

A Survey for Transient Astronomical Radio Emission at 611 MHz

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ABSTRACT. We have constructed and operated the Survey for Transient Astronomical Radio Emission (STARE) to detect transient astronomical radio emission at 611 MHz originating from the sky over the northeastern United States. The system is sensitive to transient events on timescales of 0.125 s to a few minutes, with a typical zenith flux density detection threshold of approximately 27 kJy. During 18 months of around-the-clock observing with three geographically separated instruments, we detected a total of 4,318,486 radio bursts. Of these events, 99.9% were rejected as locally generated interference, determined by requiring the simultaneous observation of an event at all three sites for it to be identified as having an astronomical origin. The remaining 3898 events have been found to be associated with 99 solar radio bursts. These results demonstrate the remarkably effective radio frequency interference rejection achieved by a coincidence technique using precision timing (such as GPS clocks) at geographically separated sites. The nondetection of extrasolar bursting or flaring radio sources has improved the flux density sensitivity and timescale sensitivity limits set by several similar experiments in the 1970s. We discuss the consequences of these limits for the immediate solar neighborhood and the discovery of previously unknown classes of sources. We also discuss other possible uses for the large collection of 611 MHz monitoring data assembled by STARE.

1. INTRODUCTION

Transient astronomical electromagnetic radiation is the signature of some of the most fascinating physical phenomena in the universe. Anywhere the physical conditions change with time, there is the potential for transient radiation. The detection of transient astronomical radiation presents challenges not encountered in observations of persistent sources. Sources that produce radiation sporadically cannot easily be studied with typical observatories and their schedules of observing time allocation; other techniques are required. Detecting transient astronomical signals at radio wavelengths in particular requires overcoming an even greater difficulty: the pervasive presence of radio frequency interference (RFI). The ever-growing use of wireless services means that the radio spectrum is crowded

with a wide variety of signals, a large fraction of which are transient. Since it is the very nature of transient signals of terrestrial or astronomical origin to disappear unpredictably, they cannot reliably be distinguished from each other by repeated observing. Surveyors for transient astronomical radio signals must devise other methods to separate the desired astronomical signals from the seemingly ubiquitous RFI.

We describe here the Survey for Transient Astronomical Radio Emission (STARE), a system for detecting transient astronomical radio signals. Sensitive to transient radio signals at 611 MHz on timescales of 0.125 s to a few minutes, STARE rejects RFI by requiring simultaneous observation of signals at three geographically separated sites.

1.1. Sources of Transient Astronomical Radio Emission

Many sources have been observed to produce transient astronomical radio emission. Perhaps the most familiar is the Sun, from which a large variety of transient radio signals emanate. From microwave spike bursts lasting ~10 ms to type III

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storms lasting weeks, the characteristics of solar radio bursts span wide ranges of brightness temperature, duration, frequency, and polarization. Associated with many different aspects of solar activity, the mechanisms producing the bursts run the gamut, from thermal bremsstrahlung to plasma radiation. Dulk (1985) and Hjellming (1988) provide reviews. Other stars have been seen to produce radio bursts as well. Events observed on flare stars are similar in character to those seen on the Sun but imply radio luminosities 10^4 times that of solar flares (Dulk 1985). RS CVn systems, close binaries with orbital periods of ~ 1 –30 days, have been observed to produce transient radio emission on timescales of minutes to days. The signals are thought to be due to two separate phenomena: the acceleration of electrons in the magnetic fields between the stars and coherent emission from the individual stars (Hjellming 1988). X-ray binaries as well are known to produce transient radio signals following X-ray events, although the mechanism in this case is thought to be quite different from that of the RS CVn binaries (Hjellming & Han 1995). Jupiter was discovered many years ago to produce transient radio emission at decimeter wavelengths (Burke & Franklin 1955), thought to be due to synchrotron radiation from high-energy electrons trapped in the magnetic field of the planet. Details are reviewed in Carr, Desch, & Alexander (1983). Brown dwarfs have been seen to flare in the radio: a recent VLA observation of a such a flare measured a flux density much higher than that expected from an empirical relation between the luminosities of brown dwarf radio flares and X-ray flares (Berger et al. 2001). Some radio pulsars are observed occasionally to produce “giant pulses.” For example, about 0.3% of the pulses from the Crab pulsar have amplitudes greater than 1000 times the average pulse height (Lundgren et al. 1995). High-energy cosmic rays can cause transient radio signals at the surface of the Earth. The interaction of high-energy particles from space and the Earth’s atmosphere produces an “extensive air shower.” Pair production in the shower creates populations of electrons and positrons that are systematically separated by the magnetic field of the Earth, setting up a current that produces a radio pulse (Kahn & Lerche 1966). These are only a few examples of known sources of transient astronomical radio emission.

Other sources have been postulated, but not observed, to produce short radio pulses. For example, Colgate, McKee, & Blevins (1972) and Colgate (1975) have predicted that a Type I supernova should radiate an electromagnetic pulse at radio frequencies: during the collapse, the expanding envelope of the white dwarf acts as a “conducting piston,” compressing the transverse magnetic field, thus producing a short pulse of radio emission. Efforts to detect such pulses are described by Meikle & Colgate (1978) and Phinney & Taylor (1979). Another example is “exploding” black holes, predicted by Hawking (1974): the decrease in black hole mass due to quantum radiation causes an increase in surface gravity, which in turn increases the emission rate. Black holes near the ends of their

lives would radiate intensely, releasing 10^{30} ergs in the last 0.1 s. Rees (1977) has speculated that the expanding sphere of electrons and positrons would act like the conducting piston described by Colgate for supernovae, similarly producing a short radio pulse. Meikle (1977) and Phinney & Taylor (1979) have reported unsuccessful searches for these pulses.

Of particular interest for radio transient searches is the association between high-energy emission and radio emission. Mattox (1994) reports searching the *Compton Gamma-Ray Observatory*/EGRET phase 1 full-sky survey for gamma-ray emission from X-ray-selected BL Lac objects and from the 200 brightest radio-quiet quasars. None was detected, while EGRET did detect ~ 40 radio-loud quasars and radio-selected BL Lac objects. This seems to suggest that “apparent gamma-ray emission is intimately linked to apparent radio-emission” (Mattox 1994), which is perhaps not surprising since the conditions that produce high-energy emission (relativistic particles), in the presence of even a weak magnetic field, produce radio emission through the synchrotron mechanism. This association has been noticed by others as well (e.g., Paczyński & Rhoads 1993). The presence or absence of radio emission from high-energy sources can yield clues about their workings.

Gamma-ray bursts (GRBs) have been observed to produce emission at longer wavelengths following the gamma-ray event (see van Paradijs, Kouveliotou, & Wijers 2000 for a review). These so-called afterglows were first detected at radio wavelengths in the GRB of 1997 May 8 (Frail et al. 1997), and the field has since matured such that a catalog of radio afterglows is possible (Frail et al. 2003). The afterglows are believed to be due to emission from shocks produced when a relativistic fireball interacts with an ambient medium (Mészáros 2002 reviews models). Another possibility, which has not been detected, is a prompt radio burst associated with the GRB event itself. Again, energetic charged particles in a magnetic field might serve as a source; for example, Usov & Katz (2000) suggest that strong low-frequency radio emission might be generated by time variability in the current sheath surrounding a magnetized jet. Examples of other ideas relevant to the detection of prompt radio emission from GRBs may be found in Palmer (1993), Hansen & Lyutikov (2001), and Sagiv & Waxman (2002).

Energetic particles can produce radio emission under other conditions as well. It was suggested some time ago (Askar’yan 1962, 1965) that high-energy neutrinos and cosmic rays would generate coherent Cerenkov emission as they travel through a dense dielectric medium such as water, ice, the Earth, or the Moon. The physical process is similar to that of the extensive air shower discussed earlier, involving the production of a shower with an imbalance of charge. The spectrum of Cerenkov light from such an event would be very broad, including radio and optical emission. The generation of coherent radio bursts has been verified in accelerator experiments (Saltzberg et al. 2001). The pulses generated by particles traveling through the

lunar regolith are expected to be very bright and very short: more than thousands of janskys for the highest energy particles, with durations on the order of a nanosecond (Alvarez-Muniz & Zaz 2000). Hankins, Ekers, & O'Sullivan (1996) report an unsuccessful search for such emission.

1.2. Other Work

Experiments to detect transient astronomical radiation at radio wavelengths have traditionally followed one of two approaches. When transient radio emission is thought to originate from a particular source or region of the sky, a high-gain, small solid-angle approach is used. A high-gain radio telescope pointed at the region of interest provides good sensitivity and rejection of signals outside the region. When the location of the source of radiation is unknown, a low-gain, large solid-angle approach is more appropriate. Radio telescopes with large beams provide coverage of large fractions of the sky, but at the cost of reduced sensitivity, since the angular extent of any discrete source is likely to be much smaller than the telescope beam.

Some good examples of the high-gain, small solid-angle approach are those that were prompted in the early 1970s by Weber's reports of detections of pulses of gravitational radiation (e.g., Weber 1970). Since the gravitational waves were reported to have originated from the Galactic center, attempts to detect radio frequency activity focused on that region. Partridge & Wrixon (1972) monitored the Galactic center with two radiometers separated by 100 km. The first, at 16 GHz, provided a beamwidth of $\sim 12'$, sensitivity of ~ 100 Jy, and response time of 0.5 s. The other, at 19 GHz, provided a beamwidth of $\sim 12^\circ$, sensitivity of $\sim 10^6$ Jy, and response time of 3 s. Astronomical events were to be identified by their simultaneous appearance in the records at both sites. After 90 hours of monitoring, they detected no coincidences. Hughes & Retallack (1973) observed the Galactic center at 858 MHz with beamwidth 1.4° , sensitivity 85 Jy, and response time 1 s. In 207 hours of monitoring the Galactic center, they report 97 detections of pulses. However, their interference rejection scheme is unclear, making uncertain their conclusion of the existence of discrete radio pulses from the Galactic center. O'Mongain & Weekes (1974) used the Mount Hopkins Observatory 10 m optical reflector (which was fitted with two outboard 4.6 m radio reflectors) to make a more general search including the Galactic center, the Coma cluster of galaxies, and the Andromeda galaxy at three radio frequencies and one optical frequency. In approximately 200 hours of observing, they detected no events of extraterrestrial origin, which were to be identified by the differences in pulse arrival times among frequencies, due to dispersion by the interstellar medium.

Other work has attempted to observe a much larger fraction of the sky with lower sensitivity. For example, Charman et al. (1970) assembled a system of five receiving stations in Great

Britain and Ireland with station separations ranging from 110 to 500 km. Each station had similar receiving systems at 151 MHz, consisting of two half-wave dipole antennas operating as phase-switched interferometers, and receivers with sensitivities of $\sim 10^5$ Jy and response times of ~ 1 s. Interference rejection was accomplished by the requirement of fivefold coincidence. After ~ 2400 hours of observations, they detected no events. Mandolesi et al. (1977) used four receiving systems at Medicina (Bologna, Italy) operating at 151, 323.5, 330.5, and 408 MHz. On 1976 August 16 all four instruments detected a radio burst, while 60 s earlier, a gamma-ray burst was detected by three satellites and one balloon-borne detector. Strong rejection of local interference was provided by an independent observation made at 237 MHz at the Astronomical Observatory of Trieste (400 km distant from Medicina). The investigators estimated the probability of a random coincidence between the fivefold radio event and the gamma-ray burst at 8×10^{-5} . Using geometric arguments, they localized the radio burst to a region on the sky. Unfortunately, later work on the gamma-ray burst data from the balloon-borne detector (Sommer & Müller 1978) produced a position for the gamma-ray event that was well outside the radio emission error box, apparently ruling out a common origin for the gamma-ray and radio events. But the possibility remains that the radio event was astronomical in origin. Hugenin & Moore (1974) used two receiving systems separated by several hundred kilometers to monitor the sky at 270 MHz. Each station consisted of a helical antenna with beam area of ~ 1 sr centered on the north celestial pole and a multi-channel receiver that provided a sensitivity of $\sim 10^4$ Jy (1σ). The data were displayed with response times $\tau = 20$ ms to 1 s on an oscilloscope and recorded by continuously photographing the oscilloscope screen. Interference was rejected by requiring coincidence between sites and by examining for the frequency dispersion expected in extraterrestrial signals due to the interstellar plasma. In 213 hours of observing, they detected no events. Amy, Large, & Vaughan (1989) constructed the Molonglo Observatory Transient Event Recorder (MOTER), which operated at 843 MHz in parallel with normal Molonglo Observatory Synthesis Telescope (MOST) synthesis observations. This system used 32 total-power fan beams spaced at full beamwidth intervals of $44''$. When a transient event with flux density ≥ 10 mJy and duration $1\ \mu\text{s}$ to 800 ms occurred in the field of view, MOTER compared the signals in the fan beams. Sources closer than about 3000 km were significantly out of focus, and thus appeared in many beams simultaneously, while signals appearing in one beam only were thought to be due to random noise. In this way MOTER was able to reject signals of local origin. A signal that was not rejected was localized to an arc segment on the sky corresponding to the fan beam in which its maximum appeared. Over a full synthesis observation, the resulting ensemble of arc segments intersected at a point, the location of the source. While MOTER lacked instantaneous large solid-angle coverage, in time much of the

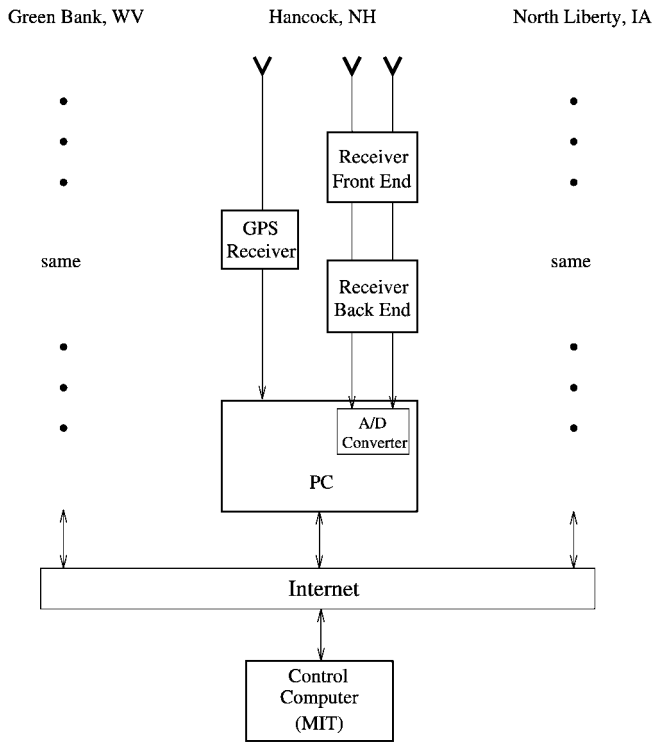


FIG. 1.—STARE system organization.

southern sky was surveyed. In ~4000 hours of observations, Amy et al. (1989) detected only previously known pulsars.

1.3. STARE

We describe here a large solid-angle, low-gain system for detecting transient astronomical radio emission at 611 MHz on timescales of a few minutes or less. Similar in spirit to the work of Charman et al. (1970) and Mandolesi et al. (1977), STARE updates previous efforts through the use of modern technology. The wide availability of fast computers and other hardware permits the collection of data in digital form. Such a data record makes possible a variety of analyses both during data collection and afterward, presenting a greater opportunity for discovery than the data sets from the 1970s that were generally in the form of analog chart records.

2. METHODS

STARE was designed to be simple and inexpensive and was intended to be a first look that might eventually foster further work with new instrumentation. The system operates at a frequency of 611 MHz in a bandwidth of 4 MHz, corresponding to a frequency band protected in the United States for radio astronomy; if not protected, this band would contain the signal for channel 37 in the UHF television spectrum. Scientific arguments fail to indicate a clear choice of observing frequency: at higher frequencies, optically thick sources are brighter, while

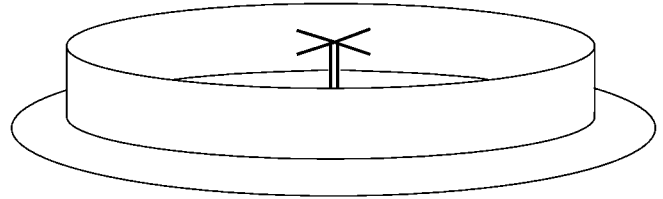


FIG. 2.—Schematic illustration of “crossed dipoles in a cavity” antenna.

at lower frequencies, optically thin nonthermal processes radiate more intensely—too low, however, and the sky brightness temperature becomes prohibitive. The choice of 611 MHz was a compromise among these considerations, bolstered by technical factors such as the relative ease and low cost of constructing radio astronomy apparatus for this frequency range and the existence of a protected band for astronomy.

2.1. Apparatus

The STARE system consists of detectors at three geographically separated sites: one at the VLBA³ station in Hancock, New Hampshire, another at the VLBA station in North Liberty, Iowa, and the third at NRAO in Green Bank, West Virginia. The sites are close enough that they see the same part of the sky, while they are distant enough that radio frequency interference at one of the sites (from terrestrial or low-altitude transmitters) will not be detected at the others. This provides a powerful filter for selecting signals of celestial origin: any signal that does not appear simultaneously at all three sites is rejected. These locations were chosen because they all have operating radio telescopes, and so are expected to have low levels of RFI, and because NRAO was kindly willing to support STARE operations. The STARE instruments are highly self-sufficient, requiring only a standard AC electrical power connection, an Internet connection, space for the antennas and electronics, and a staff member willing to perform occasional minor crisis intervention. The apparatus at a site consists of several systems: an analog receiving system, a Global Positioning System receiver for providing accurate time, and a PC that collects data and controls everything at the site. The entire system is overseen by a workstation at MIT, which is also where the data are archived. Figure 1 shows the organization of the entire system.

The analog receiving systems each consist of an antenna, a receiver, and a detector. The antennas are of the “crossed dipoles in a cavity” type, shown schematically in Figure 2. This style of antenna provides broad sky coverage, although at the expense of sensitivity. Laboratory measurements (by J. Barrett, P. McMahon, and W. Baumgartner) on a scale model of the

³ The VLBA is part of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

antennas found a broad beam with effective solid angle 1.4 sr, yielding a sensitivity of $6.1 \times 10^{-5} \text{ K Jy}^{-1}$. The receivers are dual-channel superheterodyne total-power radiometers and are each divided between a front end that is outdoors attached to the antenna and a back end that is indoors. The front end begins with low-noise ambient temperature preamplifiers (Harris & Lakatos 1987) with effective noise temperatures in the range 100–150 K. The front end also includes a laboratory-calibrated noise source for gain calibration and system temperature measurements. The back end performs bandpass filtering, further amplification, frequency downconversion, square-law detection, and antialias filtering at 25 kHz. The analog receiving systems were designed to provide sensitivity to the two orthogonal circular polarizations, with beam patterns independent of source azimuth. However, on account of an error in the construction of the feeds, they receive two orthogonal elliptical polarizations, which vary with source azimuth. We avoid this problem by summing the two received polarizations. It can be shown (Katz 1997), and is evident from symmetry, that the orthogonality of the received elliptical polarizations means that their sum is independent of the azimuth of the source. Thus in practice we are able to calibrate only the sum of the total power in both polarizations.

In order to reject local interference, we must be able to determine simultaneity from site to site, requiring an accurate timekeeping method. This is provided by the Global Positioning System (GPS). At each STARE site is a GPS antenna and receiver. When initially installed, each GPS system was allowed to compute its position continuously for several days. The data were then suitably averaged to increase the accuracy of the position determinations. Those positions were then programmed into the GPS systems, allowing four satellites to be used for timekeeping alone. In this “static timing mode,” the GPS receivers have a claimed timing accuracy of $\pm 100 \text{ ns}$.

Data acquisition and all other activity at each site are controlled by a standard desktop PC. The filtered square-law detector outputs are digitized at 50 kHz by a 12 bit analog-to-digital converter card which is clocked by a 100 kHz signal from the GPS receiver. Time stamps are assigned to the data by switching in a short pulse from the GPS receiver and finding the sample during which the pulse is detected, yielding a time stamp accuracy of $20 \mu\text{s}$. The samples are boxcar integrated, then collected and saved on the disk for some specified period, then are transferred to a workstation at MIT. In addition to performing overall coordination and data archiving, the workstation is responsible for the data analysis: the data files from each site are analyzed individually to produce a record of transient radio signals there. The site event records are then compared to find three-way coincidences.

The entire STARE system runs automatically, producing a daily report of site events and coincidence detections. The computer systems are set up so that most routine maintenance can be performed without traveling to the sites. The system is quite robust, having required human attention on average less than

once a month. Sometimes attention is necessary to clear a fault condition, but most often routine maintenance (e.g., clearing a full disk) is the cause. Occasionally a phone call to a site is necessary (e.g., to identify and replace an electrical fuse blown during an electrical storm).

In normal operation, the power received by each antenna at 611 MHz in 4 MHz bandwidth and two polarizations is boxcar averaged for 0.125 s and recorded. Every 15 minutes, the noise source in the front end is switched on for 2 s, to provide receiver gain calibration. Each hour, the data from the previous hour are uploaded to the workstation at MIT, where they are processed and archived.

2.2. Coincidence Detection

Coincidences among sites are detected by the simplest possible method: the records of each site are examined to find events at that location, then the lists of single-site events are compared to find instances where all three sites recorded events simultaneously. Note that with this simple scheme, the overall sensitivity to three-way coincidences is determined by the site with the poorest detection sensitivity. If one site fails to detect an event, the event cannot be identified as a three-way coincidence. More sophisticated schemes could no doubt produce better detection sensitivity.

The first step, the detection of events at each site individually, is performed using a two-pass sliding-window baseline fit. On the first pass, a quadratic model is fitted to the data in a 240 s window using a least-squares algorithm, and the dispersion σ of the data around this fit is calculated. On the second pass, the model is again fitted to the data in the 240 s window, this time using the robust estimation method described by Press et al. (1992, § 15.7). We implemented the method with a Lorentzian weighting distribution with the width set to the dispersion σ calculated in the first pass. This method was chosen so that we could follow the wandering baseline in the data without our fit being skewed by outlier points, of which there are many, including the transient signals we are trying to detect. Note that this results in a loss of sensitivity to events longer than a few minutes. Greater sensitivity to long-lived events could be achieved by increasing the width of this boxcar averaging window, at the expense of reducing the baseline-removal effectiveness for shorter time periods.

Once the baseline fit is determined, the data are examined for samples that deviate from the baseline by more than some threshold specified as a multiple of σ . When a sample is seen to deviate by more than the threshold, an event is considered to be in progress, and the next sample is examined. This continues until the deviation falls below one-half of the threshold, at which time the event is considered to have ended. We use this adaptive threshold to reduce the incidence of long, temporally spiky events being broken up into multiple events as the flux density level varies around the threshold. Once the events are detected, they are classified as “single point” or

“multipoint,” depending on whether the thresholds were exceeded only in a single sample (i.e., event duration ≤ 0.125 s) or in more than one consecutive sample.

The thresholds for event detection were chosen so that from site to site, the flux density required to trigger an event is about the same. Using receiver noise temperature 150 K, zenith antenna sensitivity 6.1×10^{-5} K Jy $^{-1}$, integration time 0.125 s, and bandwidth 4 MHz, we calculate a theoretical zenith flux density sensitivity for our systems of about 4 kJy. Of course, in practice the system temperatures are higher than the receiver temperatures because our 1.4 sr beam admits RFI from sources far and wide, degrading the system sensitivity. We found that the system temperatures also vary widely with time. At Green Bank and North Liberty, the median system temperatures through 18 months of observations were similar at about 200 K. At Hancock, the system temperatures were typically higher by a factor of 2. To make the zenith flux density sensitivities consistent from site to site, we chose a threshold of 5σ for transient detection at Green Bank and North Liberty and 2.5σ at Hancock. These thresholds correspond to a zenith flux density triggering threshold of about 26 kJy. For sources away from zenith, the threshold is of course higher due to the decrease in antenna gain.

Once the single-site event lists are produced, they are compared to find events detected simultaneously at all three sites. Three-way coincidences are classified as “single point” if the three single-site events are all single-point events, “multipoint” if they are all multipoint events, and “mixed type” if the simultaneous single-site events are a combination of single point and multipoint. To assess the coincidence detection sensitivity of STARE, we examined the flux density sensitivity at each site for every minute of time that all three sites were on-line. We then chose the poorest sensitivity of the three as the STARE coincidence sensitivity, since the site with the poorest sensitivity would determine the overall sensitivity. The results are shown in a normalized histogram in Figure 3. Not shown are the 5.6% of the values that lie beyond the right side of the plot, due to noisy times at one or more of the sites. The median overall STARE zenith sensitivity of 26.7 kJy is very close to the median single-site detection sensitivity of 26 kJy, indicating that most of the time, the three sites run with comparable sensitivities.

2.3. Calibration

Event data were calibrated in several steps. First, the receiver gains were determined using the noise source on/off data. These were used to convert the data to antenna temperatures in each polarization channel. The antenna temperatures were summed to find the total antenna temperature and to avoid the problem with the unknown polarizations of the feeds (see the discussion of the analog receiving systems in § 2.1). Then, using the antenna sensitivity determined from measurements on a scale model of the antennas, the antenna temperatures were converted

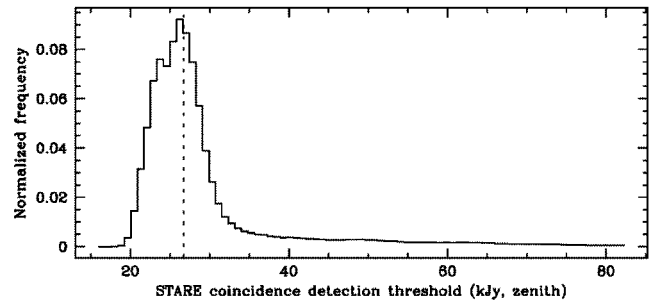


FIG. 3.—Normalized histogram of minute-by-minute STARE zenith coincidence detection threshold for 711,456 minutes of three-site observations; 5.6% of the values lie beyond the right extreme of the plot. The dotted line shows the median value of 26.7 kJy.

to the flux densities that would be measured if the source were at the zenith. This resulted in a lower limit on the flux density of the source. For sources of known elevation, such as the Sun, the zenith flux densities were corrected for the elevation response of the antenna, yielding a source flux density measurement.

The calibration is rather coarse. In practice we find that the flux densities of solar radio bursts measured by the STARE systems generally agree from site to site only within a factor of 2 or so. Comparing measurements between sites, we find that the Green Bank instrument systematically reports flux densities approximately a factor of 2 larger than those reported by Hancock, which in turn are approximately a factor of 2 larger than those reported by North Liberty. In addition, there is significant variation of these ratios from event to event. We believe this is due primarily to uncertainties in two parts of the receiving systems. First, the beam patterns of the antennas were determined on a 1/10 scale model and may not transfer very well to the actual feeds. This would cause elevation-dependent variations in the calibration and could account for the scatter in the systematic differences between sites. Second, the excess noise temperatures of the noise sources used for gain calibration were measured when the systems were constructed and may have changed over the several years of aging they have experienced. This could be the cause of the overall systematic differences between sites.

Clearly the calibration accuracy could be improved by measuring or computing numerically the antenna beam patterns and by measuring the present noise source characteristics. But for our purpose here, we consider the calibration accuracy of a factor of a few to be adequate and defer the improvements to later work.

3. RESULTS

The first STARE site was set up at the VLBA station in Hancock, New Hampshire. A subsequent period of site evaluation and debugging led to the final configuration with sites

TABLE 1
SINGLE-SITE EVENT DETECTION RESULTS, 1998 MAY 27 TO 1999 NOVEMBER 19

Parameter	Hancock	Green Bank	North Liberty
Detection threshold	2.5σ	5σ	5σ
Number of single-point events	3,654,485	183,851	100,692
Mean single-point event rate (hr^{-1})	281.5	14.2	7.8
Number of multipoint events	168,833	95,496	115,129
Mean multipoint event rate (hr^{-1})	13.0	7.4	8.9

at Hancock, New Hampshire; North Liberty, Iowa; and Green Bank, West Virginia. The system operated in this state for approximately 18 months. We describe here the results obtained from the data collected from 1998 May 27 through 1999 November 19.

3.1. Single-Site Event Detection

In 18 months of operation, STARE detected hundreds of thousands of events at Green Bank and North Liberty and millions at Hancock with its weaker triggering threshold. The exact numbers are given in Table 1.

Using the mean single-point event rates computed from the single-site event detection results, we can estimate the rate of accidental single-point coincidences among the sites. For a mean event rate r , the probability that a time interval δt contains an event is $r\delta t$ (assuming $r \ll 1/\delta t$, which is true for STARE since $\delta t = 0.125$ s). Thus for three sites with mean event rates r_1 , r_2 , and r_3 , the probability that a time interval δt contains an event at all three sites is $r_1 r_2 r_3 (\delta t)^3$. The mean time ΔT between accidental three-site coincidences is then $\Delta T = 1/r_1 r_2 r_3 (\delta t)^2$. Using the rates given in Table 1, we find $\Delta T \approx 3$ years. With only two sites (even those with the lowest event rates, Green Bank and North Liberty), this time is $\Delta T = 1/r_1 r_2 \delta t \approx 11$ days. This illustrates the power of the coincidence requirement in filtering out local radio frequency interference. It also makes clear that the third site is required to reduce the accidental coincidence rate to a manageable level.

A similar examination of accidental coincidence rates for multipoint events is not necessary, since their temporal structure provides much more information than is available with single-point coincidences. Accidental coincidences may be ruled out simply by direct comparison of the time-series data from each of the sites. Unless the events have the same shape, they can be rejected as events of interest.

3.2. Coincidence Detection

In approximately 18 months of data collection, the three STARE sites recorded well over 4 million radio bursts. Of these, 3898 were identified to be in temporal coincidence among all three sites: 1859 at Hancock, 1069 at Green Bank, and 970 at North Liberty. The numbers are unequal because of the spiky temporal nature of many of the events. Despite the use of the adaptive threshold algorithm described in § 2.2,

the event detection algorithm tended to break up long events into multiple events, depending on exactly how the measured power varied around the detection thresholds. In many instances, a single long event observed at one site was broken up into multiple events at the others, due to sensitivity differences between sites. In this case, STARE reported multiple coincidences despite one site reporting only a single event. To account for this effect, the data for each reported coincidence were examined visually to determine which of these multiple events were really just parts of the same overall event. After this reduction step, we found that the reported coincidences collapsed into 126 distinct events. Examining each of these more carefully, we found that 27 were accidental. Accidental events were identified using two criteria: the time dependence of the events differed obviously among the sites, and/or one or more of the sites showed a temporarily very high event rate, due to some local RF emitting phenomenon. Ignoring the accidental events, we find that STARE detected 99 events that appear to be of astronomical origin.

Since we expect that the Sun is the most intense source of transient radio emission in the sky, we compared the STARE events with those detected independently by a solar monitoring station. The US Air Force operates a worldwide Radio Solar Telescope Network (RSTN) for the purpose of producing warnings about solar weather events that could disrupt terrestrial systems. Conveniently for us, one of the stations of the RSTN is Sagamore Hill Solar Radio Observatory in Hamilton, Massachusetts, approximately 80 km distant from our STARE instrument in Hancock, New Hampshire. The RSTN monitors the Sun for transient activity at eight fixed frequencies, one of which is 610 MHz, the same as the STARE observing frequency. Thus the record from the Sagamore Hill RSTN station is useful to us for comparison and verification purposes.⁴ The RSTN 610 MHz system operates on an 8.5 m dish, using a dipole feed to measure a single linear polarization, recording the solar flux density once per second (Heineman & Ambrisco 1997).

During the 18 months of STARE three-site data collection, the RSTN Sagamore Hill station reported 146 solar radio bursts at 610 MHz. After combining these events with the 99 detected by STARE during this time, we divided the ensemble of events

⁴ Data from the RSTN are available through the National Geophysical Data Center of the National Oceanic and Atmospheric Administration.

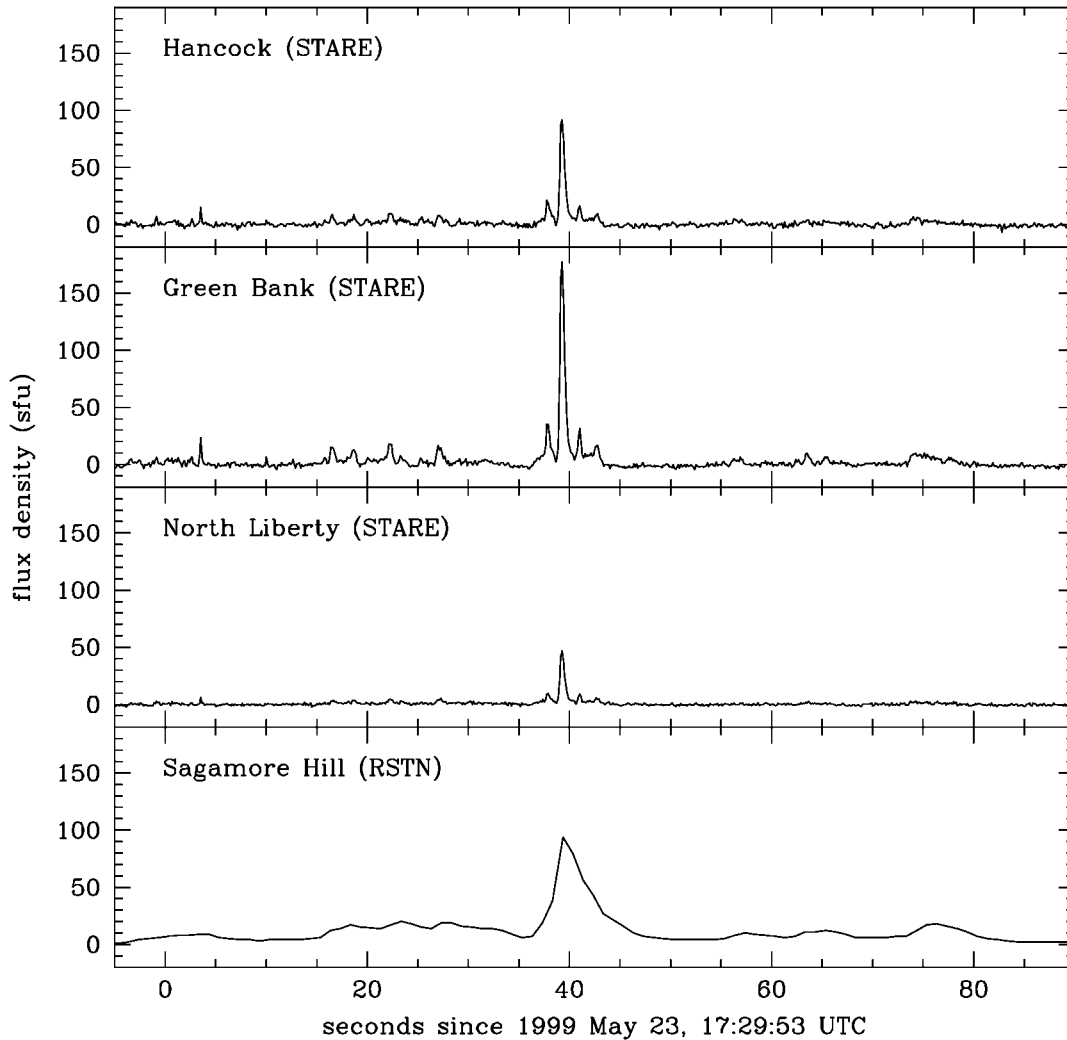


FIG. 4.—Solar radio burst detected by STARE and RSTN at 610 MHz on 1999 May 23. Flux densities are in solar flux units ($1 \text{ sfu} = 10^4 \text{ Jy}$).

into three groups: those detected by STARE only (58 events), those detected by RSTN only (105 events), and those detected by both STARE and RSTN (41 events). Of course, the first group is potentially the most interesting as it may include transient astronomical radio emission from nonsolar sources. The other groups are useful in understanding the behavior of the STARE system. To illustrate a typical event, we show in Figure 4 the event detected by STARE and RSTN on 1999 May 23 at 17:30 UTC.

We first compared the peak flux densities of the events measured by STARE and RSTN, and we found that the Hancock site produces flux density estimates that are on average closest to those of the RSTN. The Green Bank site produces higher values, and the North Liberty site produces lower values, more or less consistent with the systematic flux density scale differences described in § 2.3, although with a large scatter around these averages. Note however that we do not expect particularly

good agreement between STARE and RSTN flux density measurements since STARE measures the total flux density in both polarizations, while RSTN measures a single linear polarization. The exact ratios of the measurements depend on the polarization of the received radiation.

We used the full ensemble of 204 events to help characterize the triggering criteria of STARE and RSTN. Figure 5 shows plots of event flux density against event duration for both RSTN-measured values and STARE-measured values (from Hancock, since it is in closest agreement with RSTN). We can draw several conclusions from these plots. From the left plot, we see that STARE is more sensitive to short-duration events. This is to be expected, since STARE takes eight samples per second, while the RSTN takes one. From the right plot, we see that the RSTN has better sensitivity. This is also to be expected, since RSTN uses a parabolic dish that tracks the Sun. To properly interpret the right plot in Figure 5, note that RSTN reports

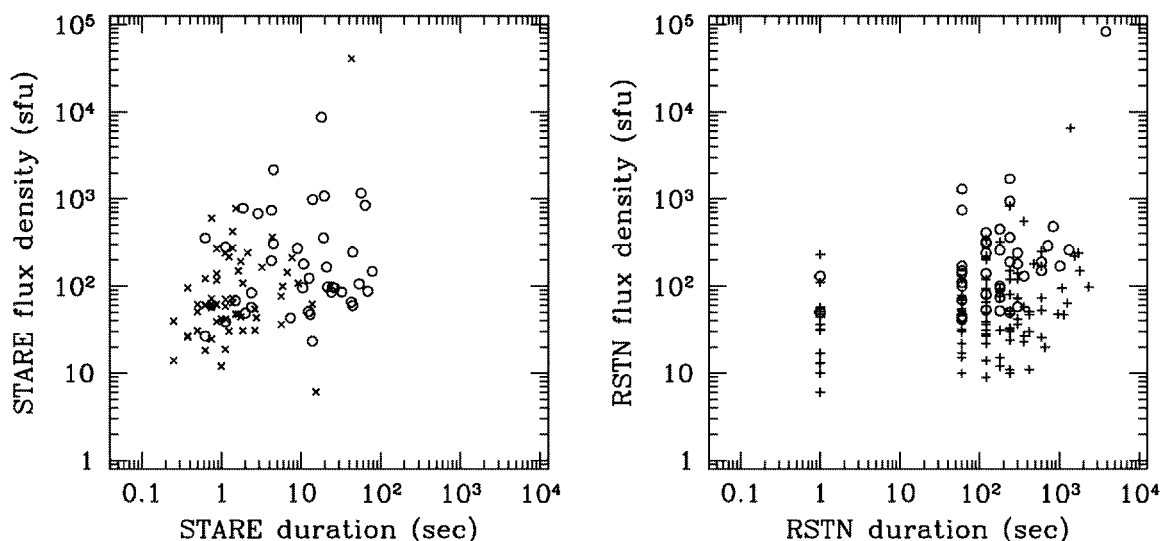


FIG. 5.—Measured flux densities ($1 \text{ sfu} = 10^4 \text{ Jy}$) of events vs. event durations, using STARE-measured values (*left*) and RSTN-measured values (*right*). The circles indicate events detected by both RSTN and STARE, the crosses indicate events detected by STARE only, and the plus signs indicate events detected by RSTN only.

only the start and end times for events, with 1 minute accuracy, accounting for the distinct columns of points in the plot. For this plot, we arbitrarily assigned a duration of 1 s to events listed as starting and ending in the same minute.

We then examined the 105 events detected by RSTN only and found three reasons that they were not detected by STARE. A subgroup of 74 events was simply too faint for detection by STARE. For another 25 of the events, manual examination of the STARE data showed that the events were indeed recorded but that they did not exceed the trigger threshold at all three sites, so they were not identified as three-way coincidences. For the remaining six events, there were no data recorded by one or more STARE sites at the time of the RSTN event, on account of the systems being off the air for maintenance or other purposes. From these results we gain confidence that during the 18 months of three-site data collection, STARE detected the events we expected it to detect.

Finally, we examined the final group of 58 events: those detected by STARE but not by the RSTN. From the left plot in Figure 5, we see that many of these events are of short duration, suggesting that they might have been of solar origin but were too short to trigger a radio burst alert from RSTN. In addition, all of the events occurred during daytime hours. To determine unequivocally whether these events were from the Sun, we obtained the RSTN 1 s data stream and compared it directly with the STARE records. For 51 of the events, the signal was easily discernible in the Sagamore Hill RSTN record, matching the STARE event well in time and shape. A somewhat deeper investigation into why these events were not reported by RSTN determined that when events are detected by RSTN, a human examines the data to decide whether burst

alerts should be issued (Heineman & Ambrisco 1997), so we should not count on the burst alerts as a complete record. The other seven events were not found in the Sagamore Hill RSTN record because of gaps in the data, due to equipment outages or calibration. For these, we obtained and examined the data from two other RSTN sites: San Vito, Italy, and Palehua, Hawaii. Five of the remaining events were unambiguously identified in these records. The two remaining events occurred at times when no RSTN data were available; at San Vito, the Sun had already set, and at Palehua, the events occurred during gaps in the data. However, we suspect that these two are due to solar radio bursts as well. For one event, the Sagamore Hill data resume several seconds after the STARE event time and show the final moments of an event in progress. For the other, a large solar radio burst (detected by both STARE and RSTN) occurs less than 30 minutes after the event. In both the RSTN and STARE records we see that events tend to be clustered in time, so it would not be unusual if this event were related to the following large burst. In addition, both of the unidentified STARE events are very short ($<0.5 \text{ s}$) and so are unlikely to have been detected by RSTN, as discussed above in reference to Figure 5. Although we cannot definitively associate these two events with solar radio bursts, we believe that the indirect evidence indicates that such an association is warranted. From these results we deduce that all of the astronomical signals detected by STARE were due to solar radio bursts.

4. DISCUSSION

We have presented evidence that all of the astronomical events detected by STARE are of solar origin. With this result

we can speculate about astrophysical scenarios that could result in STARE detections. To do this we establish a fiducial flux density detection threshold for the system. From the results in § 2.2, we begin with 26.7 kJy, the observed median STARE zenith coincidence detection sensitivity. Then, since most events would happen away from zenith, we multiply by 3, the approximate factor by which the antenna response is reduced at 45° elevation. This yields approximately 80 kJy, which we adopt for this section as the typical STARE coincidence detection sensitivity.

To interpret this limit in an astrophysical context, it is useful to recast it in terms of brightness temperature T_B . For a source with a uniform spatial brightness distribution, the flux density is $S_\nu = I_\nu \Omega$, where I_ν is the specific intensity of the source and Ω is its solid angle. Then in the Rayleigh-Jeans limit ($h\nu \ll k_B T$), the source has brightness temperature

$$T_B = \frac{c^2 S_\nu}{2k_B \nu^2 \Omega}. \quad (1)$$

Using our detection limit fixes $S_\nu \sim 80$ kJy. An object of linear size l at distance d occupies a solid angle $\Omega \sim (\pi/4)(l/d)^2$, yielding

$$T_B \approx \left(\frac{2c^2 S_\nu}{\pi k_B \nu^2} \right) \left(\frac{d}{l} \right)^2 = 8.9 \text{ K} \left(\frac{d}{l} \right)^2. \quad (2)$$

Figure 6 shows this relation plotted for several choices of l . For a source of linear size l at a distance d , this plot indicates the brightness temperature required to produce a flux density that would trigger a detection by STARE. It is immediately obvious that at this sensitivity STARE has no hope of detecting distant objects. For nearby objects, say within a few kiloparsecs, the required brightness temperatures are high but not unprecedented. For example, we have shown the unequivocal detection of solar radio bursts. Typical flux densities of these events are ~ 1 MJy, corresponding to a brightness temperature of

$$T_B \approx \frac{2c^2 S_\nu d^2}{\pi k_B \nu^2 l^2} = 5.1 \times 10^6 \text{ K} \left(\frac{1 R_\odot}{l} \right)^2. \quad (3)$$

Many of the observed solar radio bursts display intensity variations at the STARE time resolution of 0.125 s, which with a light travel-time argument yields an upper limit on the size of the emission region of $l \leq 37,500 \text{ km} \approx 0.05 R_\odot$. Using these values, we find a brightness temperature limit of $T_B \gtrsim 2 \times 10^9 \text{ K}$. This combination of duration and brightness suggests that the detected events are type I or type III solar bursts, both of which arise from coherent plasma radiation (Dulk 1985).

Although it is unlikely that any members of known classes of nonsolar sources would be near enough for detection by STARE, it is illustrative to consider what conditions would be required of them for detectability. One example of a class of source known to produce very high brightness temperatures is that of the radio pulsars. As mentioned in § 1.1, the Crab pulsar

has been observed to produce individual giant pulses with flux densities exceeding 2000 Jy. With observing frequency $\nu = 800 \text{ MHz}$ (Lundgren et al. 1995), distance $d = 2 \text{ kpc}$ to the pulsar, and choosing $l = 100 \text{ km}$ for the size of the emission region, the brightness temperature is

$$T_B \geq \frac{2c^2 S_\nu d^2}{\pi \nu^2 k_B l^2} \approx 8 \times 10^{28} \text{ K}. \quad (4)$$

The steep spectrum of pulsar emission would make this even brighter at 611 MHz (Lyne & Graham-Smith 1990). This is close to the detection threshold for STARE, but since the pulses are significantly shorter than the STARE averaging time, the signal would be too diluted to detect. However, this suggests that another closer pulsar that produced such bright giant pulses might be detectable.

We can consider more generally the radio emission due to a particular emission mechanism. For example, many sources produce radio emission at 611 MHz by the synchrotron mechanism, in which high-energy electrons are accelerated through a spiral path by a magnetic field. It is well known that in general a source emitting incoherent synchrotron radiation cannot shine with brightness temperature greater than $T_B \sim 10^{12} \text{ K}$, since inverse Compton scattering becomes the dominant energy sink (e.g., Shu 1991). From Figure 6 we see that a synchrotron source with $T_B = 10^{12} \text{ K}$ would be detectable by STARE only if it were improbably large and close. For example, a source of size 1 AU would have to be within a few tens of parsecs to produce a flux density above the STARE detection threshold. However, it is possible for such sources to exceed the $T_B \sim 10^{12} \text{ K}$ limit temporarily during a phenomenon that causes an impulsive injection of energy and a corresponding flare (Hughes & Miller 1991). One class of source that is known to radiate via the synchrotron mechanism and produce rapid variability is Galactic “microquasars” (Mirabel & Rodríguez 1999). Rodríguez et al. (1995) monitored the microquasar GRS 1915+105 for several months, observing large outbursts, reaching a maximum of 1.5 Jy at 1.4 GHz. Using this flux density and the observed spectral power-law index of -0.87 , we obtain the expected flux density at 611 MHz; with the source distance of 12.5 kpc and assuming a source size of 1 AU, we can calculate a brightness temperature of $T_B \approx 10^{15} \text{ K}$ for this outburst. Figure 6 shows that with these physical parameters, such an outburst might be detectable by STARE if it were closer than a kiloparsec or so.

To view the radio sky somewhat differently, STARE could operate with a shorter boxcar averaging period than the 0.125 s (6250 samples of 20 μs each) used for the data presented here, yielding better time resolution (at the expense of sensitivity, of course). If the averaging length were shortened to less than the light-travel time from one STARE station to another, the localization of sources in the sky would be possible in principle by comparing arrival times of signals at the STARE stations. In addition to source positions, this method would provide another filter for rejecting terrestrial interference. At

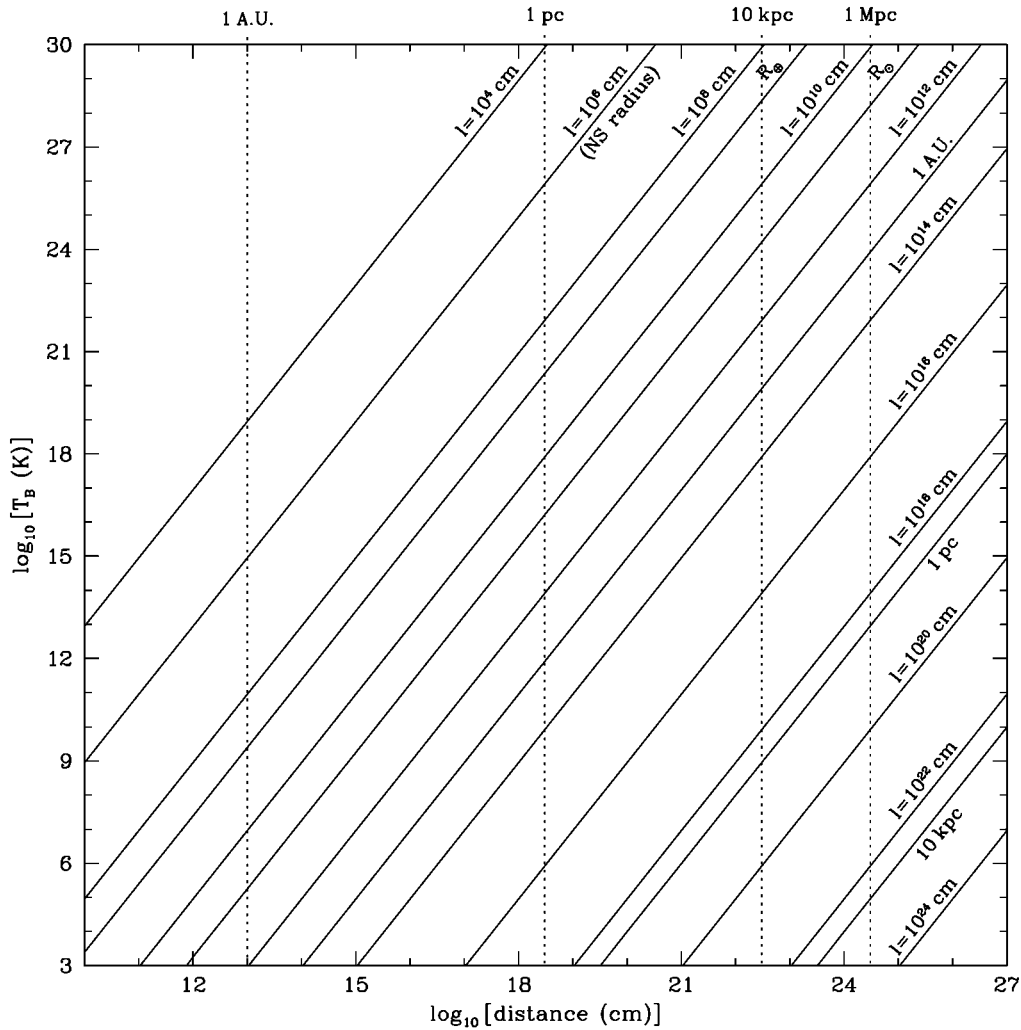


FIG. 6.—Brightness temperature required of a source to produce, under typical conditions, a detection by STARE: any combination of source linear size (*diagonal lines*) and distance (*horizontal axis*) yields the brightness temperature that produces a flux density greater than 80 kJy.

the highest data acquisition rate (50 kHz), the three STARE stations could theoretically produce localizations of transient astronomical radio sources to better than 1° over much of the sky (Katz 1997). In practice, operating STARE in such a mode would require further technical development to handle the high data rate described. With the dizzying pace of computer technology advancement, however, the required technical improvements are much more tractable at this writing than they were just a few years ago when STARE was constructed. A burst localization mode like that described here will likely be an important feature of future work.

STARE has assembled in digital form a large record of the temporal behavior of the radio sky at 611 MHz, presenting wide opportunity for further analysis. One possibility is to take advantage of the multiple sampling of the same region of sky every 24 hours by averaging and performing a frequency domain analysis to search for periodic signals. This would be very much in the same vein as the work of Chakrabarty et al.

(1995) and Bildsten et al. (1997), who analyzed the archived BATSE 1.024 s data stream to find previously unknown X-ray pulsars. While the sensitivity of the BATSE large-area detectors is well below its optimum at the typical peak energies of X-ray pulsars, the large volume of data collected by BATSE allowed excellent sensitivity by averaging. The situation is much the same with STARE. By averaging many months worth of data, good sensitivity can in principle be achieved for periods greater than 0.25 s. A significant number of radio pulsars have periods longer than this, with many exceeding 1 s (Taylor, Manchester, & Lyne 1993). Unknown radio pulsars with such long periods would be candidates for detection by STARE through this technique.

5. CONCLUSIONS

We have operated the Survey for Transient Astronomical Radio Emission from 1998 May 27 to 1999 November 19,

monitoring the 611 MHz radio sky to detect transient radio signals of astronomical origin with durations of a few minutes or less. STARE observed the sky above the northeastern part of the United States using three geographically separated zenith-looking detectors that made eight measurements per second, 24 hours per day. In 18 months of observing we detected a total of 4,318,486 radio bursts at the three STARE stations. Of these, 99.9% were determined to be due to local sources of radio noise. The remaining 3898 were found to be associated with 99 solar radio bursts observed in coincidence at the three stations. These results demonstrate the remarkable effectiveness of an RFI discriminator based on a coincidence technique using precision timing (such as the GPS) at geographically separated sites.

Technological advances have allowed STARE to update similar experiments performed in the 1970s. With the STARE data stored digitally, the potential for further analysis is much greater than for those experiments that recorded data on chart paper. The data could easily be reanalyzed to detect transients on longer timescales. In addition, the large temporal and solid-angle coverage could make the data useful for a variety of other purposes, such as searches for periodic signals and studies of the radio frequency interference environment at the observatory sites.

We can interpret the nondetection of extrasolar transient astronomical radio emission as indicative of the absence of bright bursting or flaring sources within 1 kpc or so of the solar system, over the 18 months of our observations. This rules out the existence of any known classes of sources in the solar neighborhood. Perhaps more importantly, it rules out the existence of nearby sources of previously unknown types that might produce short-timescale transient radio emission. The absence of quiescent radio emission from such sources means that they would not have been detected by traditional pencil-beam surveys; through their flaring activity they may have revealed their existence only to a program such as STARE.

The detection of transient astronomical electromagnetic radiation requires different observing techniques than those offered by the typical observatory with its scheduled blocks of time. Since signals may appear unexpectedly in time and space, their detection requires a different class of temporal and spatial coverage than that provided by traditional telescopes. In a simple system like STARE, spatial coverage is achieved at the expense of reduced brightness sensitivity, while temporal coverage is achieved by the use of dedicated automated unattended instruments that can monitor continuously. STARE has been a

useful exercise for exploring the techniques required to detect unexpected signals from astronomical sources. We consider this to be preliminary work in this area, which we expect will progress to the development of more sophisticated techniques and instruments providing better coverage with higher sensitivity. Indeed, we observe in the planning for new radio telescopes such as the Square Kilometer Array and the Low-Frequency Array for Radioastronomy renewed interest in the transient radio sky, with discussions of sources such as neutron star magnetospheres, gamma-ray burst sources, planetary magnetospheres and atmospheres, accretion disk transients, and even extraterrestrial intelligence, to name a few. And of course the most exciting prospect for such work is the detection of entirely new types of sources. It appears that the detection of transient astronomical radio emission will be a topic of great interest for many years to come.

We thank the many people who have made STARE possible. At the National Radio Astronomy Observatory, M. Goss offered the use of VLBA stations for STARE receivers, while F. J. Lockman offered the use of space at Green Bank. Development and operation of STARE would have been impossible without the help of T. Baldwin and D. Whiton at the Hancock VLBA station, D. J. Beard and B. Geiger at the North Liberty VLBA station, and M. McKinnon and R. Creager at Green Bank. Some initial STARE testing was performed at Hat Creek Radio Observatory, where space and support were offered by D. Backer, and the work was aided by R. Forster and M. Warnock. Development of the STARE instrumentation was helped along by advice from A. Rogers, L. Beno, and P. Napier. J. Ellithorpe contributed to the computer work, and J. Barrett provided many hints and lessons. H. Coffey and E. Irwin at the National Geophysical Data Center provided the data from the RSTN telescopes, and TSgt C. Hoffman, USAF, of the Sagamore Hill RSTN station answered many questions about RSTN operations and methods. Finally, we thank the anonymous referee whose insightful comments led to significant improvements in this article.

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