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GAMMA-RAY BURST ARRIVAL TIME LOCALIZATIONS: SIMULTANEOUS OBSERVATIONS BY *MARS OBSERVER*, *COMPTON GAMMA RAY OBSERVATORY*, AND *ULYSSES*

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ABSTRACT

Between 1992 October 4 and 1993 August 1, concurrent coverage by the *Compton Gamma Ray Observatory* (*CGRO*), *Mars Observer* (*MO*), and *Ulysses* spacecraft was obtained for 78 gamma-ray bursts (GRBs). Although most of these were below the *MO* and *Ulysses* thresholds, nine were positively detected by all three spacecraft, with data quality adequate for quantitative localization analysis. All were localized independently to $\sim 2^\circ$ accuracy by the *CGRO* Burst and Transient Source Experiment (BATSE). We computed arrival-time error boxes with larger dimensions ranging from a few arcminutes to the diameters of the BATSE-only boxes and with smaller dimensions in the arcminute range. Three events are of particular interest: GB 930704 (BATSE 2428) has been described as a possible repeater. The arrival-time information is consistent with that hypothesis, but only just so. The GB 930706 (2431) box, at $\sim 1' \times 4'$, is the only one this small obtained since *Pioneer Venus Orbiter* (*PVO*) entered the Venusian atmosphere in 1992 October. Sensitive radio and optical observations of this location were made within 8 and 9 days of the burst, but no counterpart candidates were identified. GB 930801 (2477) is the first GRB that had its localization improved by taking into account BATSE Earth occultation.

Subject headings: gamma rays: bursts — gamma rays: observations

1. INTRODUCTION

During the years immediately following the discovery of gamma-ray bursts (GRBs), many researchers believed that a few accurate locations would lead quickly to an understanding of the GRB phenomenon. Thus, beginning in the late 1970s GRB detectors were placed on various interplanetary and solar system probes, achieving interplanetary networks (IPNs) that produced arminute-sized error boxes calculated by arrival time analysis. While the original optimistic expectations were not realized, accurate locations continue to be of paramount interest. Applications include the classical deep counterpart searches, archival searches, and error box monitoring, the purpose of which is to reveal specific burster counterparts. Unfortunately, while these activities have led to considerable interesting work and a few possible detections (see Schaefer 1994 for a review; Hurley et al. 1996), they have not yet given us a breakthrough. Attempts to detect prompt counterparts have lately received increased effort, but such measurements are very difficult and may not fare any better. Therefore, it is necessary to also explore indirect means of determining the general sites of the bursts (as opposed to the site of a specific GRB). These include (but are not limited to) global distribution analyses, repetition studies, and field characterization. For example, if the sources are found to repeat, they are unlikely to be at cosmological distances because the required burst energies would almost certainly be destructive. An example of field characterization to determine the probability of a cosmological origin is a recent study involving luminous galaxy counts in the vicinity of unpublished small error boxes (Larson, McLean, & Becklin 1995; but see Schaefer 1994 for a discussion of the so-called "no host galaxy problem"). Distribution analyses have used statistical tests to search for correlations with known, primarily Galactic, populations. All of these applications—with the possible exception of the simplest distribution analyses—require relatively large numbers of locations with accuracies that only the IPNs have been able to produce thus far.

In this paper we present quantitative localization infor-

mation on nine events that were simultaneously detected by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* (*CGRO*), *Mars Observer* (*MO*), and *Ulysses*. A previous paper (Laros et al. 1995) covered these same events, plus two others having lower data quality, from the standpoint of verifying the BATSE accuracy. We found that the average angular separation between the BATSE and IPN locations was 2°.0, which is entirely compatible with the claimed precision of all the boxes. Our best localization has arcminute accuracy and was observed by the VLA and at KPNO 1 week after the fact (Barthelmy, Palmer, & Schaefer 1994; Palmer et al. 1995). We will review those observations, but apply a refined error box. One error box was improved by using BATSE Earth occultation analysis. The other seven error boxes are long and narrow, but still 1 order of magnitude smaller than the best BATSE 3B Catalog (Meegan et al. 1996) localizations. One of the new boxes involves a possible repeater (Kippen et al. 1995). This paper is one of a series with the aim of publishing essentially all of the accurate and semiaccurate GRB localizations from the Interplanetary Network (IPN). The next paper in this series will present locations for approximately 40 BATSE/*PVO*/*Ulysses* events.

2. INSTRUMENTATION

The BATSE and *Ulysses* burst detectors have been described elsewhere (Fishman et al. 1989; Hurley et al. 1992). The gamma-ray spectrometer on *MO* operated from 1992 October to 1993 August. Its sensor was a 5.5 cm × 5.5 cm high-purity Ge detector, and its useful energy range was 0.1–10 MeV. Although the energy resolution was 2–5 keV, the data were combined into 120 keV wide bands for the localization analysis. Time resolution was ≤ 0.05 s for GB 930706, 60 s for GB 930120 and GB 930127, and 25 s otherwise. Based on the best available information, the *MO* timing uncertainty from all systematic sources is conservatively estimated to be no more than ± 0.1 s. The loss of the spacecraft in 1993 August means that this is not strictly verifiable, but we have done everything possible to quantify the sources of *MO* timing uncertainty. We met with JPL personnel specifically to discuss timing shortly before the spacecraft was lost. During that meeting a probable ± 0.07 s uncertainty in the time required for the gamma-ray experiment to accept spacecraft clock words was identified, and this dominates the systematic error. Telephone conversations and email exchanges in 1994 did not reveal any additional uncertainties and resulted in more highly refined spacecraft clock calibrations. Additional confidence in the *MO* uncertainty estimate is derived from the fact that *MO* and *Ulysses* use much of the same standard ephemeris and timing software developed at JPL. The most crucial information—namely, the correlation between spacecraft clock words and universal time—is derived for both spacecraft using the same, well-proven routines. *Ulysses* timing accuracy has been periodically verified to an accuracy of a few milliseconds with complete end-to-end system checks (Hurley & Sommer 1994).

3. OBSERVATIONS

Between 1992 October 4 and 1993 August 1, concurrent coverage by *CGRO*, *MO*, and *Ulysses* was obtained for 78 GRBs. Although the intensities of most of these bursts were below the *MO* and *Ulysses* thresholds, 10 or 11 were positively detected by all three spacecraft. Table 1 identifies the simultaneously observed GRBs as reported in our previous paper. In some cases, the *MO* and/or *Ulysses* responses are only at the 3–4 σ level, but we have carried out tests, such as comparing time histories and intensity ratios between the three spacecraft, that generally give us high confidence in their reality. Two instances of possible doubt are BATSE 2149 (GB 930127) and 2475 (GB 930731B). Analysis of BATSE 2149 revealed no inconsistencies, but the low accuracy of the three spacecraft localization (the *MO* time resolution was only 60 s) and the weak *MO* response cause us to remove the event from subsequent quantitative analysis. The *MO* response near the expected arrival time of BATSE 2475 is also questionable. It has the characteristics of a GRB, but its magnitude is inconsistent with the BATSE count rate data. Also, the arrival time at *MO* is more than 1 minute different from the prediction based on the intersection of the BATSE error box and the BATSE/*Ulysses* IPN annulus. Scrutiny of all the data for this event (carried out largely after our previous paper was written) yielded nothing that could explain the inconsistencies in terms of a single event, so we can only assume that the apparent *MO* response was to something other than BATSE 2475. (We also were able to rule out the radical hypothesis that a single burst took place somewhere in the solar system.) Therefore, we remove BATSE 2475 from further consideration. Spacecraft coordinates and timing information for the remaining nine events are listed in Table 2. Coordinates

TABLE 1

BURSTS OBSERVED BY *CGRO*, *MO*, AND *Ulysses*

Date	Time at *CGRO*	BATSE Number	Fluence >100 keV (ergs cm^{-2})
1993 Jan 20.....	23:31:40	2138	3.1E−05
1993 Jan 27.....	16:14:26	2149	7.1E−06
1993 Jun 12.....	00:44:18	2387	1.7E−05
1993 Jun 12.....	08:53:58	2389	1.8E−05
1993 Jul 4.....	16:49:06	2428	1.2E−05
1993 Jul 6.....	05:13:31	2431	1.5E−05
1993 Jul 20	14:35:10	2450	2.1E−05
1993 Jul 24	16:46:27	2461	[a]
1993 Jul 31	03:16:31	2475	[a]
1993 Jul 31	06:23:57	2476	4.3E−06
1993 Aug 1	02:12:14	2477	[b]

[a] Could not be determined because of data gaps.

[b] Listed in the 3B Catalog as 1.6E−06, but not corrected for Earth occultation.

TABLE 2

SPACECRAFT COORDINATES AND TIMES

BATSE Number	Spacecraft	R.A., Decl. (J2000)	Distance (km)	Relative Time (s)
2138.....	*CGRO*	331.3050, 20.9660	6743	0.0
	MO	77.9652, 18.8502	58608500	158 ± 10
	Ulysses	163.4785, −14.0159	652139538	577.86 ± 0.75
2387.....	*CGRO*	314.6540, −10.2290	6720	0.0
	MO	147.6138, 13.0130	267301600	−36 ± 12
	Ulysses	143.9744, −11.1839	728594970	−1068 ± 2.0
2389.....	*CGRO*	83.7730, 26.6640	6719	0.0
	MO	147.8032, 12.9504	267780700	828 ± 10
	Ulysses	144.0013, −11.1882	729219338	2188.0 ± 1.5
2428.....	*CGRO*	290.2400, 24.8500	6718	0.0
	MO	159.8258, 8.6361	296283100	−344.7 ± 12
	Ulysses	146.1465, −11.8228	761445389	−311.3 ± 5.0
2431.....	*CGRO*	245.8450, 28.4100	6718	0.0
	MO	160.6462, 8.3202	298073517	519.81 ± 0.3
	Ulysses	146.3294, −11.8936	763275831	1471.94 ± 0.2
2450.....	*CGRO*	110.9870, 24.6550	6721	0.0
	MO	168.3894, 5.2355	313852600	780.5 ± 13
	Ulysses	148.2143, −12.7222	777512551	1612.5 ± 1.0
2461.....	*CGRO*	280.1380, −27.8700	6715	0.0
	MO	170.5964, 4.3283	317946000	452 ± 10
	Ulysses	148.7969, −13.0107	780521557	−61.0 ± 1.0
2476.....	*CGRO*	91.1890, 25.9700	6714	0.0
	MO	174.1512, 2.8491	324135330	−277 ± 13
	Ulysses	149.7717, −13.5246	784361546	−971.0 ± 2.0
2477.....	*CGRO*	92.8750, 24.2650	6714	0.0
	MO	174.6030, 2.6600	324886700	310 ± 20
	Ulysses	149.9022, −13.5962	784770313	1850 ± 10

are J2000, and the distances are in kilometers from the geocenter. We also show our best determinations of the arrival times at *MO* and *Ulysses* relative to the BATSE times, which are shown as zeros. Listed uncertainties are approximately 3 σ (usually rounded upwards to the next whole second) and include all known statistical and systematic sources of error. The statistical errors were calculated using a χ^2 method similar to that described by Hurley (1994).

4. RESULTS

Table 3 lists quantitative information on the localizations. All of the arrival-time calculations were carried out independently at the University of Arizona, UC Berkeley, and GSFC. For each event we first tabulate, in order, coordinates and radii of the IPN annuli for the *CGRO*/*MO*, *CGRO*/*Ulysses*, and *MO*/*Ulysses* spacecraft pairs. The annulus entries are not corrected for aberration, but the accurate intersections mentioned later have been corrected. In the last column we give the most probable (aberration-corrected in the case of GB 930706) event location, which involves a weighted combination of the IPN, BATSE, and Comptel error boxes. For GB 930706 (BATSE 2431) it is simply the center of the IPN box, and for GB 930801 (BATSE 2477) it incorporates the *CGRO* occultation data. Comptel locations (Kippen 1995; Kippen et al. 1995) are taken into account for GB 930612 (BATSE 2387) and GB 930704 (BATSE 2428). Additional information for selected bursts is supplied in the sections below.

4.1. *GB 930704 (BATSE 2428)*

This burst, together with one on 1994 March 1 (BATSE 2855), has been discussed by the Comptel team in the context of repetitions from a single source (Kippen et al. 1995). This region of the sky was subsequently targeted by *ROSAT* (Greiner et al. 1996) in an (unsuccessful) effort to find a flaring or fading object. The published papers, which present early analyses of IPN data, mention that those data are compatible with the assumption of a single source. Our

TABLE 3

LOCALIZATION DATA

BATSE Number	Annulus Center (R.A., Decl.)	Radius (deg)	Location (R.A., Decl.)
2138	257.9714, −18.8474	36.28 ± 4.96	266, 16
	343.4783, 14.0159	74.595 ± 0.020	
	348.5073, 15.6633	78.896 ± 0.321	
2387	147.6135, 13.0129	87.686 ± 0.772	105, −70
	143.9743, −11.1837	63.932 ± 0.052	
	141.8929, −23.8803	51.567 ± 0.617	
2389	327.8044, −12.9499	21.97 ± 1.72	347, −1
	324.0017, 11.1885	25.905 ± 0.081	
	321.8232, 23.8732	35.020 ± 0.721	
2428	159.8249, 8.6354	69.608 ± 0.765	98, 62
	146.1462, −11.8229	82.960 ± 0.114	
	317.5949, 23.2864	88.869 ± 0.508	
2431	340.6451, −8.3196	58.479 ± 0.020	281.244,
	326.3289, 11.8938	54.681 ± 0.006	−20.091
	317.3416, 23.2362	55.818 ± 0.012	
2450	348.3903, −5.2351	41.78 ± 1.07	22, 23
	328.2146, 12.7225	51.556 ± 0.028	
	315.1645, 22.7175	61.186 ± 0.568	
2461	350.5954, −4.3288	64.773 ± 0.597	46, −48
	148.7966, −13.0104	88.657 ± 0.022	
	134.6212, −22.5591	72.817 ± 0.414	
2476	174.1523, 2.8486)	75.154 ± 0.713	101, 37
	149.7721, −13.5249	68.215 ± 0.047	
	133.8275, −22.3034	66.689 ± 0.534	
2477[a].....	354.6045, −2.6591	73.27 ± 1.10	294, 47
	329.9026, 13.5964	45.030 ± 0.309	
	313.7393, 22.2743	28.88 ± 1.70	

[a] The location is further restricted by occultation analysis to lie between Earth horizon annuli defined by (R.A., decl., radius) = (272.597, −24.360, 73.12) and (273.708, -24.079, 74.12).

refined localization remains compatible, but just barely. The center of our 3 σ error box for GB 930704 lies within the 1 σ Comptel contour for that event and just outside the corresponding BATSE contour. On the other hand, only the extreme tip of the IPN box intersects the Comptel 2 σ contour for GB 940301 (Fig. 1). Given the relative sizes of the various error boxes and the fact that the Comptel boxes overlap, the chance probability for this level of agreement between the IPN GB 930704 box and the Comptel GB 940301 box is $\sim$20%, which is considerably higher than the probability that the IPN box and the GB 940301 Comptel boxes were produced by repetitions of a single source.

4.2. *GB 940706 (BATSE 2431)*

The region around this error box was observed at KPNO 8.07 days after the gamma-ray emission (Barthelmy, Palmer, & Schaefer 1994) and by the VLA 1 day later (Palmer et al. 1995). The refined error box is defined by annulus intersections at (R.A., decl.)$_{J2000}$ = (281°.2524, −20°.1137), (281°.2359, −20°.0678), (281°.2214, −20°.0669), (281°.2669, −20°.1146), (281°.2674, −20°.1259), and (281°.2209, −20°.0557). It is shown superposed on the VLA data in Figure 2. As is typical for GRBs, the box contains nothing that could be construed as a counterpart. Specifically, there is no radio source brighter than $\sim$1 mJy (20 cm), and there is no variable optical source (as determined by comparison with Palomar prints) brighter than magnitude 18.5. Nevertheless, this error box is useful for all of the types of studies mentioned in our introduction. This burst was also observed by the Phebus experiment on the Russian *Granat* spacecraft.

4.3. *GB 930801 (BATSE 2477)*

This event is distinguished by having been occulted by the Earth in midburst. Because the location of the *CGRO* horizon is known to an accuracy of 0°.5 at all times (McCollough, Meegan, & Pendelton 1996), this information restricts the burst position to an $\sim$1° wide annulus which can be combined with the arrival-time annuli. For GB 930801, the combination of annuli results in a 1 deg^2 error box (Fig. 3) with corners at (R.A., decl.)$_{J2000}$ = (292°.597, 46°.477), (293°.473, 46°.264), (294°.615, 47°.341), (294°.772, 47°.570), and (293°.9434, 47°.768). We believe that it is possible to achieve significantly higher accuracy with a more elaborate occultation analysis, and we have estimated that a few (5–10) additional BATSE events should have been similarly occulted. More work along these lines is indicated.

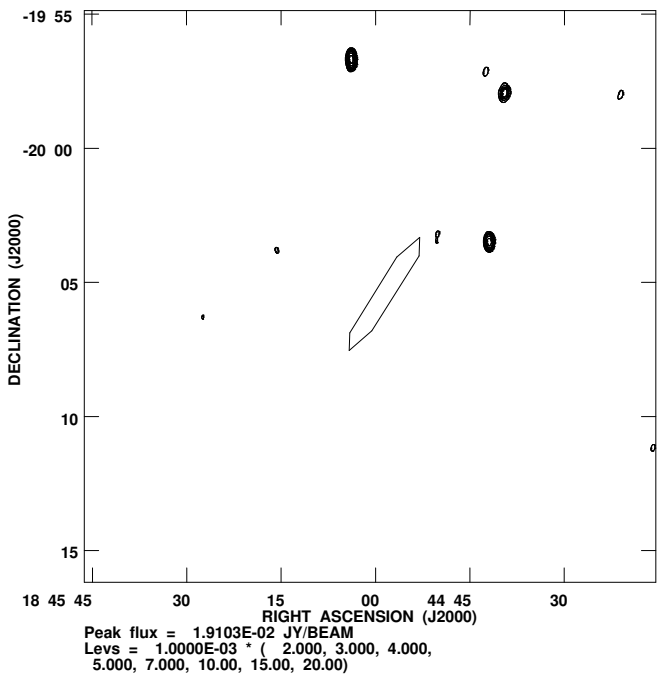

FIG. 2.—GB 930706 error box superposed on the VLA data. The lowest radio contour is 2 mJy, and the rms noise level of the image is 0.44 mJy (20 cm). The beam is a 34″ × 18″ ellipsoid.

5. SUMMARY

Using data from *CGRO*, *MO*, and *Ulysses*, we computed nine GRB error boxes, the largest dimensions at which range from a few arcminutes to the diameters of the BATSE-only boxes, and the smaller dimensions of which are in the arcminute range. All the boxes are at least 1 order of magnitude more accurate than the 3B Catalog localiza-

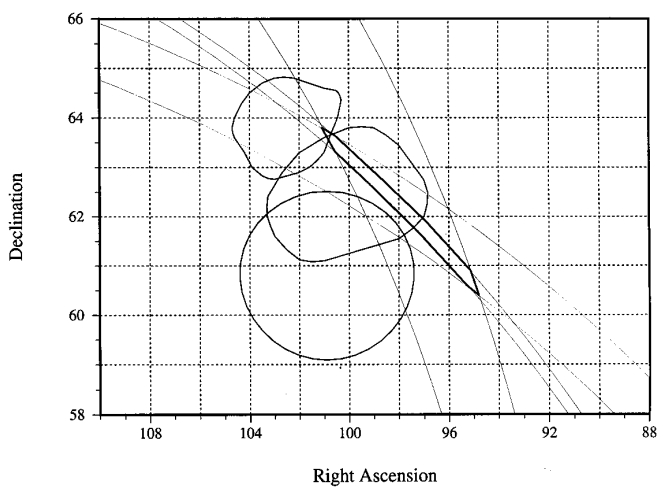

FIG. 1.—GB 930704 and GB 940301 error boxes. The IPN error box for GB 930704 (*heavy lines*) just touches the 2 σ contour of the Comptel GB 940301 localization (*northernmost medium-line contour*). The Comptel and BATSE 1 σ GB 930704 boxes (*medium-line contour and circle*) are also plotted.

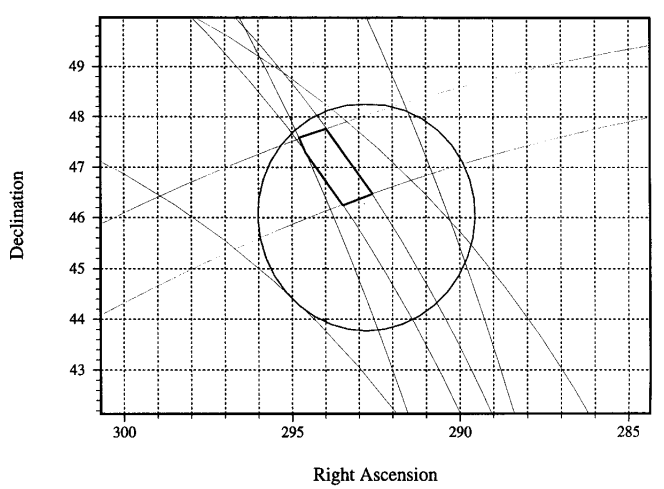

FIG. 3.—GB 930801 error boxes. The final error box (*heavy lines*) is the intersection of the horizon annulus (*upper left to lower right*) with the IPN annuli. The circle (*medium line*) is the BATSE 1 σ region.

tions. Three events are of particular interest: GB 930704 (BATSE 2428) has been described as a possible repeater. The arrival-time information is consistent with that hypothesis, but is perhaps more consistent with the random coincidence alternative. The GB 930706 (BATSE 2431) box, at $\sim 1' \times 4'$, is the first really small one to be obtained since *PVO* entered the Venusian atmosphere in 1992 October. Sensitive radio and optical observations of this location were made about 1 week after the burst, but no counterpart candidates were identified. This error box should continue to be studied. GB 930801 (BATSE 2477) is the first GRB that had its localization improved by taking into account BATSE Earth occultation.

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