PROCEEDINGS OF SCIENCE

Gamma Ray Burst localization with GECCO's BGO anti-coincidence shields

Alessandro Armando Vigliano,[a,b] **Francesco Longo,**[b,c] **Israel Martinez-Castellanos,**[d,e,f] **Eric Alan Yates,**[d] **Alexander Moiseev**[d,e,f] **and Andreas Zoglauer**[g]

[a] *Department of Mathematical, Computer and Physical Sciences, University of Udine, Udine, Italy*
[b] *Istituto Nazionale di Fisica Nucleare (INFN), sezione di Trieste, Trieste, Italy*
[c] *Department of Physics, University of Trieste, Trieste, Italy*
[d] *Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA*
[e] *NASA Goddard Space Flight Center, Greenbelt, MD 20771*
[f] *Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, Maryland 20771, USA*
[g] *University of California at Berkeley, Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94703, USA*

E-mail: Alessandro.Armando.Vigliano@ts.infn.it

Abstract: Accurate localization of transient sources, which carries critical information about their nature, especially given recent discoveries of the GW and high-energy neutrino events, falls within the potential capabilities of gamma-ray telescopes. Presently, the ability for accurate localization in the MeV photon energy range is limited by measurements complications. The Galactic Explorer with a Coded Aperture Mask Compton Telescope ("GECCO") will provide such capabilities thanks to the innovative use of a deployable coded aperture mask in combination with a Compton telescope mode. The spatial arrangement of GECCO's thick and efficient BGO anticoincidence panels can be used to quickly estimate the localization of transient events, allowing a prompt slew of the telescope. GECCO has 8 heavy-scintillator shield panels, arranged on the instrument sides. The ratios between the counts recorded by the panels depends on the direction of the signal with respect to the telescope axis. Simulations were conducted to assess the localization capabilities of the BGO shields, simulating the detection of Gamma Ray Burst signals from the Fermi-GBM catalog with various spectral shapes and time profiles, in order to assess the evolution of their localization error radius with time. The results show how the GECCO shields can achieve localization radii of a few degrees in a short time.

PoS(ICRC2023)748

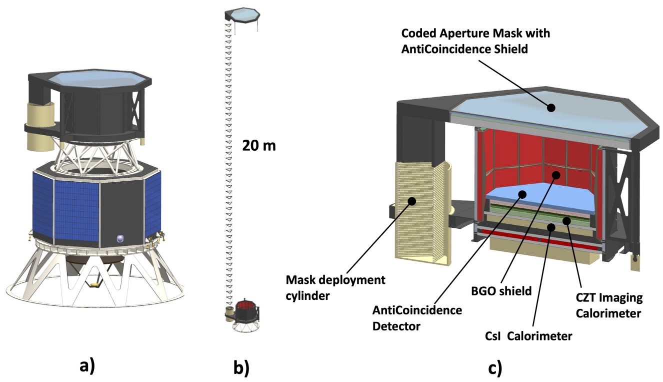

Figure 1: GECCO design concept: a) with mask in stowed position and notional spacecraft bus; b) with mask in deployed position; c) cutaway. [1]

1. Introduction

Undoubtedly, the energy range of MeV gamma-rays is among the most uncharted territories in observational astronomy, which holds significant implications for understanding high-energy astrophysical phenomena. Yet, the ability to observe transient events with really high angular and energy resolutions in this energy range is currently lacking in today's astrophysics. These capabilities are fundamental for understanding the mechanism of emission of these signals, their geometry and the nature of their progenitors.

Using a novel combination of a deployable coded aperture mask with a Compton telescope, the Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO) [1][2] has the potential to revolutionize high energy sky observations. As a cutting-edge concept for a next-generation γ-ray telescope, GECCO is currently being evaluated for possible inclusion in a future NASA Explorer mission and will perform high sensitivity measurements of cosmic γ radiation, creating intensity maps with elevated spectral and spatial resolution in the poorly explored energy range from 50 keV to $\sim$ 10 MeV. The combination of coded mask imaging and a Compton telescope will enable GECCO to carry out high sensitivity measurements with a superb angular resolution of the γ-ray sky.

In addition to a high slewing rate, obtaining the precise location of sources is key for the effective observation of transient sources with a coded mask. This is particularly critical for GECCO, which boasts exceptional angular resolution in aiming mode at the expense of a limited field of view. However, GECCO's heavy scintillator shield and plastic scintillator anti-coincidence detectors (BGO shields) offer a compelling solution to this challenge. The spatial arrangement of the shields enables swift estimation of the localization of a transient event relative to the instrument. This facilitates a prompt slew of the telescope and subsequent camera observation of the event. In this paper we investigated this scenario simulating the localization measurement of transient (GRB) signals using GECCO's BGO anti-coincidence shields.

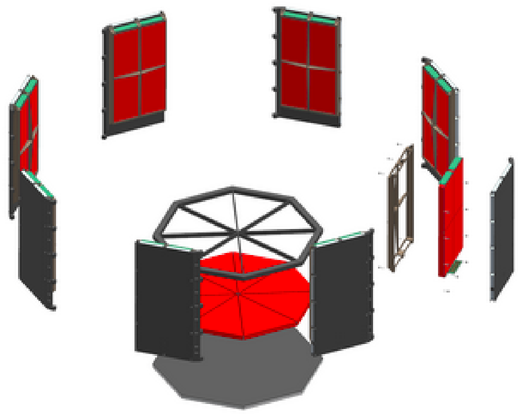

Figure 2: Use of 8+1 GECCO's heavy-scintillator, 4 cm-thick shield panels, 2800 cm^2 area each, as a sensitive GRB locator (BurstOctagon).

2. Transient Sources Localization

For effective observation of transient sources it is necessary, in addition to the high slewing rate, to promptly obtain the precise location of the sources to be targeted with the coded mask. This step is difficult because, in aiming mode, GECCO will have an exceptional angular resolution, at the cost of a very small field of view. It would therefore very difficult to identify transient signals using only the Compton detector.

To overcome this problem, we explored the potential of using GECCO's anti-coincidence scintillator shields to obtain the localization of transient signals, in particular of GRBs. GECCO is provided with 8 heavy-scintillator, 4cm-thick shields panels (BGO shields), arranged on the 8 sides of an octagon and below the Compton instrument (BurstOctagon, fig.2). As the signal from a source (GRB) reaches the instrument as a parallel wavefront, it illuminates the panels differently depending on the angle of impact. The ratios between the counts recorded by the various panels return an estimate of the direction of the signal with respect to the telescope.

To evaluate the localization sensibility of the BGO shields, as well as characterizing their behaviour, a series of Montecarlo simulations were conducted, using the MEGAlib software [3], to simulate the interaction between transient signals and a model of the instrument. To reproduce the worst visibility conditions for the use of BGO panels as detectors, the model of the instrument was set with the coded mask bestowed right on top of the octagon of the shields. The whole instrumentation has been included in the model as passive material, thus ensuring that the measurement are carried out just by the BGO panels.

In order to accurately simulate realistic GRB signals we used the data reported in the Fermi GBM catalog [4] for such signals. All 2309 signals, divided into 1875 long GRBs and 433 short GRBs, were used for two types of simulations. The first type of simulations are *catalog simulations*, where we simulated simultaneously all the signals reported in the Fermi GBM catalog in order to have a high statistics. This kind of simulations have been limited by the IT resources at our disposal and therefore we were able to exclusively simulate signals without temporal evolution, using the spectral and light curve parameters averaged over the duration of the single bursts. We modeled the

Background estimate		
	AGILE	GECCO
material	Bicron palstic scintillator	BGO scintillator
MIP	$\sim 2.02\, MeV\, cm^{-1}$	$\sim 9\, MeV\, cm^{-1}$
thickness	$\sim 1.8\, cm$	$\sim 4\, cm$
threshold	$\sim 70\, keV$	$\sim 100\, keV$
side dimension	$\sim 2538\, cm^2$	$\sim 2734.2\, cm^2$
bottom dimension		$\sim 7366\, cm^2$
orbit	equatorial	equatorial
observed rate	$\sim 3\, kHz$	
simulated rate side		$\sim 6\, kHz$
simulated rate bottom		$\sim 17.6\, kHz$

Table 1: Background estimation: comparison between GECCO and AGILE values. [5]

spectra of all signals using the Band function.

To characterize the response of the panels to more realistic signals, we simulated the detection of single, time evolving burst signals. Also in this case the spectrum has been modeled with a Band function. The time evolution of the photon flux, the light curve, was modeled with a profile *Fast Rise Exponential Decay*, while the spectral time evolution have been modeled with different profiles.

These two complementary sets of simulations have allowed the characterization of the response of the BGO panels to a wide range of transient signals and the evaluation of possible systematic effects affecting the simulations.

The appropriate celestial background rate to be used have been estimated simulating the measurement of a diffuse source over the entire sky with cosmic and albedo photon fluxes of $1\,\gamma\, cm^{-2} s^{-1}$ and a duration of $1\, s$. We compared the obtained values (approximately $1.7\, kHz$ on the side panels and $5.2\, kHz$ on the bottom panel) with the ones observed by AGILE [5]. The results are shown in table 1. As can be seen in the table, although the two missions use different materials for the anti-coincidence panels (Bicron plastic for AGILE and BGO for GECCO), taking into consideration the dimensions and thickness of the panels and the orbits, the two missions are rather comparable. It was therefore decided to scale the values in order to have at least the same background rates on the side panels as the one observed by AGILE; and then add a multiplicative factor of 2 in order to fully consider the worst case scenario. This way we obtained the background values of $6\, kHz$ on the side panels and $17.6\, kHz$ on the bottom panel that were utilized throughout this work.

3. Results

To fully asses the possibility to use GECCO's BGO panels to localize transient signals (GRBs) in an adequate time span to re-point towards the detected transient event and localize it with the full power of the Coded Mask (sub-arcmin accuracy), several analysis were made. In particular the localization of GRB signals were simulated for various spectral and flux shapes and parameters, reproducing the signals reported in the Fermi-GBM burst catalog.

3.1 Single time evolving bursts

The detection of single bursts were simulated many times, to characterize the temporal response of the BGO panels. Several models for the sources (GRB) were used with different spectral and light curve time profiles, implementing spectra modeled according to the Band function as well as a more simplified broken power law. To reproduce the temporal variations of the photon flux, the light curve, a *FRED* (Fast Rise Exponential Decay) profile were used, as proposed in [6]

$$I(t) = \begin{cases} A\exp\{-(|t-t_{max}|/\sigma_r)^\nu\} & t \le t_{max} \\ A\exp\{-(|t-t_{max}|/\sigma_d)^\nu\} & t > t_{max} \end{cases}, \tag{1}$$

where t_{max} is the time of the pulse's maximum intensity; A is the peak value; σ_r and σ_d are the rise $(t \le t_{max})$ and decay $(t > t_{max})$ time constant respectively; and ν is the "peakedness", a measure of the pulses sharpness.

The temporal evolution of the spectrum have been modelled following the results in [7], where they used both a FRED profile and a decreasing power law profile for the temporal variation of the spectrum break energy. Assuming $\sigma_d/\sigma_r = 2.5$, as suggested by a population study in [6], it has been possible to equate the integrated values of the flux and break energy profiles over the duration of the single pulses to the mean values that can be found in the Fermi-GBM catalog [**?**]. This way the performances in the localization of these signals obtained by GBM could be compared with those simulated for the GECCO panels. The results can be seen in fig.3.

A fixed, casual, direction of arrival was kept for all the signals to help compare the results for different bursts. As expected, the size of the equivalent error radius decreases over time in all models, with the different evolution for the spectrum break energy weakly influencing the performance of the measurement.

The simulations showed how, in some impressive cases, the areas of uncertainty obtained with BGO panels could be even lower than those obtained with Fermi GBM. This impressive result finds a natural explanation in the different dimensions of the effective areas of the two instruments: indeed for energy values around 200 keV (average peak energy of the Fermi catalog signals) GBM has an effective area $\sim 120\,cm^2$ [8]. However, in the same energy range, GECCO's BGO panels have an effective area more than an order of magnitude higher, with a value of $\sim 8470.127\,cm^2$.

The results were then compared with the GBM systematic uncertainties [9] as we can conservatively expect similar values for GECCO's BGO shields. The median value for GBM's systematics, $\sim 2°$, can be seen in fig.3 as a red line. This value limits the localization precision that can be achieved by the BGO panels, setting a sort of lower boundary.

These simulations showed how even very different transient signals can be localized by the BGO panels in a short period of time, comparable with the time elapsed from the trigger to the emission peak, with accuracies mainly limited by the systematics ($\sim 2°$).

3.2 Catalog simulations

In this case, in order to get a high statistics through the parallel simulation of many sources, simpler signals were simulated, with fixed average properties for the duration of the single bursts

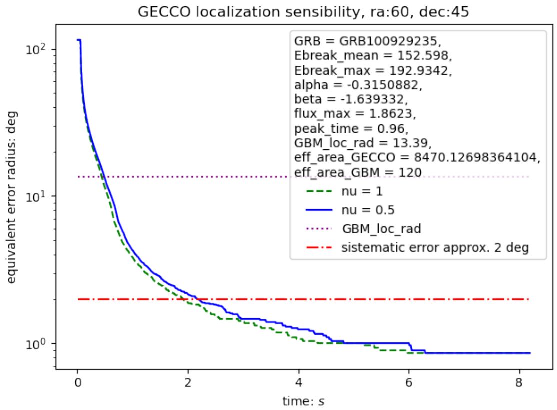

Figure 3: Equivalent localization error radius for GRB100929235 as reported in the Fermi GBM catalog, simulated with two different values of ν, the exponent of the FRED profile of the lightcurve. The time evolution of the break energy follows a decreasing powerlaw. The signal arrives at the spacecraft with an azimuth angle of 60° and a zenith angle of 45°. In purple is reported localization error radius reported in the GBM catalog. In red is shown the systematic uncertainty given by the reconstruction process. BGO panels achieve lower localization than GBM by about 1 order of magnitude in less than $2s$. This difference is due to the different dimensions of the effective area of the two instruments.

(no temporal evolution). This way it was possible to simulate all 2309 signals, divided between 433 short GRBs and 1875 long GRBs, reported in the Fermi GBM catalogue [4]. Each signal was simulated with a random direction of arrival relative to the spacecraft.

In order to cross check the algorithm of reconstruction of the 90% confidence localization error region, each signal was simulated further 9 times, Poisson fluctuating the flux each time (i.e. inject random integer counts, not the average expected counts). This way possible to ascertain that $\sim$ 91.6% of the time the injected GRB location is contained within the 90% containment for each random sample or at least inside the error area defined by the systematic uncertainty ($\sim 2°$), thus verifying the correctness of the reconstruction algorithm.

With this big set of data we could some more analysis such as the number of GRBs localized within a certain error area (fig.4) and the distribution of the localization error area as a function of the duration of the burst (t90, fig.5), obtaining some impressive results: 99.4% of the signals are localized with $A_{loc} \leq 12.6\, deg^2$ (the minimum localization area achievable given the systematics) and of these, 2419 ($\sim$ 20.4%) in less than 10 seconds, less than the mean value of the peak emission time of the signals of the catalog ($\sim 12.7\, s$). These preliminary results are extremely encouraging about the possibility of achieving localization precise enough to be pointed with the coded mask, in time to catch at least the tail of the emission for many of these signals.

4. Conclusions

GECCO have the potential to significantly advance our understanding of the MeV sky and transient astrophysical phenomena. The combination of a Deployable Coded Aperture Mask with a Compton telescope will allow the observation of the MeV sky with exceptional angular and energy

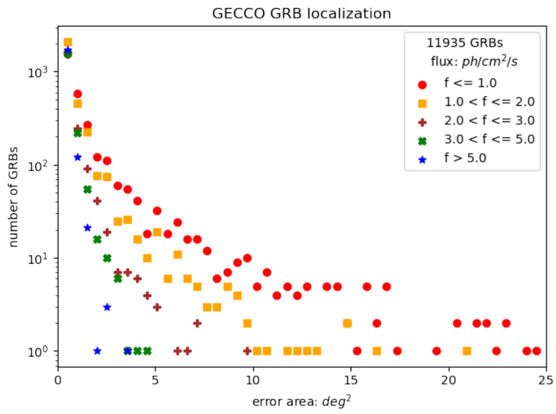

Figure 4: Number of GRBs vs localization error area.

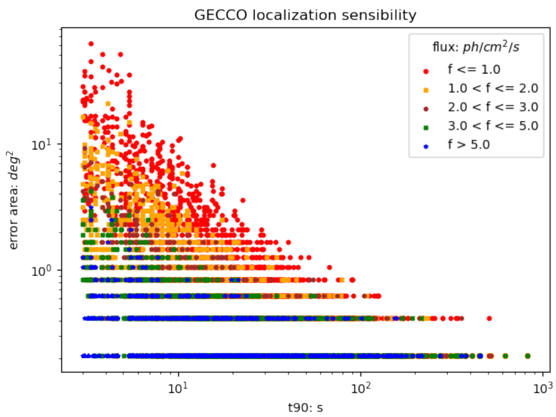

Figure 5: Localization error area vs duration of the burst.

resolutions. Due to the narrow field of view in aiming mode, however, a precise pointing strategy is crucial for effectively capturing transient signals.

GECCO's octagon of BGO anticoincidence shields can be leveraged to promptly detect and localize certain transient signals, enabling timely repointing of the main camera for further observation and analysis: catalog simulations have demonstrated that GECCO's BGO shields exhibit remarkable sensitivity to transient signals originating from all directions in the sky, while single burst simulations have shown how the BGO shields are capable of achieving high precision localization of these signals in very short time intervals.

By combining the unique capabilities of deployable coded aperture masks, Compton telescopes, and precise pointing strategies, GECCO will be a valuable instrument for future astrophysics observations, offering unprecedented opportunities for studying and unraveling the mysteries of the high-energy universe.

References

[1] E. Orlando, E. Bottacini, A. Moiseev, A. Bodaghee, W. Collmar, T. Ensslin et al., *Exploring the mev sky with a combined coded mask and compton telescope: The galactic explorer with a coded aperture mask compton telescope (gecco)*, *JCAP* **2022** (2021) 036.

[2] A. Moiseev, *Pos(icrc2021)648 new mission concept: Galactic explorer with a coded aperture mask compton telescope (gecco)*, .

[3] A. Zoglauer, R. Andritschke and F. Schopper, *Megalib – the medium energy gamma-ray astronomy library*, *New Astronomy Reviews* **50** (2006) 629.

[4] A. von Kienlin, C.A. Meegan, W.S. Paciesas, P.N. Bhat, E. Bissaldi, M.S. Briggs et al., *The fourth fermi-gbm gamma-ray burst catalog: A decade of data*, *The Astrophysical Journal* **893** (2020) 46.

[5] F. Perotti, M. Fiorini, S. Incorvaia, E. Mattaini and E. Sant'Ambrogio, *The agile anticoincidence detector*, *Nuclear Instruments and Methods in Physics Research Section A, Volume 556, Issue 1, p. 228-236.* **556** (2006) 228.

[6] J.P. Norris, R.J. Nemiroff, J.T. Bonnell, J.D. Scargle, C. Kouveliotou, W.S. Paciesas et al., *Attributes of pulses in long bright gamma-ray bursts*, *ApJ* **459** (1996) 393.

[7] H.X. Gao, J.J. Geng and Y.F. Huang, *Evolution patterns of the peak energy in the grb prompt emission*, *Astronomy and Astrophysics* **656** (2021) A134.

[8] C. Meegan, G. Lichti, P.N. Bhat, E. Bissaldi, M.S. Briggs, V. Connaughton et al., *The fermi gamma-ray burst monitor*, *Astrophysical Journal* **702** (2009) 791.

[9] A. Goldstein, C. Fletcher, P. Veres, M.S. Briggs, W.H. Cleveland, M.H. Gibby et al., *Evaluation of Automated Fermi GBM Localizations of Gamma-Ray Bursts*, ApJ **895** (2020) 40 [1909.03006].

PoS(ICRC2023)748