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AN EVALUATION OF THE SOLAR RADIO BURST LOCATOR (SRBL) AT OVRO

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ABSTRACT

The Solar Radio Burst Locator (SRBL) is a spectrometer that can observe solar microwave bursts over a wide band (0.1–18 GHz) as well as detect the burst locations without interferometry or mechanical scanning. Its prototype has been operated at Owens Valley Radio Observatory (OVRO) since 1998. In this study, we have evaluated the capability of the SRBL system in flux and radio burst location measurements. For this, we consider 130 microwave bursts from 2000 to 2002. The SRBL radio fluxes of 53 events were compared with the fluxes from USAF/RSTN and the burst locations of 25 events were compared with the optical flare locations. From this study, we found: (1) there is a relatively good correlation ($r = 0.9$) between SRBL flux and RSTN flux; (2) the mean location error is about 8.4 arcmin and the location error (4.7 arcmin) of single source events is much smaller than that (14.9 arcmin) of multiple source events; (3) the minimum location error usually occurred just after the starting time of burst, mostly within 10 seconds; (4) there is a possible anti-correlation ($r = -0.4$) between the pointing error of SRBL antenna and the location error. The anti-correlation becomes more evident ($r = -0.9$) for 6 strong single source events associated with X-class flares. Our results show that the flux measurement of SRBL is consistent with that of RSTN, and the mean location error of SRBL is estimated to be about 5 arcmin for single source events.

Key words : instrumentation: spectrographs — Sun: radio radiation — techniques: miscellaneous

I. INTRODUCTION

Since its first discovery of solar radio emission (Appleton & Hey 1946), the radio emission has been regarded as an important subject not only for scientific investigations but also for the examination of space weather effects such as radio interference. According to Lanzerotti et al. (1999), Bala et al. (2000), and Gary et al. (2004), cellular phones and their stations can be easily affected from strong solar radio emissions, especially when there are strong radio bursts during sunrise and sunset.

The radio emission can be classified largely into two categories: the slowly varying quiet sun emission and the abrupt radio bursts. Of these two categories, the radio bursts associated with solar flares have been observed in a wide range of wavelengths from millimeter to decameter by using ground based instruments. The characteristics of the bursts vary with wavelength. Solar microwave observations at frequency of 1–20 GHz (1.5–30cm) are used to study the characteristics of hot plasma (thermal emission) and nonthermal high energy electrons (gyrosynchrotron emission) in the upper chromosphere and the corona (Bastian 2004). The microwave bursts are known to be caused by the gyrosynchrotron emission due to the energetic electrons moving in strong magnetic field. Their spectra often show impulsive and gradual emission patterns. Overall intensity, duration and spectral hardness are known to correlate with the energetic solar particles.

The Solar Radio Burst Locator (SRBL) is a spectrometer that can simultaneously observe solar microwave emission from chromosphere to corona with a wide range of frequency from 0.1–18 GHz (Dougherty 2000; Dougherty et al. 2000). It also has a unique capability to detect the location of a solar radio burst using a single dish antenna system, which is distinguished from interferometry or mechanical scanning. The burst location can be determined by analyzing the characteristics of spectral modulations of the feed that is located at the focal plane.

A prototype of the SRBL has been operated at Owens Valley Radio Observatory (OVRO) since 1998 February. There are a few reports (e.g. Dougherty 2000; Dougherty et al. 2000) on the hardware and software system of the SRBL. According to the reports, the flux and location estimated from SRBL are compa-

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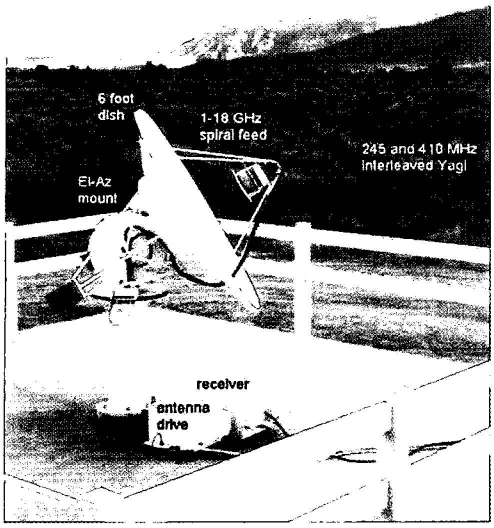


Fig. 1.— SRBL (Solar Radio Burst Locator) system installed at OVRO. It consists of a single 6-foot parabolic antenna, interleaved Yagi antennas, and stabilized 0.5–18 GHz frequency-agile superheterodyne receiver.

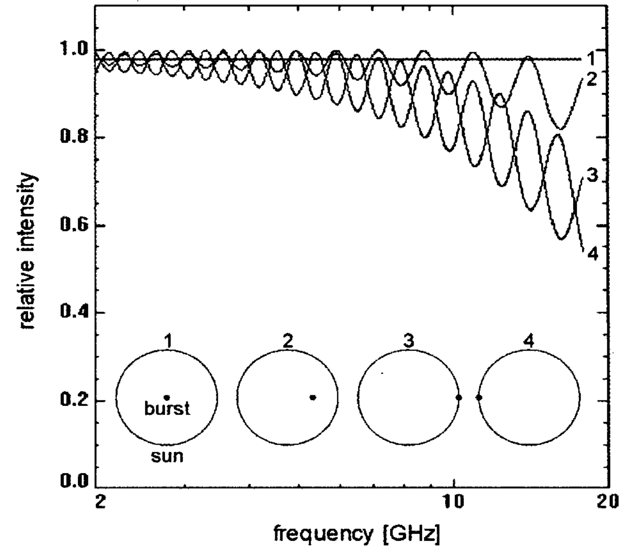


Fig. 2.— Relative intensity versus frequency for different burst locations: 1) at sun-center, 2) half way to East limb, 3) at East limb, 4) at West limb, when the sun-center is at the antenna center. From the technical report in SRBL website (http://www.ovsa.njit.edu/srbl/book).

rable to the flare location estimated from the US Air Force Radio Solar Telescope Network (RSTN) and Solar Observing Optical Network (SOON) data. For 7 strong bursts in 1998, Dougherty et al. (2000) found that the average rms location uncertainty is about 5 arcmin. Considering 12 events observed during the time period between 2000 January and 2000 September, Dougherty (2000) found that the mean location errors are about 4 arcmin for 7 limb events and 2.8 arcmin for 5 disk events, respectively. They also noted that the 7 events within 3 arcmin from the optical flares are all strong bursts, which have the radio emission greater than 2000 sfu (solar flux unit, 1 sfu = 10^4 Jy = 10^{-22} $\mathrm{Wm^{-2}Hz^{-1}}$).

This paper purposes evaluating the performance of the SRBL system using a large sample of data. For this we consider 130 microwave burst events from 2000 to 2002. For the comparison of the radio fluxes from SRBL with those from RSTN, we select 53 events whose maximum-flux frequency is consistent with that of RSTN (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/BURSTS) within 10 %. To make a comparison between the burst location from SRBL and the flare location reported by National Geographical Data Center (NGDC, ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA /FLARES), we use 25 burst events whose emission structures are well identified in their dynamic spectra. The main purpose of our study is to look for possible origins of the location error of SRBL. To achieve this goal, we examine if there are multiple emission sources on the solar disk during the burst time by inspecting SOHO/EIT full disk images and YOHKOH soft X-ray images. The time of minimum error (hereafter, M-E), i.e. when a burst has the best agreement between SRBL location and NGDC location, is also inspected. In addition, we examine a relationship between the location error and the antenna pointing error. In §2, we introduce the SRBL system and data analysis. In section §3, we describe flux and location comparison, and the M-E time of the burst with respect to the SRBL start/peak time. The relationship between location error and pointing error is also presented in §3. A brief summary and discussion are given in §4.

II. SRBL SYSTEM And DATA ANALYSIS

SRBL is a novel spectrometer that can automatically detect and locate microwave solar radio bursts with a wide band of radio spectrum (0.1–18 GHz). As shown in Figure 1, the system is composed of antennas, tracking driver, and a receiver system. The antenna system consists of a single 6-foot parabolic antenna with a planar, circularly-polarized feed, and interleaved Yagi antennas tuned to 245 and 410 MHz. The receiving system is a stabilized 0.5–18 GHz frequency-agile superheterodyne receiver. More details on the hardware system are well described in Dougherty et al. (2000), Dougherty (2000), and the technical report in SRBL website (http://www.ovsa.njit.edu/srbl/book). In particular, the system has a unique capability to detect the location of a solar radio burst without interferometry or mechanical scanning. The detection of the burst location can be made from the analysis of spectral modulations as shown in Figure 2. The log-spiral geometry of the feed introduces spectral modulations that vary

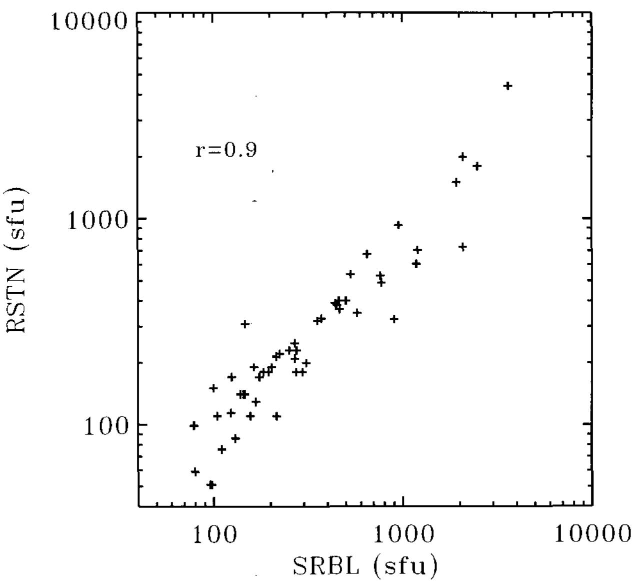


Fig. 3.— Comparison of the flxues of RSTN and SRBL.

in phase and amplitude depending on where the source is located. The depth of the modulation increases with the frequency and the off-center distance of the source, and its phase changes according to the position angle. From this modulation pattern, we can determine the location of the source with respect to the antenna center. To determine the burst location with respect to the solar center, we use two spectra: pre-burst (quiet sun) and burst spectra. From these spectra we first obtain the solar center and the locations of burst with respect to the antenna center, and then from the difference between them we determine the location of the burst with respect to the solar center.

We analyzed 130 bursts observed by the SRBL at OVRO using data processing routines in Table 1. The data processing procedure can be summarized as follows. First, we find the raw data files containing calibration data using arcdump.exe, which extracts the basic information (e.g., date, time, and type) of recorded data. Second, three routines (rcvrcal.exe, ntnacal.exe, fluxcal.exe) are used to determine the information related with the calibrations of the system. If there are no calibration data during the observation time, we use the nearest earlier calibration information. To make a flux calibration, we use the RSTN calibration data for given frequencies. Third, we determine the receiver parameters of the day of interest for the set of observing frequencies. Fourth, we calibrate the data to obtain the solar spectrum and burst location using solrmtr.exe. The dynamic spectrum and the modulation pattern can be shown by using plotdat.exe.

The event selection procedure is as follows. First, we extract burst information such as burst flux and location by applying the data processing routine to all SRBL data obtained during the period from 2000 January to 2002 July. Second, we compare the burst information with the burst list from SRBL website (http://www.ovsa.njit.edu/srbl) to choose well defined radio bursts. As a result, we have selected 130 burst events.

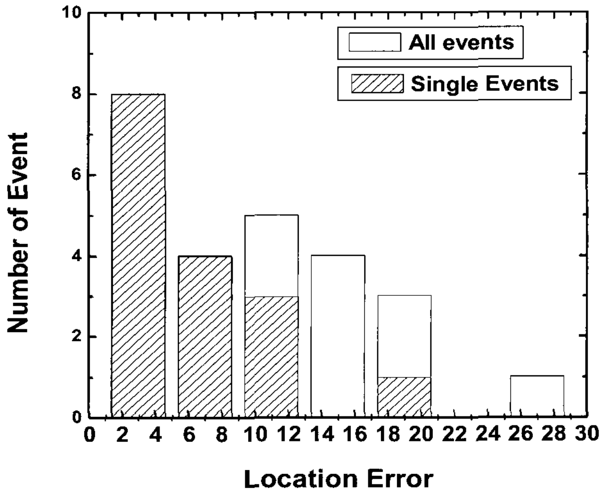


Fig. 4.— Histogram showing the number distribution of location errors.

III. RESULTS

(a) Flux Comparison (2000 ~ 2002)

We compared the SRBL radio fluxes to those of other radio observatories for our selected events. For this comparison, we used the solar radio flux recorded in the NGDC/NOAA website (http://www.noaa.gov) by the RSTN spectrometers. We choose 55 SRBL events whose maximum-flux frequency is consistent with one of the RSTN frequencies to within 10 %. Then we exclude two events showing erroneously large flux differences greater than 2500 sfu. Figure 3 shows the comparison between SRBL flux and RSTN flux for the 53 events. There is a good correlation (r = 0.9) between these two fluxes. There is a good correlation (r = 0.9) between these two fluxes. Considering that RSTN has typical site-to-site scatterings of 5–10 % (B. L. Dougherty, private communications), this fact implies that the flux measurement by the SRBL is consistent with that by the RSTN, demonstrating the proper measurement of solar microwave burst flux by SRBL system.

(b) Location Comparison

We considered 25 events whose burst locations were estimated from SRBL and whose information is available at the burst list (http://www.ovsa.njit.edu/srbl/e

Table 1.
Data analysis procedure and related routines

Procedure	Main Function	Related Routines
1	Find the raw data files containing calibration data	arcdump.exe
2	Determine receiver parameters of calibration data for full frequency set	rcvrcal.exe
3	Determine antenna parameters from calibration data for full frequency set	ntnacal.exe
4	Determine the flux calibration factors using RSTN flux	fluxcal.exe
5	Determine receiver parameters of the day of interest	rcvrcal.exe
6	Calibrate data to obtain solar spectrum and burst location	solrmtr.exe

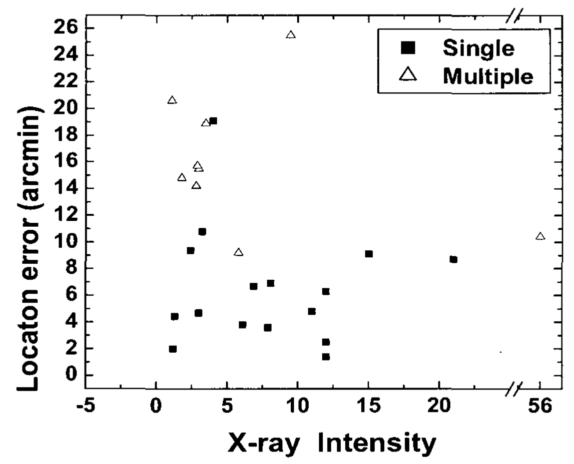


Fig. 5.— Relationship between the location errors and soft X-ray flare strengths for different flaring patterns (single or multiple). In the figure, the X-ray intensity is scaled by M1 class; that is, M1 class corresponds to 1, and X1 class corresponds to 10.

vents.txt). We found that all 25 burst events are associated with the X-ray flares reported by NGDC. Since the radio burst imaging data are not available, we assumed that the location of the solar radio burst is the same as the flare location data taken from NGDC, which usually collects the flare information from worldwide optical (Hα) flare observations. The SRBL location was taken at the time nearest to the peak time of a GOES X-ray flare.

Table 2 summarizes the details of 25 bursts and their related flares. The table includes the event date, the burst time nearest to the flare peak time, the location of the bursts, the location difference between burst and flare, the pointing error of the antenna, the flare time, the flare location, the flare strength taken from NGDC, and the multiplicity of events. For further analysis, we classified the events into two subgroups: single and multiple. While "single" implies a dominant single source on the disk, "multiple" correspond to multiple brightening sources (or relatively high background levels) in SOHO/EIT (Extreme Imaging Telescope) and YOHKOH SXT (Soft X-ray Telescope) images. From these investigation, we found 16 single source events and 9 multiple source events among 25 events.

Figure 4 shows the distributions of the difference (location error) between NGDC flare location and SRBL burst location for the single (16) and multiple (9) source events. The mean location errors are estimated to be about 10 arcmin for all 25 events and about 6.5 arcmin for 16 single source events. It is also noted that the mean location error of half of the single source events is found to be about 3.0 arcmin.

Figure 5 shows the relationship between location error and X-ray peak flux for the 25 events. As shown in Figure 5, the location error is much more widely scattered for multiple source and weak intensity events than single source and strong intensity events. The multiple source events usually have larger location errors than the single source events. For multiple source events associated with weak flares, the errors are widely distributed, ranging from 9.2 to 25.5 arcmin. For single source events associated with strong (X-class) flares, the errors range from 1.4 to 9.1 arcmin, with a mean error of 5.5 arcmin. There are two possibilities for the large error distribution of multiple sources. One possibility is that the major radio burst location is different from the reported optical flare location. In this respect, we examined multiple source events with the large location errors ($\geq$ 15 arcmin). In most cases the SRBL radio bursts were located around other active regions far from where the optical flares were reported, and some of them showed multiple peaks in their dynamic spectra. Another possibility is that such multiple sources may result in a wrong estimation of solar center, which is determined from pre-burst data. That is, if the pre-burst data are contaminated by complex brightening sources, the estimation of solar center as a reference would not be correct. Some events in which the estimated burst locations were in the middle of quiet regions may reflect such a possibility.

During the burst time, we usually have several burst locations for a given flare. One may have a question

TABLE 2.
DETAILS OF OBSERVED SOLAR RADIO BURSTS AND THEIR RELATED SOLAR FLARES

Events Date yy/mm/dd(Doy)	Burst Time (hhmmss)	Burst Location (degree)	Location Diff. (arcmin)	Pointing Error (arcmin)	Flare Peak Time (hhmmss)	Flare Location (degree)	Flare Int.	Multiple Source
2000/02/05(36)	192752	N16E44	2.5	14.6	192800	N26E52	3B/X1.2	X
2000/03/07(67)	160316	S28E84	2.0	9.7	160700	N22E77	1F/M1.2	X
2000/03/22(82)	184338	S03W51	4.8	6.9	184800	N14W57	2N/X1.1	X
2000/05/02(123)	144622	S19W16	14.2	6.0	145100	N22W68	1N/M2.8	O
2000/05/15(136)	165046	S30W37	20.6	2.7	164400	S15E51	SF/M1.1	O
2000/06/03(155)	191857	N08E59	3.8	7.5	192400	N20E49	2B/M6.1	X
2000/06/23(175)	142506	N21W37	4.7	2.8	143100	N26W72	1F/M3.0	X
2000/07/17(199)	202444	S56E83	9.4	6.3	202700	S11E36	1N/M2.4	X
2000/09/30(274)	231917	N12W89	1.4	17.9	232100	N07W91	SF/X1.2	X
2001/04/06(96)	191849	S06W06	10.4	3.5	192100	S21E31	SF/X5.6	O
2001/04/09(99)	152520	S11W13	3.6	8.5	153400	S21W04	2B/M7.9	X
2001/04/22(112)	204202	S06W15	10.8	0.9	204400	N14E18	1N/M3.2	X
2001/04/24(114)	222145	S11W50	14.8	2.8	222400	N17E01	1N/M1.8	O
2001/08/25(237)	000111	N44E01	18.9	13.4	001700	S18E44	SF/M3.5	O
2001/08/30(242)	203614	N22W19	15.5	2.6	203800	N15E44	1N/M3.0	O
2001/08/31(243)	224053	S13W28	15.7	2.6	224200	N14E25	2N/M2.9	O
2001/09/05(248)	190850	X08E17	4.4	2.9	191300	S16E35	1N/M1.3	X
2001/09/09(252)	204411	N14W91	25.5	4.9	204500	S31E26	2N/M9.5	O
2001/09/17(260)	154839	S58W77	6.9	11.5	155000	S32W73	1N/M8.1	X
2001/10/22(295)	175027	S30W05	6.3	11.3	175900	S18E16	2B/X1.2	X
2001/11/28(332)	163339	N04W08	6.7	16.7	163500	N04E16	1B/M6.9	X
2002/03/17(76)	192813	S08W68	19.1	5.6	193100	S22E16	SF/M4.0	X
2002/05/20(140)	152520	X08E42	8.7	4.4	152700	S21E65	2N/X2.1	X
2002/07/03(184)	021152	N07W90	9.1	3.1	021300	S20W51	1B/X1.5	X
2002/07/11(192)	144817	N06E24	9.2	3.7	145100	N21E58	2N/M5.8	O

what is the most proper time to estimate the location of the burst. To give an answer to this question, we examined the time of minimum error (M-E time), defined as the time when the location error is minimum. For this we chose 13 events out of 16 single source events because 3 single source events have just one location. We present the relationship among the M-E time, burst start time, and burst peak time in Figure 6. As shown in the figure, there is a strong tendency for the M-E time to be located just after the starting time (upper panel). We also estimated the location error at the M-E time. The relationship between location error and X-ray intensity at the M-E time, not shown here, is quite similar to that in Figure 5 but the estimated values are a little smaller. In this case, the mean location errors are estimated to be about 8.4 arcmin for all 25 events, and about 4.7 arcmin for 16 single source events (for comparison, see Table 3).

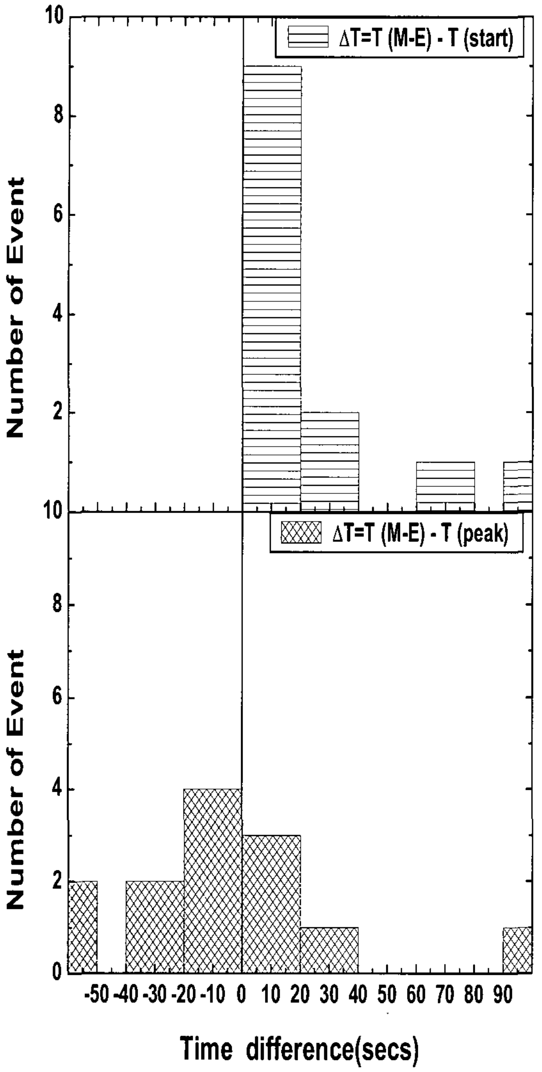
TABLE 3.
COMPARISON OF RADIO BURST LOCATIONAL ERROR

Type	Peak Time (arcmin)	M-E Time (arcmin)
Total (25)	10.0	8.4
Single (16)	6.5	4.7
X-class Single (6)	5.5	4.0

Figure 7 shows a relationship between the pointing error and the location error. Here, the pointing error is defined as the difference between solar center and antenna center, which is estimated from the quiet sun spectrum taken just before the burst. For all 25 events, there is a weak anti-correlation ($r = -0.4$) between the location error and the pointing error, as shown in the upper panel of Figure 7. The anti-correlation becomes more evident ($r = -0.9$) when we only consider 6 single source events related with strong (X-class) flares, as shown in the lower panel of the figure. Although the reason why they show the anti-correlation is not clear, our guess is like the following. With larger pointing error, bursts probably occur farther from the antenna center. As Figure 2 shows, the depth of the modulation increases with the off-center distance of the source. With larger modulation, the source location could be determined more accurately. Therefore the large pointing error may lead to the more accurate source location.

IV. SUMMARY AND DISCUSSION

In this paper, we have evaluated the capabilities of SRBL system in flux and burst location measurements. For this, we considered 130 microwave bursts from 2000 to 2002 and then selected 53 events for flux comparison between SRBL and RSTN. In addition, 25 burst events were chosen to inspect the location capability of SRBL. For this the burst locations were compared with the flare locations from NGDC. We then examined if



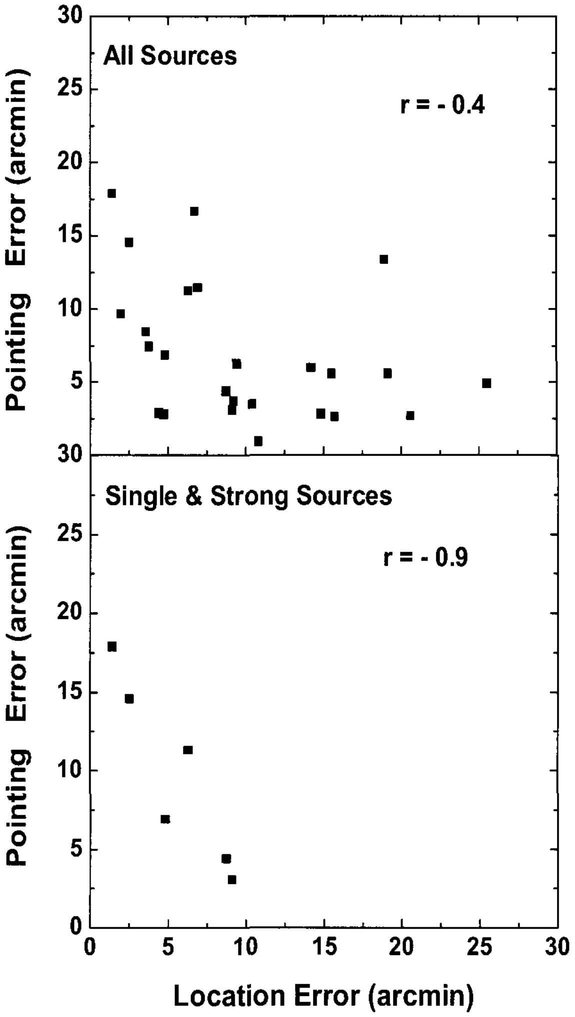


Fig. 6.— Histograms showing the time differences between the M-E time (time of minimum error in location) and the burst start time (upper panel), and the difference between the M-E time and the burst peak time (lower panel).

Fig. 7.— Scatter plot showing the relationship between the location error of the bursts and the pointing error of the SRBL for all 25 events (upper panel) and 6 strong single source events (lower panel).

multiplicity of brightening sources in UV or soft X-ray images affect the location accuracy. The most appropriate time (i.e., the M-E time) to estimate the burst location was also inspected. Our results are summarized as follows;

(1) There is a relatively good correlation ($r = 0.9$) between SRBL flux and RSTN flux. This result indicates that the SRBL flux is consistent with the RSTN flux.

(2) The multiple source events usually have larger location errors than those of the single source events. It is also noted that the mean location error near the flaring time for single source events is found to be about 6.5 arcmin. The mean location error at the M-E time for single events is estimated to be about 4.7 arcmin.

(3) The most proper time (or the M-E time) to estimate the burst location, when the error is minimum, is found to be just after the burst starting time, mostly within 10 seconds.

(4) There is an anti-correlation ($r = -0.4$) between the pointing error and the location error. Such an anti-correlation becomes more evident ($r = -0.9$) for 6 strong single source events associated with X-class flares.

Our results show that the flux measurements of SRBL are consistent with those of RSTN and the location mean error for single source events is estimated to be about 4.7 arcmin, similar to the conclusions of Dougherty et al. (2000) and Dougherty (2000) based on a smaller number of events. Considering that the mean error is greatly reduced for single source events, we think that the main reason of the location error is the occurrence of multiple source flare brightenings or relatively complex background contaminating the modulation patterns of the burst and/or the pre-burst (quiet sun) spectra. Regarding this, an independent determination of pointing position by a very accurate tracking system with high precision encoders, without using the pre-burst spectrum, may be helpful for improving the location error. The anti-correlation between the pointing error and the location error suggests a possibility to improve the location accuracy by using an intentional offset in tracking. However, these possibilities should be further examined in the future. Finally, we hope that the present study would be helpful for improving the capability of Korean-SRBL (K-SRBL), which is an upgraded version of the SRBL under development and is supposed to be installed at Korea Astronomy and Space Science Institute (KASI) in a few years.

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