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A Search for Optical Counterparts of Gamma-Ray Bursts
Final Report

Hye-Sook Park

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1. INTRODUCTION

Gamma Ray Bursts (GRBs) are mysterious flashes of gamma rays lasting several tens to hundreds of seconds that occur approximately once per day. GRB have been detected since the 1960s by various orbiting satellites carrying gamma sensitive sensors. Recently, NASA launched the orbiting Compton Gamma Ray Observatory (CGRO) to study GRBs and other gamma ray phenomena. CGRO carries the Burst and Transient Experiment (BATSE) specifically to study GRBs. Although BATSE has collected data on over 600 GRBs, and confirmed that GRBs are localized, high intensity point sources of MeV gamma rays distributed isotropically in the sky, the nature and origin of GRBs remains a fundamental problem in astrophysics.

BATSE's 8 gamma ray sensors located on the corners of the box shaped CGRO can detect the onset of GRBs and record their intensity and energy spectra as a function of time. The position of the burst on the sky can be determined to $< \pm 10°$ from the BATSE data stream by comparing the intensities in each detector. This position resolution is not sufficient to point a large, optical telescope at the exact position of a GRB which would determine its origin by associating it with a star inside our galaxy or an external galaxy.

Because of their brief duration it is not known if GRBs are accompanied by visible radiation. Their seemingly large energy output suggests that some visible radiation should accompany the gamma ray output. Simply scaling the ratio of visible to gamma ray intensities of the Crab Nebula to the GRB output suggests that GRBs ought to be accompanied by visible flashes of magnitude 10 or so. A few photographs of areas containing a burst location that were coincidentally taken during the burst yield lower limits on visible output of magnitude 4. The detection of visible light during the GRB would provide information on burst physics, provide improved pointing coordinates for precise examination of the field by large telescope and provide the justification for larger dedicated optical counterpart instruments.

The purpose of this experiment is to detect or set lower limits on optical counterpart radiation *simultaneously* accompanying the gamma rays from GRB. This experiment is a collaboration between Lawrence Livermore National Laboratory (LLNL), University of Michigan, the Goddard Space Flight Center, and the Marshall Space Flight Center. The names of the collaborators are : Elden Ables, Richard Bionta, Linda Ott, Hye-Sook Park, Eric Parker from LLNL, Scott Barthelmy, Thomas Cline, Neil Gehrels from NASA/Goddard Space Flight Center, Carl Akerlof, Brian Lee from University of Michigan, and Don Ferguson from WorldView Imaging Corp.

2. APPROACH AND TECHNICAL OBJECTIVES

Our approach begins with the BATSE real time telemetry stream which is relayed to NASA / Goddard Space Flight Center (GSFC) in Washington, DC. Our collaborators at GSFC have implemented a real time computer system called BACODINE (BAtse COordinate DIstribution NEtwork), that monitors the BATSE telemetry stream for indications of a burst and when detected, calculates the burst coordinates then sends these coordinates to LLNL's Wide-Field-Of-View (WFOV) tracking telescope [Ref. 1,2] over the Internet. The WFOV tracking telescope which spends its idle time systematically taking reference images of the entire sky, quickly slews over to the burst position and records images of the ±10° GRB error box over the next 20 minutes. An analysis of the speed of the GRB position algorithm, the telescope slewing rates and the results of timing experiments performed on the Internet show that the first images should be obtained within 5 to 15 seconds after burst onset which is just prior to the time of maximum gamma ray intensity for most bursts. Evidence for or upper limits on brightness of the optical counterpart are determined by comparing the images taken during the burst with the reference images taken of the same area. Assuming 8 hours per night observing time we expect a burst to occur in the field-of-view (FOV) of the WFOV system every 22 nights of observation.

The current WFOV telescope system consists of a single 89 mm aperture, 60° FOV popeye lens covered by 23 fiber-optic-coupled intensified CCD cameras. Each camera has 576 x 384 pixels. The lens and cameras are mounted on a computer controlled Contraves pointing platform capable of rapidly pointing the cameras to any part of the sky. The system achieves a limiting magnitude of 8.5.

Our technical objectives were to 1) optimize the current WFOV system and CGRO link for the GRB counterpart search to the extent allowable by the hardware, 2) collect data on any simultaneous optical data on as many GRBs as possible, 3) develop image analysis code to analyze GRB imagery and set interesting limits on any observed GRBs, and 4) prototype a replacement camera system capable of reaching a limiting magnitude of 13 for a possible upgrade in FY1995.

3. RESULTS

The first objective is completed as we have been routinely running the GROCSE system each night when no rain is forecast. The basic pointing and data acquisition system was operational at the end of FY1993. In FY1994, we added several features to improve the system reliability and to protect the sensitive image intensifiers from damage due to overexposure to bright light. These improvements included 1) an exposure algorithm that optimizes the camera exposure for a given field, 2) a lunar avoidance algorithm which skips fields near the moon, 3) a hardware timer that cuts camera power prior to sunrise to protect against computer failures, 4) reconstruction of the main tracking mount controller cable to correct an intermittent failure in the tracking mount, 5) stand-alone data acquisition computer which is dedicated to communicate with Goddard's BACODINE only, and 6) rain detection system which shuts down the WFOV telescope when it detects rain.

We developed a real time experimental link across the continent (between Goddard in Maryland and LLNL in California) using Internet. We persuaded Scott Barthelmy at Goddard to use Internet "sockets" to send out BASTE real time data analysis results (i.e. GRB coordinates for our case) to any remote site and helped him to implement sockets between Goddard and LLNL. With the GROCSE system at LLNL monitoring BACODINE 24 hours a day, it was fully debugged of all errors and we measured its performance. We measured the response time between Goddard and LLNL to be ~0.4 seconds. Now BACODINE distributes its coordinates to 19 different sites worldwide [Ref. 3].

The second objective is completed as we have logged 1559 hours of observing time between Jan. 5. to Nov. 5, 1994. The total available observation time during this period was 2937 hours yielding 53% efficiency. Most downtime was due to tracking mount hardware failures before we fixed the controller cable. During this time we imaged 8 star fields in coincidence with BATSE's GRB triggers. Table 1 summarizes their characteristics, such as weather condition, burst duration, burst intensities, and the coordinate error between BACODINE and best estimate of BATSE calculated by Marshall Space Flight Center a few days after the GRB occurred.

This is the largest collection of events recorded in conjunction with BATSE triggers in less than one year and the fastest response to BACODINE broadcasting in the world as of today.

BATSE Trig #	UTC Date (1994)	Weather	Moon	Nearest Camera Δt (sec)	Burst Duration (sec)	Burst Intensity (cnts/sec)	Images per Camera	BACO - Huntsville Coordinate (deg)
2793	1/29	clear	~full	35	6	20500	23	4
2896	3/29	clear	~full	128	0.5	37000	21	5.3
2952	4/28	clear	~full	BACODINE error too big	0.8	21000	66	63
3040	6/23	clear	full	24	37	6000	123	4.8
3139	8/27	patch clouds	none	15	8	7600	137	9.6
3141	8/28	clear	none	21	4	2100	140	8.4
3159	9/7	clear	new	22	25	4300	160	18.7
3241	10/14	fog	half	22	90	55000	161	12.7

Table 1 GROCSE recorded BATSE Triggers (as of Nov. 5, 1994)

The third objective is completed as we have written the data analysis code which is an algorithm that performs field flattening (corrects for variations of intensifier sensitivity across the image) then locates the positions of all "blobs" (star-like clusters of bright pixels) in the image. By matching selected stars by hand in images from each camera we determined the 23 x 3 alignment parameters that specify the relative positioning of the cameras. Once aligned the coordinate transform code will automatically determine absolute RA and DEC coordinates of each blob in all of the images and will associate blobs from different images that have the same RA and DEC. This code will catalogue and track all objects imaged during the sky patrols as they cross the sky throughout the night. Matching the sky patrol catalogue against the SAO catalogue will measure the systems limiting magnitude and accidental rate.

Using this analysis we can set upper limits on the optical flux relative to the gamma ray flux. Unfortunately as of November 5, 1995, we could not reach the best limit compared with other optical counterpart search experiments. These are due to mostly natural causes; some are deteriorated by bad weather condition (8/27/94, 10/14/94 events); or big error on BACODINE coordinate estimate which made our GROCSE telescope point outside the field of view of the GRB (4/28/94, 9/7/94 events); or very short burst duration (1/29/94, 3/29/94 events); or very short duration and weak burst intensity (8/28/94 event). Nonetheless, the first optical flux limits for 6/23/94 and 10/14/94 events were presented at the 185th American Astronomical Society Meeting in Tucson, AZ, January 12, 1995. These results are listed in Table 2 along with the limits given by other optical counterpart search experiments.

Experimenter	Experiment Type	UTC Date	Limiting Magnitude	f (optical) ergs/cm^2-sec	f (γ) ergs/cm^2-sec	f (γ) / f (optical)	Detection Probability
LLNL GROCSE	CCD Imaging	6/23/94	7.0	1 x 10^{-8}	2 x 10-8	2	~ 40%
LLNL GROCSE	CCD Imaging	10/14/94	~5.0	6 x 10^{-8}	2.7 x 10^{-6}	40	0
Schaefer	Photo Plate	11/19/78	~3	4 x 10^{-7} *	2.6 x 10^{-4} *	800	?
MIT ETC	CCD Imaging	6/16/91	8.0	2.3 x 10^{-9}*	2.12 x 10^{-7}*	120	17%
MIT ETC	CCD Imaging	7/2/91	6.6	8.5 x 10^{-9}*	1.55 x 10^{-7}*	25	72%

* fluence in ergs/cm^2.

Table 2. Gamma Ray Burst Optical Counterpart Sensitivity (as of Nov. 5, 1994)

We are almost certain to have the world's best limit or even to see a optical counterpart to a GRB (up to Mv ~ 8.5) by logging more observing time. The GROCSE I system is fully automated and requires very little operator's intervention.

The fourth objective, to prototype a replacement camera having 100 times more sensitivity, is completed. Our prototype camera has ~ 50 electron noise level at room temperature. We assembled a Loral 2048 x 2048 CCD (15 µm x 15 µm pixel size) with the evaluation boards from Loral and tested its performance. Many modifications were added to the Loral's evaluation boards to lower its noise level down to ~50 electrons at room temperature. By assembling this prototype camera with a 10 cm aperture and 33 cm focal length refractive optics manufactured by Tele Vue Optical Company, we expect to see Mv ~ 13.5 objects with 5 second integration times and Mv ~ 16 with 100 second integration times at signal to noise ratio (SNR) of 10. Figure 1 and 2 shows the calculation of SNR vs. Mv at 2 different integration times (5 and 100 seconds) using this camera system.

Based on the modified evaluation board design, we are developing new camera analog/digital control boards. These boards are expected to be much lighter, less power consuming and to have less noise as we add thermal electric cooler and use better driver electronics. Evaluation of other lenses (e.g. Nikkor ED 200 mm f/2 IF lens manufactured by NICON and SP 300 mm f/2.8 LD lens manufactured by Tamron) are under way. We expect that the performance of these lenses will be similar to the Tele Vue lens but much lighter and smaller in size which allows us to mount multiple cameras to one telescope mount. We are also developing a custom frame interface which transfers digital image data to the host computer via SBUS .

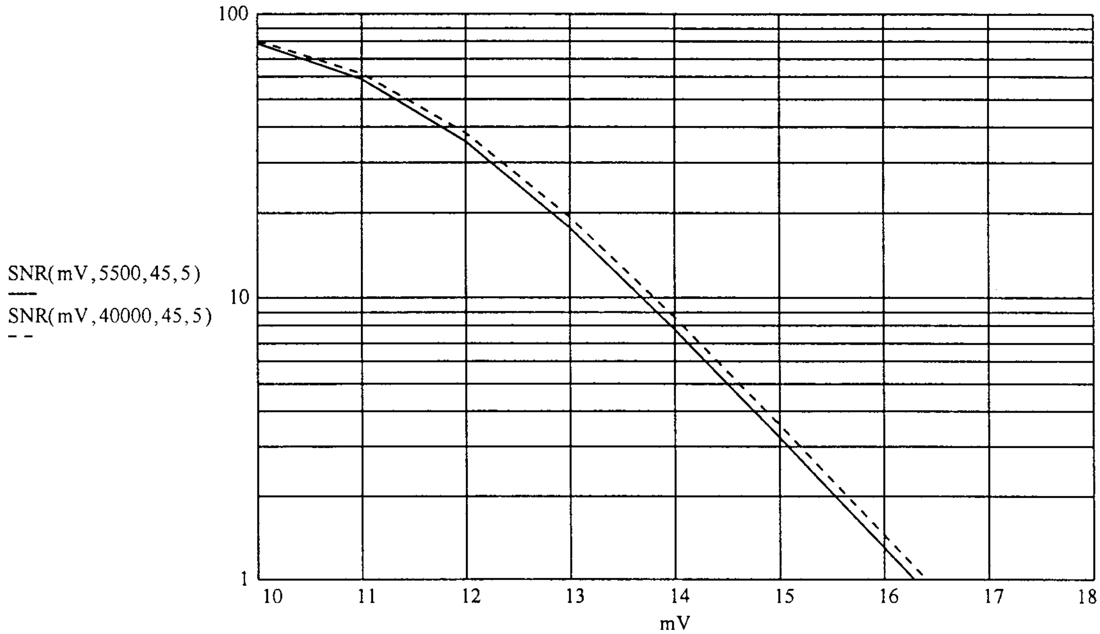

Figure 1. Expected Signal to Noise Ratio vs. Mv of GROCSE II System at 5 sec Integration Time

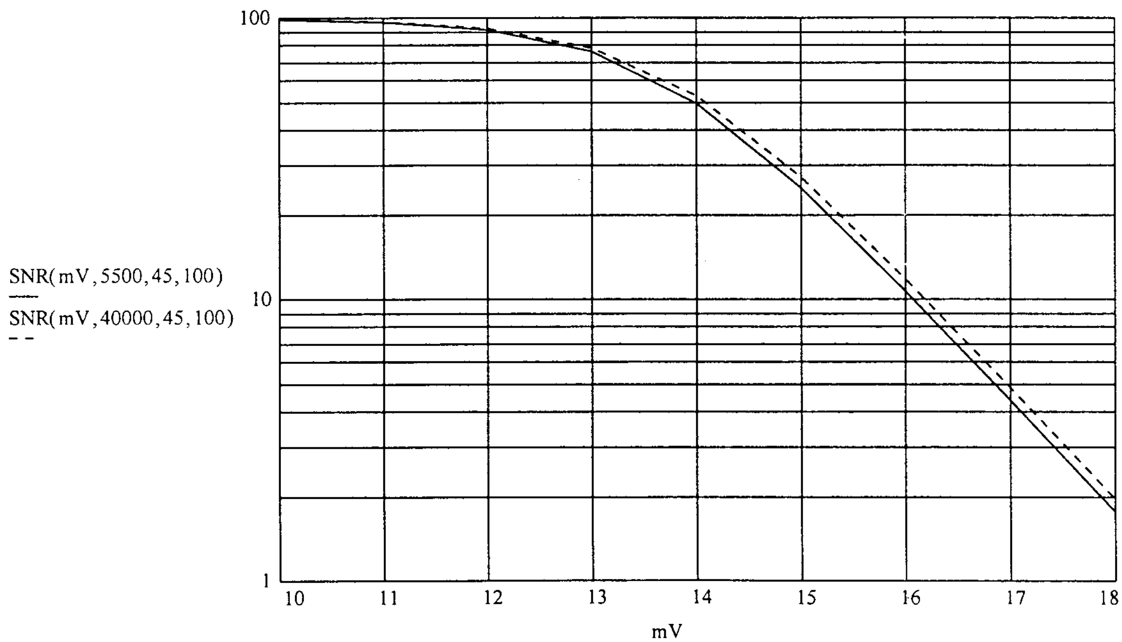

Figure 2. Expected Signal to Noise Ratio vs. Mv of GROCSE II System at 100 sec Integration Time

4. RESOURCES

LLNL LDRD program funded GROCSE $85K for FY1993 and $112K for FY1994. We have received a grant of $30K from NASA Compton Gamma Ray Observatory Cycle 4 Guest Investigator Program for FY1995. Our collaborator, Carl Akerlof, received the grants: $25K from the University of Michigan, $10K from NASA, and $12K from the Planetary Society for FY1995. NASA is fully supporting Scott Barthelmy at Goddard all costs and equipment necessary for BACODINE system.

5. PUBLICATIONS AND MEETINGS

Non-refereed report : UCRL number - JC 114984

C. Akerlof et al., AIP Conference Proceedings 307, Gamma Ray Bursts Second Workshop, "Gamma-Ray Optical Counterpart Search Experiment", Oct. 20-22, 1993.

Poster session presentation : UCRL number - JC 113191

H. Park et al., AAS High Energy Astrophysics Division Meeting, "A Search for the Optical Counterparts of Gamma Ray Burst Events', Nov. 2, 1994.

Oral presentation

E. Ables et al., 185th AAS Meeting, Tucson, AZ, "Results from GROCSE, A Real-Time Search for the Optical Counterparts of Gamma-Ray Bursts", Jan. 12, 1995.

6. CONCLUSION

We have shown that a wide-field-of-view telescope system originally built for a SDI program is successfully converted to perform an astrophysics experiment. The system is fully automated and recorded 1559 hours of observing time registering 8 events in coincidence with BATSE triggers. The optical fluence limits for a couple of these events are 1 x 10^{-8} and 6 x 10^{-8} ergs/cm^2-sec respectively. Better limits or a chance to see a real optical counterpart to a GRB can be obtained only by logging more observing time while connected CGRO's BATSE detectors in real time through BACODINE.

We have shown that a real time connection across the continent for experimental data transfer can be accomplished using the abundant Internet network.

We have developed a prototype camera system which is ~100 time more sensitivity than the existing intensified CCD cameras. Using these second generation system, we can search for the GRB optical counterparts as deep as Mv ~ 13.5. By locating GRB's positions to better than many degrees one can associate the GRB with known astronomical objects thus leading to clues of the origin of gamma ray burst. We also proposed to search for faint comets near the Sun using the second generation GROCSE system while it is in idle position waiting for a GRB trigger. The region where solar elongations less than 90 degrees is not well covered by any near term Near Earth Object Survey programs. The best current survey program is only good to Mv ~ 12 and mostly done by amateurs and Palomar Schmidt Survey which is almost decomissioned now. Using 100 seconds of integration times we expect to see comets as faint as Mv~16.

7. REFERENCES

1] H. S. Park et al., "Real time Tracking System for the Wide Field of View Telescope Project", SPIE Vol. **1111**, pp. 196~203 (1989).

2] H. S. Park et al., "Multiple Target Tracking in a Wide-Field-of-View Camera System", SPIE Vol. **1304**, pp. 293~298 (1990).

3] S. Barthelmy et al., AIP Conference Proceeding 307, Gamma Ray Bursts Second Workshop, "The Real-Time BATSE Gamma-Ray Burst Coordinates Distribution Network", Oct. 22, 1993, pp. 643 ~ 647.

Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551