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DISCLAIMER

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Abstract. LOTIS (Livermore Optical Transient Imaging System) is a gamma-ray burst optical counterpart search experiment located near Lawrence Livermore National Laboratory in California. The system is linked to the GCN (GRB Coordinates Network) real-time coordinate distribution network and can respond to a burst trigger in 6–15 seconds. LOTIS has a total field-of-view of 17.4° × 17.4° with a completeness sensitivity of $m_V \sim 11$ for a 10 second integration time. Since operations began in October 1996, LOTIS has responded to over 30 GCN/BATSE GRB triggers. Seven of these triggers are considered *good* events subject to the criteria of clear weather conditions, < 60 s response time, and $> 50\%$ coverage of the final BATSE 3σ error circle. We discuss results from the first year of LOTIS operations with an emphasis on the observations and analysis of GRB 971006 (BATSE trigger 6414).

INTRODUCTION

Our knowledge of the nature of gamma-ray bursts (GRBs) has greatly increased as a result of recent detections of X-ray, optical, and radio counterparts. X-ray observations of several GRBs including but not limited to GRB 970228 and GRB 970508 by BeppoSax [1,2] and GRB 970828 by XTE/ASCA [3] have provided precise localizations which have allowed for deep optical follow-up searches. These searches have resulted in the identification of two GRB optical counterparts, namely GRB 970228 [4] and GRB 970508 [5] and a single radio counterpart, GRB 970508 [7]. Despite the wealth of information that has been obtained from these discoveries, the physical mechanisms which cause a gamma-ray burst remain a mystery. The lack of a bright host galaxy for either optical counterpart has further confused matters. Although the identification of the "Hurley 100" [8] may pin down the nature of the afterglows, multiwavelength observations of GRBs *simultaneous* with the gamma-ray emission may be a more direct method of probing their origin. If the physical processes which produce the prompt gamma-ray emission and the lower energy afterglow differ, as Katz and Piran [6] have suggested, a broad band spectrum revealing the nature of the source environment can only be produced from simultaneous observations. Small, wide field-of-view telescopes, such as LOTIS, which were originally designed to provide more precise burst locations by detecting the simultaneous optical emission may assist in producing or constraining this broad band spectrum.

OBSERVATIONS

LOTIS is a second generation simultaneous optical counterpart search experiment. The precursor experiment, called Gamma-Ray Optical Counterpart Search Experiment (GROCSE), found no evidence of simultaneous optical activity brighter than $m_V = 7.5$ [10].

TABLE 1. LOTIS GRB Triggers

Trig	UTC Date	Fluence/10^{-6} (erg cm^{-2})	Stat Error (deg)	Hunt-GCN Error (deg)	t_{res} (sec)	Duration (sec)
5634	961017	0.51	2.9	2.7	11	3
5719	961220	1.8	1.5	3.6	9	15
6100	970223	48.0	0.73	2.0	11	30
6117	970308	0.81	5.8	13.6	14	2
6307	970714	1.7	2.8	7.1	14	1
6388	970919	2.3	3.0	5.1	12	20
6414	971006	9.3	0.6	6.8	17	150

The LOTIS telescope, located 25 miles East of Livermore, CA, consists of four individual cameras arranged in a 2×2 array. Each camera has a field-of-view of $8.8° \times 8.8°$ which yields a total field-of-view of $17.4° \times 17.4°$ allowing for a 0.2° overlap. A detailed description of the system is provided in Park *et al.* [11] as well as at http://hubcap.clemson.edu/~ggwilli/LOTIS/.

From the start of routine operation in early October 1996 through early October 1997 LOTIS has responded to 36 GCN/BATSE GRB triggers [9]. Six of these triggers were a result of particle events occurring in the BATSE detectors. Two triggers were caused by known soft gamma-ray repeaters (SGRs).

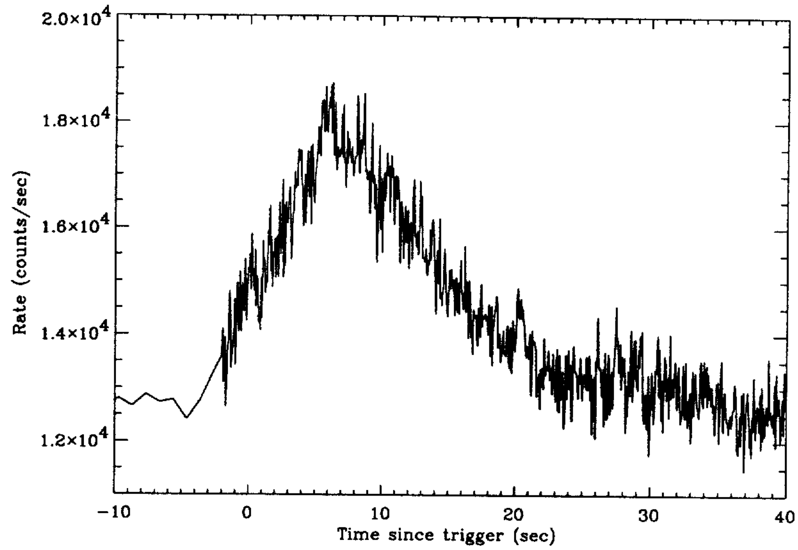

FIGURE 1. GRB 971006 gamma-ray light curve. The shaded area represents the integration time of the first LOTIS image

Of the remaining 28 triggers 26 were unique GRBs while two were refined coordinates of previously triggered GRBs (GCN LOCBURST). Of the 26 unique triggers 7 were considered *good* events subject to the criteria of clear weather conditions, < 60 s response time, and $> 50\%$ coverage of the final BATSE 3σ error circle. By far the hardest criterion to meet was the coverage criterion owing to the difficulty in determining accurate GRB locations from the first few seconds of gamma-ray emission. Based on these statistics LOTIS responds to ~ 1 good GRB event every 52 days.

Data from the seven good events which LOTIS responded to is given in Table 1. The fluence values were determined by summing the fluence in the four energy channels given in the current BATSE GRB catalog with the exception of triggers 6100 and 6414 which are discussed below. The fourth column gives the statistical error in the final BATSE postion while the fifth column gives the angular difference between the initial and final BATSE coordinates. The LOTIS response time and the total duration of the burst are given in the last two columns. In four cases LOTIS began imaging while gamma-rays were still being emitted making the observations truly simultaneous.

The event with the largest gamma-ray fluence was GRB 970223 which was among the top 3% of all BATSE GRBs. Although no optical transients were identified for this burst LOTIS placed an upper limit on the ratio of optical flux at 700 nm to gamma-ray flux at 100 keV of $R_{F_{\mathrm{simultaneous}}}(\mathrm{t} = 11 - 21\mathrm{s}) = F_{\mathrm{opt:700nm}}/F_{\gamma:\mathrm{100keV}} < 475$ and on the ratio of optical to gamma-ray fluence of $R_L = L_{\mathrm{opt:500-850nm}}/L_{\gamma:\mathrm{20-2000keV}} < 1.1 \times 10^{-4}$. The full analysis of this event is given in Park *et al.* [11].

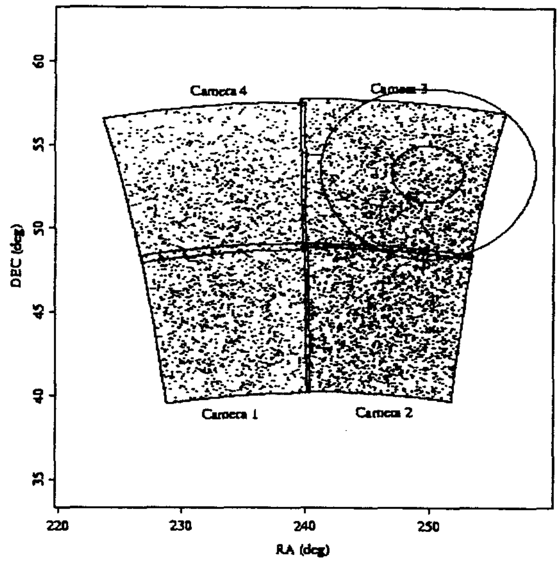

FIGURE 2. LOTIS coverage of GRB 971006. Each of the individual points represent a stellar object above the 4σ threshold. The small and large ellipses represents the BATSE 1σ and 3σ error circles respectively. LOTIS obtained approximately 75% coverage of the BATSE 3σ error circle.

The longest burst which LOTIS responded to was GRB 971006. This burst had a main pulse duration of $\sim$ 30 s but exhibited weak pre- and post-burst emission resulting in a total duration of $\sim$ 150 s. The light curve of GRB 971006 is shown in Figure 1. LOTIS began imaging the field centered on the initial GCN coordinates (RA = 241.1, Dec = 49.2 J2000) $\sim$ 17 s after the start of the burst. The shaded region of Figure 1 represents the 10 s integration time of the first LOTIS image. The final BATSE coordinates of GRB 971006 (RA = 249.8, Dec = 53.3) were well within the LOTIS field-of-view. Figure 2 shows the LOTIS coverage for this burst. The small and large ellipses represent the BATSE 1σ and 3σ error circles (including the 1.6° systematic error) respectively. There was no Interplanetary Network (IPN) [12] localization available for this burst and therefore it was necessary to search the entire 3σ error circle for transient objects. This search found no transients with a point spread function (psf) consistent with the stellar psf.

From a histogram plot of stellar magnitudes in camera 3 we determined the completeness magnitude (the faintest magnitude for which 100% of the stars were detected) for this event to be $m_V \sim 11.0$. Following the analysis in Park *et al.* [11] this yields an upper limit to the flux density at 700 nm of $F_\nu(700\mathrm{nm}) < 2.7 \times 10^{-24}$ erg cm^{-2} s^{-1} Hz^{-1}. The BATSE flux density at 100 keV was found by fitting the spectrum from LAD3 during the integration time of the first LOTIS image to the Band GRB functional form [13] which yielded a value of $F_\nu(100\mathrm{keV}) = 1.7 \times 10^{-27}$ erg cm^{-2} s^{-1} Hz^{-1}. The resulting upper limit of the optical to gamma-ray flux for this event is $R_{F_{\text{simultaneous}}}(\mathrm{t}=17-27\mathrm{s}) = F_{\text{opt:700nm}}/F_{\gamma\text{:100keV}} < 1600$.

The total gamma-ray fluence was determined by integrating the Band GRB functional form for the entire burst from 20 keV to 2000 keV. The total gamma-ray fluence was $L_{\gamma\text{:20-2000keV}} = 9.3 \times 10^{-6}$ erg cm^{-2} while the upper limit to the GRB's optical fluence, again following Park *et al.* [11], is $L_{\text{opt:500-850nm}} < 5.4 \times 10^{-9}$ erg cm^{-2}. The resulting upper limit for the optical to gamma-ray fluence ratio is $R_L = L_{\text{opt:500-850nm}}/L_{\gamma\text{:20-200keV}} < 5.8 \times 10^{-4}$.

DISCUSSION

Although LOTIS has already placed upper limits on the simultaneous optical to gamma-ray flux for specific events we hope to further constrain the ratio with an upgrade to thermo-electric cooled CCDs in January 1998. In the future we plan to investigate GRB spectral evolution focusing on how the low energy power law index, α, of the Band GRB functional form [13] effects optical constraints. We also plan to implement Super-LOTIS [14], a dedicated 0.6 m reflector with a design sensitivity of $m_V \sim 19$ (10 s integration time) early next year.

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