# GAMMA-RAY BURST ARRIVAL-TIME LOCALIZATIONS:

# SIMULTANEOUS OBSERVATIONS BY MARS OBSERVER, COMPTON 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 ~2-degree accuracy by the CGRO Burst and Transient Source Experiment (BATSE). We computed arrival-time error boxes whose larger dimensions range from a few arcminutes to the diameters of the BATSE-only boxes and whose smaller dimensions are in the arcminute range. Three events are of particular interest: GB930704 (BATSE #2428) has been described as a possible repeater. The arrival-time information is consistent with that hypothesis, but only just so. The GB930706 (#2431) box, at ~1 x 4 arcmin, 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 eight to nine days of the burst, but no counterpart candidates were identified, GB930801 (#2477) is the first GRB whose localization was improved by taking into account BATSE Earth occultation.

*Subject heading:* gamma rays: bursts

## INTRODUCTION

During the years immediately following the discovery of Gamma-nay 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 (IPN) that produced arcminute-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 [he classical deep counterpart searches, archival searches, and error box monitoring, whose purpose 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 et al. 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 information on 9 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 degrees, 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 a week after the fact (Barthelmy, Palmer, and 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 7 error boxes are long and narrow, but still an order of magnitude smaller than the best BATSE 3B Catalog (Meegan et al. 1996) localization. One of the new boxes involves a possible repeater (Kippen et al. 1995). This paper is one of a series whose aim is to publish essentially all of the accurate and semi-accurate GRB localization from the Interplanetary Network (IPN). The next paper in this series will present locations for approximately 40 BATSE/PVO/Ulysses events.

## 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 x 5.5 cm HPGe with 30% efficiency *re* NaI. The useful energy range was O. I - 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 $\leq 0.05$ s for GB930706, 60 s for GB930120 and GB930127, 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 $\pm 0.1$ sec. 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 ms with complete end-to-end system checks (Hurley and Sommer 1994).

## OBSERVATIONS

Between 1992 October 4 and 1993 August 1, concurrent coverage by CGRO, MO, and Ulysses, was obtained for 78 GRBs. Although most of these 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- to 4-sigma 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 (GB930127) and #2475 (GB930731B). Analysis of #2149 revealed no inconsistencies, but the low accuracy of the 3-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 #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 a 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 #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 #2475 from further consideration. Spacecraft coordinates and timing information for the remaining 9 events are listed in Table 2. Coordinates are J2000, and the distances are in km 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-sigma (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 chi-square method similar to that described by Hurley (1994).

## 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 GB930706) event location, which involves a weighted combination of the IPN, BATSE, and Comptel error boxes. For GB930706 (BATSE #2431) it is simply the center of the IPN box, and for GB930801 (#2477) it incorporates the CGRO occultation data. Comptel locations (Kippen 1995; Kippen et al. 1995) are taken into account for Ci13930612 (#2387) and GB930704 (#2428). Additional information for selected bursts is supplied in the sections below.

a) GB930704 (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), The published papers, which present early analyses of IPN data, mention that those data are compatible with the assumption of a single source, Our refined localization remains compatible, but just barely. The center of our 3-sigma error box for GB930704 lies within the l-sigma 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-sigma contour for GB940301 (Figure 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 GB930704 box and the Comptel GB940301 box is approximately 20%, which is considerably higher than the probability that the IPN box and the GB940301 Comptel boxes were produced by repetitions of a single source,

b) GB940706 (BATSE #2431)

The region around this error box was observed at KPNO 8.07 days after [he gamma-ray mission (Barthe lmy, Palmer, and Schaefer 1994) and by the VLA a day later (Palmer et al. 1995). The refined error box is defined by annulus intersections at (ra, dec)$_{J2000}$ = (281.2524, -20. 1137), (281.2359, -20.0678), (281.2214, -20.0669), (281.2669, -20,1 146), (281 .2674, -20. 1259), and (281 ,2209, -20.0557). It is shown superimposed on the VLA data in Pig. 2. As is typical for GRBs, the box contains nothing that could bc construed as a counterpart. Specifically, there is no radio source brighter than - 1 mJy (20 cm), nor is there a 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.

C) GB930801 (BATSE #2477)

This event is distinguished by having been occulted by the Earth in mid-burst. Because the location of the CGRO horizon is known to an accuracy of 0,5 degrees at all times (McCullough, Meegan, and Pendleton 1996), this information restricts the burst position to an ~1 degree wide annulus which can be combined with the arrival-time annuli. For GB930801, the combination of annuli results in a 1 sq. deg. error box (Fig. 3) with corners at $(ra, dec)_{J2000}$ = (292.597, 46.477), (293.473, 46.264), (294615, 47.34 1), (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.

## SUMMARY

Using data from CGRO, Mars Observer, and Ulysses, we computed nine GRB error boxes whose largest dimensions range from a few arcminutes to the diameters of the 13 ATSE-only boxes and whose smaller dimensions arc in the arcminute range. All the boxes are at least an order of magnitude more accurate than the 3B Catalog localization. Three events are of particular interest: GB930704 (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 hypothesis. The GB930706 (#2431) box, at ~1 x 4 arcmin, 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 within about a week of the burst, but no counterpart candidates were identified. This error box should continue to be studied. GB930801 (#2477) is the first GRB whose localization was improved by taking into account BATSE Earth occultation.

## ACKNOWLEDGMENTS

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## Table 1: Bursts Observed by CGRO, MO, and Ulysses

| Date | Time @ CGRO | BATSE # | BATSE Fluence >100 keV |
|---|---|---|---|
| 93/ 1/20 | 23:31:40 | 2138 | 3.1E-05 |
| 93/ 1/27 | 16:14:26 | 2149 | 7.1E-06 |
| 93/ 6/12 | 00:44:18 | 2387 | 1.7E-05 |
| 93/ 6/12 | 08:53:58 | 2389 | 1.8E-05 |
| 93/ 7/ 4 | 16:49:06 | 2428 | 1.2E-05 |
| 93/ 7/ 6 | 05:13:31 | 2431 | 1.5E-05 |
| 93/ 7/20 | 14:35:10 | 2450 | 2.1E-05 |
| 93/ 7/24 | 16:46:27 | 2461 | * |
| 93/ 7/31 | 03:16:31 | 2475 | • |
| 93/ 7/31 | 06:23:57 | 2476 | 4.3E-06 |
| 93/ 8/ 1 | 02:12:14 | 2477 | ** |

*Could not be determined because of data gaps.
**Listed in the 3B Catalog as 1.6E-06, but not corrected for Earth occultation.

## Table 2: Spacecraft Coordinates and Times

| Burst # | Spacecraft | R.A. (J2000) | Dec. (J2000) | Distance (km) | Relative Time |
|---|---|---|---|---|---|
| 2138 | CGRO "--" " | 3311305-0 | ''20.9660' | 6743 | 0.00 |
| | MO | 77.9652 | 18.8502 | 58608500 | 158 ± 10 |
| | Ulysses | 163.4785 | -14.0159 | 652139538 | 577.86 ± .75 |
| 2387 | CGRO | 314.6540 | -10.2290 | 6720 | 0.0 |
| | MO | 147.6138 | 13.0130 | 267301600 | -36 ± 12 |
| | Ulysses | 143.9749 | -11.1039 | 728594970 | -1068 ± 2 |
| 2389 | CGRO | 83.7730 | 26.6640 | 6719 | 0.0 |
| | MO | 147.8032 | 12.9504 | '267780700 | 828 ± 10 |
| | Ulysses | 144.0013 | -11.1882 | 729219330 | 2188.0 ± 1.5 |
| 2428 | CGRO | 290.2400 | 24.8500 | 6718 | 0.0 |
| | MO | 159.8258 | 8.6361 | 296283100 | -344.7 ± 12 |
| | Ulysses | 146.14651 | -11.8228 | )761445389 | ]-311. 3 ± 5 |
| 2431 | CGRO | 245.8450 | 28.4100 | 6718 | 0.00 |
| | MO | 160.6462 | 8.3202 | 298073517 | 519.81 ± .3 |
| | Ulysses | 146.3294 | -11.8936 | 763275831 | 1471.94± .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 |
| 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 |

## Table 3: Localization Data

| BATSE TRIG. # | IPN Annuli | | Location |
|---|---|---|---|
| | (ra, dec)$_{center}$ | Radius | (ra,dec) |
| 2138 | (257.9714, -18.8474) | 36.28 ± 4.96 | (266,16) |
| | (343.4783, 14.0159) | 74.595 ± .020 | |
| | (348.5073, 15.6633) | 78.896 ± ,321 | |
| 2387 | (147.6135, 13.0129) | 87.686 ± .772 | (105,-70) |
| | (143.9743, -11.1837) | 63.932 ± .052 | |
| | (141.8929, -23.8803) | 51.567 ± .617 | |
| 2389 | (327.8044, -12.9499) | 21.97 ± 1.72 | (347,-1) |
| | (324.0017, 11.1885) | 25.905 ± .081 | |
| | (321.8232, 23.8732) | 35.020 ± .721 | |
| 2428 | (159.8249, 8.6354) | 69.608 ± .765 | (98,62) |
| | (146.1462, -11,8229) | 82.960 ± .114 | |
| | (317.s949, 23.2864) | 88.869 ± .508 | |
| 2431 | (340.6451, -8.3196) | S8.479 ± .020 | (281.244, -20.091) |
| | (326.3289, 11.8938) | 54.681 ± .006 | |
| | (317.3416, 23.2362) | 55.018 ± .012 | |
| 2450 | (348.3903, -5.2351) | 41.78 ± 1.07 | (22,23) |
| | (328.2146, 12.7225) | 51.556 ± .028 | |
| | (31S.1645, 22.7175-) | 61.186 ± .s68 | |
| 2461 | (350.5954, -4.3288) | 64.773 ± .597 | (46,-48) |
| | (148.7966, -13.0104) | 88.657 ± .022 | |
| | (134.6212, -22.5591) | 72.817 ± .414 | |
| 2476 | (174.1523, 2.8486) | 75.154 ± .713 | (1.01,37) |
| | (149.7721, -13.5249) | 68.215 ± .047 | |
| | (133.8275, -22.3034) | 66.609 ± .534 | |
| 2477[a] | (354.6045, -2.6591) | 73.27 ± 1.10 | (294,47) |
| | (329.9026, 13.5964) | 45.030 ± .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 (ra, dec, radius) - (272.597, -24.360, 73.12) and (273.708. -24.079, 74.12).

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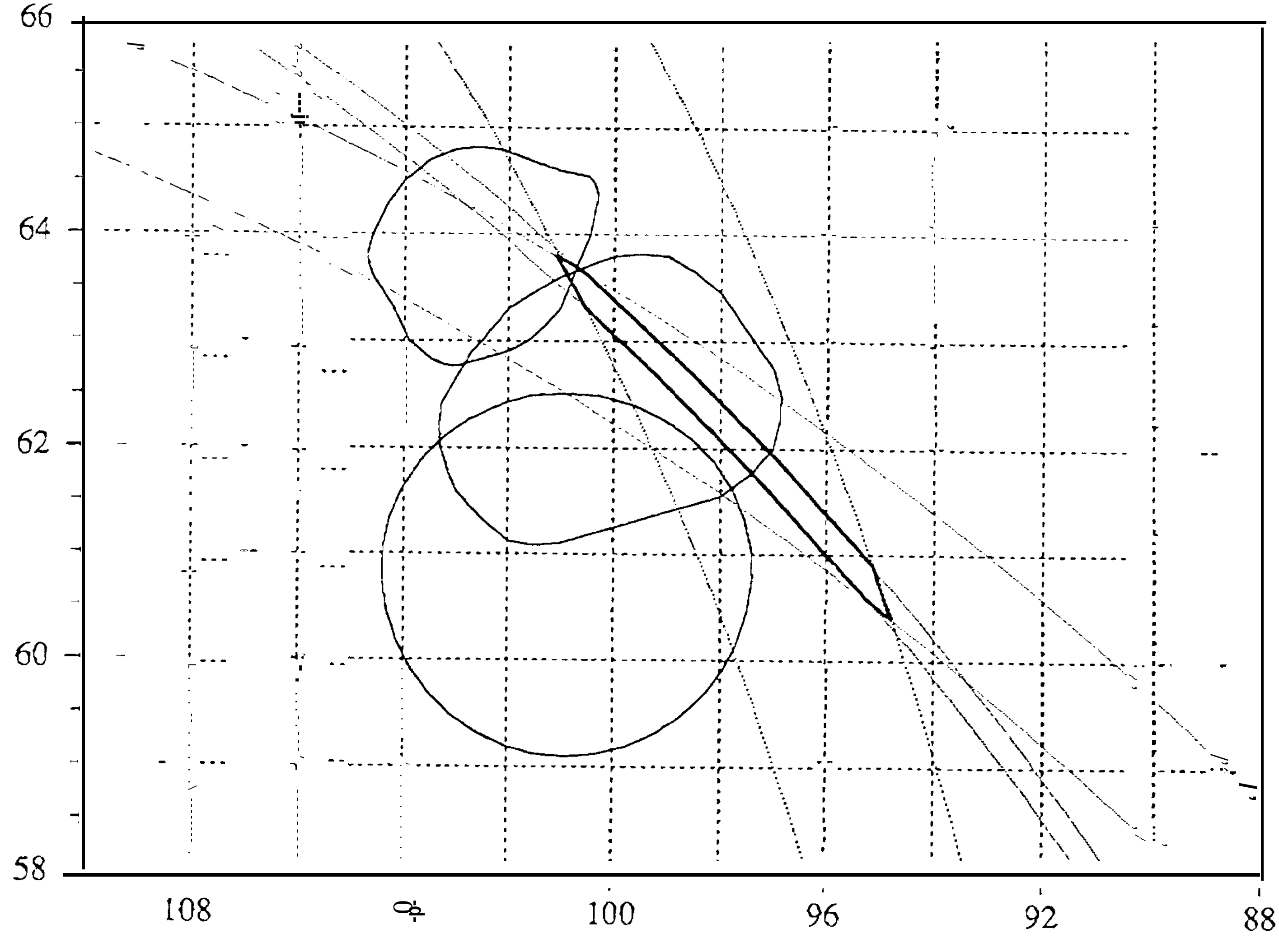
## FIGURE LEGENDS

Fig. 1 (a) GB930704 and GB940301 Error boxes. The IPN crror box for GB930704 (heavy lines) just touches [he two-sigma contour of the Comptel GB940301 localization (northernmost medium-line contour). The Comptel and BATSE onc-sigma GB930704 boxes (medium-line contour and circle) arc also plotted.

Fig. 2 GB930706 error box superimposed on the VLA data. Thc lowcst radio contour is 2 mJy, and the RMS noise level of [he image is 0.44 mJy (20 cm). The beam is a 34 x 18 arcsecond ellipsoid.

Fig. 3 (a) GB930801 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 one-sigma region.

# GB930704



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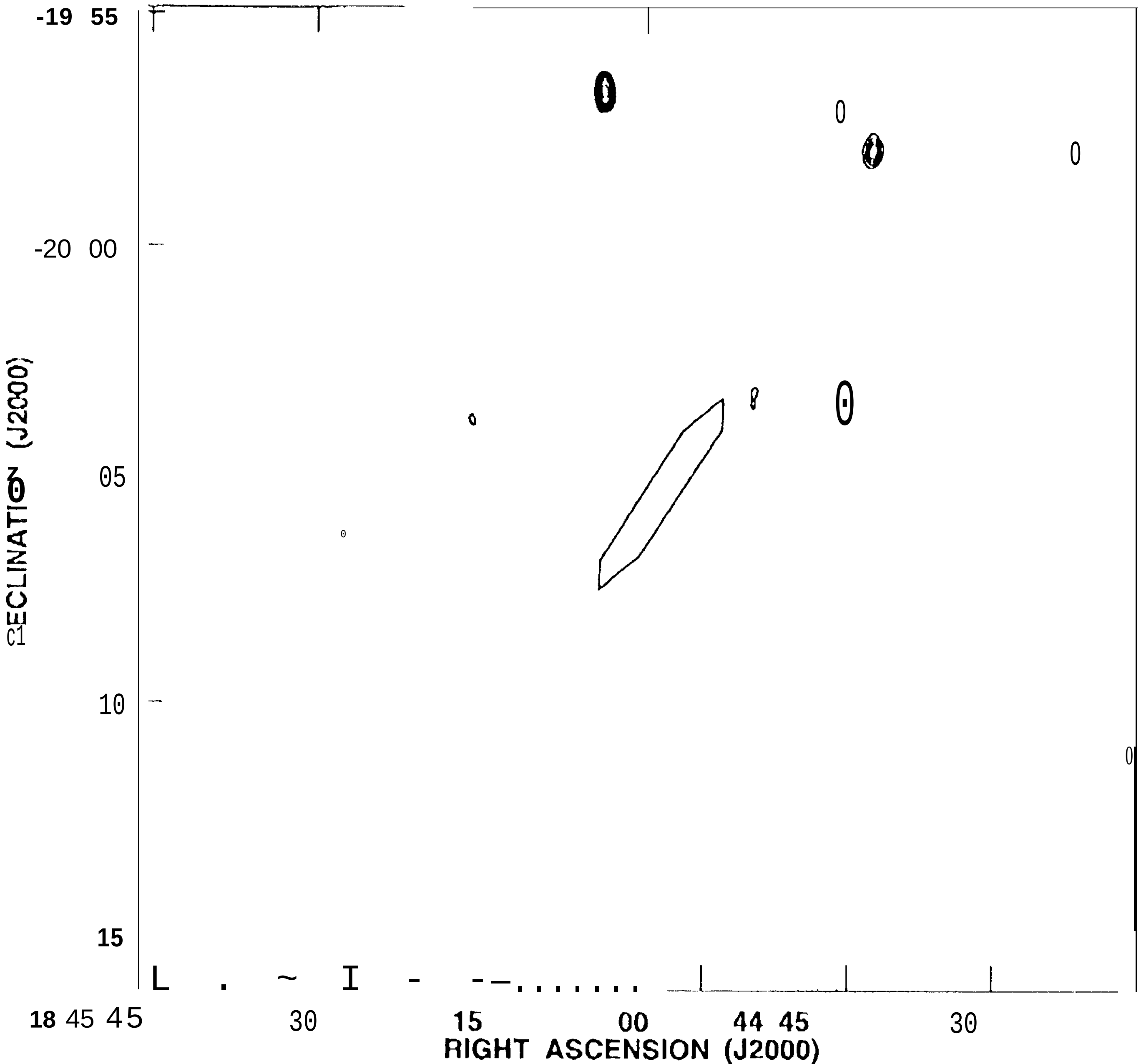
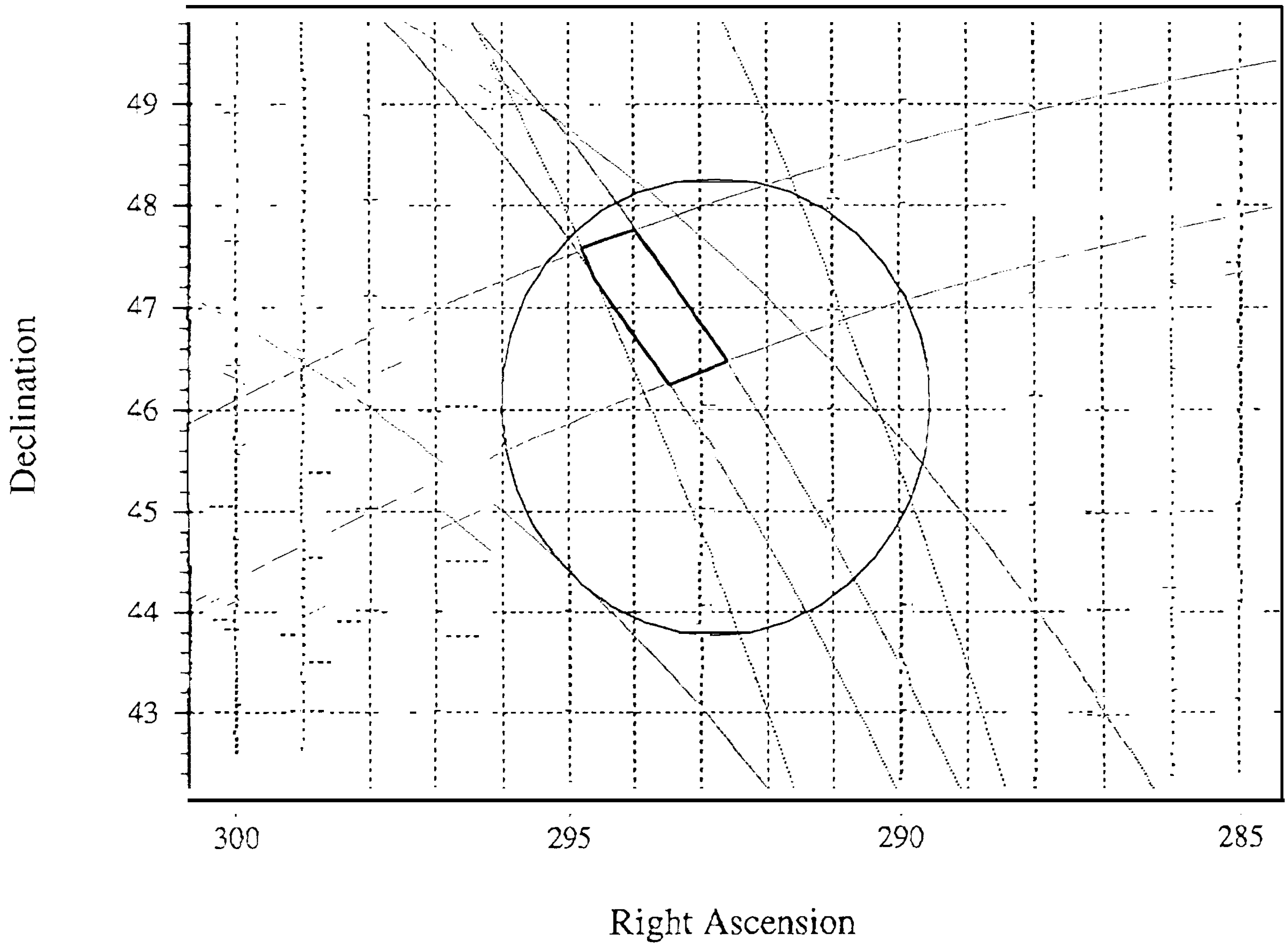
G930706 IPOL 1464.900 MHZ G930706IF1.ICLN.1




Peak flux = 1.9103E-02 JY/BEAM
Levs = 1.0000E-03 * ( 2.000, 3.000, 4.000,
5.000, 7.000, 10.00, 15.00, 20.00)

# GB930801


49
48
47
46
45
44
43
Declination
300
295
290
285
Right Ascension