Associations between Fermi GBM Terrestrial Gamma-ray Flashes and sferics from the WWLLN.

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Abstract. We report on a search for correlations between Terrestrial Gamma-Ray Flashes (TGFs) detected by the Fermi Gamma-Ray Burst Monitor (GBM) and lightning strokes measured using the World Wide Lightning Location Network (WWLLN). We associate 15 of a total 50 GBM-detected TGFs with individual discharges. We establish the relative timing between the TGF and the lightning stroke to an accuracy of $< 50 \mu s$, and find that in 13 of these 15 lightning-TGF associations, the lightning stroke and the peak of the TGF are simultaneous to $\approx 40 \mu s$. This suggests that a large fraction of TGFs are coincident with lightning discharges. The two non-simultaneous associations do not show a consistent TGF-lightning stroke temporal sequence. All 15 associations are with sferics within 300 km of the sub-spacecraft position. For those TGFs not correlated with a particular lightning stroke, we find storm activity within 300 km of the sub-spacecraft position in all but four of the TGFs. For three of these four TGFs, we find storm activity very close to one of the magnetic footprints of the spacecraft position. We associate the sub-spacecraft TGFs with gamma-ray events and the footprint events with electrons traveling along magnetic field lines before hitting the Fermi spacecraft.

1. Introduction

From the discovery of TGFs by the Burst And Transient Source Experiment (BATSE) [Fishman et al., 1994], their association with thunderstorm activity has been clear. Correlations of TGFs with individual lightning strokes have been deduced using temporal and spatial coincidences between Very Low Frequency (VLF) radio signals of lightning and - or sferics - and gamma-ray data from both BATSE (Inan et al. [1996]; Cohen et al. [2006]) and the Reuven Ramaty High-Énergy Solar Spectroscopic Imager (RHESSI) (Cummer et al. [2005]; Stanley et al. [2006]; Inan et al. [2006]; Lay [2008]; Hazelton et al. [2009]; Cohen et al. [2010]; Shao et al. [2010]). Whilst these correlations provide compelling evidence for the link between lightning and TGFs, the temporal sequence between lightning and TGFs has not been conclusively established. The VLF-BATSE results were limited by the 1 ms timing accuracy of the radio experiments and had only four matches. The VLF-RHESSI correlations are more numerous, but the relative timing is difficult to gauge because of a $\approx 2$ ms uncertainty in the absolute accuracy of the RHESSI clock [Grefenstette et al., 2009]. With most TGFs lasting less than 1 ms, it is not clear whether the relationship between the two phenomena is causal, either before or after, or otherwise associated with some common factor. Establishing the temporal sequence of the correlation has thus been hindered by low statistics and uncertainties in timing in both the radio and gamma-ray experiments. Furthermore, the lack of localization capability in some of the reported VLF-TGF temporal matches leaves open the possibility that a correlation might be coincidental.

The World Wide Lightning Location Network (WWLLN) [Rodger et al., 2009] has participated in several searches for correlations with RHESSI TGFs (Lay [2008]; Hazelton et al. [2009]). WWLLN sferics have an average RMS timing accuracy of $30 \mu s$, and are localized to about 20 km. With several microsecond absolute accuracy provided by an onboard link to GPS timing, the Fermi Gamma-Ray Burst Monitor (GBM) is an ideal partner in a search for coincidences with WWLLN sferics. Using the TGF lightcurve and knowledge of the Fermi sub-spacecraft position at the time of a TGF detection, one can find both the relative timing of TGFs and lightning strokes to within tens of $\mu s$, and the angular offset of the TGF from the point of detection.

An increasing number of WWLLN stations improves the detection efficiency and the timing of WWLLN sferics. A current estimate of WWLLN efficiency [Rodger et al., 2009] is 30-35% for discharges with peak current $> 50$ kA, and about 10% overall, with lower sensitivity in Africa than elsewhere, and daytime efficiency lower than at night. The WWLLN is most efficient at detecting cloud-to-ground (CG) lightning but is also sensitive to some intra-cloud (IC) lightning. Estimates are that of the strokes detected by WWLLN, 85% are CGs and 15% ICs, but a definitive study has yet to be conducted. Inan and Lehtinen [2005] suggest that because CGs tend to have higher peak currents, they are more conducive to the production of TGFs, but Stanley et al. [2006], Cummer et al. [2005], Williams et al. [2006] and Shao et al. [2010] found that it is more likely that TGFs are associated with IC lightning. Recent observations with the Lightning Mapping Array show a clear association between a TGF seen by RHESSI and the initial development of an IC lightning event [Lu et al., 2010].

Briggs et al. [2010a] report four associations between GBM TGFs and WWLLN sferics, with both simultaneous and non-simultaneous cases. We expand this work to a larger sample of GBM TGFs and we perform a more careful analysis of the simultaneous cases. We also associate GBM TGFs with WWLLN storms when no match is made to an individual sferic.

2. Method

From 14 July 2008 to 31 March 2010, GBM triggered on 50 TGFs. GBM is sensitive to gamma rays between 8 keV and 40 MeV and triggers on timescales as short as 16 ms. A detailed description of GBM is given in Meegan et al. [2009]. On 10 November 2009, onboard software changes were implemented that made GBM more sensitive to weaker TGFs,
leading to a higher event rate (15 up to this time, 35 since then). Briggs et al. [2010a] and Fishman et al. [2010] give details of the capabilities of GBM for TGF science and detailed descriptions of the early TGF observations made with GBM.

The technique adopted here is similar to that in previous searches; a direct match is defined as a WWLLN stroke detection within 5 ms of the peak of a TGF after correction for light-travel time and GBM clock drift, and each peak of a multi-peaked TGF is treated separately. Sferic correlations with TGFs have been reported with storms up to 1000 km from the sub-spacecraft position (Hazeltone et al. [2009]; Cohen et al. [2010]) and we search here for geographical matches out to this distance. In order to account for differing light travel times, a preliminary search window of 10 ms is used and TGF times falling in this window are corrected according to light travel time from the location of the associated sferic to Fermi (between 542 and 570 km above the Earth), assuming an event originates at 20 km altitude (Dwyer and Smith, 2005). Peak times are also adjusted for the drift of the GBM onboard clock, which is synchronized with GPS once per second and can drift up to 20 µs between GPS synchronizations, depending on its temperature. A close match occurs when the peak of the TGF lies within 5 ms of the sferic after these corrections. The time of the TGF peak is used rather than the start time of the TGF, since the WWLLN can measure the time to peak of power. The WWLLN does not provide information regarding the temporal development of the sferic, but comparisons with other radio networks [Jacobson et al., 2006] indicate the peak time measured by WWLLN typically occurs well within 30 µs of the onset of the discharge, and usually within a few µs.

In order to establish whether any TGF-WWLLN match could have occurred by chance, we also search for matches near the sub-spacecraft position at the time of the TGF trigger and within 5 ms of 1000 control times, taken at 1 s intervals 500 s either side of the trigger time. Any matches in these control searches would presumably occur by chance and the result of this control search allows us to calculate the chance probability of any positive match with the real TGF peak. Any match outside the search radius would also be considered a coincidence rather than a correlation. After performing these control searches, any close match of a sferic that is shown to be statistically significant is considered a likely association between the sferic and the GBM TGF.

Based on the efficiency of the WWLLN and on previous reported TGF-sferic matches, it is likely that in many cases a correlation between a TGF and an individual sferic will not be found. The WWLLN efficiency does, however, allow us to identify regions of strong lightning activity that could be the storms with which a TGF is associated. We adopt a similar definition of a storm as Splitt et al. [2010], with at least five flashes within 500 km and 10 min of the TGF, and a root mean square (rms) spread in distance of < 100 km from their average position. We use a smaller time window than Splitt et al. [2010] (20 min) because of the increased efficiency of the WWLLN since that study.

A match with an individual sferic (providing its chance probability is not found to be high in the control experiment) gives us a unique solution for the location and offset for the storm from the sub-spacecraft point. In the absence of an association with a specific sferic, an association with a storm system based on a cluster of flashes may not be unique, and even in the case where a single storm system is identified in the defined region, may not be conclusive. We hope, nonetheless, with enough events, to address the issue of the maximum offset from which GBM detects a TGF, and relate this to beaming angles and/or non-vertical electric fields at the source position.

3. Results

3.1. Associations with Individual Lightning Strokes

In the sample of 50 GBM TGFs, 15 have at least one WWLLN sferic within our established criteria of a 5 ms offset in time after correcting for light travel and clock drift, and 1000 km from the sub-spacecraft position. TGF 100207.843 is connected with two sferics. Before correcting for light travel time to the spacecraft and the GBM clock drift, there was an additional sferic within the initial search window, but after time corrections TGF 091118.985 falls outside the 5 ms window defined as a likely association. No matches were found farther than 300 km from the sub-spacecraft position.

Table 1 shows the 15 likely associations and their inferred temporal and spatial separations. Columns 2 and 3 give the time offset in ms from the peak of the TGF pulse to the WWLLN stroke time, and the uncertainty on this measurement. The uncertainty in timing in Column 3 is the sum in quadrature of ≈ 3 µs absolute accuracy of the GBM data after clock correction, the estimated WWLLN uncertainty for a particular sferic, and the error associated with the determination of the TGF peak. We do not include any uncertainty in the light travel time associated with the 20 km uncertainty of the WWLLN geolocation, because this contributes only about 1.2 µs to a typical light travel time of 1.85 ms. We find that there is an uncertainty of ± 300 km in the position of the TGF peak. Any match outside the search window, but after time corrections TGF 091118.985 falls outside the 5 ms window defined as a likely association. No matches were found farther than 300 km from the sub-spacecraft position.

Manual inspection of the WWLLN data to refine the localizations and peak times obtained using the WWLLN automated processing revealed further matches using a less stringent detection requirement of four independent station measurements. These matches included two new matches within 300 km of the Fermi sub-spacecraft position and 5 ms of the TGF peak, two new sferics for TGFs with existing matches, and one match within the 10 ms initial selection criterion that failed the 5 ms test when corrected for light travel time. These new matches were retrieved painstakingly in a process that does not allow us to compile a 1000 s control sample of similarly selected events. We do not include them in our table or in the following analysis, because we cannot establish the probability that they occurred by chance, and their timing and positional information may not be as reliable as those in Table 1.

A maximum distance of 300 km is seen for the associated lightning strokes, equivalent to an angular distance of 31° for a TGF at a height of 20 km. We do not detect any sferics within even the raw 10 ms window at distances beyond 300 km of the sub-Fermi position. With 15 associations, we consider this a fairly firm limit on the distance out to which GBM can detect a TGF.

The number of matches in the control sample in a 300 km search radius is also listed, giving us the inferred probability that the match with the actual TGF occurred by chance. The average rate of WWLLN lightning detections within 300 km remained constant over the ±500 s span of the controls, making this a suitable interval to measure the rate of false matches. Owing to the variation in lightning stroke density from storm to storm and the varying efficiency of the WWLLN with geographical location, time of day, and improvement with time, the controls for the various TGFs are not homogeneous. The probability that these matches occurred by chance ranges from less than 1 in 1000
The temporal offsets between the TGF and the lightning strokes are mostly consistent with zero, implying simultaneity within timing uncertainties. TGFs 081113.322 and 090828.147 each have two gamma-ray pulses, leading to two possible separations with the WWLLN sferic. In each case, the "b" pulse seems the more likely association since most of the other TGF-sferic pairs are simultaneous. The top left panel in Figure 1 shows the superposition of the sferic time (and its band of uncertainty) on the GBM lightcurve of TGF 081113.322, corrected for light travel time and clock drift. It is clear from this figure that associating the "b" pulse with a sferic is justified. The remaining panels in this figure show other cases where the sferic and the peak of the GBM TGF are simultaneous. It is not clear that the WWLLN stroke is coincident with any particular part of the TGF pulse, but instead that it can occur on the rising edge, during the peak, or after the peak of a pulse. For two TGFs, there are, however, offsets of both signs that are too large to be consistent with zero, even if one assumes a time other than the peak of the TGF as the time to be aligned with the peak of the sferic. Figure 2 shows for these two events the offset between the corrected TGF lightcurves and the WWLLN sferic. Neither of the two sferics showing offsets with large signs has any matches in the control sample, meaning there is a low probability that the matches occurred by chance. The probability that both non-simultaneous matches occurred by chance is negligible.

3.2. Correlations with storm systems

In addition to looking for tight matches in time and location, we also found in most cases storm systems in which the TGF might have been produced. We use a time window of 10 minutes before and after the TGF and look at all the lightning accompanying the WWLLN stroke. The WWLLN stroke is superimposed on a map covering the region 15° in latitude and longitude in each direction from the Fermi sub-spacecraft point (shown as a red cross). The 300 km radius region which contains all these associations is shown as a red circle. Individual lightning strokes are shown as open green squares, with the TGF-WWLLN matches identified above shown as closed purple squares. Figures 4(a) through (f) show 6 of the cases where no association is found with an individual sferic, but lightning activity is seen within the 300 km radius of the spacecraft position. In these cases, the nearest lightning region is only 35 km. The variances on these numbers (17 km and 67 km) are large enough, however, that more instances of both types of TGFs are needed to confirm this trend.

4. Discussion

The match rate of GBM TGFs with WWLLN sferics is about 30%. This is the detection rate of WWLLN for high-current lightning strokes, so the observation is consistent with all TGFs being associated with sferics. Previous TGF correlative studies using the WWLLN found match rates with RHESSI TGFs of about 4% [Luy, 2008] but these were done when the WWLLN was less efficient than now, so a direct comparison is not possible. If the higher GBM-WWLLN match rate is not entirely attributable to the enhanced WWLLN detection efficiency, another possibility is that GBM is detecting only

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the stronger TGFs, which may be more likely to be associated with stronger sferics that can be more easily detected by WWLLN. An argument against this explanation is that the sensitivity of GBM to weaker TGFs greatly increased on 10 November 2009, with onboard software adjustments leading to a factor of about 8 increase in the GBM TGF rate, but a constant match rate with WWLLN sferics is seen throughout the 19 months reported here.

For the first time we present a large sample of close matches with both the gamma-ray and radio experiments having timing accuracy at the sub-TGF-duration level. We find that within the uncertainties of these experiments, the TGFs and lightning sferics are mostly consistent with occurring simultaneously, but that exceptions exist.

Previous TGF-VLF sferic associations find that the TGF precedes the sferic by \(-3.1 \pm 1\) ms [Cummer et al. [2005]], but applying the \(-1.8\) ms clock correction to the RHESSI data makes this result consistent; \(-3.2 \pm 5\) ms [Lay, 2008]; follow the sferic (Cohen et al. [2006]; Inan et al. [2006], by 1-3 ms); or are offset by up to 2 ms in either direction [Cohen et al., 2010]. These earlier measurements are, however, hindered by the 2 ms uncertainty in the RHESSI clock, or by the poor statistics of the matches to BATSE data (only four events with sferics).

The results presented here suggest a close connection between individual lightning discharges and TGFs. The two exceptions suggested that either the TGF or the lightning occasionally occur before the other, and one might infer that causality in either direction cannot be a defining factor in any phenomenology explaining these events. Another possibility is that the lightning associated with a TGF might have multiple strokes, and that the stroke we associate with the TGF is not always the one that is directly related to it [Briggs et al., 2010a]. We do find one case with two sferics in coincidence with the TGF, and given the incomplete sampling of the WWLLN and the 2 ms deadtime of an individual VLF station following a hit, missing the sferic that is part of a lightning event, but simultaneous with the TGF peak, is not implausible. Looking at the stream of sferics detected in coincidence with RHESSI TGFs in Cohen et al. [2010], this appears a likely explanation, and one also suggested by Shao et al. [2010]. Shao et al. [2010] also see statistically significant coincidences between the detection of Narrow Bipolar Events (NBE) and TGFs, with the NBE offset in time from the TGF by several (up to 9) ms, and having an origin deeper in the atmosphere (10 - 14 km) than is predicted in TGF models [Dwyer and Smith, 2005]. They hypothesize that the NBE are related to the same disturbance as the TGF, but not directly associated with the TGF, and that the strokes actually associated with the TGF are weaker and thus less frequently detected. WWLLN cannot distinguish between types of lightning, or establish their altitude, but the presence of sferics that are not quite consistent with simultaneity (including one which was selected in the 10 ms window but found to be outside the 5 ms window after correction for light travel time and not included in Table 1) may support this hypothesis. It is also possible that with 50 trials, this match with a sferic 9 ms after TGF 091118.985 occurred by chance. From Table 1 we can see, in addition, that the probability that one of our likely associations occurred by chance is about 5%.

The observation of simultaneous TGF-sferic pairs is predicted in lightning leader models for TGFs [Dwyer [2008], Dwyer et al. [2009], Carlson et al. [2009a]], in which production mechanisms are driven by current pulses along developing lightning leader channels. The high local field in these channels provides the breakdown conditions required for the production of \(1-3\) MeV seed electrons. These are accelerated by the electric fields enabling the runaway particle multiplication necessary to produce, via bremsstrahlung radiation, the observed TGF emission. These lightning leader models postulate a causal lightning stroke with radio emissions from the current pulse seen simultaneously with the TGF emission. One might expect that with such a causal relationship, the TGF-sferic time sequence be consistent, and perhaps that the radio emission be associated with the start of the TGF rather than the peak.

It can be seen in Figure 1 that the sferic can fall before, at, or after the pulse peak, suggesting no consistent sequence. Figure 6(a) shows the distribution of time differences between the peaks of the GBM TGFs and the WWLLN sferics. The median offset is 12 \(\mu\)s and for the majority of the events, the sferic and the peak of the TGF are coincident to within \(40 \mu\)s, without any indication of a preferred order. This distribution could be shifted if our assumption of a source altitude of 20 km above the Earth is incorrect, or modified if TGFs are produced at a range of altitudes. Each 5 km difference from 20 km contributes 16 \(\mu\)s to the light travel time so that the issue of source height is critical to resolving the question of simultaneity. In Figure 6(b) we show the distribution of time differences between the onset of the TGF and the peak sferic current. The TGF onset is defined as the time at which 10% of the peak count rate is reached (as determined from the pulse fit parameters [Briggs et al., 2010a]). This is typically around 100 \(\mu\)s before the TGF peak. The onset of the sferic discharge is usually 30 \(\mu\)s or less before the sferic peak discharge time used in this analysis [Jacobson et al., 2006], but its value for individual WWLLN sferics is unknown. We find a looser correlation between the peak of the sferic discharge and the TGF pulse start than between the peak of the sferic discharge and the TGF pulse peak. With more TGF-sferic matches observed over time, it may be possible to establish a preferred sequence but we find here that the sferic discharge peak is closer to the TGF peak than its start, and can occur before or after the TGF peak.

Another prediction of the lightning leader model described in Carlson et al. [2009a] is a broad directional distribution of observed TGFs. This spread in observation angles arises because of the varied electric field structures generated along lightning leader channels. Unlike Cohen et al. [2010] who report, in 36 associations with sferics, 13 more than 300 km (up to 900 km); Hazelton et al. [2009], who report 4 associations up to 600 km; Lay [2008] (700 km); and Shao et al. [2010] (373 km), all from the sub-RHESSI point, we find that the sferics associated with GBM TGFs all lie within 300 km of the sub-Fermi position. This is in agreement with Cummer et al. [2005] who found 13 matches with RHESSI TGFs using VLF stations at Duke University, all of them within 300 km of the sub-RHESSI position, and with Stanley et al. [2006] who report an average distance from the sferic of 130 km using the Los Alamos array. Detecting TGFs up to 300 km from the sub-spacecraft position implies an angle of 51° from a source at 20 km above the Earth. This opening angle could be a combination of the beaming of the emission, and any tilt of the electric field or broadening resulting from the scattering of the emission. It is possible the beam angle is wider, even before scattering, but that gamma rays emitted at large angles are absorbed in the atmosphere.

Hazelton et al. [2009] suggest that TGFs viewed from longer distances, i.e. through more atmosphere, have softer spectra, so it is possible that GBM is not detecting those types of events. We also expect these long-distance events to be weaker, though there should be more of them owing to the larger solid angle with increasing distance off-axis. It is worth noting that the maximum distance for TGF-WWLLN matches reported here remained constant throughout the experiment, even after lowering the GBM threshold and increasing its rate by a factor of about 8. One might expect weaker events to be detected with the lower threshold, even
if they are softer, given that GBM is sensitive between 8 keV and 40 MeV and can trigger on energy ranges much lower than those that typically trigger the instrument for TGFs. The increase in TGF detection rate after the software change does not imply that we are seeing TGFs that are about 8 times weaker than before, but it does bring the GBM TGF detection rate within a factor of 2 of the RHESSI detection rate and some of the events that GBM is now detecting have substantially fewer total counts than before the flight software change. If the ability of RHESSI to see TGFs at large offsets to the sub-spacecraft position can be explained by its sensitivity to weak events, one might expect that with a lower threshold, GBM would be able to see TGFs that are farther away from the nadir than before the software change. Although this has not occurred, instrumental effects leading to non-detection of weaker and softer events cannot be ruled out. Another explanation is instrumental effects leading to non-detection of weaker and softer events cannot be ruled out. Another explanation is

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Table 1. TGF-WWLLN coincidences within 1000 km and 5 ms, showing the true temporal and spatial offset between the WWLLN sferic and the Fermi sub-satellite position after correcting for light travel time and the drift of the GBM clock. The minimum opening angle is derived from the Fermi-sferic distance and includes both intrinsic beaming and scattering. The temporal offsets are for the TGF peak relative to the time of peak sferic discharge. When the TGF has two peaks, each peak is listed separately as “a” and “b”. The last column shows the chance probability of finding this close match given the number of matches obtained in the control sample, shown in column 6.

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<th>TGF Name (date)</th>
<th>TGF-sferic temporal offset (ms, corrected)</th>
<th>Uncertainty in offset (ms)</th>
<th>Spatial offset (km)</th>
<th>Minimum opening angle (°)</th>
<th>No. Control Matches</th>
<th>Chance Probability</th>
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Figure 3. GBM TGF lightcurves (histogram), corrected for light travel time and clock drift, with WWLLN stroke time and uncertainty band (dotted).
Figure 4. continued
Figure 5. GBM TGF lightcurves (histogram), corrected for light travel time and clock drift, with WWLLN stroke time and uncertainty band. These are the two cases for which the WWLLN sferics are not simultaneous with the GBM TGF peak.
Figure 6. Fermi spacecraft position and 300 km radius (red) with WWLLN lightning strokes (green) within 10 min of the GBM trigger time. An exact match (within 5 ms and 1000 km) is shown as a filled purple square. The peak time (UT, corrected) of the GBM TGF is shown on the bottom left of the plot.
Figure 7. ctd.
Figure 8. Fermi spacecraft position and 300 km radius (red) with WWLLN lightning strokes (green) within 10 min of the GBM trigger time. An exact match (within 5 ms and 1000 km) is not found, but lightning activity is seen within 300 km of the sub-spacecraft point. These panels show 6 of 31 such cases, with the other maps provided in the Supplementary Material. The peak time (UT) of the GBM TGF is shown on the bottom left of the plot.
Figure 9. Lightning activity at sub-spacecraft point (left) and a magnetic footprint (right). Lightning at magnetic footprint may have instigated a TGF with electrons traveling to Fermi along field lines. WWLLN lightning strokes 10 min either side of the GBM trigger time are shown as green squares.
Figure 10. Distribution of temporal offsets between (a) top, the peak and (b) bottom, the start of the GBM TGF and the WWLLN sferic. The two TGF-sferic pairs with large separations are excluded. For the TGF with two simultaneous sferics, only the one closer in time is included. For TGFs with two peaks, the peak closer in time to the sferic is used. One TGF-peak match from (a) was omitted in (b) because the TGF peak partially overlapped another TGF peak and its start time could not be reliably determined.