Results from GROCSE: A Real-time Search for Gamma Ray Burst Optical Counterparts

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ABSTRACT

The Gamma-Ray Optical Counterpart Search Experiment (GROCSE) has searched for contemporaneous optical counterparts to gamma ray bursts (GRBs) using an automated rapidly slewing wide field of view optical telescope at Lawrence Livermore National Laboratory. The telescope was triggered in real time by the Burst And Transient Source Experiment (BATSE) data telemetry stream as processed and distributed by the BATSE COordinates DIstribution NEtwork (BACODINE). GROCSE recorded sky images for 28 GRB triggers between January 1994 and June 1996. The analysis of the 12 best events is presented here, half of which were recorded during detectable gamma ray emission. No optical counterparts have been detected to limiting magnitudes $m_V \leq 8.5$ despite near complete coverage of burst error boxes.

Subject headings: gamma rays: bursts
1. Introduction

Nearly three decades after their discovery, the phenomenon of gamma ray bursts is still an outstanding mystery. Results from the Burst and Transient Source Experiment (BATSE) (Fishman et al. 1989; Meegan et al. 1996) aboard the Compton Gamma Ray Observatory (CGRO) have shown that the sources are isotropically distributed on the sky, limited in radial extent, and from quite compact sources which are most likely outside the disk of our galaxy. No theory has yet been proposed which satisfactorily describes all the observed characteristics. Optical counterpart searches could reveal two additional kinds of information inaccessible to BATSE that might resolve the mystery. First, the BATSE error boxes are several degrees across, including countless possible astrophysical objects. Positive detections of transient optical counterparts would pinpoint source coordinates to arc-second accuracy and possibly identify quiescent sources. Second, gamma ray bursts have only been observed in the gamma- and X-ray energy bands. Additional spectral information can significantly constrain models of the production mechanism.

No optical counterparts of $m_V \leq 24$ (Schaefer 1994) have appeared in follow-up observations made from hours to days after bursts. Archival searches for repeating counterparts have yielded some potential non-contemporaneous candidates (Schaefer 1991; Hudec & Soldán 1994) but the lack of temporal correspondence has left these candidates in doubt. Simultaneous observations have been attempted by groups such as the Explosive Transient Camera (ETC) (Krimm et al. 1996) and the Ondřejov network (Hudec et al. 1984). But sufficiently deep wide field of view stationary instruments are prohibitively expensive, and even with a steradian field of view, would only observe one or two events per year. Fortunately, following the tape failure onboard CGRO, real time telemetry was required, and the BATSE COordinates DIstribution NEtwork (BACODINE) (Barthelmy et al. 1994) was created in 1993 to distribute real time BATSE trigger information. Thus the GROCSE collaboration (Akerlof et al. 1994, 1995; Lee et al. 1996; Park et al. 1996) commenced an ambitious contemporaneous optical counterpart search program. With its
wide field of view and rapid slewing abilities, GROCSE was able to observe the entire error box of several bursts a year within seconds of their detection by BATSE, and in many cases while BATSE was still recording gamma ray emission. No counterparts were detected.

2. The GROCSE Instrument

In the summer of 1993, we initiated the GROCSE collaboration to adapt a camera array originally designed for the Strategic Defense Initiative program to the task of detecting GRBs. This Wide-Field-Of-View (WFOV) system was designed to be a high frame rate, multiple target tracking instrument (Park et al. 1989, 1990), and thus had requirements rather different from those of a normal CCD camera. The WFOV system consisted of a single 60° wide-field-of-view lens, 23 image intensified CCD imaging systems, and associated readout electronics. The $f/2.8$ lens had an effective aperture of 89 mm and a focal length of 250 mm. Twenty-three reducing fiber optic bundles transported light from the spherical focal plane to image intensifiers. The output of each intensifier was transmitted through a second reducing fiber bundle to a $384 \times 576$ CCD covering a $7.5 \times 11.5°$ field of view. The 23 cameras covered 75% of the lens’ field of view for an effective solid angle of 0.621 steradians. The exposure duration was set to 0.5 second shuttered by the image intensifiers. The quantum efficiency was constrained by the limited acceptance of the fiber optic reducing bundles and the photoelectric conversion in the image intensifiers, which combined with the local bright sky background, lead to a detection threshold of $m_V = 8.5$. The entire assembly was mounted on a Contraves computer-controlled inertial guidance test system.

The analog CCD outputs were serially multiplexed into a single Datacube image processing system under the control of a Sun 4/330 host computer. To compensate for saturation and variable brightness of the night sky, the intensifier gain was dynamically adjusted, camera by camera, to achieve the best performance. The spectral response of the GROCSE image intensifiers extended from 400 to 900 nm with peak sensitivity around 650 nm according to data supplied by the manufacturer. This was experimentally verified by
comparing the GROCSE response for stars with widely different surface temperatures.

GROCSE operated in two modes: sky patrol and burst. It spent most of its time in sky patrol mode using all 23 cameras and seven camera array positions to image the fraction of the sky with elevation angle greater than 30° every half hour. (Adjacent buildings obscured most of the sky below 30°.) GROCSE skipped any position within 30° of the moon in order to protect the image intensifiers from damage. Burst mode occurred whenever GROCSE received a burst trigger via BACODINE. The GROCSE host computer maintained a link to BACODINE 24 hours a day, trading packets once per minute. BACODINE is capable of distributing BATSE burst trigger information and approximate coordinates within 6 seconds after the BATSE trigger although for some slow rise triggers the delay exceeded 20 seconds. If GROCSE received a trigger with coordinates safely distant from the moon, any current operation was interrupted and the system started burst mode. The camera array would slew to the approximate burst position in less than 10 seconds and take images as rapidly as possible for 20 minutes. If the sky conditions had changed significantly from previous exposures, the auto-gain code would require a few additional seconds of processing time before the first image was recorded. The median response time for BACODINE triggers was 16 seconds from the initial detection onboard the CGRO to the first GROCSE image. After recording images for 20 minutes, the system returned to sky patrol mode. This protocol insured a substantial number of images both before and after each burst.

3. Data Analysis

Analysis of the GROCSE data required several steps. First, the relative location of each camera with respect to the central one was determined by comparison of star images to corresponding elements of the SAO catalog. Next, “warp” maps were generated to correct the 2-D distortions introduced by the intensifiers and fiber optic reducing bundles. These warps, unique to each camera, were typically on the order of 6 arc-minutes but could be as large as 20 arc-minutes. By examining several images and measuring the residual between
the apparent and real positions of stars, our code created a 23×36 warp map for the entire camera field with which we could correct a star’s position to within 3 arc-minutes. These first two calibration steps had to be done only once for the entire analysis. The only remaining degree of freedom was the position of the entire camera array for each event.

Once the star images were accurately mapped to celestial coordinates, the BATSE error box (Meegan et al. 1995) was examined for transients using the BATSE 3-σ statistical (three times the quoted 1-σ error) plus 1.6° average systematic errors added in quadrature. When IPN (Interplanetary Network) arcs (Hurley et al. 1994) were available, we further limited the search region to the overlap between this arc and the BATSE error box. Often, the error box covered more than one camera.

To search for transients in the image, our code first performed a “pseudo field flattening” to correct for variations of intensifier sensitivity across the image. (Since intensifier response varied with gain which was automatically adjusted by the online code to optimize peak image quality, we could not use true flat field images.) All pixels at least 5-σ above the surrounding background were then identified, and the centroids of all connected clusters of pixels were computed.

Using the camera alignment parameters and warp maps previously determined, the coordinate transform code automatically found the absolute RA and DEC coordinates of each pixel cluster centroid in all of the images. Any cluster would be considered a counterpart candidate if it could not be identified with an SAO cataloged star and was present in at least two consecutive frames, ruling out satellite glints or cosmic ray hits.

Since GROCSE did not track the sky, stars moved from one image to the next while pixel defects did not. Thus we could compare these remaining clusters to similar lists for sequential images and identify them as belonging to one of three classes: star-like objects, bad pixels, and single-frame noise.

Star-like objects were those which retained the same RA and DEC in multiple images,
and thus were likely to be real celestial bodies. These were identified by comparison to other star and object catalogs as well as to sky patrol images from earlier and later in the same night and other nights. A few were galaxies or variable stars but most were simply normal stars near threshold but not included in the SAO catalog. Any such object we could not identify would have been a potential counterpart. However, all such objects eventually proved to be consistent with known celestial bodies. Once we had identified a repeating pixel cluster, we entered it into our own catalog, and compared all subsequent images to both the SAO catalog and our own.

Bad pixels were pixels which always had much higher counts than any surrounding pixels, a common problem in the GROCSE system. Unlike hot pixels in a normal CCD camera system, the counts of these bad pixels could still vary widely from frame to frame. Once identified, these locations (at most a few hundred per camera) were appropriately cataloged.

Single-frame noise consisted of any cluster of pixels which appeared above threshold in only one frame, matching no other cluster in pixel position or RA and DEC. The majority of these clusters were “bad pixels” as described above which were a few standard deviations above all surrounding pixels in most frames, but more than 5-σ above the background for only one frame, and thus could be identified by the code. A few were dim stars visible in many frames but above 5-σ for only one, and were identified by hand. A very small number were satellites, which we easily detected by their streaked appearance and passage through predictable positions in several cameras across our total field of view. All single-frame objects were identified leaving no possible candidates for an optical counterpart for any of these events.
4. Results

GROCSE recorded images for BACODINE triggers corresponding to 28 actual bursts during its operation from January 1994 through June 1996. BACODINE sent two kinds of burst triggers: “type 1” triggers, which were received approximately 6 seconds after the BATSE detection; and “type 11” triggers, which arrived some 10 minutes later. Twelve of the twenty-two “type 1” triggers were useful for later analysis; the rest were marred by clouds or large BACODINE coordinate errors. Prior to January 1995, GROCSE used only the 7 central cameras in burst mode. Since the final burst position was often outside of this field, we switched to using all 23 cameras, greatly increasing our coverage of many events but also increasing the readout time between consecutive images. Burst 940129 and all post-1994 bursts had on the order of 25 seconds separating consecutive images in the same camera; the other three 1994 bursts had consecutive images separated by an average of only 5 seconds. For the events analyzed, images were sequentially taken during and after the burst for typical durations of 20 minutes. (Only 10 minutes of data are available for burst 940129.)

Results and limits are listed in table I. The $T_{90}$ values listed are from the BATSE 3B catalog (Meegan et al. 1995) for the first four bursts, and are rough duration estimates from the BATSE Collaboration for later bursts. “First image” is the time after the BATSE burst trigger that the GROCSE camera overlapping the burst location was recorded. Coverage was determined primarily by modeling the BATSE error box with a circular Gaussian probability surface. When IPN arcs were available, they were modeled with Gaussian errors and used to restrict the error box further. The 6 arc-minute square error boxes used for matching to the SAO catalog effectively mask part of the image, approximately 5% in most cases, so this area must be included in correcting estimates of the detection probability.

The failure to detect an optical transient provides us with an upper limit on any possible optical emission at the time of the image. First, we have listed approximate limiting V-band magnitudes. A comparison of the V-band filter to the GROCSE response
function showed that for most stellar types the calibrated GROCSE response would be within 0.1 magnitudes of the listed SAO catalog \( m_V \). Stellar classes B and K could vary by up to \( \pm 0.3 \) magnitudes, as GROCSE is relatively more sensitive to red stars than the V-band. Independent of color, observed magnitudes of a single star often varied by as much as \( \pm 0.5 \) from one frame to the next due to fluctuations in intensifier sensitivity and discontinuities in optical collection across the fiber optic bundles. Thus any comparison to V-band magnitudes is approximate at best.

The quoted limiting visual magnitude was determined by comparison to SAO catalog stars. The percent of detected SAO stars of a given visual magnitude falls from near 100% to near zero over slightly more than a magnitude of brightness for most GROCSE images. After binning stars in 0.1 \( m_V \) intervals, we set our limit at the dimmest magnitude where at least 50\% of the SAO objects of the same \( m_V \) were detected. This corresponded to the detection of approximately 85\pm5\% of the SAO stars brighter than or equal to the listed limit. In most cases, some stars one or more visual magnitudes dimmer than the quoted limit were visible in the image, but because the system has much more noise than a normal CCD camera, such detections are not reliable measures of sensitivity. Under ideal conditions (a moonless, clear night) this system could reliably identify stars as dim as \( m_V = 8.5 \). These limiting magnitudes have an error of \( \pm 0.5 \) \( m_V \).

Our second optical emission limit is independent of the \( m_V \) limit. Since a spectral distribution must always be assumed, we adopt a bremsstrahlung photon number density for the GRB spectrum, \( dN \propto dE/E \). If the power law dependence of the spectral distribution is drastically different, then either optical counterparts would have been discovered long ago or will never be detectable. This distribution implies an integral flux \( N = \gamma \ln(E_b/E_a) \) where the bandpass is from \( E_a \) to \( E_b \), and the constant \( \gamma \) has units of \( \text{photons cm}^{-2} \text{s}^{-1} \). This assumed distribution defines a robust measure insensitive to small variations in the true spectral shape. We convolve such a spectrum with the GROCSE response curve to place an upper limit on \( \gamma_{\text{opt}} \) listed in table I. This method is also applied to the BATSE
gamma-ray band to find $\gamma$.  

The GROCSE optical flux limit is determined directly from detector response. For each image we convolved the GROCSE response curve with the black-body spectral distributions of a number of reference stars with known spectral type and brightness. The result was compared to the actual detector response to estimate the optical flux corresponding to a signal 5-$\sigma$ above the background noise. This determined the constant $\gamma_{\text{opt}}$ described above and the limiting observable burst optical flux for the GROCSE waveband. Note that the uncertainty in this number is approximately a factor of 2 and the real limit may be as much as 1 magnitude less than what is reported. When the error box was contained within several cameras, limits for the camera with the highest detection probability are given.

We list gamma ray fluences from 20 to 2000 keV integrated up to the time of the first observation which in most cases was near the end of the burst. We used a number of methods to derive the best fluence based on available data, as noted in table I. The Band et al. four parameter GRB model (1993) was used to fit BATSE High Energy Resolution Burst (HERB) or Spectroscopy High Energy Resolution Burst (SHERB) data (Fishman et al. 1989) when possible. When these data were unavailable, we used fluences from the BATSE 3B catalog (Meegan 1995) instead. For the remaining bursts, we employed fits to Spectroscopy Time-Tagged Event (STTE) data (Fishman et al. 1989). The STTE data can be accumulated over a variety of time ranges to form spectra, but the data do not cover the entire burst and thus the background subtraction for these events is less certain. An estimate of $\gamma$ is then made using the fluence divided by the time between the BATSE trigger and the GROCSE observation.

GROCSE imaged half of the dozen observed bursts while BATSE was still recording gamma ray flux above background. For four of these six bursts, the GROCSE observation occurred late in the burst for the cameras with high detection probabilities and difficulties with background subtraction made determination of accurate simultaneous gamma ray flux numbers impossible. For the other two, 951124 and 951220, the flux was still high above
background and, using the BATSE HERB data type, we determined the simultaneous gamma ray flux. This is used below to find an instantaneous $\gamma_\gamma$ in addition to the fluence over time to image figure used in the table. For 951124 (Figure 1) the first camera imaged the burst at t+23 seconds, and spatial coverage for that camera alone was 21%. Our instantaneous fit for the gamma ray flux gives $\gamma_\gamma = 0.42 \text{ photons cm}^{-2} \text{ s}^{-1}$ at t+23 seconds, or a ratio $\gamma_{\text{opt}}/\gamma_\gamma = 4700$. The remainder of the error box, with an additional 64% coverage, was imaged by another camera at t+29 seconds. The instantaneous gamma ray fit at t+29 seconds gives $\gamma_\gamma = 0.23 \text{ photons cm}^{-2} \text{ s}^{-1}$, or $\gamma_{\text{opt}}/\gamma_\gamma = 9700$. The second of these two bursts, 951220, was imaged by a single camera with 95% spatial detection probability. Our instantaneous gamma ray flux fit gives $\gamma_\gamma = 0.21 \text{ photons cm}^{-2} \text{ s}^{-1}$ at the exposure time of t+15 seconds, for a instantaneous ratio $\gamma_{\text{opt}}/\gamma_\gamma = 15000$.

5. Discussion

The GROCSE contemporaneous optical counterpart emission limits are the deepest yet established in this field, with the most extensive spatial coverage. While no single event can claim complete coverage, the spatial probability of GROCSE having missed all 12 counterparts is less than 1 in $10^6$.

ETC has reported similar visual magnitude limits for six bursts (Krimm et al. 1996). The ETC spatial detection probability is much less than for GROCSE in most cases, but three of their simultaneous five second exposures observed portions of the burst error box over the entire period of gamma ray emission recorded by BATSE. Their best published of these limits is for burst 940305 for which they quote a limiting $m_V(1 \text{ sec flash}) = 7.7$ and an optical limit across their 400 to 750 nm bandpass of $2.8 \times 10^{-9} \text{ erg cm}^{-2}$. This gives an approximate ratio $\gamma_{\text{opt}}/\gamma_\gamma = 17500$. Other ETC events produce ratios similar to those reported here for GROCSE.

It is not entirely surprising that GROCSE and other experiments have not yet detected
optical counterparts. Using the bremsstrahlung assumption for the low energy GRB tail as discussed above, the very brightest bursts would have optical counterparts of $m_V > 9$, with a typical burst producing an $m_V \sim 14$ flash, and the brightest 10% of all bursts would have $m_V \sim 10$. Ford and Band (1996) presented a more detailed prediction, fitting spectra to 54 bright bursts using Band’s four parameter model to extrapolate a flux in the optical V-band. Under the most optimistic assumptions, the results predict, at best, that the brightest counterpart in their sample would have been just beyond detection by GROCSE under even the best seeing conditions and none of the bursts in the GROCSE sample could have been detected. GROCSE only observed approximately 2% of the bursts detected by BATSE, and only one of the 12 bursts was observed under ideal conditions. Thus the detection of a “once a year” burst bright enough to produce a counterpart at the GROCSE detection limit was unlikely in the two year span of these observations.

6. Conclusions

In over two years of operation, GROCSE has ruled out any possible counterpart candidates for twelve bursts down to magnitudes as dim as $m_V = 8.5$ with near complete spatial coverage. Further, GROCSE has demonstrated the feasibility of simultaneous optical counterpart searches using realtime BATSE data processed by BACODINE. The GROCSE limits are consistent with the results of Ford and Band (1996) which predict observable optical counterparts no lower than $m_V \sim 10$. Many GRB theories (Mészáros & Rees 1996; Katz 1994) predict optical counterparts of $m_V \sim 9 - 14$ fading rapidly within a few $\times 1$ to $10^3$ seconds after the burst. Faster and more sensitive searches in this region are now commencing and should provide results within a year.

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Fig. 1.— Coverage of the error box for GRB951124 in three GROCSE camera images. The BATSE error box (circle) is centered on right ascension 73.3° declination 51.7° and has a 3-σ statistical plus 1.6° average systematic error radius (added in quadrature) of 3.8°. The IPN arc width is 0.18°. North is approximately towards the top of the figure, and the bright star visible in the lower left image is Capella.
Table 1. GROCSE Observations

| Name      | Trigger | $T_{90}$ | First IPN Error | mV | $F_{\text{opt}}$ | 20-2000 keV Fluence$^b$ | 20-2000 keV Fluence$^b$ | $\gamma_{\text{opt}}$ | $\gamma_{\text{opt}}/\gamma$ |
|-----------|---------|----------|-----------------|----|-----------------|--------------------------|--------------------------|-----------------|-----------------|
| 940129    | 2793    | 7.0      | 35 y            | 80%| 7.3             | 3200                     | 1.53 x 10^{-5}$^e$     | 16.1            | 4000            |
| 940623    | 3040    | 26.0     | 24$^d$ n        | 77%| 7.3             | 4100                     | 3.28 x 10^{-6}$^f$     | 30.9            | 5000            |
| 940828    | 3141    | 2.3      | 21 n            | 65%| 8.5             | 1100                     | 1.67 x 10^{-7}$^f$     | 1.24            | 1400            |
| 940907    | 3159    | 18.2     | 22$^d$ n        | 27%| 7.0             | 2400                     | 1.42 x 10^{-6}$^f$     | 12.3            | 2900            |
| 950531    | 3611    | 3        | 23 n            | 71%| 7.1             | 3600                     | 2.44 x 10^{-7}$^h$     | 4.43            | 4400            |
| 950907    | 3779    | 7        | 35 n            | 71%| 7.5             | 2200                     | 3.89 x 10^{-7}$^h$     | 15.7            | 2700            |
| 950918    | 3805    | 40       | 20$^d$ n        | 78%| 7.7             | 2200                     | 8.21 x 10^{-7}$^f$     | 3.80            | 2800            |
| 950922    | 3814    | 5        | 46 n            | 72%| 7.2             | 3800                     | 1.04 x 10^{-6}$^h$     | 4.68            | 4600            |
| 951117    | 3909    | 25       | 25$^d$ y        | 90%| 6.8             | 3100                     | 3.15 x 10^{-6}$^f$     | 29.5            | 3800            |
| 951124    | 3918    | 150      | 29$^d$ y        | 81%| 7.7             | 1800                     | 1.56 x 10^{-5}$^f$     | 50.5            | 2200            |
| 951208    | 3936    | 3.5      | 20 y            | 48%| 6.5             | 6000                     | 2.67 x 10^{-6}$^g$     | 3.39            | 7400            |
| 951220    | 4048    | 17       | 15$^d$ y        | 95%| 7.9             | 2600                     | 1.24 x 10^{-5}$^f$     | 42.2            | 3200            |

Note. — (a): photons cm$^{-2}$ s$^{-1}$ optical flux; (b): integrated fluence up to time of first GROCSE image; (c): fit constant for bremsstrahlung spectrum (photons cm$^{-2}$ s$^{-1}$); (d): first image taken while burst was still above BATSE threshold; (e): fluence from 3rd BATSE Catalog; fluence calculated from spectral fit to (f): HERB data; (g): SHERB data; (h): STTE data.
This figure "plate1.jpg" is available in "jpg" format from:

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