LIMITS ON GAMMA-RAY BURST PROMPT RADIO EMISSION USING THE LWA1

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ABSTRACT

As a backend to the first station of the Long Wavelength Array (LWA1), the Prototype All Sky Imager has been imaging the sky for 26° declination during 34 gamma-ray bursts (GRBs) between 2012 January and 2013 May. Using this data, we were able to put the most stringent limits to date on prompt low-frequency emission from GRBs. While our limits depend on the zenith angle of the observed GRB, we estimate a 1σ rms sensitivity of 68, 65, and 70 Jy for 5 s integrations at 37.9, 52.0, and 74.0 MHz at zenith. These limits are relevant for pulses ≥5 s and are limited by dispersion smearing. For 5 s pulses, we are limited to dispersion measures (DMs) ≤220, 570, and 1600 pc cm−3 for the frequencies above. For pulses lasting longer than 5 s, the DM limits increase linearly with the duration of the pulse. We also report two interesting transients, which are, as of yet, of unknown origin and are not coincident with any known GRBs. For general transients, we give rate density limits of 6.2 yr−1 deg−2 with pulse energy densities >1.3 × 10−22, 1.1 × 10−22, and 1.4 × 10−22 J m−2 Hz−1 and pulse widths of 5 s at the frequencies given above.

Key word: gamma-ray burst: general

Online-only material: color figures

1. INTRODUCTION

Since the discovery of gamma-ray bursts (GRBs) by Klebesadel et al. (1973), several groups have proposed mechanisms capable of producing prompt low-frequency (<100 MHz) radio emission observable from Earth. Usov & Katz (2000) suggested that low-frequency radiation could be created by oscillations in the current sheath that separates a strongly magnetized jet and the surrounding ambient plasma. This emission would peak at 1 MHz and drop off following a power law at higher frequencies. The bulk of the emission lies below the ionospheric cutoff of about 10 MHz, but the high-frequency tail of this might extend up to frequencies observable by ground-based telescopes. The flux density of the high-frequency tail is approximated with a power law ν−1.6. As an example, they provide a best case estimate of ~107 Jy at 30 MHz.

Sagiv & Waxman (2002) also predict that low-frequency emission will occur in the early stages of the afterglow (10 s after the GRB). In this scenario, a strong synchrotron maser condition is created at frequencies below 200 MHz due to an excess of low-energy electrons. The excess is created by a buildup of injected electrons that cool to low energies through synchrotron radiation. The effect is amplified when the jet propagates into a medium denser than the interstellar medium. Such a dense environment would exist around high-mass Wolf–Rayet stars, which are thought to be the progenitors of long-duration GRBs.

While no prompt low-frequency emission has yet been detected, a future detection would yield a number of constraints on the parameters of GRBs. The dispersion measure (DM) of prompt radio emission would allow estimates of the physical conditions of the region immediately surrounding nearby (z < 0.5) GRBs, which would inform us about the environment in which GRB progenitors are formed. For more distant GRBs, the DM would be dominated by the intergalactic medium (IGM), thus giving a measurement of the number of baryons in the universe (Ginzburg 1973). For extremely distant (z > 6) GRBs, a DM could act as a probe of the reionization history (Ioka 2003).

Over the past three decades, there have been many searches for prompt low-frequency GRB emission (Baird et al. 1975; Dessenne et al. 1996; Koranyi et al. 1995; Benz & Paesold 1998; Balsano 1999; Morales et al. 2005; Bannister et al. 2012). Of these studies, two have been below 100 MHz. Benz & Paesold (1998) covered the range from 40 to 1000 MHz, had an rms sensitivity of ~105 Jy, and observed during seven GRBs between 1992 February and 1994 March. Balsano (1999) covered 72.8–74.7 MHz, observed 32 GRBs between 1997 September and 1998 March, and had a wide range in rms sensitivities for each GRB. The best limit reported in Balsano (1999) was ~200 Jy for 50 ms integrations. Both of these studies used BATSE triggers, which had a position uncertainty typically around a few degrees. Morales et al. (2005) reported on a planned study centered at 30 MHz.

In this paper, we present a search for prompt low-frequency emission from 34 GRBs using the all-sky imaging capabilities of the Prototype All Sky Imager (PASI), a backend to the first station of the Long Wavelength Array (LWA1). While our objective was to find or place limits on prompt emission from GRBs, we also conducted a search for generic transients occurring during our observations but located elsewhere in the

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5 A redshift of 0.5 is chosen because above this point the DM contribution from the intergalactic medium (IGM) would be roughly equal to the maximum contribution from a galaxy similar to our own (Ioka 2003). However, if the DM of the host galaxy is larger than that of our own, “nearby” would include larger redshifts.
images the visibilities, displays them on the LWA TV\textsuperscript{6} website, and stores time-lapse movies from each day (K. S. Obenberger et al., in preparation).

While PASI has recorded at dozens of different frequencies since it began operating, the majority of its recordings have been at 37.9, 52.0, and 74.0 MHz. Being within protected radio astronomy bands, 37.9 and 74.0 MHz are subjected to a minimal amount of radio frequency interference (RFI). While 52.0 MHz is not protected, the amount of RFI is typically similar. For this paper, we have analyzed 112.6, 29.7, and 59.8 hr, respectively, at the above frequencies. These hours represent both the data taken during the GRBs and the data taken for calibration purposes.

Using the CASA clean algorithm (McMullin et al. 2007), PASI produces dirty images that have not been flux calibrated, self-calibrated, flagged for RFI, or deconvolved. An example all-sky image is shown in Figure 1.

For this paper, flux calibration at 74.0 MHz was achieved by fitting the measured flux of Taurus A with its known flux density of 1811.3 ± 3.07 Jy at 74 MHz from the VLA Low-Frequency Sky Survey (VLSS) provided in Cohen et al. (2007). The same was done at 52.0 and 37.9 MHz using scaled flux densities from Baars et al. (1977). By fitting a third-order polynomial to the measurement of Taurus A as it transits the sky, we were able to model the zenith angle-dependent power pattern to a good approximation. Figure 2 shows the normalized measured power pattern of Taurus A.

Our rms sensitivity is a function of zenith angle and frequency. To estimate these dependencies, we measured the pixel noise for a quiet off-source region as it transits the sky, passing through zenith. We then scaled the amount of scatter with the power pattern derived from Taurus A. Finally, we calculated the rms of the scaled noise every 50 integrations (250 s or 1° of change). For each frequency, we repeated this process on two separate days, using a different off-source location each day. This resulted in averaged zenith angle rms sensitivity estimates, with zenith values of 68, 65, and 70 Jy for 37.9, 52.0, and 74.0 MHz for 5 s integrations. Figure 3 shows a scatter plot of the rms for 37.9 MHz calculated using the method described on the two occasions mentioned above. A lognormal model yielded a good fit for zenith angles <65°.

The spectrum of each visibility is broken into six channels, covering the 75 kHz of bandwidth. While this is not a large bandwidth, it is sufficient to exclude much of the RFI, which is often narrower than our 75 kHz. RFI is also excluded based on the location in the sky; transients with a zenith angle greater

\textsuperscript{6} http://www.phys.unm.edu/~lwa/lwatv.html
than 60° are not considered to be of celestial origin. PASI also preserves all four Stokes parameters, which can be used for further analysis of transient events.

3. GCN TRIGGER ARCHIVE

Currently, we use the NASA GCN/TAN trigger archive7 from Swift (Burrows et al. 2005; Barthelmy et al. 2005), Fermi gamma-ray burst monitor (GBM; Meegan et al. 2009; Briggs et al. 2009), and Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009). MAXI provides the fewest triggers with about 1 GRB month−1 and has 1 arcmin resolution. Swift is more favorable with 2 GRBs week−1 and an arcsec resolution with the X-Ray Telescope and UV/Optical Telescope and an arcmin resolution with the Burst Alert Telescope covering the electromagnetic spectrum from optical to hard X-rays. Fermi GBM is the most prolific with a large field of view, enabling the detection of 20 GRBs month−1, but only a position accuracy of 1°−10° at best.

For this study, we used the GCN GRB triggers that occurred during PASI operation between 2012 January 1 and 2013 May 25. Furthermore, we excluded triggers with initial zenith angles greater than 60° (with six exceptions8 in the eastern sky) and that occurred during periods of exceptionally high RFI.

4. DELAY AND DISPERSION

A prompt pulse is delayed and stretched out in time at low frequencies. A dispersion measure, DM, is proportional to the number of electrons between an observer and a source. For a pulse of constant frequency (expansion is negligible), the delay time of a pulse of frequency υ with DM is given by

$$\tau(\nu) = k_{DM} \times DM \times \frac{1}{\nu^2},$$

(1)

where the dispersion constant $k_{DM} = c^2/(2\pi m_e c) = 4149$ MHz² cm⁻³ s. The total DM can be broken up into three regions: our own Galaxy $DM_{Gal}$, the IGM $DM_{IGM}$, and the GRB’s host galaxy $DM_{host}$. The DM of our Galaxy varies based on the orientation to the plane and ranges from $DM_{Gal}^{min} \sim 30$ pc cm⁻³ to $DM_{Gal}^{max} \sim 10^3$ pc cm⁻³ (Taylor & Cordes 1993; Nordgren et al. 1992). Using Equation (1), this range of DM corresponds to a range in time delay of 46 s to 25 minutes at 52 MHz.

The DMIGM depends on the number of electrons in the IGM between us and the GRB and is therefore dependent on the redshift of the galaxy. However, because of the expansion of the universe, the frequency of the radiation emitted in our direction will decrease. Thus, a generalization of Equation (1) must be used to calculate the delay caused by DMIGM. Ioka (2003) estimates the redshift-dependent DMIGM would be

$$DM_{IGM} = \frac{3cH_0\Omega_b}{8\pi Gm_p} \int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}.$$  

(2)

The actual frequency, υ, of a photon seen by the electrons at redshift z is related to the observed frequency, $\nu_{ob}$ by

$$\nu = \nu_{ob} \times (1+z).$$

(3)

Therefore, the time delay of an emitted photon observed to be at frequency $\nu_{ob}$ is given by

$$\tau(\nu) = \frac{3cH_0\Omega_b}{\nu_{ob}^2 8\pi Gm_p} \int_0^z \frac{dz}{(1+z)[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}.$$  

(4)

With $(\Omega_m, \Omega_\Lambda, \Omega_b, h) = (0.3175, 0.6825, 0.04810, 0.6711)$ (Planck Collaboration 2013), the values for the time delay, $\tau(\nu_{ob})$, due to the IGM are shown in Figure 4. $DM_{host}$ is the most difficult quantity to estimate and may dominate the total DM in some cases. Examining Equations (1) and (3), it is easy to see that at higher redshifts the DM of a host galaxy similar to ours would play a very small role in the delay. However, if the GRB progenitors dwell in dense star-forming regions, such as the case may be for some long GRBs, then a very small optical depth may make it difficult to detect any signal at all.

Since we do not dedisperse the bursts, we are subject to dispersion smearing across our entire 75 kHz band. In seconds, the dispersion smearing time is given by

$$\tau_{smear} = 8242 \times DM \times \nu^{-3} \times \Delta \nu,$$

(5)

where $\nu$ is the center frequency in MHz and $\Delta \nu$ is the bandwidth in MHz. Therefore, bursts $\lesssim 5$ s would become smeared out across our band to at least 1.5 times their duration at

Figure 3. Estimated zenith angle-dependent rms sensitivity for 37.9 MHz, calculated for two separate days. Dates in MJD.

(A color version of this figure is available in the online journal.)

Figure 4. Time delay due to the IGM dispersion for 37.9, 52.0, and 74.0 MHz as a function of redshift. These are numerical calculations of Equation (4) derived from Equation (2) of Ioka (2003).

(A color version of this figure is available in the online journal.)
5. DATA, ANALYSIS, AND RESULTS

When given a set of GRB coordinates, a date, and time, we used our archived visibility data to image the entire sky and track the GRB’s position. While we expect a maximum combined delay of <1 hr from the IGM and the Milky Way, we allow for large delays from the host galaxies. After the prompt γ-ray emission, we analyze the observations for 2 hr at 74.0 MHz, 3 hr at 52.0 MHz, and 4 hr at 38.0 MHz. We track the source by mapping the images onto a right ascension (R.A.) and declination (decl.) coordinate system and selecting the pixels of one beam around the source location. We can then analyze the light curve of that region and look for detections.

From our data, there have not been any significant (>5σ) transient events corresponding spatially and temporally to any GRB triggers. However, we can provide limits to the peak intensity of a transient.

Given the zenith angle of the GRB at the time the γ-ray emission arrives, we estimated the 1σ limit with the rms sensitivity model described in Section 2. See Table 1 for our GRBs and estimated limits. Since we are using only the dirty images from PASI, which undergo neither a phase self-calibration nor deconvolution, these estimates can be improved following planned algorithm development work.

These limits reflect the rms noise for 5 s integrations. If a pulse was shorter than 10 s, our signal-to-noise ratio (S/N) would be decreased by the ratio of time spent in any one time bin to the size of the bin itself. For instance, consider a 7 s, 1000 Jy pulse that occurred at zenith at 38 MHz and spent 3 s in the first bin and 4 s in the second. In the second bin, the observed flux density would be 1000 × (0.8) Jy. Therefore, our S/N would decrease by a factor of 0.8.

6. INTERESTING TRANSIENTS NOT ASSOCIATED WITH GRBS

While searching for prompt radio emission from GRBs, we also searched our data for generic transients in our field of view. We automated our search using image subtraction methods, which inherently increased our noise by √2, but allowed us to investigate changes on the order of 10 s by subtracting the third previous image from every image and setting the threshold at 6σ. Below 6σ, the number of events detected displayed Gaussian behavior, as expected, with an additional bump at 5σ from false detections from RFI. Above 6σ, we found 18 events at 37.9 MHz, 7 at 52.0 MHz, and 2 at 74.0 MHz. Except for one event at 37.9 MHz and two events at 52.0 MHz, nearly all of these events were immediately identified as RFI.

The two events at 52.0 MHz each lasted for only one integration (5 s) and appeared to be broadband across the 75 kHz. However, upon further investigation, these events were found to have significant linear polarization, which indicates that they were most likely reflected man-made RFI, possibly from the ionosphere or from ionized trails left by meteors.

The 37.9 MHz event, however, was a Fast Rise/Exponential Decay (FRED) transient candidate. The event occurred on 2012 October 24 (121024) at 08:37:39 UT, lasted for 75 s, and had an R.A. and decl. of 04°14′00″ + 76°54′00″, with an estimated error of ∼1:5. The light curve of the transient displayed a rise time of ∼15 s and decay of ∼60 s (Figure 5). At peak intensity, this source appears to be ∼2.4 Jy and is constant across the 75 kHz band. However, upon examining all four Stokes parameters, there is a slight bump of linear (-U) and left-hand circular (-V) as shown in Figure 5. The exact percentage of polarization is difficult to quantify since both the -U and -V components each last for one integration and are both <5σ. When compared to the entire 75 s burst, the -U and -V components are 5% ± 1% and 4% ± 1%. While this polarization may be real, instrumental leakage is very likely the cause. The leakage into the three Stokes polarizations on the LW A1 is a function of a source position in the sky that has not yet been characterized. As a reference, we measured the leakage of Cassiopeia A, an unpolarized source at 38 MHz, during the same period the transient was detected. During this time, we measured...
- $Q$, $U$, and $V$ leakages of $\sim$3%, 8%, and 3%. Cassiopeia A was at approximately the same zenith angle as the transient.

A second event occurred on 2012 November 18 (121118) at 09:53:40 UT, lasted for 100 s, had an R.A. and decl. of $0^\circ 722^m 24^s +41^d 18^m 00^s$, and was observed at 29.9 MHz. The light curve shows similar properties to the 121024 event with a rise time of $\sim 25$ s, a decay time of $\sim 75$ s, and a maximum flux density of 3.2 kJy and is also constant across the band. A second event occurred on 2012 November 18 (121118) at 09:53:40 UT, lasted for 100 s, had an R.A. and decl. of $0^\circ 722^m 24^s +41^d 18^m 00^s$, and was observed at 29.9 MHz. The light curve shows similar properties to the 121024 event with a rise time of $\sim 25$ s, a decay time of $\sim 75$ s, and a maximum flux density of 3.2 kJy and is also constant across the band. However, during this event, there were no detectable polarized components (Figure 5).

Examining the 75 kHz bandwidths, we see no signs of any dispersion for either event. However, we are able to limit the DMs of the 121024 and 121118 events to be approximately $< 450$ and $< 250$ pc cm$^{-3}$.

Using the NASA/IPAC Extragalactic Database,$^{10}$ we found five sources above 20 Jy at 38 MHz within $3^\circ$, twice our estimated position error, of the 121024 event and none above 20 Jy at 38 MHz within $3^\circ$ of the 121118 event. All of the 121024 sources were part of the revised source list of the Rees 38-MHz (8C) survey (Hales et al. 1995; Rees 1990), and no additional sources were found using that catalog. Also, there were no additional sources above 7 Jy at 74 MHz found using the VLSS within $3^\circ$ of either event (Cohen et al. 2007).

Table 2 lists the sources near the 121024 event. It is possible for any one of these five sources to be focused on by the ionosphere and temporarily increase in brightness. However, this is a regular occurrence with sources in our field of view. There will often be periods when several sources in the sky will fluctuate up to 15 times their normal brightness. The effect usually covers the entire sky, in that many sources across the sky will fluctuate (shimmer) for up to several hours. This is likely caused by turbulence in the ionosphere; similar variation has been observed by other instruments at the same frequency (Bezrodny et al. 2008).

At these times of high shimmering, sources that lie below our detectable limit will sometimes be magnified above our threshold and appear for a short period of time. While the vast majority of events occur for sources above 100 Jy, there have been four at lower flux densities in the 112 hr of observations at 37.9 MHz reported on in this paper. The typical shape for a light curve of one of these events is a fast rise, fast decay, often lasting for just one integration. Occasionally, the source will stay bright for up to 1 minute, displaying several peaks as it dims and brightens. Figure 6 shows two typical light curves from brightening events. The first is 3C249, which is the dimmest object (37 Jy at 38 MHz) to be magnified above 6$\sigma$ in the data reported in this paper. The second is 3C230 (76 Jy at 38 MHz), which displayed a brightening event lasting $\sim 75$ s, during which it peaked several times.

There are several reasons why we believe the 121024 event was not simply one of these focusing events. The first is that this would be one of the strongest focusing events we have seen that is a factor of $\sim 60$ if it is 8C 0422 + 770 and $\sim 120$ if it is 8C 0415 + 763. The second is that during the hours before and after, the other sources in the sky were shimmering only slightly. Finally, the light curve is very similar to the light curve of the 121118 event for which there is no corresponding bright source and is dissimilar to a light curve of a typical shimmering event. Therefore, it is our belief that these events are not ionospheric focusing of objects just below our sensitivity limit.

Many astrophysical sources have been theorized to produce low-frequency transient emission. Possible sources include neutron star mergers (Hansen & Lyutikov 2001), primordial black holes (Rees 1977; Blandford 1977; Kavic et al. 2008), and flaring stars (Loeb et al. 2013). However, a highly likely RFI candidate is a meteor reflection. The ionized trails of meteors have long been known to reflect man-made RFI. In particular, there is a population of long-duration meteor reflections that last up to several minutes and have a similar temporal evolution to these two events (Bourdillon et al. 2005). These meteor reflections tend to be linearly polarized, a property that the

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$^{10}$ http://ned.ipac.caltech.edu
121118 event is lacking, and the 121024 event displays no more than what we expect from leakage.

7. RATE DENSITY LIMITS

With 112.6 hr of data analyzed at 37.9 MHz, a 6σ rms sensitivity of \( \lesssim 1260 \) Jy above a zenith angle of 60° and \( \pi \) sr of observable sky, we estimate an event rate of \( \lesssim 7.5 \times 10^{-3} \) yr\(^{-1}\) deg\(^{-2}\) for events with pulse energy densities \( \gtrsim 1.3 \times 10^{-22} \) J m\(^{-2}\) Hz\(^{-1}\) and pulse widths of 5 s.

The same can be done for events at both 52.0 MHz and 74.0 MHz, which have 29.7 and 59.8 hr of analyzed data and 6σ rms sensitivities \( \lesssim 1104 \) and 1440 Jy. The rate densities for these frequencies are \( \lesssim 2.9 \times 10^{-2} \) yr\(^{-1}\) deg\(^{-2}\) and \( \lesssim 1.4 \times 10^{-2} \) yr\(^{-1}\) deg\(^{-2}\) for events with pulse energy densities \( \gtrsim 1.1 \times 10^{-22} \) and \( 1.4 \times 10^{-22} \) J m\(^{-2}\) Hz\(^{-1}\) and pulse widths of 5 s. This is similar to the rate densities found in the past by similar experiments in this frequency range. A comparison with Kardashev et al. (1977), Lazio et al. (2010), and Cutchin (2011) is shown in Table 3.

8. DISCUSSION

We have carried out a search for prompt low-frequency radio emission from 34 GRBs at 37.9, 52.0, and 74.0 MHz. In this search, we found no burst-like emission but have placed limits at these frequencies. Our 1σ limits for each frequency are listed in Table 1 and range from \( \sim 200 \) to 80 Jy for \( \gtrsim 5 \) s bursts. The range of DMs that we are sensitive to depends on the duration of the burst. For 5 s bursts, we could see to a maximum of 220, 570, and 1600 pc cm\(^{-3}\) for 37.9, 52.0, and 74.0 MHz.

While these limits do not disprove any of the possible emission mechanisms discussed in the introduction of this paper, they are the most stringent to date. In the future, we plan to improve our sensitivity by applying deconvolution and phase calibration to our images.

We also report on two transient events, 121024 and 121118, at 37.9 and 29.9 MHz, respectively, which lasted for 75 and 100 s. We limit their DMs to be approximately \( \lesssim 450 \) and \( \lesssim 250 \) pc cm\(^{-3}\).

We also have placed rate density limits on general transients with pulse energy densities \( \gtrsim 1.3 \times 10^{-22} \), \( > 1.1 \times 10^{-22} \), and \( 1.4 \times 10^{-22} \) J m\(^{-2}\) Hz\(^{-1}\) and pulse widths of 5 s at 37.9, 52.0, and 74.0 MHz. Using the entire sky higher than 30° above the horizon, we find maximum rate limits of \( \lesssim 7.5 \times 10^{-3} \), \( > 2.9 \times 10^{-2} \), and \( 1.4 \times 10^{-2} \) yr\(^{-1}\) deg\(^{-2}\) for the frequencies above.

If it is true that we should see one FRED transient for every \( \lesssim 115 \) hr of observation at 37.9 MHz, then a full analysis on the hundreds of hours of data PAFI has collected at this frequency should yield several more. A forthcoming paper will address the results of such a large-scale search.

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| Name                  | Frequency (MHz) | Rate Density (yr\(^{-1}\) deg\(^{-2}\)) | Pulse Energy Density (J m\(^{-2}\) Hz\(^{-1}\)) | Pulse Width (s) |
|-----------------------|-----------------|----------------------------------------|---------------------------------------------|-----------------|
| Kardashev et al. (1977)| 60              | \( \sim 10^{-3} \)                      | 3.1 \times 10^{-22}                         | 0.5             |
|                       | 38              | \( \sim 1.5 \times 10^{-3} \)           | 2.1 \times 10^{-22}                         | 0.5             |
| Lazio et al. (2010)    | 73.8            | \( \lesssim 10^{-2} \)                  | 1.5 \times 10^{-20}                         | 300             |
| Cutchin (2011)         | 38              | \( \sim 2.5 \times 10^{-1} \)           | 2.6 \times 10^{-23}                         | 3               |
| This paper             | 37.9            | \( \sim 7.5 \times 10^{-3} \)           | 1.3 \times 10^{-22}                         | 10              |
|                       | 52.0            | \( \sim 2.9 \times 10^{-2} \)           | 1.1 \times 10^{-22}                         | 10              |
|                       | 74.0            | \( \sim 1.4 \times 10^{-2} \)           | 1.4 \times 10^{-22}                         | 10              |
Obenberger et al.

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