3-1996

Ground-based Gamma-Ray Burst Follow-up Efforts: Results of the First Two Years of the BATSE/COMPTEL/NMSU Rapid Response Network

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Recommended Citation

B. McNamara, T.E. Harrison, J. Ryan, R.M. Kippen, M. McConnell, J. Macri, C. Kouveliotou, G.J. Fishman, C.A. Meegan, D.A. Green, D.M. Koranyi, P.J. Warner, E.M. Waldram, L. Hanlon, K. Bennett, T.A.Th. Spoelstra, V.G. Metlov, N.V. Metlova, E. Feigelson, A.J. Beasley, D.M. Palmer, S.D. Barthelmy, D.E. Gary, E.T. Olsen, S. Levin, P.G. Wannier, M.A. Janssen, The MACHO Collaboration, J. Borovicka, P. Pravec, R. Hudec, and M.J. Coe. GROUND-BASED GAMMA-RAY BURST FOLLOW-UP EFFORTS: RESULTS OF THE FIRST TWO YEARS OF THE BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK. 1996, Ap. J. Suppl., 103, 173.

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THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 103:173–181, 1996 March

GROUND-BASED GAMMA-RAY BURST FOLLOW-UP EFFORTS: RESULTS OF THE FIRST TWO YEARS OF THE BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK

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Received 1995 June 15; accepted 1995 September 18

ABSTRACT

In this paper we describe the capabilities of the BATSE/COMPTEL/NMSU Rapid Response Network and report on results obtained during its first 2 years of operation. This network is a worldwide association of 22 radio and optical observatories that perform follow-up searches of newly discovered gamma-ray burst error boxes by the *Compton Gamma Ray Observatory.* During the last 2 years, it has deeply imaged 10 gamma-ray error boxes over time frames from a few hours to a month after burst detection, and it finds no sources that can be associated unambiguously with a gamma-ray burst. *We suggest that significant optical or radio emission is not produced by gamma-ray bursts more than a day after the burst.* This result is consistent with recent theoretical models by Katz, Mészáros, Rees, & Papathanassiou, and Paczyński & Rhoads; however, our hours to days optical response time and radio sensitivity limits allow only a weak constraint to be placed on these models. Based upon this study and other published works, we suggest that future work should concentrate on acquiring deep optical images ($m \geq 12$) of small gamma-ray error boxes well within a day of the burst. Ideally, radio observations should begin as soon after the burst as possible, reach a sensitivity of ≤ 1 mJy, and be continued with occasional images being acquired for at least a month following burst detection.

Subject heading: gamma rays: bursts

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[1] NRAO is operated by Associated Universities Inc., under contract with the National Science Foundation.
[2] For a list of the membership of the MACHO Collaboration, see ApJ, 449, 28 (1995).

1. INTRODUCTION

The BATSE/COMPTEL/NMSU Rapid Response Network (BCN network) is a worldwide system of optical and radio observatories. It was established in 1993 January to obtain rapid and deep follow-up observations of small gamma-ray burst (GRB) error boxes detected by NASA's *Compton Gamma Ray Observatory* (*CGRO*). The goal of the network is to discover the celestial objects responsible for gamma-ray bursts. The BCN network consists of 22 radio and optical observatories situated around the world that have deep imaging capabilities and wide fields of view. New Mexico State University (NMSU) serves as the coordinating institution for network activities.

The network relies upon gamma-ray burst localizations provided by the *CGRO* BATSE and COMPTEL instrument teams as well as the Inter-Planetary Network (IPN) headed by K. Hurley. It employs primarily COMPTEL localizations because they are quickly available and are generally less than 2° in diameter. The BATSE BACODINE system (Barthelmy et al. 1994a) serves as a secondary source of burst localizations. Strong BATSE-detected bursts produce error boxes about 8° in diameter (Fishman et al. 1994). Weak BATSE-detected bursts produce larger error boxes which are currently beyond the capability of our network to quickly and deeply image. A third source of positional data comes from the IPN (see Cline et al. 1993; Hurley et al. 1993). IPN positions, currently based on burst timing data from the *Ulysses* and *CGRO* spacecraft, are generally available within 2 days after the burst. The main use of the IPN data is in the subsequent examination of data acquired by the network.

The nominal COMPTEL field of view is about 1 sr, and therefore approximately $\frac{1}{12}$ of all BATSE-detected bursts can be potentially imaged by COMPTEL. Not all these bursts, however, possess sufficient high-energy flux to be detected. A minimum of about 40 photons (depending on the angle between the burst and the axis of the instrument) are needed to produce a 1° error box. Bursts meeting this criterion occur at the rate of about one every 1.5 months. The procedure used to localize COMPTEL bursts has been described by Kippen et al. (1993).

In this paper we describe the BCN network and present the results of its first 2 years of operation. The implications of these studies for future GRB follow-up efforts are discussed. Finally, the approach that the BCN network will pursue for future GRB follow-up efforts is presented.

2. PREVIOUS GAMMA-RAY BURST FOLLOW-UP WORK

Since the early 1970s, numerous GRB error boxes have been examined at different wavelengths and over a variety of post-burst detection time periods. These investigations generally attempted to identify GRB counterparts by searching small IPN, WATCH (Castro-Tirado et al. 1994a), or COMPTEL error boxes for objects that possess erratic, short-term variability, an unusual energy spectrum, or a gradually fading signal. Below we summarize GRB follow-up work at optical and radio wavelengths with particular emphasis on the flux limit reached and the time between burst detection and the subsequent imaging of its error box.

2.1. *Radio GRB Follow-up Work*

Although work at radio wavelengths has not been as extensive as in the optical domain, a considerable effort has been undertaken to identify GRB counterparts. Hjellming & Ewald (1981) used the Very Large Array (VLA) at 4.8 and 1.4 GHz with a sensitivity limit of ≤ 1.0 mJy to search for variable, nonthermal emission within the error box of GRB 781119 about 1.8 yr after the occurrence of this burst. Inzani et al. (1982) used an automated radio telescope operating at 408 and 151 MHz to obtain simultaneous coverage of 65 GRBs between 1976 and 1979. The sensitivity limit of their system was $\sim 10^{-13}$ ergs cm^{-2} s^{-1} (66 Jy). Schaefer et al. (1989) surveyed 10 small GRB error boxes using the VLA at 14, 4.8, and 1.4 GHz (sensitivity 0.1–0.8 mJy) for peculiar radio emitters more than 5.5 yr after these bursts were detected. Koranyi et al. (1994) reported observations at 151 MHz made with the Cambridge Low Frequency Synthesis Telescope (CLFST) of the error box of GRB 920711 within 2 days of the BATSE burst detection. No variability with respect to the 6C images of this field were found to ±40 mJy. Frail et al. (1994) used the Dominion Radio Astrophysical Observatory Synthesis Telescope at 1.4 and 0.4 GHz to search for a flaring or fading source to GRB 940301. Their sensitivity limits were 3.5 mJy and 55 mJy, respectively. The extensive temporal coverage of the Frail et al. study is unique: Observations were obtained during the period 3–15 days after the burst and additional observations were obtained at 26, 47, and 99 days after the burst. Hanlon et al. (1995) report on Westerbork observations of this burst, including the detection of a number of radio sources within the final error annulus. They found an upper limit of 40 mJy at 92 cm for any variable sources.

2.2. *Infrared and Optical Follow-up Work*

In the infrared, Apparao & Allen (1982) scanned three small GRB error boxes using the 3.9 m Anglo-Australian telescope. All three boxes were examined to $J \sim 17.5$. Schaefer et al. (1987) searched seven additional GRB error boxes to a magnitude limit of $K = 13.6$–19 and used *IRAS* observations at 12, 25, 60, and 100 μm to examine the error boxes of 23 GRBs at a sensitivity of about 0.5 Jy. These IR studies examined the GRB error boxes at least 1.5 yr after burst detection.

Numerous optical studies of GRB error boxes have been completed. Recent deep searches covering the magnitude range 15–20 have been reported by Castro-Tirado et al. (1994b), Schaefer et al. (1994), McNamara & Harrison (1994), and Barthelmy, Palmen & Schaefer (1994b). These studies commenced 12 hr to 16 days after burst detection and employed either *CGRO* or WATCH positions. A recent effort by Boer et al. (1994) is summarized in Table 1. That study employed the ESO Schmidt telescope and reached a limiting magnitude of 15–20. Its quickest response time was 0.98 days, and its average response time was 7.6 days. That study serves as a good example of the type of response time that can be expected from a target-of-opportunity program at a national observatory. *Simultaneous* optical observations have also been reported by Hudec & Soldan (1994) for 30 BATSE GRB error boxes using a network of 12 fish-eye cameras at 10 stations.

TABLE 1

THE ESO-SCHMIDT SURVEY OF GRBS
(BOER ET AL. 1994)

GRB	$T_{\rm OBS} - T_{\rm GRB}$ (days)	Limiting Magnitude
920311	2.09	$R = 17$
	10.9	$B = 18$
	13.9	$R = 20$
920406	16.2	$R = 18$
	26.2	$B = 18$
	33.2	...
	34.2	...
920501	11.1	$R = 17$
	13.1	$B = 20$
	20.1	$R = 22$
920517	1.9	$R = 17$
	3.01	$B = 15$
	3.03	...
920525	7.1	$B = 17$
920830	1.0	$R = 16$
921123	4.8	$B = 16$
930118	1.6	$V = 18$
930131	17.5	...
	22.4	$V = 19$

This system can reach a limiting stellar magnitude of 7–11 and can detect a 1 s optical flash provided it is brighter than third magnitude. The Explosive Transient Camera (ETC) project (see Krimm, Vanderspek, & Ricker 1994; Vanderspek & Ricker 1995) has reported four simultaneous images of GRB error boxes. Their limiting magnitude for a 1 s flash ranged from 5.8 to 8.0. They also obtained data with a limiting magnitude of 10.2 for GRB 941014 90 s after the end of the burst. Greiner et al. (1994) examined 16 BATSE error boxes with response times ranging from 1–25 hr. Their plate material typically covered 74% of a BATSE error box and would have detected a 1 s flash if it had been brighter than about 6.4 mag. Their deepest, quickest search would have detected a 10th magnitude GRB counterpart 3.2 hr after the burst.

3. THE BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK

The global distribution of the BCN network is shown in Figures 1*a* and 1*b*. It currently consists of five radio and 17 optical observatories. Observing time at some of these sites has been granted to individuals on a target-of-opportunity basis. Our network supports those efforts by providing COMPTEL localizations. These figures show that the network possesses a redundant geographic coverage, especially in optical sites. This redundancy improves the network's ability to image GRB error boxes by alleviating problems associated with locally bad weather, observatory instrument problems, and scheduling conflicts. The last point is an important consideration. Our network is intended to respond quickly to *randomly* occurring events. Because of their very nature, not all sites are able to respond to each alert.

An important contributor to the BCN network is the Air Force GEODSS system (see Beatty 1982). This subnet consists of three observatories located at Socorro, New Mexico; Maui, Hawaii; and Diego Garcia in the Indian Ocean. The primary mission of these facilities is to track Earth-orbiting debris, but their capabilities are very well suited to our GRB follow-up program. The instrumentation available at each GEODSS site is listed in Table 2. The advantages of the GEODSS to our effort are (1) they employ the largest wide-field-of-view telescopes in the world, (2) their 40 inch telescopes can reach a limiting magnitude of 17.3 in less than 4 s, (3) they are a global network, (4) their near-equator location augments our southern sky coverage, (5) their data can be obtained in either a video or digital form (the digital images can be manipulated using IRAF, while the video allows the field to be monitored *continuously* for many tens of minutes), (6) their imaging sites can be contacted directly by telephone to insure a rapid response time, and (7) their sites are continuously manned, regardless of lunar phase. This last feature is vital, since it is rare for large astronomical wide-field-of-view telescopes to be operating near full moon. The GEODSS system provides the bulk of our optical data during periods of bright moon.

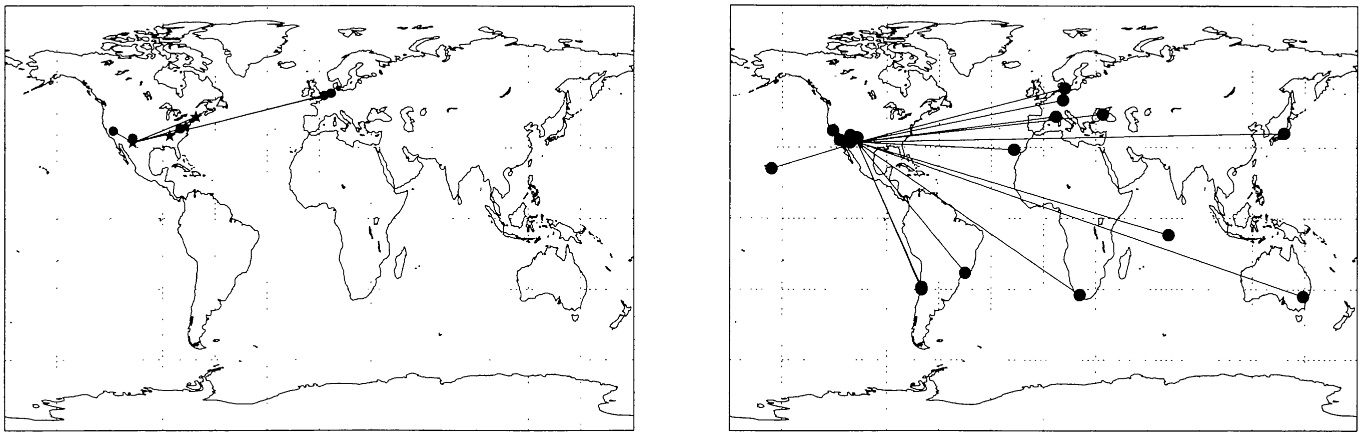

FIG. 1*a*

FIG. 1*b*

FIG. 1.—The BATSE/COMPTEL/NMSU Rapid Response Network's global coverage. (*a*) Radio sites (*filled circles*) and data processing sites (*filled stars*); (*b*) optical sites (*filled circles*).

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TABLE 2

THE GEODDS NETWORK

Site	Instrumentation	Field of View	$M_{\lim}$ (0.6 s exposure)
Socorro, NM	Two 40 inch telescopes	2° × 2°, or 1° × 1°	$V \leq 17.0$
	One 16 inch telescope	6° × 6°, or 3° × 3°	$V \leq 15.0$
Maui, Hawaii	Two 40 inch telescopes	2° × 2°, or 1° × 1°	$V \leq 17.0$
	One 16 inch telescope	6° × 6°, or 3° × 3°	$V \leq 15.0$
Diego Garcia	Three 40 inch telescopes	2° × 2°, or 1° × 1°	$V \leq 17.0$

4. RESPONSES BY THE BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK

A list of the BCN network responses during its first 2 years of operation is given in Table 3. We note that significant progress has been made at decreasing the optical response time during our first 2 years of operation. The average optical response for the first three bursts was 1.6 days, compared to 0.46 days for the last three bursts. As will be shown below, our radio response times have often been significantly less than 1 day. Since the network consists of large-aperture instruments, faint flux limits are reached in both the optical and radio. Below we discuss three interesting bursts imaged by our network.

4.1. *GRB 940301*

This burst was detected by the CGRO on March 1, 20:10:37 U.T. It was a strong, hard burst having a fluence above 0.6 MeV of 1.8×10^{-5} ergs cm^{-2}. It possessed similarities to an earlier burst, GRB 930701. Both bursts were sufficiently strong and hard to be detected by COMPTEL, and had similar durations (around 40 s), light curves, and celestial positions. Kippen et al. (1995) found that the likelihood that two unassociated COMPTEL bursts would randomly appear this close together in the sky was less than 3%. The IPN tracks of these bursts intersect within the COMPTEL 1.5 σ error box. These similarities have led to the suggestion that they arose from the same source. If true, this would be the first classical GRB observed to repeat and would make untenable cosmological models for the origin or gamma-ray bursts that rely on one time events. Based upon a pre-alert by our network, the error box of GRB 940301 was first monitored (in a special radio spike-detection mode) at the Mullard Radio Astronomy Observatory at Cambridge 1.03 hr after burst detection (see Koranyi et al. 1995). A second radio observation, and the first optical image, were obtained about 7 hr after burst detection. These response times established new records in their wavelength regions. The complete network response (adapted from Harrison et al. 1995) is shown in Table 4. Although no unusual objects were discovered, two important constraints were established. The limit to the optical flux of the GRB counterpart soon after its occurrence was decreased by a factor of 2000, from $F_{\rm opt} < 5 \times 10^{-3}\, F_\gamma$ (Greiner et al. 1994) to $F_{\rm opt} < 2.5 \times 10^{-6}\, F_\gamma$. Second, no new radio sources were detected within hours of the burst, and none developed in the days and weeks following the GRB. The theory by Paczyński & Rhoads (1993) predicts that a short-lived radio transient should arise from a GRB.

4.2. *GRB 940217*

GRB 940217 is particularly noteworthy because it was one of the strongest long-duration GRBs detected by *CGRO* since

TABLE 3

BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK COVERAGE

Name	Burst Origin	Δt (days)	Depth of Earliest Response Covering Error Box	Notes
GRB 930131	COMPTEL	0.28/1.46	$m = 6.5/20.5$	First network alert
GRB 930309	COMPTEL	. . .	. . .	No observations were obtained
GRB 930805	BATSE	1.5	3° of IPN to $V = 15.0$	Tape was classified
GRB 931014	BATSE	1.45	2.5° of IPN to $V = 15.0$	Only sent to GEODSS
GRB 931031	BATSE	2.87	3° of IPN to $V = 15.0$	13$^{\rm m}$ Optical Transient 2′ from IPN
GRB 931204	BATSE	. . .	. . .	No observations were obtained
GRB 931221	COMPTEL	. . .	. . .	No observations were obtained
GRB 931226	BATSE	3.66	3° of IPN to $V = 12.0$	No unusual objects found
GRB 940128	COMPTEL	1.69	14° of IPN to $V = 12.0$	Very weak COMPTEL burst
GRB 940210	BATSE	3.0	10° × 10° to $V = 13.0$	Northern burst to Crimea only
GRB 940217	COMPTEL	0.71	±500 mJy at 151 MHz	Unusual, long-duration burst; Good network radio coverage
GRB 940301	COMPTEL	0.31	4.5° of IPN to $V = 16$	Possible repeating burst? Good temporal and wavelength coverage
GRB 940520	COMPTEL	0.37	4.5° of IPN to $V = 16$	. . .
GRB 940728	COMPTEL	. . .	. . .	Only UK Schmidt was notified
GRB 940921	COMPTEL	. . .	. . .	Quickest COMPTEL localization (0.06 day); No observations made

TABLE 4

Network Response to GRB 940301

Network Site	Δt(observed − burst) (days)	Instrument	Areal Coverage (deg^2)	Wavelength, Depth
MRAO	0.04	CLFST	12	151 MHz[a]
DSS 13, Goldstone, CA	0.28	34 m BWGA, WBSA[b]	12	8.42 GHz, ≥80 mJy
GEODSS, Socorro	0.29	1 m Schmidt	10	$m_V = 16$
GEODSS, Maui	0.38	1 m Schmidt	10	$m_V = 16$
MRAO	0.745	CLFST	16	151 MHz, ≥200 mJy
	1.742	CLFST	16	151 MHz, ≥200 mJy
Crimea Astrophysical Observatory	1.90	0.5 m Maksutov	9	$m_{pg} = 18$
Observatory de la Cote d'Azur	2.08	0.9 m Schmidt	25	$m_R = 19.5$
Sonneberg	2.96	0.4 m Astrograph	64	$m_{pg} = 17$
Upice Observatory	3.10	0.35 m Astrograph	56	$m_{pg} = 15$
Penticton	3.15[c]	DRAO Synthesis	4	21 cm, ≥5 mJy,
			64	74 cm, ≥50 mJy
Observatory de la Cote d'Azur	4.04	0.9 m Schmidt	25	$m_B = 22$
	4.95	0.9 m Schmidt	25	$m_B = 22$
MRAO	6.73	CLFST	16	151 MHz, ≥200 mJy
Sonneberg	8.96	0.4 m Astrograph	64	$m_{pg} = 17$
Copenhagen University Observatory	9.05	0.5 m Brorfelde Schmidt	1.6	$m_R = 18$
Upice Observatory	10.04	0.35 m Astrograph	56	$m_{pg} = 15$
MRAO	15.70	CLFST	16	151 MHz, ≥200 mJy
Westerbork	32.0	Westerbork Synthesis Radio Telescope	27	92 cm, ≥30 mJy

[a] These observations were made using the CLFST in a special spike-detection mode, and the limiting flux is presently unknown.

[b] BWGA = beam-waveguide antenna; WBSA = wide-band spectrum analyzer.

[c] Observations with the Dominion Radio Astronomy Observatory (DRAO) Synthesis Telescope began on 4.99 March (UT) and continued daily for the next 13 days (except for 9.0 March).

its launch in 1991 April. It also possessed a hard spectrum and was detected by the EGRET, BATSE, and COMPTEL instruments of the CGRO, and by the *Ulysses* spacecraft. BATSE and *Ulysses* detected this event for approximately 170 s and found that it possessed several well-separated, discrete emission peaks. COMPTEL observed six separate emission peaks during this time (Winkler et al. 1995). EGRET detected 28 photons from this burst in energy from 44 MeV to 18 GeV over a 90 minute time period (Hurley et al. 1994). The network response to GRB 940217 is presented in Table 5. The radio coverage was quite good, starting 0.32 days after burst detection. This burst was not well suited for optical observations because of its proximity to the Sun. The first optical response was obtained 26.5 hr after burst detection. Despite the timely response of our network, we were unable to identify any new optical or radio sources inside this burst's error box.

4.3. *GRB 940520*

Figure 2*a* shows the various localizations for GRB 940520 provided to the network by the BACODINE, COMPTEL, and IPN teams. The order in which these positions became available were BACODINE (seconds), COMPTEL (3.0 hr), and IPN (6 months). There is an inverse relation between the accuracy of these localizations and the postburst time over which they become available. For a medium-strength burst such as

TABLE 5

Network Response to GRB 940217

Network Site	Δt (days)	Instrument	Areal Coverage	Wavelength, Depth
Australia Telescope	0.32	Compact Array	$22' \times 17'$	1.4 GHz, ≥0.01 Jy
Westerbork	0.70	WSRT	0.57 deg^2	1.4 GHz, ≥30 mJy
VLBA	0.75	VLBA	5.0 deg^2	1.6 GHz, ≥15 Jy
Owens Valley, CA	0.84	OVRO Solar Array	1 deg^2	1.4 GHz, ≥0.80 Jy 1.6 GHz, ≥0.48 Jy
VLA	0.94	VLA, D	2 deg^2	N/A
DSS 13, Goldstone	1.0	34 m, BWGA	3 σ error box	8.42 GHz, ≥100 mJy
UK Schmidt	1.39	1.2 m Schmidt	6° × 6°	$R = 20$
MACHO Project	1.42	1.3 m Cassegrain	$10' \times 20'$	$R = 20$
Ondrejov Observatory	1.79	0.18 m Astrograph	2 σ box	$R = 14$
DSS 13	5.0	34 m, BWGA	1.2 deg^2	8.4 GHz, ≥50 mJy
Westerbork	11.0	WSRT	0.02 deg^2	4.874 GHz, ≥30 mJy

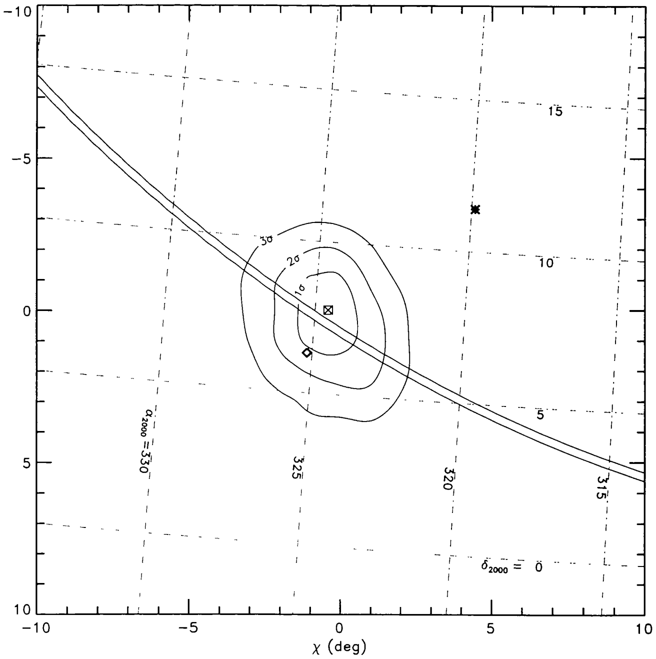

FIG. 2*a*

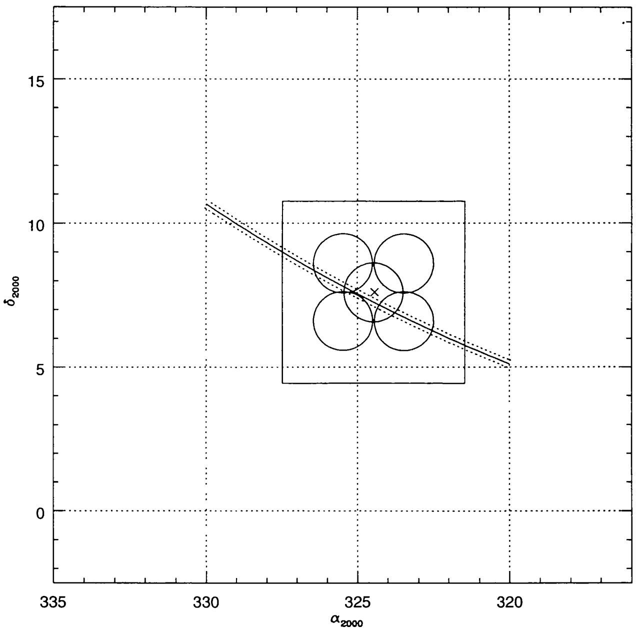

FIG. 2*b*

FIG. 2.—(*a*) The BACODINE (*stars*), BATSE (*open diamonds*), COMPTEL (*circular contours*), and IPN (*concentric annuli*) localizations for GRB 940520. (*b*) The network coverage of the GRB 940520 error box. The filled circles represent the field of view of the Airforce GEODSS telescopes, while the filled square is the coverage of the UK Schmidt plate. The IPN localization is indicated by the parallel arc, while the cross marks the COMPTEL maximum likelihood position. The GEODSS observations were obtained 0.37 days after the burst, and the UK Schmidt plate was obtained 0.77 days after the burst.

GRB 940520, BACODINE positions can have an error circle up to 10° in diameter, BATSE error circles typically have a diameter of at least 5°, and COMPTEL localizations have an error box of about 2°. The IPN annulus is a few arcminutes wide but extends around the entire sky. Figure 2*b* shows our network's optical coverage for this burst. The five filled circles represent GEODSS images that extend to $V \sim 16.0$. Each circle represents a cumulative exposure time of 20 s. The entire series of five images required less than 2 minutes of telescope time. This figure illustrates the value of the GEODSS system. It can obtain a mosaic of deep images, over a wide field of view, in a small amount of time. GEODSS images of this field were obtained 8.9 and 22.8 hr after the burst. The solid box shows the coverage provided by a UK Schmidt plate obtained 18 hr after the burst. A careful examination of the intersection of the IPN with the COMPTEL error box revealed no new source down to the level of the POSS.

4.4. *Other Bursts with Network Follow-up*

The network responses to other bursts are listed in Table 3. Five of the 15 bursts for which alerts were sent did not have optical or radio follow-up. This was attributable either to their proximity to the Sun or other visibility-related problems (e.g., low elevation or poor weather). Three of the 15 network follow ups have been discussed above. The other bursts for which ground-based coverage exists were primarily observed by the Airforce GEODSS network. Except for GRB 931031, where a 13th magnitude optical transient was found 1′.4 from the edge of the IPN, no unusual objects were found in or near the combined COMPTEL (or BATSE) + IPN error boxes. A CCD image obtained at the position of the GRB 931031 "transient" (see Fig. 3) 104 days after the burst shows no objects brighter than $V \approx 18.0$ at this position (R. M. Wagner, private communication). The approximate position (±15″) of the optical transient was $\alpha_{2000} = 21^{\rm h}43^{\rm m}36^{\rm s}$, $\delta_{2000} = +61°56'23''$. Owing to the fact that the image was obtained on an uncalibrated, unfiltered video of 20 s duration, no exact calibration of its position or true brightness was possible.

5. IMPLICATIONS FOR FUTURE GRB FOLLOW-UP STUDIES

Past studies as well as the results presented in this paper have explored, at a variety of wavelengths and time frames, numerous GRB error boxes. *No celestial objects associated with a GRB have been convincingly detected.* The simultaneous optical imaging of GRB error boxes by Hudec & Soldan (1994) and Greiner et al. (1994) have shown that optical GRB counterparts brighter than about 5th magnitude do not exist. The work by the BCN network, and others discussed above, have also failed to find a new or fading object at optical wavelengths a day or longer after burst detection to magnitude limits of 16–22. Radio searches of small GRB error boxes, conducted with high sensitivity but long after the detection of the burst, have failed to find a counterpart. Wide field-of-view searches conducted within hours after a GRB at modest sensitivity have likewise been unsuccessful. X-ray studies of small GRB error boxes have not been successful at identifying candidate sources of these events down to a flux limit of 10^{-13} ergs cm^{-2} s^{-1}. Based on the above studies, it appears that the next optical

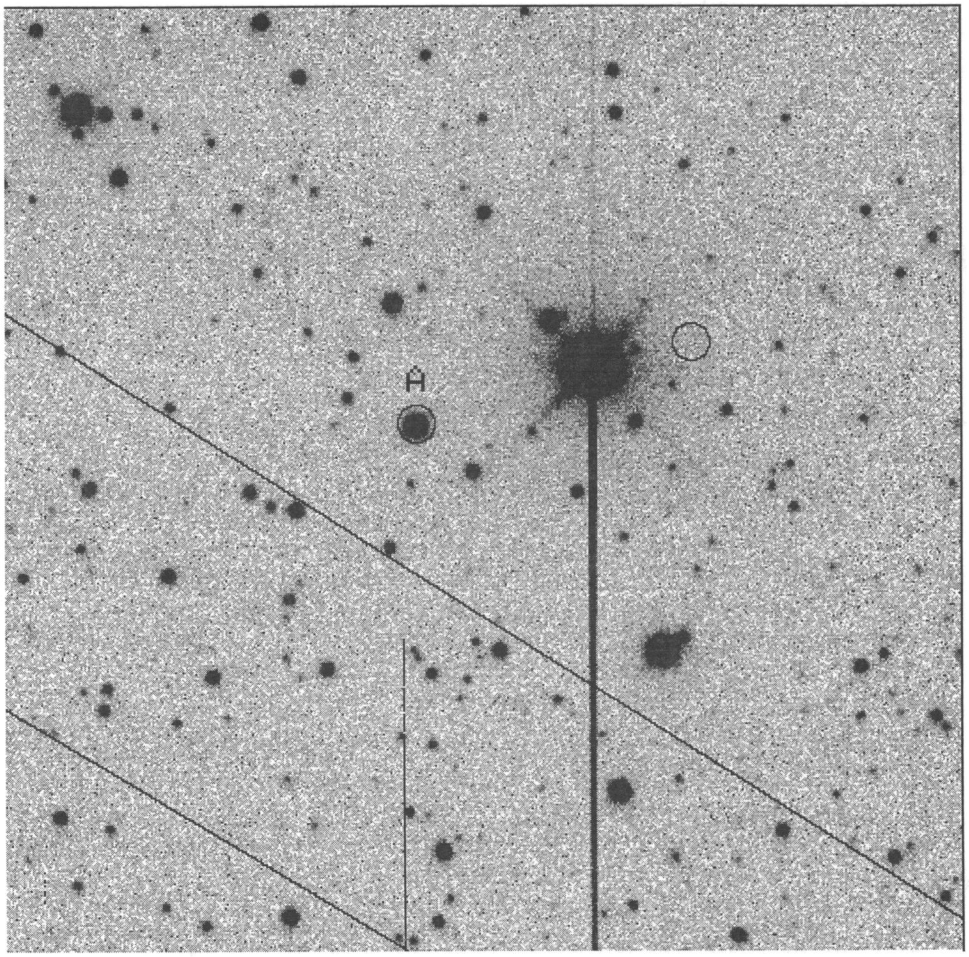

FIG. 3.—An *R*-band CCD image at the position of the optical transient (indicated by the open circle) for GRB 931031. The bright star is SAO 19604. The circled star labeled with an "A" was estimated to be the same brightness as the optical transient on the video display. The diagonal lines enclose the IPN annulus for this burst (the vertical line is a CCD defect). The position of the optical transient lies 1'.4 from the edge of the IPN annulus.

phase of burst follow-up work should concentrate on acquiring deep images ($m > 12$) of GRB error boxes, well within a day of burst detection. X-ray and radio follow-up work must be either more timely or reach lower flux limits. Like past studies, these new efforts may not be able to identify candidate GRB sites. If so, specialized ground-based telescopes or satellites, such as *HETE* (Ricker et al. 1992), may be required to make further contributions to this field.

6. FUTURE BATSE/COMPTEL/NMSU RAPID RESPONSE NETWORK PLANS

Before becoming overly pessimistic about the search for GRB counterparts at other wavelengths, it is instructive to compare Tables 4 and 5 with past efforts. Table 6 summarizes an early multiwavelength effort dealing with GRB 781119 in which response times are measured in years. Results from our *first* GRB burst network alert were included in the study by Schaefer et al. (1994). The first deep, wide field of view image acquired in that effort was obtained only 1.46 days after burst detection. Our other network responses are typically a day or less. Compared to the early study on GRB 781119, our current network response times have decreased by a factor of over 1000.

Although these times are a definite improvement over past efforts, they have not been adequate to identify a GRB counterpart; a further decrease in the deep imaging response time is therefore needed. Efforts toward meeting this goal are already underway. The time needed to generate a COMPTEL position has recently decreased from 4 hr to ~10–20 minutes. Additional software improvements should reduce this computational time to less than 5 minutes. Our new short-term goal is to constrain further the parameter space in which a GRB counterpart might exist by obtaining optical images to 17th magnitude, and radio images to ~1–3 mJy, within 15 minutes of burst detection. This radio limit imposes severe constraints on available instrumentation, as the instruments operating in this sensitivity regime have small fields of view and therefore require a mosaic to cover the appropriate areas. If radio studies at the required sensitivities are to be made, then a plan for obtaining the observations should be made a priori. An additional aspect of radio observations is the fact that previous images of the burst fields at a particular frequency may not exist. While several sky surveys at common wavelengths have been

TABLE 6

GRB 781119

Wavelength	$T_{\rm obs} - T_{\rm GRB}$ (yr)	Wavelengths/Filters	Limiting Flux/Magnitude	Reference
Optical	3	B, V	≤ 23.0	1
	3	3700–6250 Å	≤ 23.8	2
	3–4	B, V, R, g, r, i	$R = 22.9$–25.5	3
	4	U, B, V, r	$B \leq 25.0$	4
Infrared	2	1.2, 1.6, 2.2 μm	$J \leq 18$	5
	3	2.2 μm	$K \leq 18.8$	2
	7	2.2 μm	$K \leq 19.03$	6
	5	12, 25, 60, 100 μm	≥ 0.5–1.5 Jy	6
Radio	2	6 cm, 20 cm	≥ 0.9–2.5 mJy	7
	6	2 cm	≥ 0.025 mJy	8

REFERENCES.—(1) Schaefer 1981. (2) Schaefer & Ricker 1983. (3) Pederson et al. 1983. (4) Seitzer et al. 1983. (5) Apparao & Allen 1982. (6) Schaefer et al. 1987. (7) Hjellming & Ewald 1981. (8) Schaefer et al. 1989.

completed or are nearing completion (e.g., the NVSS [Condon et al. 1995] or FIRST [Becker, White, & Helfand 1994]), allowing a pre-burst comparison of the follow-up observations, multiepoch observations remain the surest way to identify an object that may have undergone an outburst.

7. DISCUSSION

Some insight into the time delay and signal strength that a GRB might produce at various energies has been provided by Katz (1994). In his model, a GRB is produced when the debris shell from a relativistic fireball interacts with the surrounding medium. After the GRB, the fireball continues to radiate at a wavelength which increases with time. The peak emission at a given wavelength follows the GRB after a time $t(\lambda) \sim (\lambda/\lambda_\gamma)^{5/12} t_\gamma$, where λ_γ and t_γ are the wavelength and duration of the burst at its detected γ-ray energy and $t(\lambda)$ is the time of peak emission at some other wavelength. The peak flux scales as $f(\lambda)/f(\lambda_\gamma) = (\lambda_\gamma/\lambda)^{1/3}$. For a typical bright GRB, this model predicts that an optical counterpart should occur within minutes of the GRB and reach a visual magnitude near 14. At radio wavelengths, the peak emission can occur a day or longer after the burst, but the signal strength is expected to be <10 mJy. If this model is even approximately correct, it will be necessary to deeply image GRB fields within minutes at optical wavelengths, or within days at radio wavelengths, in order to maximize the chance that a counterpart will be detected.

During the first 2 years of operation, the BCN network obtained radio and optical observations of 10 GRBs. Many of these set new response records for the multiwavelength, deep imaging of GRB error boxes. No fading optical or radio counterparts were discovered on timescales extending from a few hours to many days. Based upon these observations, we suggest that GRBs do not produce significant optical or radio emission over these time periods. Specifically, we find $F_{\rm opt}$ (at t = 7 hr) $< 2.5 \times 10^{-6}\ F_\gamma$, and $F_{\rm radio}$ (t = 0.3 day) $< 2.0 \times 10^{-10}\ F_\gamma$. For *simultaneous* follow-up optical work, Greiner et al. (1994) estimate that $F_{\rm opt} < 3.0 \times 10^{-3}\ F_\gamma$. These results can only be used as a modest constraint on recent theoretical models by Katz and others which suggest that a GRB produces low-level emission at other wavelengths. Optical emission is expected to peak at relatively faint magnitudes ($V > 14$) on a scale of minutes after the burst. We have not, as yet, been able to obtain a response time quick enough to test this prediction. We expect to challenge this regime seriously by fall 1995. Radio emission is expected to peak many hours or days after the burst. Although our time coverage was adequate, our flux limit (>30 mJy) was generally too high to provide a good model constraint. The study by Frail et al. (1994), whose observations are included in Table 4, reached a sensitivity limit of 3.5 mJy at 1.4 GHz. No new or fading source was detected in that study. This flux limit is near, but still above, the value needed to test the theory of Paczyński & Rhodes (1993). It is also close to the limits predicted by Katz. The reader is referred to the paper by Frail et al. for more detailed information.

The BCN network is working hard to decrease its response time and detection limits. The Air Force GEODSS system will continue to play a particularly important role. It gives our network a capability that is a factor of about 2000 better than that obtained by normal astronomical target-of-opportunity programs at national observatories. Working in its frame capture mode, a GEODSS 40 inch telescope can image a 2° × 2° field to V near 17.5 in less than 4 s. This will considerably improve our limit on $F_{\rm opt}/F_\gamma$ shortly after the occurrence of a GRB. The GEODSS system also gives us a unique capability of obtaining continuous video images of small GRB error boxes to V near 16. If the theoretical prediction that the peak optical emission follows the high-energy emission by many minutes is correct, we have a real chance of directly observing the optical counterpart of a GRB in 1995 using the GEODSS telescopes in their video data collection mode.

This work has been supported under the *Compton Gamma Ray Observatory* guest investigator program, NASA grant NAG 5-2356. The staff of the UK Schmidt at the Anglo-Australian Observatory is thanked for taking some of the films.

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