COMCUBE: A CONSTELLATION OF CUBESATS TO MEASURE THE GRB PROMPT EMISSION POLARIZATION

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Abstract.
The precise mechanism for the prompt emission of gamma-ray bursts (GRBs) is still largely debated. Polarization measurements of the prompt gamma-ray emission could help model this phenomenon, and lead to a broader understanding of GRBs and astrophysical relativistic jets. COMCUBE is a project of the European programme AHEAD2020 aiming at the development of a Compton polarimeter CubeSat mission to measure the polarization of bright GRBs. The launch of a constellation of 6U CubeSats will allow the detection of several hundred GRBs per year and make possible a full-time monitoring of the gamma-ray sky for time-domain and multi-messenger astronomy. In addition, COMCUBE will accurately measure the polarization of the prompt emission of several GRBs per year. An extensive simulation work has been conducted to design the scientific payload, and is ongoing to quantify the sensitivity of the mission to GRBs and GRB polarization. Simultaneously, a reduced prototype of the Compton polarimeter is being developed. It uses double-sided silicon stripped detectors and inorganic scintillators read by SiPMs, and it should be tested during a stratospheric balloon flight in 2023.

Keywords: Gamma-ray burst, CubeSat, Polarization, gamma-ray astronomy

1 Introduction

In 1963, the USA, the USSR and Great Britain signed the Nuclear Test Ban Treaty, that forbids testing nuclear weapons underwater, in the atmosphere and in space. To make sure that USSR complied, the Vela space program was launched by NASA. It was composed of several pairs of satellites with embedded X- and gamma-rays detectors observing in the energy range from keV to a few MeV. In 1967, Vela 4 detected a very intense emission of gamma-rays, which was not located around the Earth nor the Sun, and showed an unexpected variability. It was the first observation of a gamma-ray burst (Klebesadel et al. 1973).

This phenomenon has been extensively studied in the next decades, and still is today. In the 1990's, the BATSE experiment onboard the CGRO spacecraft observed thousands of GRBs listed in Paciesas et al. (1999). It revealed that their location on the sky was isotropic and their duration distribution is bimodal, with a clear separation around two seconds. Longer GRBs are typically associated to powerful supernovae, and short GRBs to magnetar giant flares and binary neutron star mergers, which has been confirmed by Abbott et al. (2017) coincident observation of a short GRB and a gravitationnal wave event. In both cases, the gravitationnal collapse of an object or a system generates an accretion disk and an ultra-relativistic jet. This jet then interacts in the interstellar medium, which generates an afterglow emission, detectable from radio to TeV energies. The

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acceleration of particles in the jet is the source of the gamma-ray emission. The content of that jet and the physics driving the emission is still largely debated. Polarization measurements to probe GRB prompt emissions will rule out some models (Toma et al. 2009). It gives a better understanding of the jet mechanism, that points to the physics of the progenitor. In addition, it provides a direct measurement of the Lorentz invariance violation associated to vacuum birefringence (Laurent et al. 2011).

2 COMCUBE mission design

COMCUBE is a CubeSat constellation mission to measure the polarization of bright GRBs. A Compton telescope is embedded in each CubeSat, its role is to reconstruct the energy and direction of an incoming gamma ray by reconstructing a Compton interaction. By measuring, for each gamma ray, the position and energy deposit in both the tracker and the calorimeter, we can constrain the direction of the incoming gamma-ray to an event circle. If enough interactions are correctly reconstructed, the source is where all event circles intersect (see figure 1 left panel).

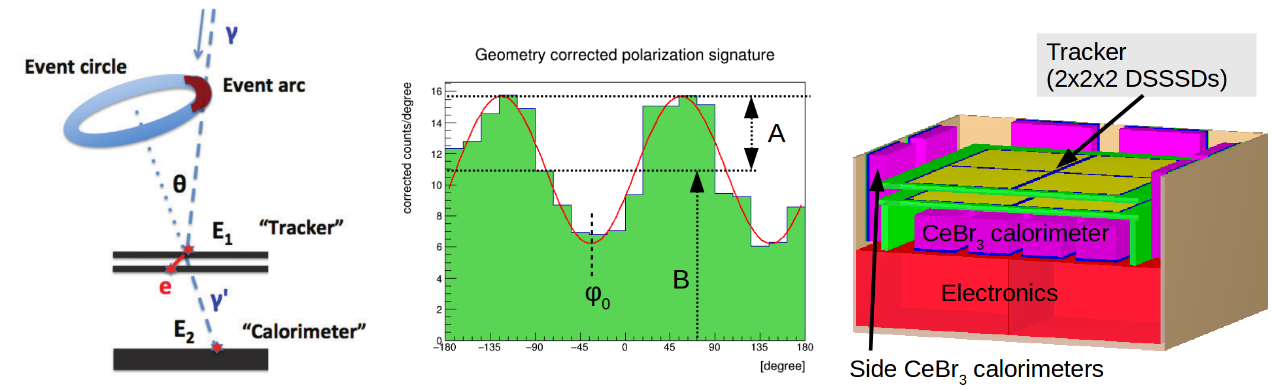

Fig. 1. Left: Scheme of a Compton telescope. **Middle:** Polarization signature (cosine squared modulation) in a Compton telescope (from simulations). The angle of polarization is ϕ_0 and the fraction of polarization is $\frac{A/B}{\mu_{100}}$, where μ_{100} is the amplitude of the modulation of a 100% polarized source. **Right:** 4U scientific payload of COMCUBE (6U).

This instrument is also sensitive to linear polarization through the azimuthal scatter angle of the Compton scattering, as shown in the 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 ϕ_0 is given by a minimum of the fitted cosine squared modulation, also called polarigram, represented in figure 1 middle panel. The polarization fraction is given by $\Pi = \frac{\mu}{\mu_{100}}$ with the amplitude $\mu = \frac{A}{B}$ (see A and B on figure 1 middle panel), and $\mu_{100}(< 1)$ the modulation of a 100% polarized source seen by the instrument.

To achieve our scientific goal, we designed the scientific payload from extensive numerical simulations using the MEGAlib software (Zoglauer et al. (2006)). It will be composed of two layers of four double-sided silicon stripped detectors (DSSSDs) for the tracker, and several calorimeter modules based on cerium bromide ($CeBr_3$ inorganic scintillator), integrated in a CubeSat. CubeSat units (U), defined as $10 \times 10 \times 10\,\mathrm{cm}^3$ in volume and 1.3 kg in mass, can be combined to form larger (2U, 3U, 6U) spacecrafts. COMCUBE instrument is $20 \times 20 \times 10\,\mathrm{cm}^3$ in size (4U) and will be embedded in a 6U spacecraft. Compared to the Compton telescope scheme (figure 1 left panel), we added calorimeters on all four sides to increase the sensitivity to polarization (see figure 1 right panel). A constellation of CubeSats, each containing its own Compton telescope, would allow all-sky monitoring, as well as time-of-arrival localization of transient with sub-degree accuracy for the brightest events, (see e.g. Werner et al. (2018) for the CAMELOT project).

3 COMCUBE performance simulations : preliminary results

Simulations are currently ongoing to better quantify the performances of our instrument. For a single 4U instrument, we simulated (so far) three long GRBs (1000 times each) from the 10 year catalog of GBM (Poolakkil et al. 2021), the secondary payload of the Fermi spacecraft. The background is assumed to be that of an equatorial low-Earth orbit at 550 km altitude. The considered GRB's peak fluxes are represented on the left of figure 2, over the peak flux distribution of the whole catalog. The two brightest ones (in red and green on figure 2 left panel) are detected with a signal to noise ratio SNR > 5 every time they are above the Earth horizon (we defined SNR $= \frac{S-B}{\sqrt{B}}$) where S is the signal (number of triggers of the GRB and the background), B is the expected background (number of triggers)). The SNR of the faintest one is represented in colorscale in the figure 2 right panel. This faint GRB is still detected frequently, mainly in the upper part of the sky near the zenith.

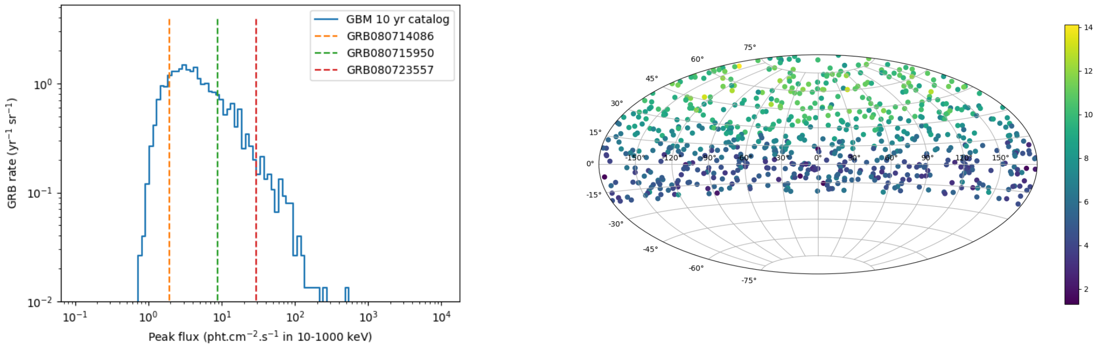

Fig. 2. Left: Histogram of the peak flux of GBM GRBs (blue) and the peak flux of the three GRBs simulated so far (yellow, green, red). **Right:** Map of the sky for the 1000 simulated GRBs of spectrum and peak flux that of GRB080714086. Each point represents a simulation, and its color the signal to noise ratio (see colorscale). The lower part of the sky has no point because it is located below the Earth horizon.

For polarization simulations, preliminary results are shown in figure 3 left and right panels. By using the BATSE or GBM catalog and 7 altitude sky bins of equal solid angle, we show on left panel that we expect to detect, on average, one GRB per year with a minimum detectable polarization at the 99% confidence level MDP_{99} ($MDP_{99} = \frac{4.29}{\mu_{100} S}\sqrt{(S+B)}$, see e.g Weisskopf et al. (2010)). We obtain similar results from the BATSE and GBM catalogs. The simulated background from cosmic and atmospheric gamma rays is calculated with the MEGAlib background generator using 5 GV cutoff rigidity. We show on the left panel of figure 3 that it has a significant effect on GRB polarization measurements.

If we observe a same GRB with several instruments (figure 3 right panel), the data can be combined to perform a more precise polarization analysis. Thus, if we suppose that we have 4 CubeSats in low-Earth orbit, with a 20% downtime, we expect to measure 5 GRBs per year with a $MDP_{99} < 30\%$.

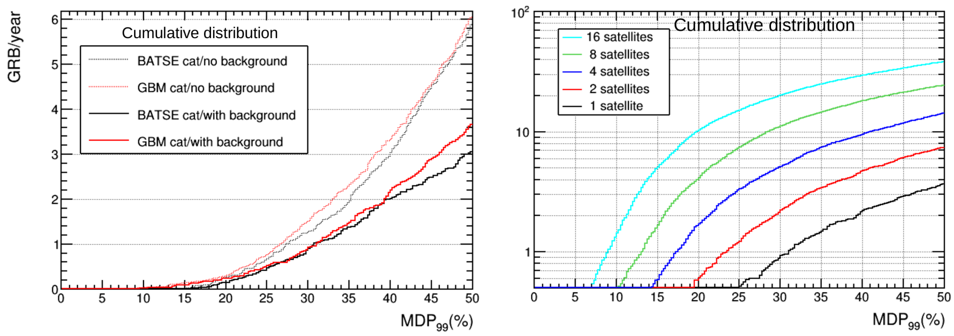

Fig. 3. Left: Number of GRB detected for one year in orbit as a function of the minimum detectable polarization achievable for the observation. **Right:** Number of GRBs observed in a year as a function of the minimum detectable polarization achievable for various numbers of CubeSats in orbit.

4 Compton telescope prototype status

A first prototype of the COMCUBE Compton telescope is being developed. Two kinds of detectors are studied. For the tracker, we developed double-sided silicon stripped detectors (DSSSD) and a low-noise readout electronics. These detectors are a single PN junction detector, of size 64 x 64 x 1.5 mm^3 with 32 strips on each side. For the calorimeter, we developed modules based on a single monolithic inorganic scintillating crystal of cerium bromide ($CeBr_3$), optically coupled to a pixelated photo-sensor. Since the scintillation light is emitted near the interaction position, the pixels closer to that position will receive more light. The position of interaction can then be reconstructed using machine learning algorithms. For more details, see Laviron et al. (2021). With these two building blocks, we assembled a first working prototype, shown on the picture figure 4 left panel.

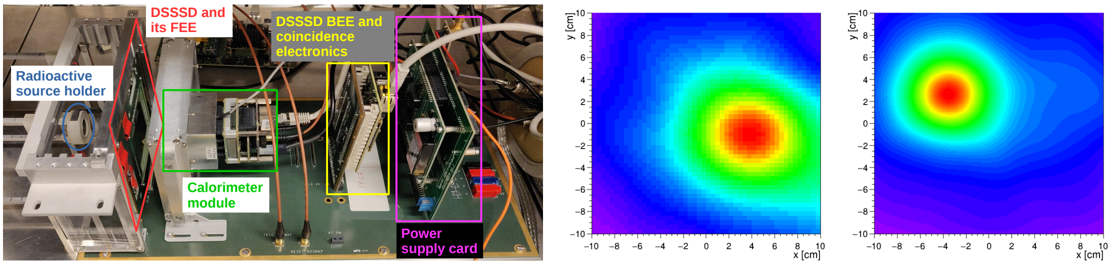

Fig. 4. Left: Picture of the first prototype with its main components. FEE and BEE stand respectively for Front-End Electronics (analog signal processing and digitization) and Back-End Electronics (data merging and communication with onboard computer) **Right:** Reconstructed images for two positions of the ^{137}Cs source. Source positions were $x, y = (36, -11)$ mm and $x, y = (-36, 23)$ mm.

One can see on figure 4 right panel, two Compton images obtained during preliminary tests with a ^{137}Cs radioactive source emitting 662 keV gamma rays. The source position was changed between the two acquisitions. We can see that it is well reconstructed. The energy resolution was 5.7 % at 662 keV.

5 Conclusions

COMCUBE is a constellation of CubeSats that will be able to measure the polarization of several GRB prompt emission per year. Simulations have been performed to design the instrument, and more simulations are ongoing to better quantify its performances. For one CubeSat, the chosen design is a 4U Compton telescope in a 6U spacecraft. The telescope is based on two layers of DSSSD detectors for the tracker and on $CeBr_3$ scintillating crystals coupled to SiPM arrays for the calorimeter. We have already built a minimal prototype and tested its imaging capabilities with success. We are building a 1U demonstrator for a stratospheric balloon flight in summer 2023 and we plan to further test the prototype with polarized gamma ray sources in the near future.

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