Abstract. The Télescope à Action Rapide pour les Objets Transitoires (TAROT-1) has as prime objective the observation of the prompt and delayed emission of cosmic gamma-ray bursts (GRBs). We have performed a search for optical emission from 6 GRBs detected by BATSE. The positioning error circle was fully covered within typically thirty minutes after the trigger. No detection of the early afterglow phase was made, and magnitude limits in the range of $m_R = 13 - 15$ were estimated using 20s exposures. These limits are compared to optical afterglow data obtained in later phases and the results are interpreted in terms of source distances. They correspond to a median redshift of $z = 0.5$. With HETE-2 and the planned instrument upgrade, TAROT-1 will be able to detect the early optical emission of GRBs up to a redshift of the order of 5.

Key words: Gamma-Ray Bursts; Optical Afterglows
Limits on the early afterglow phase of gamma-ray burst sources from TAROT-1

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1. Introduction

Since their discovery more than thirty years ago, Gamma-Ray Bursts (GRBs) have been intriguing objects for theoreticians and challenging sources for observers. Their cosmological nature was firmly established in 1997 by observations performed by the BeppoSAX satellite (Costa, 1999), which enabled the first discovery of a faint optical transient associated to the event (van Paradijs et al. 1997). With the possible exception of GRB 980425, whose association with SN 1998bw remains in doubt (Pian et al. 1999), the measured GRB source redshifts are close to, or larger than unity. The events may be decomposed, in general, in two main phases: a prompt bursting phase, with no preferred temporal pattern, with a duration ranging from few milliseconds to several minutes (Paciesas et al. 1999); a delayed emission, the afterglow, that in a first approximation decays according to a power-law of index $\approx -1$. BeppoSax wide-field observations were of fundamental importance for the discovery and the follow-up of the afterglow phase at different wavelengths (Costa et al. 1997, van Paradijs et al. 1997). The ROTSE experiment has given evidence for emission at optical frequencies from the prompt phase, detecting for the first time an optical burst occurring during the gamma-ray emission of GRB 990123 (Akerlof et al. 2000).

The detection of X-ray and optical afterglows of cosmic gamma-ray bursts supports the fireball model (Rees and Mészáros 1992, Mészáros and Rees 1997, Panaitescu et al. 1998) as a standard tool to interpret those observations. In this framework the afterglow emission is described as synchrotron and inverse Compton emission of high energy electrons accelerated during the shock of an ultra-relativistic shell with the external medium, while the prompt emission is due to the internal shocks produced by shells at different speeds within the relativistic blast wave (see Piran 1999 for a review). Both the prompt radiation and early afterglow phases provide us critical information to establish the physical processes during the burst itself, as well as the physical conditions of the surrounding environment (Kumar and Panaitescu, 2000, Kumar and Piran 2000). There is a general consensus that the fireball plasma is constituted by $e^-e^+$ pairs and $\gamma$-photons, however the ultimate energy reservoir and the mechanism of pair creation are still a challenge to theoretical models.

Since 1991 the Burst and Transient Experiment (BATSE, Fishman 1989) on board of the Compton Gamma-Ray Observatory (CGRO) has been detecting about one GRB source per day in the 50 - 300 keV energy band, with fluences ranging from $10^{-7}\text{erg.cm}^{-2}$ to $10^{-3}\text{erg.cm}^{-2}$. The GRB Coordinate Network (GCN, Barthelmy 1997) uses the raw real time data of BATSE to compute very rapidly an approximate position of the sources. In spite of the large error circle of the initial coordinates, 5° or more, the information on the source position is transmitted in a very short time, about 4 seconds af-
TAROT-1 received about one observable alert from BATSE every ten days. This is in agreement with the BATSE statistics of GRB event detection, the relative night—day duration and the accessible area of the sky (10° above the North horizon to 20° for the South part of the sky). Weather conditions prevent observation during 30% of the time. Observations are performed even during the full Moon periods, although with a reduced sensitivity. TAROT-1 is fully autonomous i.e. there is practically no human intervention. Figure 1 summarizes the different software modules and their connections. All are functionally independent and the communication is made through TCP/IP socket processes.

The Telescope Control System (TCS) takes care of the instrument, performs housekeeping, weather monitoring, etc. During the night, the control is handed over by the MAJORDOME (Bringer et al. 2000), a software package in charge of the observations. In the absence of any alert from the GCN, the instrument is in routine mode, and observations requested by various observers are sequenced. Upon receipt of an observable GCN alert from BATSE, the ongoing observation is interrupted, and the MAJORDOME sends the telescope and camera parameters to the TCS. The reconfiguration and pointing of the telescope to its new position lasts typically 1.5 second. Taking into account the various delays involved by the GCN (4-6s), and the INTERNET socket transmission (typically 0.25s), the total reaction time, from the time of the BATSE trigger to the beginning of data acquisition, is of about 7-10s. Since the positioning error circle of BATSE is larger than the telescope field of view, observations are performed inside a field of 25°, covered by a set of 5 x 5 mosaic. In the best cases this total field covers only the 68% confidence radius of the error circle, including statistical errors, as discussed in the BATSE 4B catalog (Paciesas et al. 1999). TAROT-1 reacts to BATSE LOCBURST notices (see the GCN web site: http://gcn.gsfc.nasa.gov for a description of the various notice types). After usually 20s to 10min, a new alert is sent by the GCN, called BATSE_FINAL, with improved coordinates, producing a second positioning of TAROT-1, and the start of a new mosaic. If the difference between the BATSE LOCBURST and BATSE_FINAL positions is less than 1° the telescope keeps its current position. Depending on the burst brightness, the Huntsville BATSE team may compute a better position, which is usually transmitted by the GCN 30 to 60min later. TAROT-1 moves accordingly and eventually reduces the area explored, depending on the actual uncertainty. During the remaining of the night, a continuous coverage of the area is maintained, trying to detect and to keep track of an eventual optical transient.

As soon as an image is obtained, the image processing software (called TAITAR in figure 1) produces a source catalog. Presently, the generated list of sources is compared to the USNO catalog both for astrometric and photometric reductions. Once TAROT-1 has completed a full

![Diagram](image_url)
Table 2. TAROT-1 observation log for the GRB source observations made with CGRO-BATSE

| Source name | BATSE trigger | Error circle | Matching with mosaic? | Sky conditions | Moon phase |
|-------------|--------------|--------------|-----------------------|----------------|-----------|
|             | time (UT)    | radius (°)   | (see text)            |                | (%)       |
| GRB 990802 | 01 : 04 : 44 | 2.1          | Full                  | Clear          | 70        |
| GRB 990807 | 21 : 55 : 46 | 2.5          | No match              | Clear          | No Moon   |
| GRB 990903 | 19 : 14 : 56 | 2.7          | Partial               | Partly cloudy  | No Moon   |
| GRB 990915 | 23 : 15 : 23 | 2.2          | Full                  | Clear          | No Moon   |
| GRB 990917 | 20 : 12 : 28 | 2.6          | Partial               | Clear          | 50        |
| GRB 991002 | 22 : 49 : 03 | 2.8          | Full                  | Clear          | 45        |
| GRB 991115 | 18 : 48 : 08 | 2.2          | Partial               | Cloudy         | 45        |
| GRB 991129 | 22 : 38 : 08 | 4.0          | No match              | Clear          | 50        |
| GRB 991211 | 04 : 34 : 42 | 6.1          | No match              | Clear          | No Moon   |
| GRB 000107 | 00 : 44 : 09 | 6.8          | No match              | Clear          | No Moon   |
| GRB 000111 | 02 : 41 : 58 | 5.2          | Partial               | Clear          | No Moon   |
| GRB 000201 | 03 : 02 : 09 | 2.1          | Full                  | Clear          | 25        |
| GRB 000221 | 23 : 39 : 10 | 2.0          | No match              | Partly cloudy  | 85        |
| GRB 000225 | 01 : 35 : 29 | 2.3          | Full                  | Partly cloudy  | 62        |
| GRB 000226 | 03 : 51 : 49 | 2.5          | Partial               | Clear          | 55        |
| GRB 000229 | 02 : 45 : 02 | 2.4          | Full                  | Cirrus clouds? | 35        |
| GRB 000302 | 02 : 50 : 25 | 2.1          | No match              | Clear          | No Moon   |
| GRB 000312 | 20 : 50 : 50 | 2.5          | Full                  | Clear          | 45        |
| GRB 000321 | 21 : 53 : 08 | 4.1          | Partial               | Partly cloudy  | 90        |
| GRB 000408 | 02 : 35 : 48 | 2.5          | Partial               | Clear          | No Moon   |
| GRB 000418 | 21 : 30 : 17 | 5.4          | No match              | Clear          | 100       |

a 68% confidence radius from the last available BATSE data, taking into account both statistical and systematic errors.

mosaic, an e-mail message is sent, and a scientist on duty is paged to compare the images and to look for possible new sources. The images are acquired without filter (clear position in the filter wheel) and with an exposure time of 20s. With the APOGEE camera the readout time was 30s, hence the total time needed to observe the full mosaic was 21 min.

3. Observations and reduction

TAROT-1 observations of GRBs started routinely in 1999, although the data for the first half of July 1999 has been lost because of a hardware failure of the media recorder. All observations are summarized in table 2. The first two columns give the GRB date and time. The third column give the error circle taken from the final data reduction provided by the BATSE team, including the systematic error as given in Paciesas et al. [1999]. For several sources, it appears that neither the BATSE_FINAL nor the BATSE_LOCBURST positions were accurate enough to match fully our mosaic. This indication is given in column 4, while the sky conditions are depicted in the next column, with the Moon phase in the 6th column. The influence of the Moon depends on its phase and distance to the source, and has an impact on the upper limits we computed. A phase of 30% begin to produce a higher background whatever the Moon position over the sky. No event observed by TAROT-1 as a response to a BATSE/GCN alert was detected by another instrument, whatever the wavelength. In six cases, the 68% error circle has been adequately sampled and the sky conditions were correct, hence the probability that TAROT-1 never observed a burst source (i.e. the six sources are outside their 68% error circle) is 0.0011, assuming a uniform probability distribution over the error circle. Of course, the detection probability depends on the unknown source magnitude. Hence the source detection probability will be $(1−0.68p)^6$, where $p$ represents the fraction of bursts above the TAROT-1 detection threshold at the time of observation.

Since no optical sources were detected, a $3\sigma$ upper limit to the magnitude was calculated by comparing several stars on the images with the USNO A2.0 catalog. Since observations were performed without any filter, a correction factor was estimated in order to provide a $R$-magnitude upper limit, assuming an energy spectral index equal to 1. Under this condition, one finds that the correction to be applied to the measured TAROT magnitude $m_T$ is $R = m_T − 0.4$. The limits obtained are listed on table 3 as a function of the elapsed time since the BATSE trigger. The delays mentioned in the second column corresponds to the end of the scan matching the final BATSE source position.
4. Discussion

TAROT-1 upper limits on the optical flux of GRB 990123, the only source until now detected both during its prompt and afterglow phase, were compared with ROTSE data. Figure 2 displays TAROT-1 upper limits and ROTSE measurements (Akerlof et al. 1999), as well as later data (Galama et al. 1999).

Another possibility is to compare TAROT-1 upper limits with data obtained for GRB afterglows at later times. The result of this comparison is displayed in figure 3, whereas the basic data and references are given in table 4. We note that in the time region observed by TAROT-1, GRB970508, GRB980519, GRB991208, and GRB991216, in addition to GRB990123, would have been detected by TAROT, if we extrapolate the late epoch afterglow to early times. Of course, this is a crude extrapolation which does not take into account possible breaks in the light curves.

We tried to evaluate the possible effect of the source distance on the burst afterglow detection by TAROT-1. To perform this task we have to correct for the galactic absorption and for the source distance (Boer and Gendre 2000). We have scaled the flux of sources with known distances to a common redshift of $z = 1$, applying corrections for distance, time dilation and absorption in our galaxy (Schlegel et al. 1998). We assume a flat cosmology with $\Omega = 0.7$ and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$. Table 5 gives the corrections computed and the decay indexes. The corrected light curves are displayed in figure 4 together with TAROT-1 upper limits. As it can be seen, extrapolating to
Fig. 2. Comparison between the TAROT upper limits (arrows) and the light curve of GRB 990123 (error bars). Both the prompt and the afterglow emission are shown. Data from Akerlof et al. (1999) and from Galama et al. (1999).

Fig. 3. Comparison between the TAROT upper limits (arrows, all data) and the afterglow light curve of GRB sources detected at optical wavelengths (table 4). In this figure, the light curves have not been corrected in the proper time domain, TAROT-1 would have detected 5 events, if their redshift would have been equal to $z = 1$.

These data can also be used to estimate the limiting TAROT-1 distance of detection. Assuming a limiting magnitude of 15 one hour after the burst, the corresponding distance is $z = 1.2$ for the brightest burst and 0.1 for the faintest one, the median redshift being 0.5.

Fig. 4. Comparison between the TAROT upper limits (arrows, all data) and the afterglow light curve of GRB sources. The light curves have been normalized to a common distance corresponding to a redshift of 1, according to the method described in the text (Boër and Gendre 2000) and using the data from table 5. We took into account the K-correction, distance and time dilation, and absorption from our Galaxy (table 5).

5. Conclusions and perspectives

In this paper, the lower R-magnitude limit for the early afterglow light curves of GRB is computed, for sources observed by TAROT-1 after its first year of routine operation. These limits are compared with the optical afterglow data obtained so far. A maximum source distance of $z = 1.2$ was estimated for observations made with TAROT-1 one hour after the GRB main event begins. The accuracy of HETE-2 (Ricker et al., 2001) or SWIFT (Gehrels, 2000) will allow to start the observation within few seconds after the GRB triggers the detectors, while for BATSE we had to scan the error circle, an operation lasting 30 minutes. Given the expected HETE-2 detection rate of 40 events per year in the anti-solar direction, TAROT-1 may expect to observe a source location once every month. In order to estimate the maximum source distance TAROT-1 can reach, we extrapolate the light curves plotted on figure 4 to a time of five minutes after the burst onset. In this case, the median redshift corresponding to a limiting magnitude of 15 is $z = 1.2$.

In addition, the detector will soon be replaced by a camera based on a Thomson 7899 CCD. It will have a total noise of $10^{-5}$, for a readout time of 1 second, allowing to reach the 17th R magnitude in 10 seconds. With this new device TAROT-1 will be able to monitor the GRB optical light curves, not only during the prompt event, but also the transition between the prompt and afterglow phase. After five minutes, even in the worst case discussed...
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