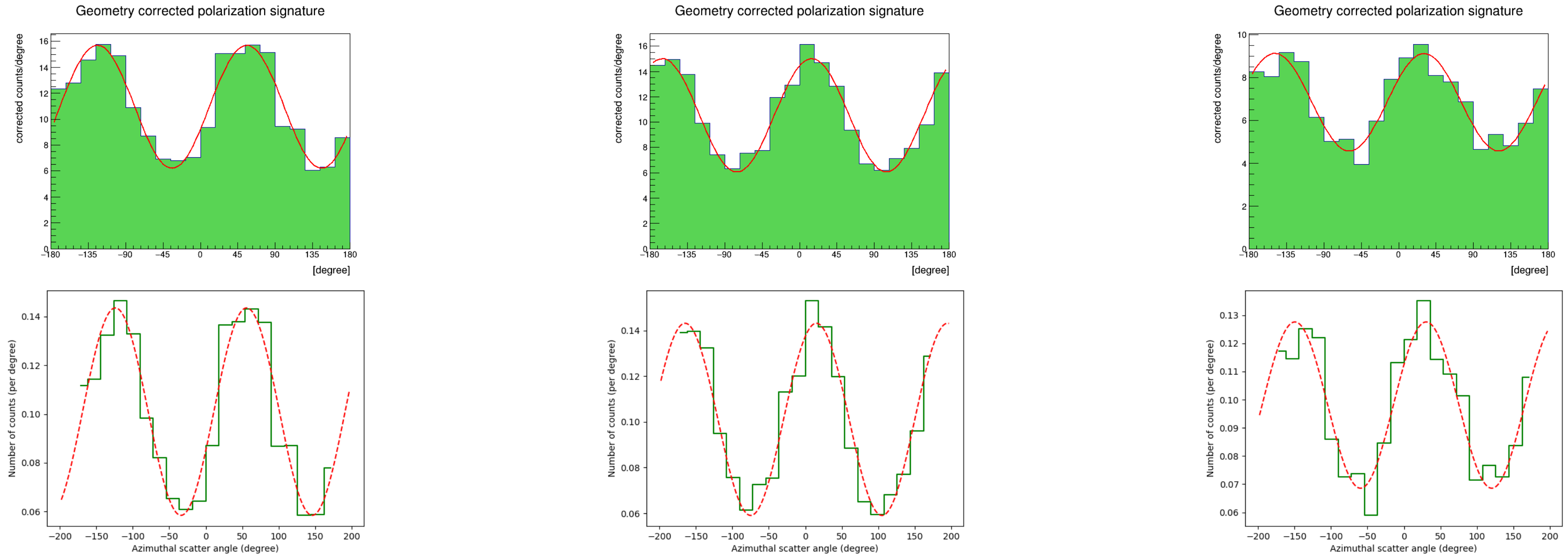


1	2	3

Backup: Geometry-corrected azimuthal angles distributions

MEGAlib

python



Fit parameter	1	2	3
μ_{100} (MEGAlib)	0.433 ± 0.098	0.425 ± 0.100	0.333 ± 0.122
PA (°, MEGAlib)	146 ± 6	105 ± 6	121 ± 10
μ_{100} (python)	0.422 ± 0.029	0.416 ± 0.022	0.301 ± 0.025
PA (°, python)	146.1 ± 1.9	105.2 ± 1.4	120.5 ± 2.4