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The High-Speed and Wide-Field TORTORA Camera: description & results

G. Greco[1], G. Beskin[2], S. Karpov[2], A. Guarnieri[1], C. Bartolini[1], S. Bondar[3], A. Piccioni[1], and E. Molinari[4]

[1] Astronomy Department of Bologna University, Bologna, Italy
e-mail: giuseppe.greco8@unibo.it
[2] Special Astrophysical Observatory of Russian Academy of Science, Russia
[3] Institute for Precise Instrumentation, Nizhnij Arkhyz, Russia
[4] INAF-TNG, Canary Islands, Spain

Abstract. We present the description and the most significant results of the wide-field and ultra-fast TORTORA camera devoted to the investigation of rapid changes in light intensity in a phenomenon occurring within an extremely short period of time and randomly distributed over the sky. In particular, the ground-based TORTORA observations synchronized with the γ-ray BAT telescope on board of the Swift satellite has permitted to trace the optical burst time-structure of the Naked-Eye GRB 080319B with an unprecedented level of accuracy.

Key words. Gamma rays: bursts Telescopes Techniques: photometry

1. Introduction

Gamma-ray Bursts (GRBs) are the most instantaneously powerful explosions in the Universe and are identified as brief, intense and completely unpredictable flashes of high energy γ-rays on the sky. The discovery and the detection of few hundred afterglows in the last past decade has revolutionized the field of gamma-ray burst research, although many open questions remain to be solved. A detailed knowledge of the source behavior of the gamma-ray bursts in optical band ***before and during*** the γ–ray emission is necessary to understand the nature of these phenomena. The dynamics of the GRBs and the processes transforming their energy into γ-ray radiation are inevitably reflected within the temporal properties of the bursts (Piran (2004) and references therein). The statistical analysis of large amount of data collected by the Gamma ray bursts Coordinates Network[1] (GCN) shows that the first available observations of the optical counterpart of a GRB (with the exception of rare cases) are affected by an instrumental and systematic delay and are usually not well sampled (sampling time ~5 s-10 s)

The technology involved in TORTORA camera allows us to observe large regions of sky with high temporal resolution.

Presently, TORTORA (Telescopio Ottimizzato per la Ricerca dei Transienti Ottici RApidi) is mounted on top of the REM robotic telescope at La-Silla Observatory in

[1] http://gcn.gsfc.nasa.gov/

Chile and has been operating since May 2006 (Molinari et al. 2006).

2. Tortora Project: Sub-Second Universe Analysis

2.1. Historical Background

During the last thirty years, we developed various research strategies in order to measure with great level of accuracy the optical emission contemporaneous with a GRB.

From early 1989 to the end of 1996, we designed and built the FIP (Fast Imaging Photometer) instrument: a fast multichannel photometer for continuous optical monitoring of gamma-ray burst error boxes. The photometer consists of a dichroic beam splitter that divides the beam in three ways, approximating the UBV passbands, and a fiber optic array mounted on the B beam; each fiber is connected to a photomultiplier linked to a measurement channel able to carry out, independently, a real time pre-analysis (Piccioni et al. 1989; 1996).

In 1998, we have discussed the project of a wide field optical telescope equipped with panoramic detectors in order to catch an optical transient simultaneously with a GRB. This telescope scans the γ-ray telescope field of view, and with 1-m mirror for 1 s of integration time would detect optical transients up to 16 mag; the probability of covering the GRB location in a field of 20° is 12%. The detection limit could be raised and the probability of catching optical transients could be over 90% using a system of special telescopes with wide aperture and large collecting area (Beskin et al. 1999).

In 2001 we have proposed to use large low-quality mosaic mirrors of air Čerenkov telescopes which ensure a broad coverage of the sky. The possibility of a contemporaneous observation in the optical band and in the VHE band with the same mirror, by using two different mirror/detector configurations, is presented in Beskin et al. (2001).

In the same year, Piccioni et al. (2001) discussed the use of very large and wide field *non-astronomical* quality mirror surfaces to capture the prompt optical emission of a GRB. In particular, the dependence of detection limits from size, beam aperture, transparency, background level, time exposition and detectors quantum efficiency of the Central Electro-Solar de Almeria (located in Spain) were considered.

From 2004 to the middle of the 2006 we developed the fast wide-field camera TORTORA that is capable of autonomously detecting and classify optical transients up to $10^m - 11^m$ on a sub-second time scale in a $24° \times 32° = 768\ \mathrm{deg}^2$ field of view. TORTORA is the second version of a prototype named FAVOR placed at North Caucasus near the Russian 6-m telescope (Karpov et al. 2004).

2.2. TORTORA Description

The camera consists of a main objective, an image intensifier used to down-scale and amplify the image, a transmission optics and a fast low-noise TV-CCD matrix based on the Sony ICX285AL chip. The main objective and the transmission optics focusing unit are controlled through the PC parallel port interface. The TV-CCD matrix operates at 7.5 frames per second with negligible gaps between consecutive exposures (Table 1).

The resulting data flow rate is about 20 MB/s. The raw data are stored on a RAID array until the next observational night and are processed in real-time by a dedicated software for detection and classification of optical transient events. The real-time data processing pipeline is based on a fast *differential imaging* algorithm described in Karpov et al. (2009). More detailed time series analysis may be performed *a posteriori* studying the images stored on the RAID array (Greco et al. 2009a).

2.3. Observations in Alert Response Mode

The TORTORA camera runs the observations in 3 automated modes of operation: the `survey mode` (scheduled programs of the REM telescope), the `alert mode` (reception of the alerts by GCN network) and `follow-up mode` (it tracks the BAT/Swift telescope). The

Table 1. Main parameters of the TORTORA Camera.

Main objective		Intensifier		CCD	
Diameter	120 mm	Photocathode	S20	Dimensions	1388 × 1036 pix
Focal Length	150 mm	Diameter	90 mm	Pixel Scale	81″ / pix
Focal Ratio	1/1.2	Gain	150	Exposures	0.13 s
Field of View	24°×32°	Scaling Factor	5.5	Pixel Size	6.5 micron
		Quantum Efficiency	10%	Readout Noise	6 e⁻/pix

Fig. 1. The High-Speed and Wide-Field TORTORA Camera mounted on the top of the 60-cm REM robotic telescope at the European Southern Observatory (ESO) at La-Silla, Chile.

field of the GRB 060719 (Guarnieri et al. 2006), GRB 061202 (Karpov et al. 2006a) and GRB 061218 (Karpov et al. 2006b) were observed in alert responce mode. Fourier analysis were performed to search for upper limit for periodic signal at the GRB position. The upper limits for the amplitude of sinusoidal variability (i.e. the mean brightness of the sinusoidally-variable object) are reported in Table 2. Flux limits have been derived by co-adding 100 single exposures.

2.4. Prompt Optical Emission Of GRB 080319B

TORTORA imaged the field of the GRB 080319B 26 minutes before the Swift/BAT trigger (hereafter t_0). No optical precursors were detected before the GRB explosion. The first frame in which we detected the optical flux started at t_0 = 9.18 s when the source became brighter than V ≈ 8_m. TORTORA tracked a fast rise of optical emission from t_0 +10 s to t_0 +15 s, followed by a complex evolution until t_0 +45 s and a slow decay thereafter. The rise from V ≈ 7.5^m to V ≈ 5.5^m may be approximated by a ∼ t^4 power-law originated at $t_0 \approx 0$ s; while γ–ray emission started earlier, at $t_0 \approx$ -4 s. The decay since t_0 +45 s is a ∼ $t^{-4.6}$ power-law (Greco et al. 2009b).

Four peaks can clearly be seen in optical data with an inter-peak separation of ∼ 8.5 s. The Power Density Spectrum between 10 s and 50 s confirms this feature with a 99.999% confidence. When we use the high resolution data from t_0+40 s to t_0+50 s a periodicity at a frequency of ∼ 0.9 Hz is detected with a 99% confidence (Beskin et al. 2009).

2.5. Untriggered Search for Prompt Optical Emission

One of the important results of our routine observations in `follow-up mode` is the estimation of the rate of the orphan transients. These are hypothetical objects which may be observed without accompanying γ-ray emission. Such orphans may be produced by collimated gamma-ray bursts viewed outside the initial jet, and studying their statistics will allow constraints to be placed on GRB collimation (Rhoads 2003).

Since May 2006 until June 2009 we accumulated approximately 200 nights of observations up to 10.5 unfiltered magnitude with 0.13 s temporal resolution for each 768 $\deg^2$ field. Thus we can state that our detection rate of prompt optical transients is less then $8 \times 10^{-9} \deg^{-2} \sec^{-1}$ for transients that are brighter

Table 2. Upper limits on the constant flux and sinusoidal variability of gamma-ray bursts observed by TORTORA in alert response mode.

GRB	Time since trigger (seconds)	mag. limit (100 frames)	Variab. timescale (Hz)	Variab. limit
GRB060719	59	12.4	0.01 – 3.5	16.5^{m}
GRB061202	92	11.3	0.1 – 3.5	14.0^{m}
GRB061218	118	11.3	0.01 – 3.5	16.4^{m}

than 10.5^m on 0.13 s timescale during at least 3 successive frames.

3. Conclusion

The complete randomness of the angular distribution of the gamma-ray bursts in the sky, along with their typical short duration, suggested us to monitor large sky regions with high temporal resolution in order to increase the probability to catch optical emissions simultaneous with the γ-ray prompt events. To perform such a task, we have proposed different search strategies (§2.1) and the high-speed and wide-field TORTORA camera represent the more recent and promising development (§2.2).

The field of the GRB 060719, GRB 061202 and GRB 061218 were observed 59 s, 92 s and 118 s after the satellite trigger, respectively. Fourier analysis were performed to search for upper limit for periodic signal at the GRB position (§2.3). In the remarkable case of the GRB 080319B, TORTORA began taking data 26 minutes before the satellite trigger and observed the optical flux coincident with the γ-ray emission with an unprecedented level of accuracy, collecting ~ 13320 images. Long and short time scale variability were detected during the naked-eye prompt emission (§2.4) .

One of the important results of our routine observation is the estimation of the rate of the short-lived orphan transients. Currently the detection rate of orphan optical transients is less than $8 \times 10^{-9}\mathrm{deg}^{-2}\mathrm{sec}^{-1}$ for transients that are brighter than 10.5^m on 0.13 s timescale (§2.5).

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