Research Article

High-Speed and Wide-Field Photometry with TORTORA

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We present the photometric analysis of the extended sky fields observed by the TORTORA optical monitoring system. The technology involved in the TORTORA camera is based on the use of a fast TV-CCD matrix with an image intensifier. This approach can both significantly reduce the readout noise and shorten the focal length following to monitor relatively large sky regions with high temporal resolution and adequate detection limit. The performance of the system has been tested using the relative magnitudes of standard stars by means of long image sequences collected at different airmasses and at various intensities of the moon illumination. As expected from the previous laboratory measurements, artifact sources are negligible and do not affect the photometric results. The following analysis is based on a large sample of images acquired by the TORTORA instrument since July 2006.

1. Introduction

The complete randomness of the angular distribution of the γ -ray bursts (GRBs) 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 [1–6] and the high-speed and wide-field FAVOR [7] and TORTORA cameras represent the more recent and promising developments. 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 Chile and has been operating since May 2006 [8].

2. Short Technical 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 TV-CCD matrix is an interline-transfer CCD with microlens raster to compensate the loss of surface area. It can operate at 7.5 frames per seconds with

negligible gaps between consecutive exposures. This frame-transfer regime is typical for CCDs and does not bring any significant artifacts in the image. The main objective and the transmission optics focusing unit are controlled through the PC parallel port interface. In Table 1 are reported the main technical parameters of the TORTORA camera.

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 [9].

The difference between an ordinary imaging with a CCD camera and fast imaging with a CCD equipped with an image intensifier tube is very significant [10]. The intensifier converts each photon, detected by the photocathode, into a luminous spot on the phosphor screen that preserves the (x, y) location of the event. This approach produces an efficient amplification of the intensity of the image afterwards recorded by the CCD. High gain of the image intensifier, which may be expressed as the number of resulting CCD counts per photon on the photocathode leads to effective reduction of the readout noise down to a subelectron values. Furthermore, the image intensifier is able to down-scale the image reducing the focal length and consequently increasing the field of view for a fixed CCD size. The gain of the image

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	$81''/\text{pix}$
Focal ratio	1/1.2	Gain	150	Exposures	0.13 s
Field of view	$24^\circ \times 32^\circ$	Scaling factor	5.5	Pixel size	6.5 micron
		Quantum efficiency	10%	Readout noise	$6 e^-/\text{pix}$

intensifier tube employed in TORTORA is 150, and the focal length is reduced from 150 mm down to 27 mm. However, the drawback of image intensifier is the decrease of the system quantum efficiency (Section 4.1) to a value defined by the characteristics of the photocathode, which is only 10% for an S20 photocathode used here.

3. Data Reduction

The real-time data processing pipeline is based on a fast *differential imaging* algorithm described in [10]. More detailed time series analysis may be performed a posteriori studying the images stored on the RAID array.

3.1. Preliminary Analysis. The first step of the postprocessing analysis is the dark current noise subtraction and flat-fielding to compensate vignetting due to the objective design. The low-noise TV-CCD matrix employed in TORTORA operates at room temperature. The dark current component is originated from thermally generated charge in the photocathode before the amplification stage and then it will be also amplified (the dark current in image intensifiers was traditionally called the Effective Background Illumination (normally abbreviated to EBI)). The dark current is generally not an issue if short time exposures are planned. Practically thermal noise has a negligible effect on the signal-to-noise ratio of the frames acquired by TORTORA, therefore no cooling is applied to the CCD camera.

The next step is the measure of the CCD frames taking into account the distribution of the background level and the statistics of photoelectrons.

3.2. Background Estimate. Faint stars at the limit of detection, photons of scattered light by the environment, satellites trails, cosmic-rays, or bad pixels can produce random fluctuations in a single frame. The variable background brightness is initially treated identifying pixels which are significantly higher than the surrounding one. The pixels deviating by a specified statistical amount are replaced by the median value. The nonuniformity of the frame background was reduced by approximately 15% in accordance with external conditions. This procedure is done on the whole frame, subsequently the background signal is determined within the circular shell of inner radius annulus and outer radius annulus surrounding the object without including other astronomical objects within this shell. The measured standard deviation in the stack of images is higher than that expected from pure

FIGURE 1: Image acquired by the TORTORA camera with an exposure time of 0.13 seconds. The selected stars are labeled using the identification number (id number) as tabulated in Tycho-2 catalogue. They have been chosen as reference stars to test the linearity and the homogeneity of the instrument (see text for more details). The center coordinates of the image are at the position: RA(J2000) = 18 h : 37 m : 05.28 s, DEC(J2000) = -06 d : 29' : 38.04''. Real time images of the TORTORA system are available using the public graphical user interface at the following address: <http://polaris.merate.mi.astro.it/trem/>.

Poisson noise especially at large count rates. Although the image intensifier overcomes the problem of readout noise, images acquired with an image intensifier suffer from gain noise. Intensifier noise is mainly caused by the discrete nature of the electron amplification process. Each photon entering the image intensifier will induce a large number of photons leaving the phosphorus screen. The variation in the gain for each incoming photon and the correlation in time of the output photons are the source of the noise. A single input photon yields a burst of output photons. The departure times of these output photons are strongly correlated in time. As a consequence, the Poisson process at the input of the intensifier yields a non-Poisson process at the output, which has an increased variance compared to ordinary Poisson-distributed noise. The number of photoelectrons generated at the photocathode depends on the binomial statistics:

$$P(r) = \binom{N}{r} p^r (1-p)^{(N-r)}. \quad (1)$$

FIGURE 2: c_{scint} versus short exposure times $t_{\text{exp}} < 0.25$ seconds for different size of telescopes ($10 \text{ cm} \leq D \leq 15 \text{ cm}$) at a fixed values of airmass: $X = 1$ (a) and $X = 2$ (b). The arrows indicate the typical scintillation noise in TORTORA observations.

$P(r)$ is the probability of obtaining r photoelectrons for N photons given a quantum efficiency of p . The mean is $\mu = Np$, and the variance is $\sigma^2 = Np(1 - p)$.

3.3. Scintillation Noise. Additional uncertainty arises from atmospheric transmission variability. Scintillation is a dimensionless measure of the flux variation of a source observed through a finite aperture due to fluctuations in the refractive index of the atmosphere. Atmospheric scintillation adds an effective constant error term to the photometry. This error can be estimated from [11] as

$$c_{\text{scint}} = 0.09 \frac{X^{7/4}}{D^{2/3} \sqrt{2t_{\text{exp}}}} \left(\frac{\lambda}{550} \right)^{-7/12} \exp\left(\frac{h}{8000} \right), \quad (2)$$

where D is the telescope diameter in centimeters, X is the airmass, h is the observatory altitude in meters, t_{exp} is the exposure time in seconds, λ is the wavelength in nanometers, and c_{scint} is the scintillation noise in magnitudes. The precise value of the exponent of the airmass X depends on the wind direction; it is equal to 2 when observing in the same direction as the wind and to 1.5 when observing perpendicular to it. Young [12] was able to show that for moderate airmass, the scintillation standard error is proportional to the 1.75 power of airmass but becomes asymptotically proportional to the $3/2$ power for very large airmass.

The $D^{-2/3}$ dependence may be applied only to exposures long enough to ignore all high-frequency content. Ryan and Sandler [13] have derived a $D^{-1.1 \pm 0.1}$ dependence for exposure times ≤ 0.25 seconds, which agrees with Ellison and Seddon's [14] experimental data and Reiger's theoretical equations [15]. We adopt this diameter dependence in (2) to describe the scintillation noise in TORTORA photometry.

Taking into account the altitude of ESO Observatory ($h = 2400 \text{ m}$) and the aperture diameter of TORTORA telescope ($D = 12 \text{ cm}$), the estimated amount of scintillation is $0.01 \lesssim c_{\text{scint}} \lesssim 0.03$ magnitudes for moderate sky conditions with an airmass value X between 1 and 2 in 0.13-seconds photometric measurements (Figure 2).

4. Photometry of the TORTORA Fields

Circular aperture photometry of the TORTORA images was performed with `PHOT/DAOPHOT` function in *IRAF* (*IRAF*: Image Reduction and Analysis Facility; <http://iraf.noao.edu/>). Typically, the optimal radius of aperture was chosen to be 5 pixels for bright sources after the experiments with growth curves. Determining an appropriate aperture size to measure a total instrumental magnitude can be done by building up a light growth curve of the object. The light growth curve is the object's flux as a function of aperture radius. The adopted aperture would then reflect the point in the light growth curve where it flattens out. This optimal aperture size, which produces the smallest photometric error, contains also the spatially varying PSF due to geometric distortions present in the final images. A temporal sequence of contiguous light growth curves for as well as the values of the ellipticity and the Full Width at Half Maximum (FWHM) of the best fit Moffat profile is displayed in Figure 3. The growth curves were calculated selecting bright and isolated stars in different location of the wide-field image. The images were acquired with a continuous exposures time of 0.13 seconds per frame under moderate sky condition. The values of the affective air mass and the seeing are estimated to be ~ 1.30 and $\sim 0.8''$, respectively (<http://www.la.eso.org/lasilla/dimm/>). At the corresponding time the percent of the Moon illuminated is 6% at a distance

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 3: Continued.

FIGURE 3: Example of growth curves acquired with a continuous exposure time of 0.13 seconds per frame, under moderate sky condition (see values in the text). The position of the stars may be found in the sky field of Figure 1 reading the Tycho-2 identification number (id number) labeled in y -axis. For each star are reported the values of the ellipticity, the FWHM using as best fit a Moffat profile, and the pixel coordinates.

of 126° from the target. The position of the star may be found in the sky field displayed in Figure 1 reading the Tycho-2 identification number (id number) labeled in y -axis. The total flux of the stars is contained within well-determined radius showing a good homogeneity of image intensifier and CCD response. The asymptotic value is immediately apparent and constant with a satisfactory degree of accuracy. The short sequence collected here shows that the stability of the TORTORA system is enough to assure the reliability of the detected short-lived periodicity in the ultra-fast optical photometry.

The correction for the finite size of the aperture is called the aperture correction. It is defined simply as the magnitude difference between the asymptotic magnitude and the magnitude at the given aperture. Corrections for the amount of missing flux from the source outside the optimal aperture size were done using a correction factor estimated from the method proposed by Stetson [16] and implemented under *IRAF* task *mkapfile*. The aperture correction is typically of order 0.10 mag at the center of the image ($10^\circ \times 10^\circ$), while it reaches a maximum value of 0.20 mag at the edges of the frame in which the field has less sharpness due to the vignetting. Proper correction factor is systematically added to our photometry. Finally, by the use of very large circular apertures we test that extra-scattered light contribution around the source is so low that it can be neglected.

Sufficiently accurate results are also obtained under relatively suboptimal sky conditions. Figure 4 shows a contiguous sequence of standard stars detected within the limits of observability permitted by the instrument before the automatic protection shutdown. The images were acquired with a continuous exposures time of 0.13 seconds per frame. The plots combine an image, a surface plot of the image data and a contour plot of the images data in a single tri-level

display. The x -axis and y -axis indicate the pixel coordinates place in the center of the FOV, and the z -axis represents the signal intensity. The values of the effective air mass and the seeing are estimated to be ~ 2.61 and $\sim 0.9''$, respectively. At the corresponding time the percent of the Moon illuminated is 98 at a distance of 58° from the target. We emphasized that the autofocus system is stable, and the stars retain their original position without emerging distortion effects.

4.1. Linearity and Dynamic Range. The spectral response of the system is primarily determined by the photocathode type used in the image intensifier. TORTORA was developed for ground optical observation, and a multialkali (S20) photocathode is employed. Its typical spectral response peaks near 440 nm (Figure 5). No photometric filter has been used with it.

By comparing the instrumental magnitudes with the standard stars tabulated in Tycho-2 catalogue (<http://archive.eso.org/ASTROM/>), we may test the linearity and the fractional coincidence loss of the instrument for a wide range of fluxes. Figure 6 shows the dependency of the measured instrumental magnitude and the standard V magnitude. This result spotlights a good linearity of the instrument. Furthermore, the fractional coincidence loss caused by dead time is negligible for the fluxes under consideration in TORTORA system. The stars with color index $(B-V) > 1$ and $(B-V) < 1$ are plotted with square and circle symbols, respectively. The reference Tycho-2 stars used to check the linear response of the camera are labeled in Figure 1. The values of the linear best-fits for the two samples (see the upper right box in Figure 6) are statistically comparable due to the large color term across the passband. Finally, using the linear fit equations reported in Figure 6, the photometry performed in instrumental system was converted to the V magnitudes of the Tycho-2 star catalogue.

FIGURE 4: An example of observations acquired with continuous exposures time of 0.13 seconds per frame, under relative extreme sky conditions. The plots combine an image (image size: $2.5^\circ \times 2.5^\circ$), a surface plot of the image data, and a contour plot of the images data in a single tri-level display. The x-axis and y-axis indicate the pixel coordinates place in the center of the image frame at the position: RA(J2000) = 14 h : 31 m : 40.7 s, DEC(J2000) = 36 d : 18' : 14.7'' and the z-axis represents the signal intensity. The values of the affective air mass and the seeing are estimated to be ~ 2.61 and $\sim 0.9''$, respectively. At the corresponding time the percent of the Moon illuminated is 98% at a distance of 58° from the target.

The calibration of the TORTORA instrumental magnitude to the visual band is preferable than the blue filter because the empirical correlation has a lower degree of dispersion and the dependence of color index is negligible.

5. Discussion and Conclusion

The photometric accuracy of the wide sky fields observed by the high speed TORTORA CCD camera equipped with an image intensifier is analyzed. The typical potential sources of instrumental artifacts such as (i) the spatial deformation

of the image produced by the electron-optical input system (after electrons are ejected from the photocathode, they are collected and focused by the electric field of an electrodes configuration), (ii) blurring introduced by imperfections in the transmission optics between the phosphor screen and CCD, (iii) broadening of the light pulse produced by a fraction of photons emitted by the phosphor screen that travel parallel to the surface and scatter, (iv) stray light that arrives to the camera through multiple reflections from various detector components in the optical interface are negligible and do not affect the photometric results as expected from the previous laboratory measurements. Long

FIGURE 5: Spectral sensitivity curve of the multialkali (S20) photocathode employed in TORTORA.

FIGURE 6: Instrumental magnitude versus standard Visual magnitude. The stars with color index $(B-V) > 1$ and $(B-V) < 1$ are plotted with square and circle symbols, respectively. The reference stars under consideration are labeled in Figure 1 using the Tycho-2 identification number (id number). The values of the linear best-fits are reported in the right upper box.

sequences of growth curves of bright and isolated standard stars show that the flux is contained within a well-determined and constant radius. Sequences of surface plot indicate that (x, y) location of the event is preserved without appreciable degradation of its intensity profile. The example given here shows the performance of the TORTORA camera within the limits of observability permitted by the instrument before the automatic protection shutdown. However proper extra-Poissonian fluctuations caused by statistical variations produced by gain variation across the image intensifier have to be considered for the reliability of the detected short-lived periodicity (Section 3.2).

Since May 2006 we accumulated approximately 200 nights of observations. The fields of the GRB 060719 [17], GRB 061202 [18], and GRB 061218 [19] were observed 59 seconds, 92 seconds, and 118 seconds after the satellite trigger, respectively. Fourier analysis was performed to search for upper limit for periodic signal at the GRB position. 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 unprecedented level of accuracy, collecting ~ 13320 images. Long and short time-scale variability was detected during the naked-eye prompt emission [20].

One of the important results of our routine observation is the estimation of the detection rate of the short-lived orphan transients (in preparation). Currently the prompt optical transient detection rate determined by observations of TORTORA is less than $8 \times 10^{-9} \text{ deg}^{-2} \text{ sec}^{-1}$ for transients that are brighter than 10.5^m on 0.13 seconds timescale.

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