Gamma-ray bursts, evolution of massive stars and
star formation at high redshifts
ASI Conference Series, 2012, Vol. 5, pp 49 – 57
Edited by S. B. Pandey, V. V. Sokolov and Yu A. Shchekinov

Searching for fast optical transients by means of a wide-field monitoring observations with high temporal resolution

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Abstract. We discuss the strategy of search for fast optical transients accompanying gamma-ray bursts by means of continuous monitoring of wide sky fields with high temporal resolution. We describe the design, performance and results of our cameras, FAVOR and TORTORA. Also we discuss the perspectives of this strategy and possible design of next-generation equipment for wide-field monitoring which will be able to detect optical transients and to study their color and polarization properties with high time resolution.

Keywords : gamma-ray bursts, high time resolution, wide field photometry

1. Introduction

The systematic study of night sky variability on sub-second time scales still remains important, but practically unsolved problem. Its necessity for the search of non-stationary objects with unknown localization has been noted by Bondi (1970). Such studies have been performed (Schaefer 1985, 1987), but due to technical limitations it has only been possible either to reach high temporal resolution of tens of milliseconds in monitoring of $5'$ - $10'$ fields, or use 5 - 10 seconds time resolution in wider fields. The wide-field monitoring systems currently in operation, such as WIDGET (Tamagawa et al. 2005), RAPTOR (Borozdin et al. 2002), BOOTES (Castro-Tirado et al.

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1999) and π of the Sky (Burd et al. 2005), while having good sky coverage and limiting magnitude, lack temporal resolution, which significantly lowers their performance in the study of transient events of sub-second duration.

Optical transients of unknown localization may be very short. For example, the rise times of flashes of some UV Cet-like stars may be as short as 0.2 - 0.5 seconds (Shvartsman et al. 1988), 30% of GRBs have the duration shorter than 2 seconds, and details of their light curves may be seen on time scales shorter than 1 ms (McBreen et al. 2001). Also, observations of very fast meteors which may be of extra-Solar system origin are of great interest (Afanasiev, Kalenichenko & Karachentsev 2007).

One more task which requires wide-field observations with high temporal resolution is the monitoring of near-Earth space. There are a number of satellites, as well as a vast amount of small space debris pieces, which have rapidly evolving trajectories, and so are difficult to observe by typical satellite tracking methods. High temporal resolution is needed here due to the fast motion of such objects on the sky.

To study the variability of large sky areas on such time scales, it has been proposed (Beskin et al. 1999) to use large low-quality mosaic mirrors of air Cerenkov telescopes. However, in (Zolotukhin et al. 2004; Karpov et al. 2005) we demonstrated that it is possible to achieve the sub-second temporal resolution in a reasonably wide field with small telescopes equipped with fast CCDs, to perform fully automatic searching and classification of fast optical transients. Moreover, a two-telescope scheme (Karpov et al. 2004; Beskin et al. 2005), able to study such transients in a very short time after detection, has been proposed. According to these ideas, we created the prototype fast wide-field camera called FAVOR (Karpov et al. 2005) and the TORTORA camera as part of the TORTOREM (Molinari et al. 2006) two-telescope complex, and operated them over several years.

The recent discovery of the brightest ever burst, GRB 080319B (the Naked-Eye Burst (Racusin et al. 2008)), by several wide-field monitoring systems – TORTORA (Karpov et al. 2008), RAPTOR (Wozniak et al. 2008) and Pi of the Sky (Cwiok et al. 2008) – and the subsequent discovery of its fast optical variability (Beskin et al. 2008) on time scales from several seconds down to a sub-second time scale (Beskin et al. 2010) demonstrated that the ideas behind our efforts in fast temporal resolution wide-field monitoring are correct.

2. General requirements for wide-field monitoring

Typical follow-up observations, performed for the detailed study of newly discovered transients, require no more than a good robotic telescope with fast re-pointing. Such instruments, however, will inevitably only begin to capture data after the first few seconds or tens of seconds of the event. To get information from the start of the event, which is essential for understanding the nature and properties of transients, one needs to observe the position of the transient before it appears. And, as transients occur in unpredictable places, the systematic monitoring of large sky regions becomes an important task.

For such monitoring, one needs to select the optimal set of mutually exclusive parameters – the angular size of the field of view, the limiting magnitude and the temporal resolution. Indeed, the area of the sky Ω, covered by an objective with diameter D and focal length F, equipped with an NxN pixels CCD with pixel size of l and exposure time of τ seconds, is

$$\Omega \propto \frac{N^2 l^2}{F^2} \tag{1}$$

while the faintest detectable object flux, for a sky background noise dominating over the CCD read-out noise, is

$$\mathrm{Flux}_{min} \propto \left(\frac{D}{F}\right) D^{-2} l \tau^{-\frac{1}{2}} \tag{2}$$

For the case of CCD read-out noise σ domination, the limit is

$$\mathrm{Flux}_{min} \propto \frac{\sigma}{D^2 \tau} \tag{3}$$

The number of detectable events, uniformly distributed in Euclidean space, is

$$\mathrm{Number} \propto \Omega \cdot \mathrm{Flux}^{-\frac{3}{2}} = D \left(\frac{D}{F}\right)^{\frac{1}{2}} \tau^{\frac{3}{4}} N^2 l^{\frac{1}{2}} \tag{4}$$

when the duration of the event T is longer than the exposure, and

$$\mathrm{Number} \propto \Omega \cdot \mathrm{Flux}^{-\frac{3}{2}} \left(\frac{\tau}{T}\right)^{-\frac{3}{2}} = D \left(\frac{D}{F}\right)^{\frac{1}{2}} T^{\frac{3}{2}} \tau^{-\frac{3}{4}} N^2 l^{\frac{1}{2}} \tag{5}$$

when it is shorter – as Flux_{min} decreases, one can detect a larger number of events in a greater volume. High temporal resolution, thus, is essential in the detection and analysis of short optical transients. On the other hand, it requires the application of fast CCD matrices, which usually have large read-out noise, that limits the detection of a faint objects.

Most of the general-purpose wide-field monitoring systems currently in operation (typical examples are listed in Table 1) chose a large field of view while sacrificing the temporal resolution to achieve decent detection limit. Our cameras, FAVOR and TORTORA, in contrast, chose high temporal resolution as a key parameter.

3. MegaTORTORA – multi-objective transforming instrument

It is important to develop the methodology of wide-field search for fast optical transients in two directions. The first is the increase of detection threshold by 2-3 magnitudes while keeping the field of view and temporal resolution. It may be achieved

Table 1. Typical general purpose wide-field monitoring cameras currently in operation (the ones used primarily for GRB optical companions search are chosen). For FAVOR, TORTORA and Mini-MegaTORTORA the limits correspond to 3σ detection on a single frame, and may differ from their real-time operational values due to non-ergodic pixel statistics when using the image intensifier.

Name	Field of View (degrees)	Temporal Resolution (seconds)	Limit (magnitudes)
WIDGET	62 x 62	5	10^{m}
RAPTOR A/B	40 x 40	60	12^{m}
RAPTOR Q	180 x 180	10	10^{m}
BOOTES	16 x 11	30	12^{m}
π of the Sky	33 x 33	10	11.5^{m}
AROMA-W	25 x 35	5-100	10.5^{m}-13^{m}
MASTER-VWF	20 x 21	5	11.5^{m}
MASTER-Net	30 x 30	1	9^{m}
FAVOR	16 x 24	0.13	10^{m}-11.5^{m}
TORTORA	24 x 32	0.13	9^{m}-10.5^{m}
Mini-MegaTORTORA	30x30	0.13-1300	12.5^{m}-17.7^{m}

by means of multi-objective (or multi-telescope) systems, by decreasing field of view of single instrument and, therefore, its pixel scale (Beskin et al. 2007). To avoid the dominance of CCD read-out noise, the quantum efficiency and amplification of image intensifier have to be increased, or the low-noise fast EM-CCDs may be used instead. The second direction is the acquisition of the spectral, or at least multi-color, and polarimetric information for the transients.

The MegaTORTORA project we develop utilizes the modular design and consists of a set of basic units, 9 objectives each, installed on a separate mounts. Each objective in a unit is placed inside the gimbal suspension with remotely-controlled micro-motors, and so may be oriented independently from others. Also, each objective possesses the set of color and polarization filters, which may be installed before the objective on the fly. It allows to change modes of observation on the fly, from routine wide-field monitoring in the color band providing best signal-to-noise ratio (or in a white light, with no filters installed), to the narrow-field follow-up regime, when all objectives are pointed towards the same point, i.e. newly-discovered transient, and observe it in different colors and for different polarization plane orientations simultaneously, to acquire all possible kinds of information for the transient (see Fig. 1). Simultaneous observation of the transient by all objectives in white light is also possible to get better photometric accuracy by co-adding frames.

Each objective is equipped with the fast EM-CCD, which has a low readout noise even for a high frame rates when the internal amplification is in effect. The data from each channel of such a system, which is roughly 20 megabytes per second, is collected by a dedicated rackmount PC, which stores it in its hard-drive as well

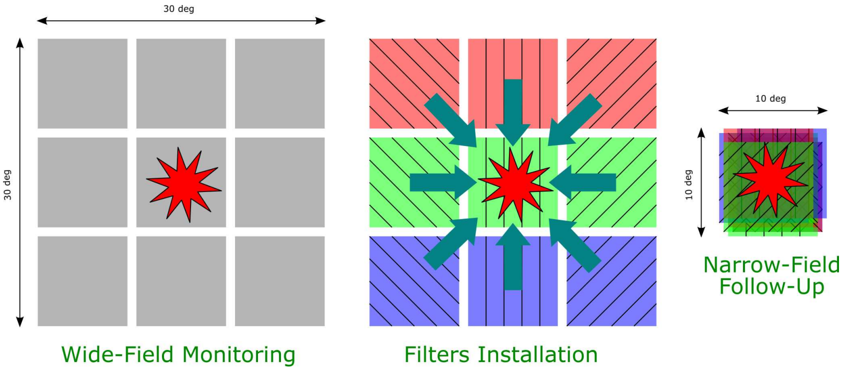

Figure 1. Different modes of operation of MegaTORTORA system. Left – wide-field monitoring mode in a single color band (or in white light). Middle – insertion of color and polarization filters as a first step of follow-up routine upon detection of a transient. Right – re-pointing of all unit objectives towards the transient. In the latter regime of operation the system collects three-color transient photometry for three polarization plane orientations simultaneously. Mode transition is expected to be less than 0.3 second.

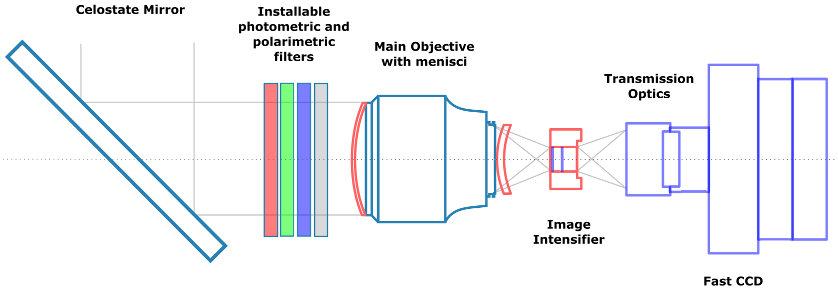

Figure 2. Optical scheme of a single channel. The main objective is surrounded by two menisci to compensate optical distortions of a thick glass on the input of image intensifier.

as performs its real-time data processing in a way similar to the current processing pipeline of FAVOR and TORTORA cameras, which currently operate under similar data flow rate. The whole system is coordinated by the central server which acquires the transient data from data-processing PCs and controls the pointing and mode of operation of all objectives in response to them.

4. Mini-MegaTORTORA as a MegaTORTORA prototype

As a limited realization of a MegaTORTORA concept we designed the prototype design – the Mini-MegaTORTORA, which is basically a model of a 3x3 unit. Main design choice was to use the celostate in a gimbal suspension for a fast re-pointing of each channel. Such a decision allows to significantly loosen the requirements for the

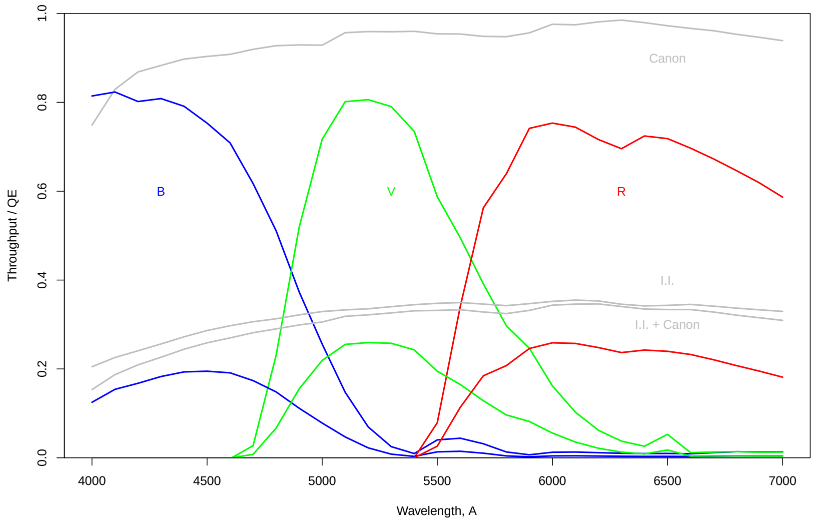

Figure 3. Quantum efficiency and throughput of the optical tract.

Table 2. Expected performance of a 6-channel Mini-MegaTORTORA in narrow-field follow-up mode (all 9 channels pointed to the same field) for different combination of photometric and polarimetric filters.

Timescale (seconds)	B filter (magnitude)	B + 3 polarizations (magnitude)	2 filters (magnitude)	2 filters + 3 polarizations (magnitude)
0.13	13.0	11.0	12.5	10.5
13	15.5	13.0	15.0	13.0
1300	18.0	15.5	17.5	15.5

structural, dynamical and precision parameters. Another design choice was the use of a combination of an image intensifier with fast CCD as a detector – the scheme analogous to the one used in FAVOR (Karpov et al. 2005) and TORTORA (Molinari et al. 2006) systems but with the non-scaling image intensifier. Such a design is the same as of typical ICCD, but with a significantly lower price (see Fig. 2).

The system as a whole will have the field of view of 972 square degrees in wide-field monitoring mode with a limiting magnitude of $B \approx 12.5^{\rm m}$ in 0.13 s; frame co-addition will allow to reach effective limits of $B \approx 14^{\rm m}$ in 13 s and $B \approx 17.5^{\rm m}$ in 1300 s. Field of view in narrow-field follow-up mode will be 108 square degrees with limits from $B = 13.7^{\rm m}$ in 0.13 s till $B = 18.7^{\rm m}$ in 1300 s, with simultaneous measurements of the transient color and/or polarization. All the channels will be mounted on a single fork mount, able to carry up to 150 kg. The complex as a whole is controlled by a dedicated PC which collects the transient information from all channels and

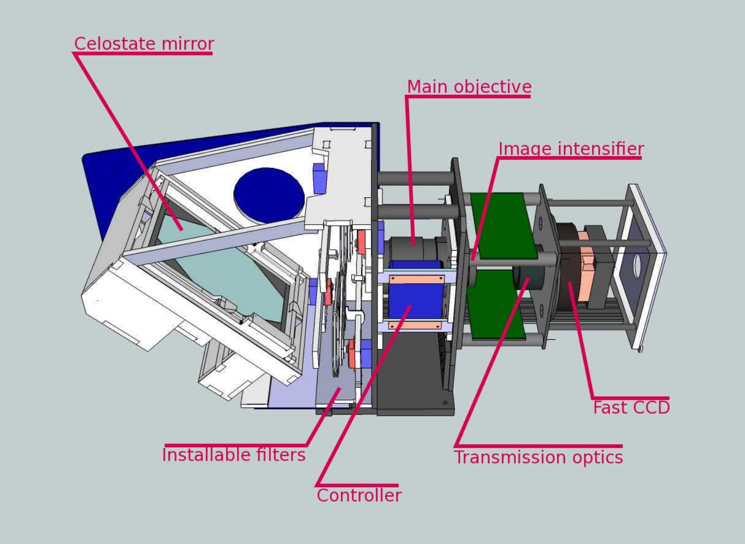

Figure 4. Schematics of a single channel design of a Mini-MegaTORTORA.

Figure 5. Photo of a 6 channels of Mini-MegaTORTORA on an equatorial mount during the test run in Jan 2011.

decides whether to re-configure the system to narrow-field mode for its follow-up, which typically requires no more than 0.3 seconds.

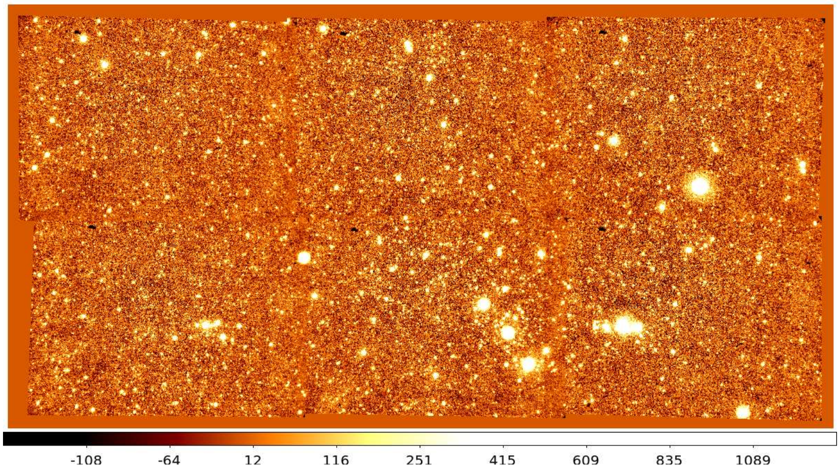

Figure 6. Mosaic image of Orion constellation region (rotated 90 degrees counter-clockwise for illustrative purposes) as seen by 6 channels of Mini-MegaTORTORA.

For the moment, we have built a 6-channel version of Mini-MegaTORTORA based on a channel design shown in Fig. 4. Complete system (right panel of Fig. 5) is presently performing test observations (Fig. 6). The performance of such 6-channel variant in follow-up mode with various combinations of filters is summarized in Table 2.

Acknowledgments

This work was supported by the Bologna University Progetti Pluriennali 2003, by grants of CRDF (No. RP1-2394-MO-02), RFBR (No. 04-02-17555, 06-02-08313 and 09-02-12053, 12-02-00743-a), INTAS (04-78-7366), by the Presidium of the Russian Academy of Sciences Program and by the grant of President of Russian Federation for the support of young Russian scientists. S.K. has also been supported by a grant of Dynasty foundation. G.B. thanks Landau Network-Cenro Volta and Cariplo Foundation for fellowship and Brera Observatory for hospitality. G.G. also gratefully acknowledges the support of Foundatione CARISBO. We thank Emilio Molinari, Stefano Covino and Cristiano Guidorzi for technical help organizing TORTORA observations and for discussions of the results.

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