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Associations between Fermi Gamma-ray Burst Monitor terrestrial gamma ray flashes and sferics from the World Wide Lightning Location Network

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[1] 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 μs, and find that in 13 of these 15 lightning-TGF associations, the lightning stroke and the peak of the TGF are simultaneous to ~40 μs. This suggests that a large fraction of TGFs are coincident with lightning discharges. The two nonsimultaneous associations do not show a consistent TGF-lightning stroke temporal sequence. All 15 associations are with sferics within 300 km of the subspacecraft position. For those TGFs not correlated with a particular lightning stroke, we find storm activity within 300 km of the subspacecraft 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 subspacecraft TGFs with gamma ray events and the footprint events with electrons traveling along magnetic field lines before hitting the Fermi spacecraft.

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1. Introduction

[2] 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, or sferics, and gamma ray data from both BATSE [*Inan et al.*, 1996; *Cohen et al.*, 2006] and the Reuven Ramaty High-Energy 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]. While 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 ~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.

[3] The World Wide Lightning Location Network (WWLLN) [*Rodger et al.*, 2009] has participated in several searches for

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correlations with RHESSI TGFs [*Lay*, 2008; *Hazelton et al.*, 2009]. WWLLN sferics have an average RMS timing accuracy of 30 μs, 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 light curve and knowledge of the Fermi subspacecraft position at the time of a TGF detection, one can find both the relative timing of TGFs and lightning strokes to within tens of μs, and the angular offset of the TGF from the point of detection.

[4] 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 intracloud (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].

[5] *Briggs et al.* [2010] report four associations between GBM TGFs and WWLLN sferics, with both simultaneous and nonsimultaneous 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

[6] 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 by *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.* [2010] and G. J. Fishman et al. (Temporal properties of terrestrial gamma ray flashes from the Gamma-Ray Burst Monitor on the Fermi observatory, submitted to *Journal of Geophysical Research*, 2010) give details of the capabilities of GBM for TGF science and detailed descriptions of the early TGF observations made with GBM.

[7] 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 multipeaked TGF is treated separately. Sferic correlations with TGFs have been reported with storms up to nearly 1000 km from the subspacecraft position [*Hazelton 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 because the WWLLN measures sferics at the time of peak 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.

[8] In order to establish whether any TGF-WWLLN match could have occurred by chance, we also search for matches near the subspacecraft 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.

[9] 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.

[10] 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 subspacecraft 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 nonvertical electric fields at the source position.

3. Results

3.1. Associations With Individual Lightning Strokes

[11] In the sample of 50 GBM TGFs, 15 have at least one WWLLN sferic within our established criteria of a 5 ms

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 Subsatellite Position After Correcting for Light Travel Time and the Drift of the GBM Clock[a]

TGF Name (Date)	TGF-Sferic Temporal Offset (ms, Corrected)	Uncertainty in Offset (ms)	Spatial Offset (km)	Minimum Opening Angle (deg)	Number of Control Matches (5 ms, 300 km)	Chance Probability
081001.392	2.714	0.073	106.22	12.34	0	$<1 \times 10^{-3}$
081113.322a	−1.271	0.015	290.38	31.15	0	$<1 \times 10^{-3}$
081113.322b	0.016	0.015	290.38	31.15	0	$<1 \times 10^{-3}$
081123.874	0.013	0.016	56.238	6.47	1	$<1 \times 10^{-3}$
090203.356	−3.856	0.018	248.93	26.43	1	$<1 \times 10^{-3}$
090828.147a	−0.245	0.047	145.82	16.29	7	7×10^{-3}
090828.147b	−0.092	0.038	145.82	16.29	7	7×10^{-3}
091130.219	0.017	0.027	224.34	24.49	5	5×10^{-3}
091213.876	0.025	0.021	121.80	13.85	1	1×10^{-3}
091227.540	0.038	0.014	113.63	12.75	2	2×10^{-3}
100110.328	0.019	0.021	133.81	15.35	4	4×10^{-3}
100129.593	−0.108	0.027	288.72	30.91	1	1×10^{-3}
100207.843	−0.035	0.020	231.61	25.56	2	2×10^{-3}
100207.843	−0.047	0.012	229.77	25.38	2	2×10^{-3}
100218.518	−0.007	0.017	200.74	22.14	0	$<1 \times 10^{-3}$
100223.288	0.032	0.034	156.91	17.32	1	1×10^{-3}
100305.806	−0.047	0.050	222.64	24.53	0	$<1 \times 10^{-3}$
100331.421	−0.093	0.074	199.96	21.87	2	1×10^{-3}

[a]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 chance probability of finding this close match given the number of matches obtained in the control sample is given.

offset in time after correcting for light travel and clock drift, and 1000 km from the subspacecraft 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 subspacecraft position.

[12] Table 1 shows the 15 likely associations and their inferred temporal and spatial separations. The time offset in ms from the peak of the TGF pulse to the WWLLN stroke time and the uncertainty on this measurement are given. The uncertainty in timing 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 the TGF peak time can be determined with an uncertainty between 6 and 70 μs by fitting a Gaussian or lognormal function, as described by *Briggs et al.* [2010], so that this is often the largest uncertainty in the TGF-sferic relative timing. The distances from the WWLLN stroke to the subspacecraft position are given, and the angular distance from the TGF to the spacecraft assuming the TGF originated 20 km above the Earth is shown.

[13] 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 subspacecraft 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 Table 1 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.

[14] 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.

[15] 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 (no matches in the control sample) to 0.7%, so that each of these matches is statistically significant and the WWLLN sferic is likely associated with the GBM TGF.

[16] 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. Figure 1 (top left) shows the superposition of the sferic time (and its band of uncertainty) on the GBM light curve of TGF 081113.322,

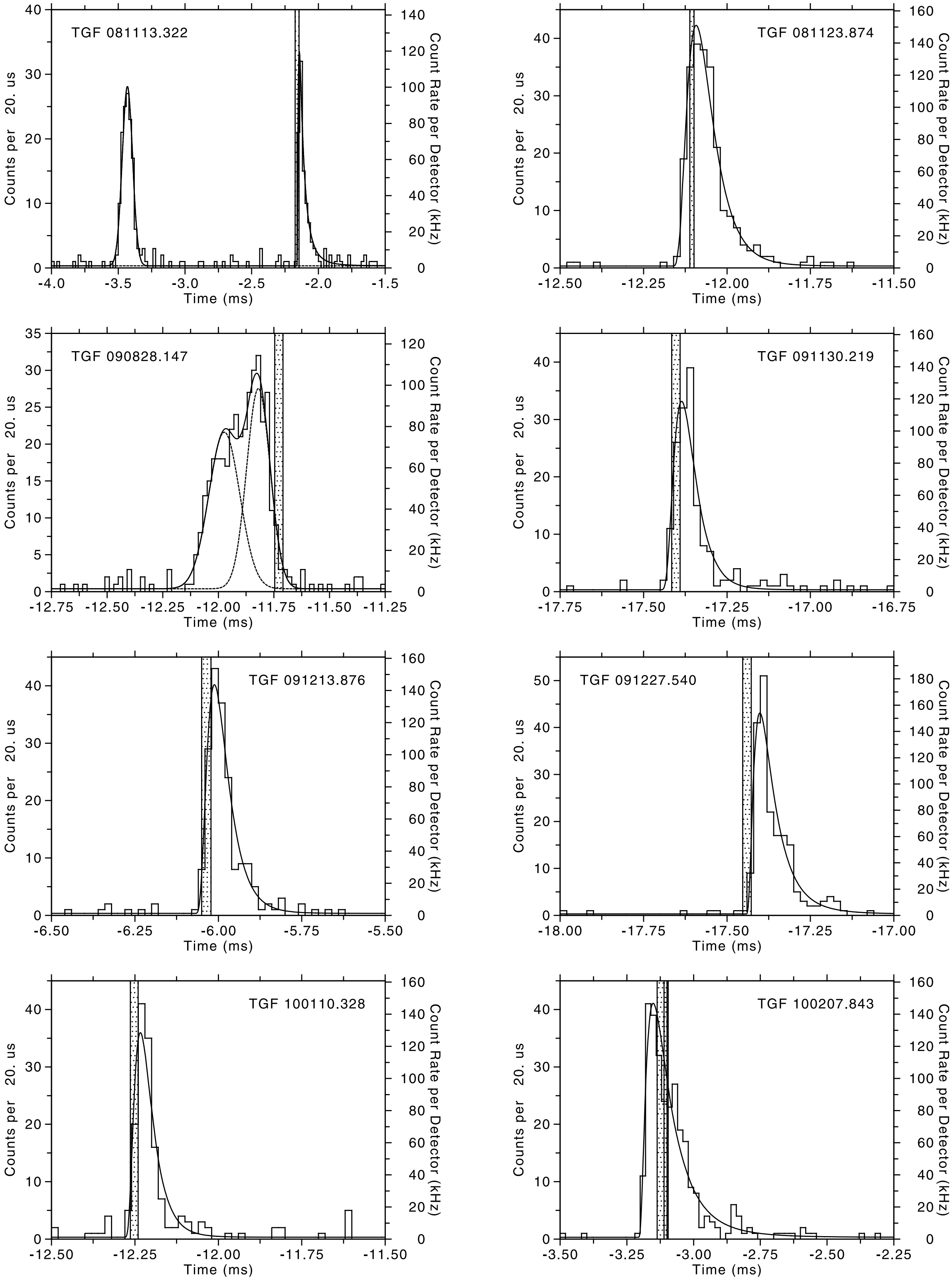

Figure 1. GBM TGF light curves (histogram), corrected for light travel time and clock drift, with WWLLN stroke time and uncertainty band (dotted).

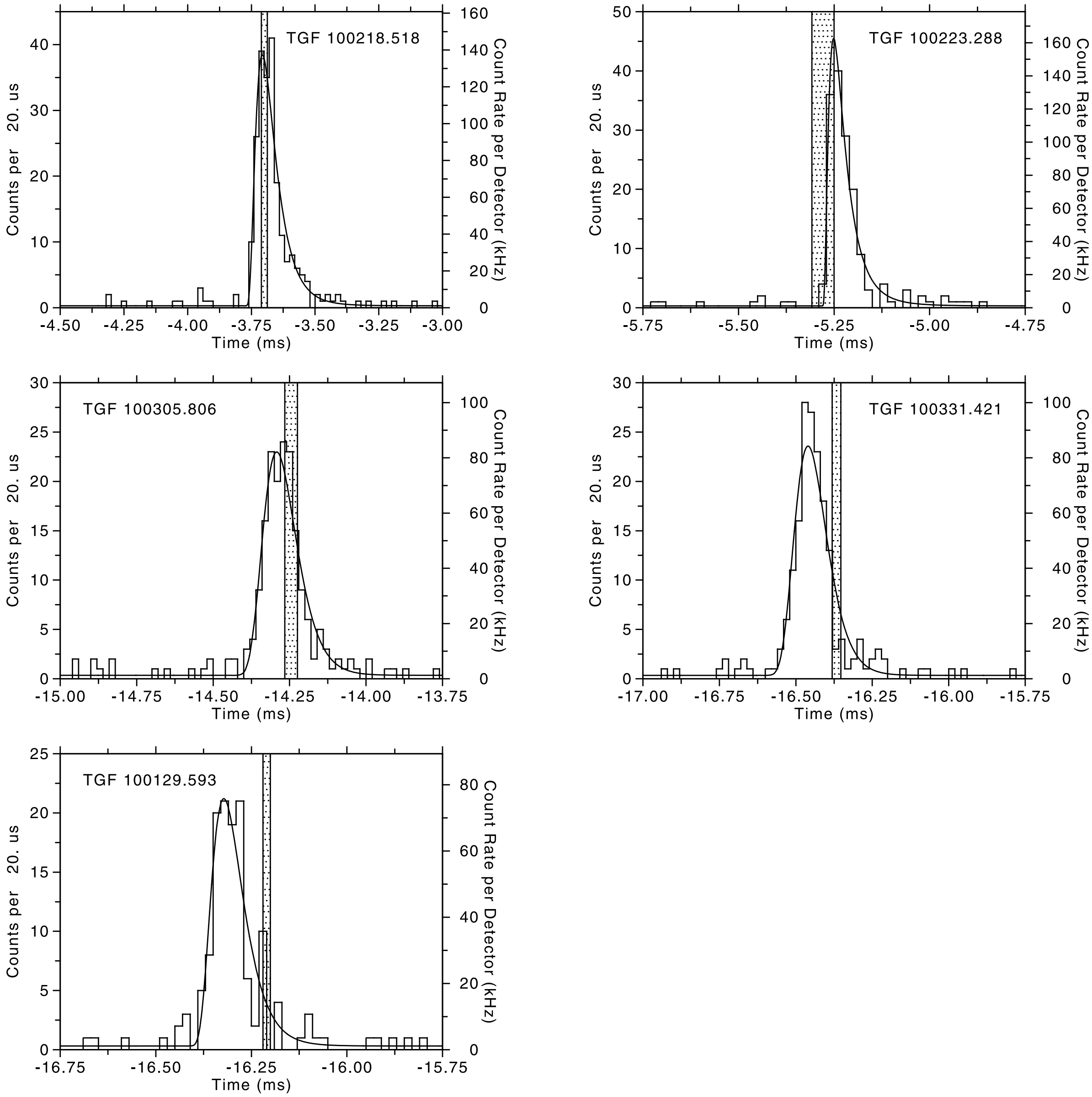

Figure 1. (continued)

corrected for light travel time and clock drift. It is clear from Figure 1 that associating the "b" pulse with the sferic is justified. The rest of Figure 1 shows 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 light curves 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 nonsimultaneous matches occurred by chance is negligible.

3.2. Correlations With Storm Systems

[17] 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 strokes registered by the WWLLN during this time. Figure 3 shows, for the 15 cases with an associated sferic, the WWLLN lightning strokes superimposed on a map covering the region 15° in latitude and longitude in each direction from the Fermi subspacecraft 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

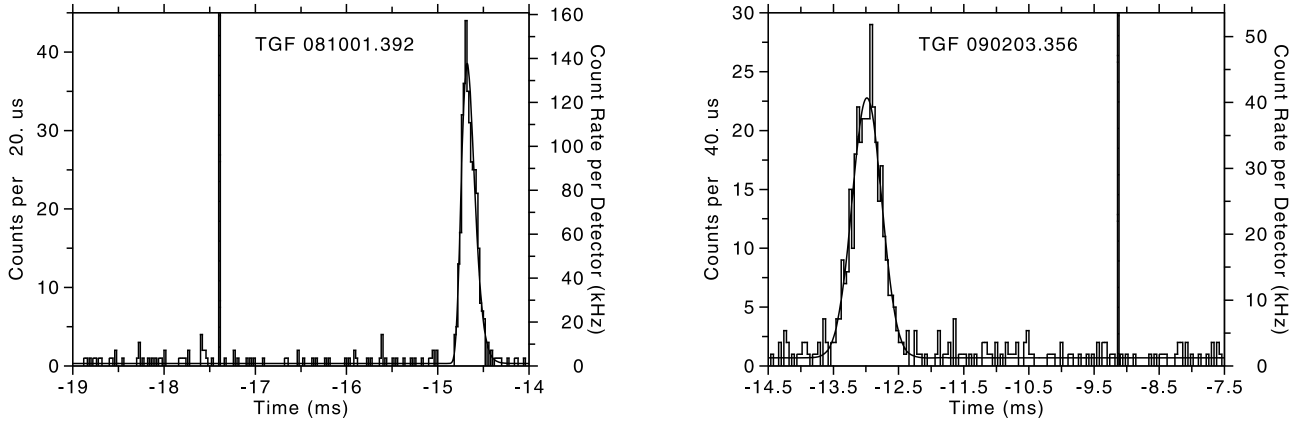

Figure 2. GBM TGF light curves (histogram), corrected for light travel time and clock drift, with WWLLN stroke time and uncertainty band. These are the two cases for which the WWLLN sferics are not simultaneous with the GBM TGF peak.

shown as open green squares, with the TGF-WWLLN matches identified above shown as closed purple squares. Figure 4 shows 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 subspacecraft position. These cases are representative of all but 4 of the 50 GBM TGFs, where there is at least one active lightning region within 300 km, with some events showing more than one concentration of lightning activity. Maps for the remaining TGFs where lightning is seen within 300 km of the subspacecraft position are provided in the auxiliary material.[1]

[18] In all four of the cases where there is neither an exact match with an individual stroke nor a region of active lightning within the 20 minute window and 300 km region (nor even within a much larger radius), the TGFs themselves are rather unusual. As noted by *Briggs et al.* [2010] and G. J. Fishman et al. (submitted manuscript, 2010), most GBM TGF pulses are only a few tenths of a millisecond long. These four unusual TGFs were shown by *Briggs et al.* [2010] and M. S. Briggs et al. (manuscript in preparation, 2010) to last longer than 1 ms and show a softer spectrum. It is most likely these events are produced by electrons originating at a distant source and traveling along the geomagnetic field line that connects the source and the spacecraft. For these four events, Figure 5 shows storm systems, as determined by WWLLN strokes, for both the Fermi subspacecraft position (Figure 4, left) and the footprint, at 20 km altitude, of the geomagnetic field lines through Fermi, along which the TGF may have traveled. TGFs 080807, 080913, and 091214 all have lightning activity at one of the magnetic footprints, and it is this footprint which is shown in Figure 5. The two earlier events are associated with the nearby magnetic footprint, and the latter with the far magnetic footprint, near which much lightning activity is seen. No matches with individual sferics from these storms are seen, even taking into account the time for the electrons to travel along the field lines from these more distant sources to Fermi. TGF 090510 remains a mystery. Its time profile is longer than the typical TGF but shorter than the other three electron events, and no storm system is associated either with the subspacecraft position (even at the larger 1000 km search radius) or either of the magnetic footprints. This TGF occurred when Fermi was over Africa where the efficiency of the WWLLN is lower.

[19] No storm activity is seen at either of the magnetic footprints of all but one of the remaining 46 TGFs unless the nearby footprint is close enough to the subspacecraft point to encompass the subspacecraft storm systems, but all of them have storm activity associated with the subspacecraft point and/or an exact match with a WWLLN sferic. This reinforces our judgment that there are two types of TGFs: one in which gamma rays are seen at the spacecraft, coming directly from the point of initiation, and one in which electrons travel along magnetic field lines from storms at one of the two magnetic footprints, with a range of pitch angles leading to a longer duration event [*Dwyer et al.*, 2008].

[20] A cluster analysis of the lightning strokes in the 300 km radius of each of the subspacecraft points (gamma ray events) or magnetic footprints (electron events) was performed, with clusters formed hierarchically [*de Hoon et al.*, 2005] according to the distances between the centroids of existing clusters until the distances between centroids became greater than the 100 km radius we used to define a storm system. This allows us to identify the distance to the closest storm system. This is not always the distance to the initiating storm system, as is seen by comparing this distance to the individual lightning strokes associated with the TGF, but it provides a measure of how far a typical storm system is from a TGF observation at the time of its initiation. The results of this cluster analysis show that for the electron TGFs, which travel along field lines from the magnetic footprints, the distance from the footprint to the nearest cluster of lightning identified by WWLLN is 35 km. For the gamma ray events, which come directly from a cone of some radius under the spacecraft, the average offset of the spacecraft to the nearest active cluster of lightning is 121 km, or 137 km if we choose the distance to the lightning stroke whenever there is an association of the TGF with a sferic. The implication is that we detect these electron events from lightning events close to the magnetic footprint, whereas the gamma ray events are seen in a cone of larger radius, up to 31°. The variances on these numbers (17 km and

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010JA015681.

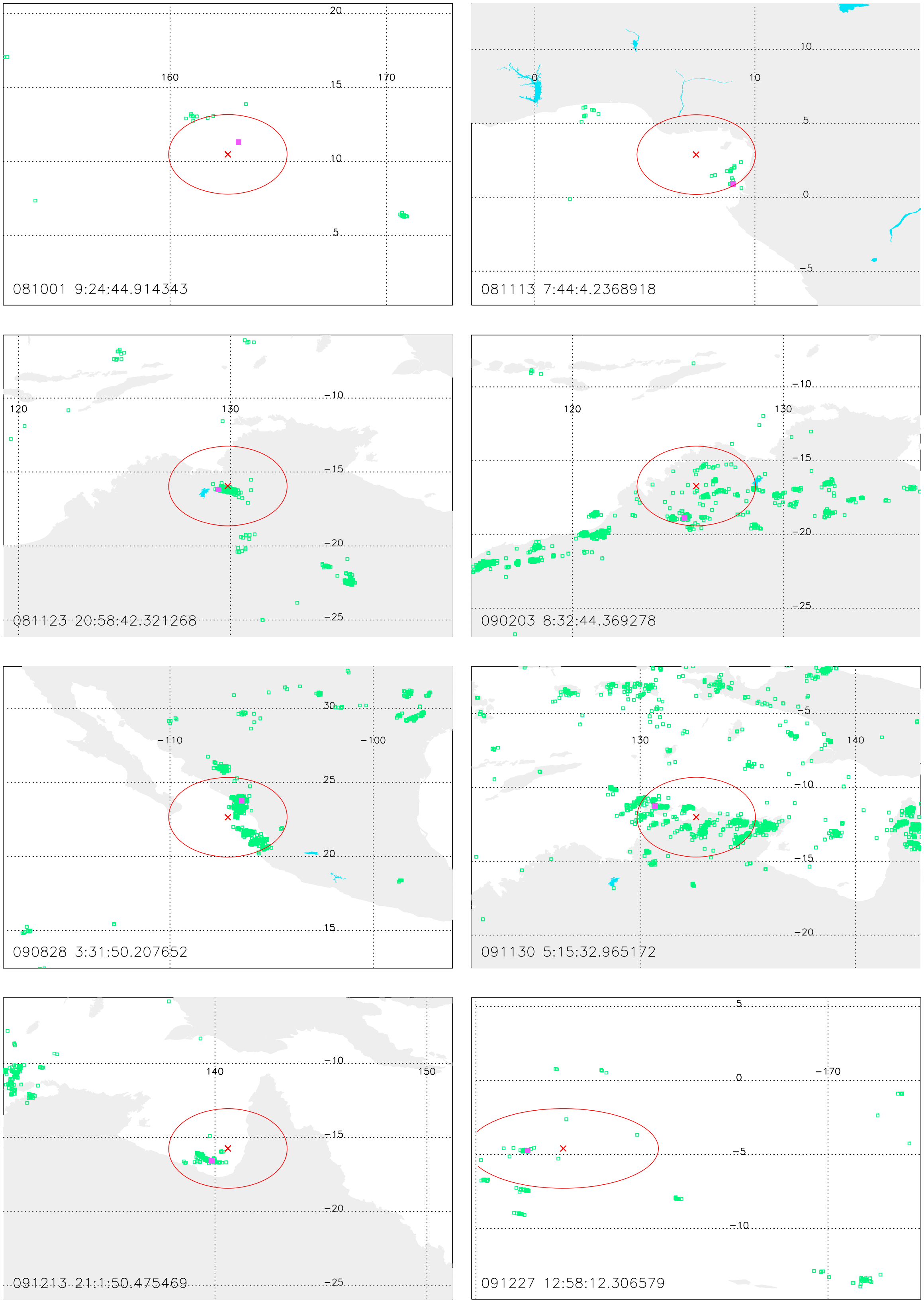

Figure 3. Fermi spacecraft position and 300 km radius (red) with WWLLN lightning strokes (green) within 10 min of the GBM trigger time. An exact match (within 5 ms and 1000 km) is shown as a solid purple square. The peak time (UT, corrected) of the GBMTGF is shown at the bottom left.

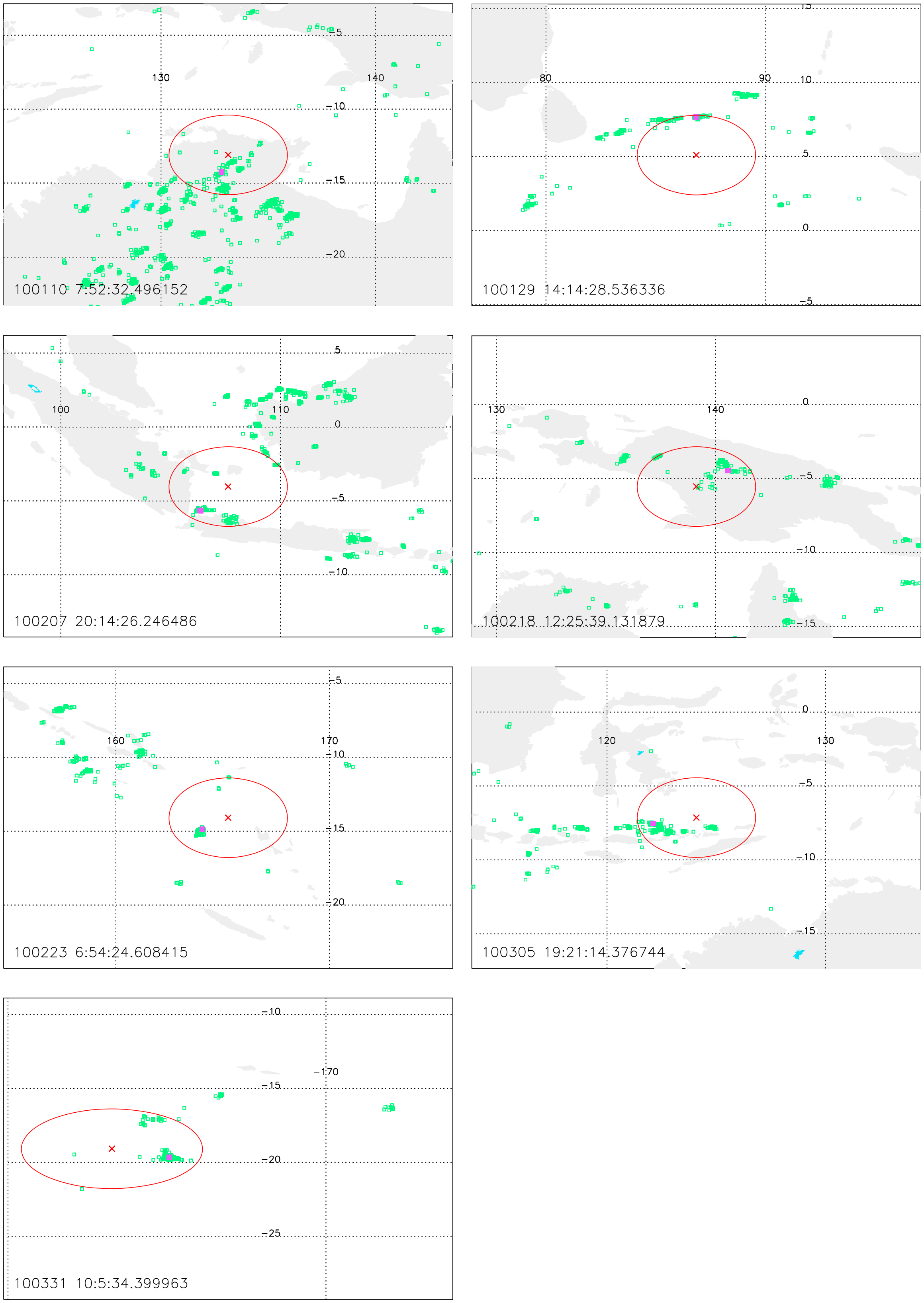

Figure 3. (continued)

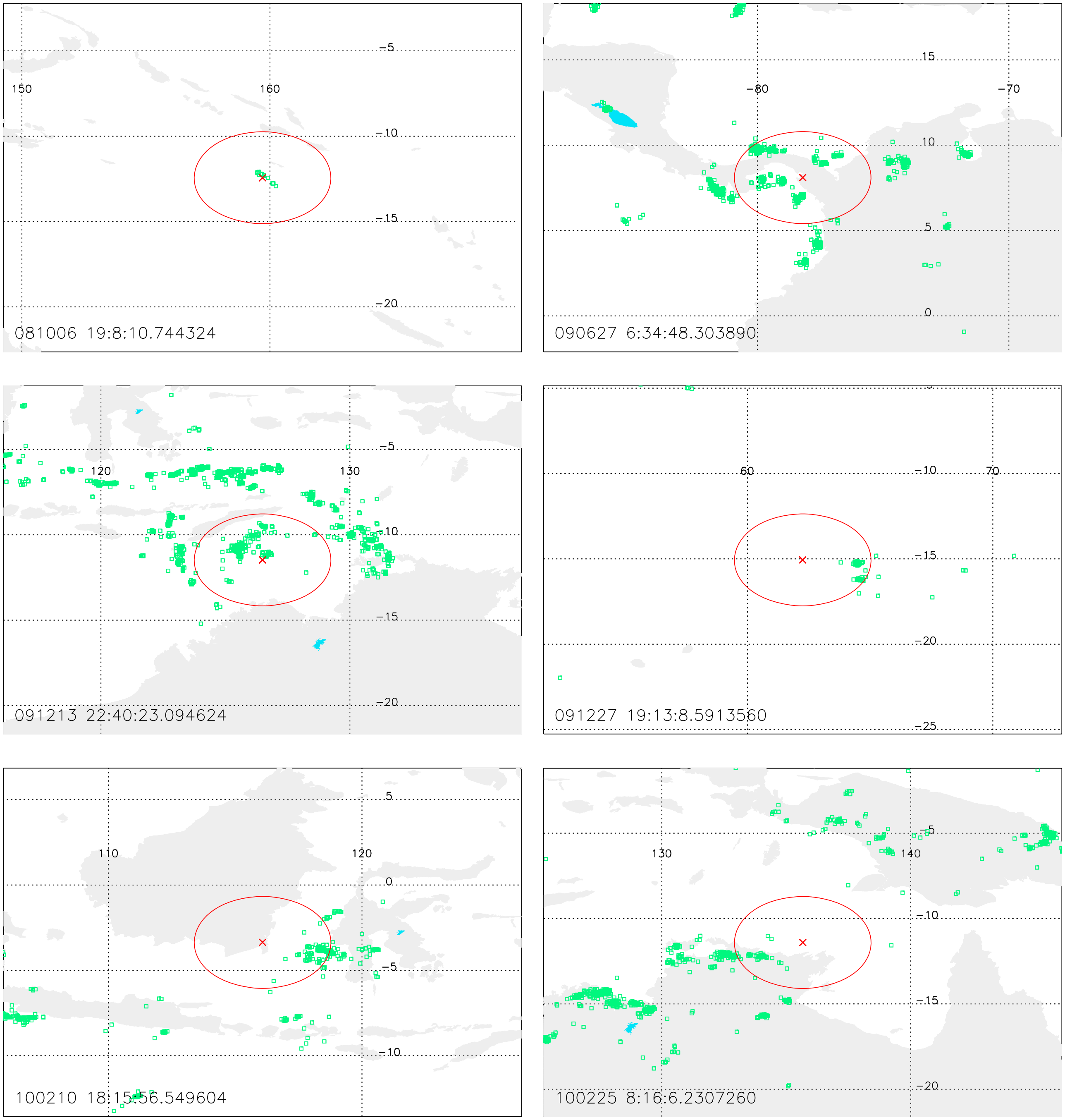

Figure 4. Fermi spacecraft position and 300 km radius (red) with WWLLN lightning strokes (green) within 10 min of the GBM trigger time. An exact match (within 5 ms and 1000 km) is not found, but lightning activity is seen within 300 km of the subspacecraft point. Six of 31 such cases are shown, with the other maps provided in the auxiliary material. The peak time (UT) of the GBM TGF is shown at the bottom left.

67 km) are large enough, however, that more instances of both types of TGFs are needed to confirm this trend.

4. Discussion

[21] 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% [*Lay*, 2008] but these were done when the WWLLN was less efficient than now, so a direct comparison is not possible.

[22] 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 the stronger

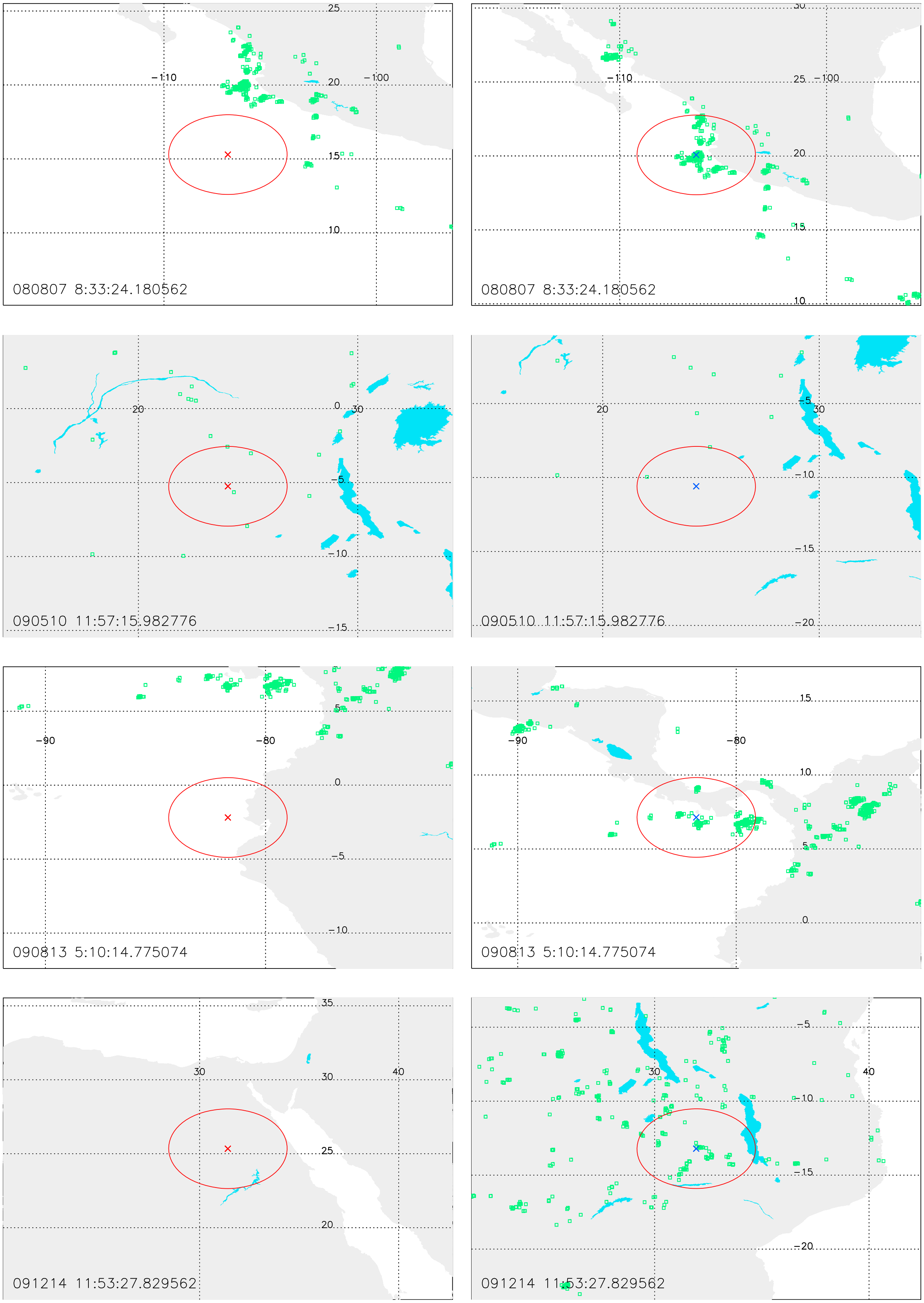

Figure 5. (left) Lightning activity at subspacecraft point and (right) a magnetic footprint. Lightning at magnetic footprint may have instigated a TGF with electrons traveling to Fermi along field lines. WWLLN lightning strokes 10 min either side of theGBM trigger time are shown as green squares.

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.

[23] 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.

[24] Previous TGF-VLF sferic associations find that the TGF precedes the sferic by -3 ± 1 ms (*Cummer et al.* [2005], but applying the -1.8 ms clock correction to the RHESSI data makes this result consistent); -3 ± 5 ms [*Lay*, 2008]; follow the sferic (*Cohen et al.* [2006] and *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).

[25] The results presented here suggest a close connection between individual lightning discharges and TGFs. The two exceptions suggest that either the TGF or the lightning can 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.*, 2010]. 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 dead time 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 by *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%.

[26] The observation of simultaneous TGF-sferic pairs is predicted in lightning leader models for TGFs [*Dwyer*, 2008; *Dwyer et al.*, 2010; *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 ~ MeV seed electrons. These are accelerated by ambient 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.

[27] 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 (top) shows the distribution of time differences between the peaks of the GBM TGFs and the WWLLN sferics. The median offset is 12 μs and for the majority of the events, the sferic and the peak of the TGF are coincident to within 40 μs, 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 μs to the light travel time so that the issue of source height is critical to resolving the question of simultaneity. In Figure 6 (bottom) 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.*, 2010]). This is typically around 100 μs before the TGF peak. The onset of the sferic discharge is usually 30 μs 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.

[28] Another prediction of the lightning leader model described by *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 subspacecraft position implies an angle of 31° 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

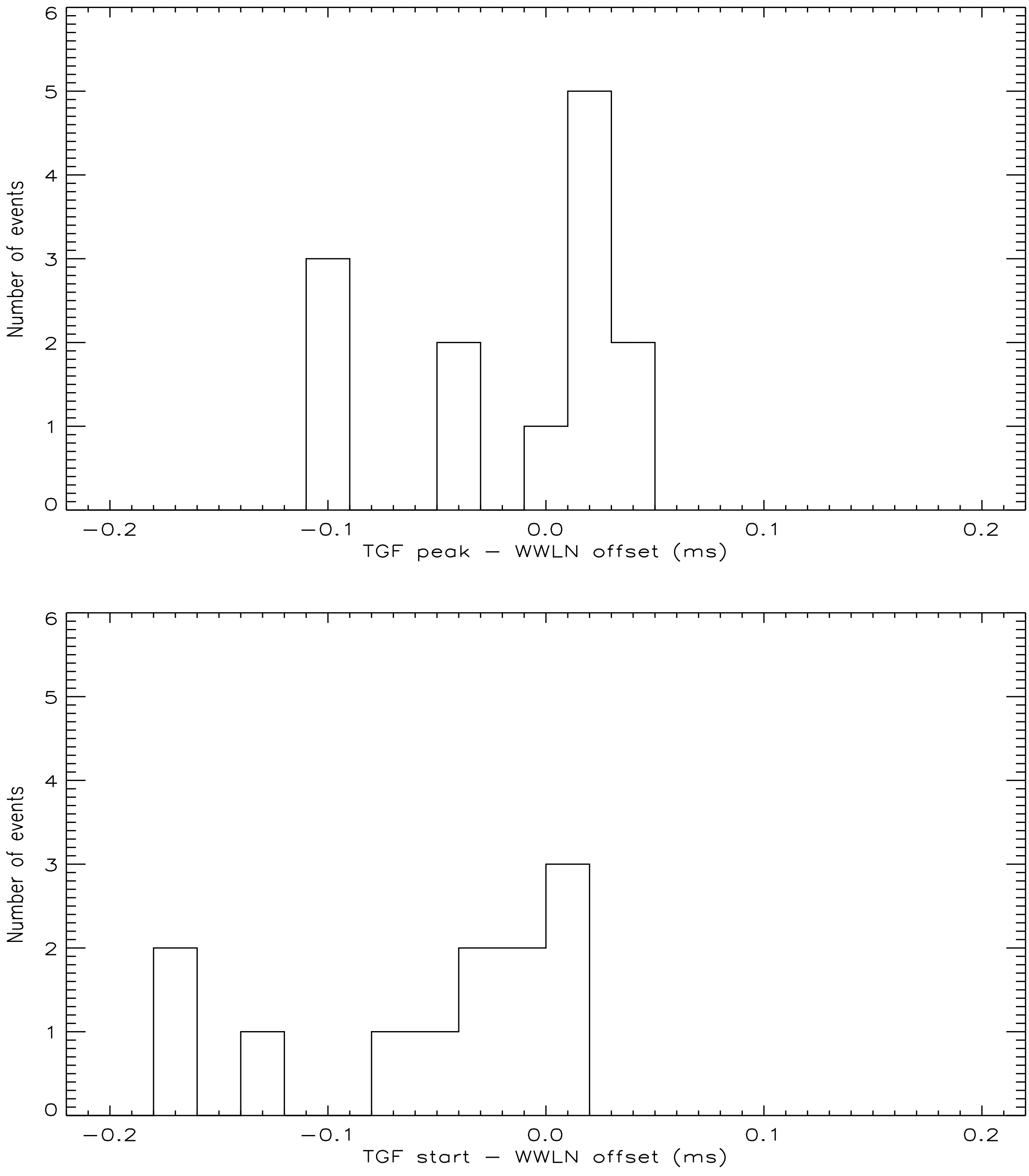

Figure 6. Distribution of temporal offsets between (top) the peak and (bottom) the start of the GBM TGF and the WWLLN sferic. The two TGF-sferic pairs with large separations are excluded. For the TGF with two simultaneous sferics, only the one closer in time is included. For TGFs with two peaks, the peak closer in time to the sferic is used. One TGF-peak match from Figure 6 (top) was omitted in Figure 6 (bottom) because the TGF peak partially overlapped another TGF peak and its start time could not be reliably determined.

resulting from the scattering of the emission. It is possible the beaming angle is wider, even before scattering, but that gamma rays emitted at large angles are absorbed in the atmosphere.

[29] *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 subspacecraft 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 that the earlier matches reported at large spatial offsets were actually coincidences, a possibility that is difficult to assess. *Cohen et al.* [2010] report, for example, an association with a sferic within 181 km of the RHESSI subspacecraft position that they consider more likely than the sferic at 373 km reported by *Hazelton et al.* [2009] and *Shao et al.* [2010]. *Cohen et al.* [2010] also find that the median distance from the sub-RHESSI point to 16 well-located sferics is 196 km, but the median distance to the 20 less confidently located sferics in their sample is 332 km, results that are not easy to reconcile if all 36 matches are real, and may suggest a large position uncertainty when only two VLF stations detect the sferic.

[30] The presence of plausible storm systems within the 300 km radius of all but one of the gamma ray TGFs lends further credibility to a smaller viewing cone for GBM TGFs than reported by *Hazelton et al.* [2009] and *Cohen et al.* [2010]. It is possible, of course, that where no exact sferic match is seen, one of the more distant storms was actually the source of the TGF, but the absence of TGFs with no lightning activity within the 300 km subspacecraft radius and lightning activity outside 300 km but within 1000 km does not lend support to this argument.

[31] Where no storm system is present and no sferic match is seen, we have established in three of the four cases the presence of storm activity at one of the magnetic footprints. This activity, and the unusual nature of these three events reported by M. S. Briggs et al. (manuscript in preparation, 2010), leads to a theory that these are actually electron events, with charged particles traveling along magnetic field lines to the Fermi spacecraft. *Lehtinen et al.* [2001] first proposed that electrons in TGFs could escape the atmosphere with observational consequences. This idea was refined by *Dwyer et al.* [2008], who suggested that electrons could be carried along field lines to the spacecraft, and identified several BATSE TGFs that displayed characteristics consistent with their model. In the analysis presented here, the average distance to the nearest storm system to the footprints is smaller in these putative electron cases than the average distance from the subspacecraft position to the nearest storm system in the gamma ray events. We do not have any matches with individual sferics in these footprint storms, but with an overall match rate of 30% this lack of a closely associated sferic in a sample of three electron TGFs is not surprising. In the absence of an associated sferic, it is possible that a more distant storm system is actually responsible for the observed events, and the number of these electron events is small, but the lower average distance to a plausible storm is consistent with *Dwyer et al.* [2008] and *Carlson et al.* [2009b], who show from simulations of electron events that these events are strongly beamed around the direction of the field line and will be seen only out to 50 km.

5. Conclusions

[32] In a sample of 50 TGFs detected by GBM, we find 15 occur within 300 km and ±5 ms of a lightning discharge detected by the WWLLN. Two of these occur milliseconds before and after the GBM TGF, but the majority, 13 of 15, are consistent with being simultaneous with the TGF. Using the combination of the 3 microsecond absolute time accuracy of GBM, the ability of GBM to determine the peak times of TGFs to tens of microseconds and the typically 30 microsecond absolute time accuracy of WWLLN, we have refined the meaning of "simultaneity" between TGFs and sferics by nearly two orders of magnitude compared to previous results, finding that the peak times of simultaneous TGFs and sferics agree to ~40 μs. We find in 46 of the 50 TGFs either an associated sferic or a storm system with lightning activity within 300 km of the subspacecraft position. Three of the remaining four events are associated with electrons traveling from storms at the magnetic footprints along field lines that reach the Fermi spacecraft.

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References

Briggs, M. S., et al. (2010), First results on terrestrial gamma ray flashes from the Fermi Gamma-ray Burst Monitor, *J. Geophys. Res.*, *115*, A07323, doi:10.1029/2009JA015242.

Carlson, B. E., N. G. Lehtinen, and U. S. Inan (2009a), Terrestrial gamma ray flash production by lightning current pulses, *J. Geophys. Res.*, *114*, A00E08, doi:10.1029/2009JA014531.

Carlson, B. E., N. G. Lehtinen, and U. S. Inan (2009b), Observations of terrestrial gamma-ray flash electrons, in *Coupling of Thunderstorms and Lightning Discharges to Near-Earth Space*, edited by N. B. Crosby, T.-Y. Huang, and M. J. Rycroft, *AIP Conf. Proc.*, 1118, 84–91.

Cohen, M. B., U. S. Inan, and G. Fishman (2006), Terrestrial gamma ray flashes observed aboard the Compton gamma ray observatory/burst and transient source experiment and ELV/VLF radio atmospherics, *J. Geophys. Res.*, *111*, D24109, doi:10.1029/2005JD006987.

Cohen, M. B., U. S. Inan, R. K. Said, and T. Gjestland (2010), Geolocation of terrestrial gamma-ray flash source lightning, *Geophys. Res. Lett.*, *37*, L02801, doi:10.1029/2009GL041753.

Cummer, S. A., Y. Zhai, W. Hu, D. M. Smith, L. I. Lopez, and M. A. Stanley (2005), Measurements and implications of the relationship between lightning and terrestrial gamma ray flashes, *Geophys. Res. Lett.*, *32*, L08811, doi:10.1029/2005GL022778.

de Hoon, M., S. Imoto, and S. Miyano (2005), The c clustering library, Inst. of Medical Sci., Human Genome Cent., Univ. of Tokyo, Tokyo.
Dwyer, J. R. (2008), Source mechanisms of terrestrial gamma-ray flashes, *J. Geophys. Res.*, *113*, D10103, doi:10.1029/2007JD009248.
Dwyer, J. R., and D. M. Smith (2005), A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash, observations, *Geophys. Res. Lett.*, *32*, L22804, doi:10.1029/2005GL023848.
Dwyer, J. R., B. W. Grefenstette, and D. M. Smith (2008), High-energy electron beams launched into space by thunderstorms, *Geophys. Res. Lett.*, *35*, L02815, doi:10.1029/2007GL032430.
Dwyer, J. R., D. M. Smith, M. A. Uman, Z. Saleh, B. Grefenstette, B. Hazelton, and H. K. Rassoul (2010), Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, *J. Geophys. Res.*, *115*, D09206, doi:10.1029/2009JD012039.
Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313–1316, doi:10.1126/science.264.5163.1313.
Grefenstette, B. W., D. M. Smith, B. J. Hazelton, and L. I. Lopez (2009), First RHESSI terrestrial gamma ray flash catalog, *J. Geophys. Res.*, *114*, A02314, doi:10.1029/2008JA013721.
Hazelton, B. J., B. W. Grefenstette, D. M. Smith, J. R. Dwyer, X.-M. Shao, S. A.Cummer, T. Chronis, E. H. Lay, and R. H. Holzworth (2009), Spectral dependence of terrestrial gamma-ray flashes on source distance, *Geophys. Res. Lett.*, *36*, L01108, doi:10.1029/2008GL035906.
Inan, U. S., and N. G. Lehtinen (2005), Production of terrestrial gamma-ray flashes by an electromagnetic pulse from a lightning return stroke, *Geophys. Res. Lett.*, *32*, L19818, doi:10.1029/2005GL023702.
Inan, U. S., S. C. Reising, G. J. Fishman, and J. M. Horack (1996), On the association of terrestrial gamma-ray bursts with lightning and implications for sprites, *Geophys. Res. Lett.*, *23*, 1017–1020, doi:10.1029/96GL00746.
Inan, U. S., M. B. Cohen, R. K. Said, D. M. Smith, and L. I. Lopez (2006), Terrestrial gamma ray flashes and lightning discharges, *Geophys. Res. Lett.*, *33*, L18802, doi:10.1029/2006GL027085.
Jacobson, A. R., R. Holzworth, J. Harlin, R. Dowden, and E. Lay (2006), Performance assessment of the world wide lightning location network (WWLLN), using the Los Alamos sferic array (LASA) as ground truth, *J. Atmos. Oceanic Technol.*, *23*, 1082–1092, doi:10.1175/JTECH1902.1.
Lay, E. H. (2008), Investigating lightning-to-ionosphere energy coupling based on VLF lightning propagation characterization, Ph.D. thesis, Univ. of Wash., Seattle.
Lehtinen, N. G., U. S. Inan, and T. F. Bell (2001), Effects of thunderstorm-driven runaway electrons in the conjugate hemisphere: Purple sprites, ionization enhancements, and gamma rays, *J. Geophys. Res.*, *106*, 28,841–28,856, doi:10.1029/2000JA000160.
Lu, G., R. J. Blakeslee, J. Li, D. M. Smith, X.-M. Shao, E. W. McCaul, D. E. Buechler, H. J. Christian, J. M. Hall, and S. A. Cummer (2010), Lightning mapping observation of a terrestrial gamma-ray flash, *Geophys. Res. Lett.*, *37*, L11806, doi:10.1029/2010GL043494.
Meegan, C. A., et al. (2009), The Fermi Gamma-ray Burst Monitor, *Astrophys. J*, *702*, 791–804, doi:10.1088/0004-637X/702/1/791.
Rodger, C. J., J. B. Brundell, R. H. Holzworth, and E. H. Lay (2009), Growing detection efficiency of the world wide lightning location network, in *Coupling of Thunderstorms and Lightning Discharges to Near-Earth Space*, edited by N. B. Crosby, T.-Y. Huang, and M. J. Rycroft, *AIP Conf. Proc.*, 1118, 15–20.
Shao, X.-M., T. Hamlin, and D. M. Smith (2010), A closer examination of terrestrial gamma-ray flash-related lightning processes, *J. Geophys. Res.*, *115*, A00E30, doi:10.1029/2009JA014835.
Splitt, M. E., S. M. Lazarus, D. Barnes, J. R. Dwyer, H. K. Rassoul, D. M. Smith, B. Hazelton, and B. Grefenstette (2010), Thunderstorm characteristics associated with RHESSI identified terrestrial gamma ray flashes, *J. Geophys. Res.*, *115*, A00E38, doi:10.1029/2009JA014622.
Stanley, M. A., X.-M. Shao, D. M. Smith, L. I. Lopez, M. B. Pongratz, J. D. Harlin, M. Stock, and A. Regan (2006), A link between terrestrial gamma-ray flashes and intracloud lightning discharges, *Geophys. Res. Lett.*, *33*, L06803, doi:10.1029/2005GL025537.
Williams, E., et al. (2006), Lightning flashes conducive to the production and escape of gamma radiation to space, *J. Geophys. Res.*, *111*, D16209, doi:10.1029/2005JD006447.

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