The lightning-TGF relationship on microsecond timescales

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[1] We analyze the count rates of two terrestrial gamma-ray flashes (TGFs) detected by the Fermi Gamma-ray Burst Monitor (GBM) with the broadband magnetic fields (1 to 300 kHz) produced by the simultaneous lightning processes. The microsecond-scale absolute time accuracy for these data, combined with independent geolocations of the source lightning, enable this analysis with higher accuracy than previously possible. In both events, fast discharge-like processes occur within several tens of microseconds of the gamma-ray generation, although not with a consistent relationship. The magnetic field data also show a slower signal component produced by a source current that in both events mirrors the gamma-ray count rate closely in shape and time. This indicates electromagnetic radiation directly associated with the gamma-ray generation process and thus provides a new means for probing the internal physics of this enigmatic phenomenon. **Citation:** Cummer, S. A., G. Lu, M. S. Briggs, V. Connaughton, S. Xiong, G. J. Fishman, and J. R. Dwyer (2011), The lightning-TGF relationship on microsecond timescales, *Geophys. Res. Lett.*, *38*, L14810, doi:10.1029/2011GL048099.

1. Introduction

[2] Terrestrial gamma-ray flashes (TGFs) [*Fishman et al.*, 1994; *Smith et al.*, 2005; *Marisaldi et al.*, 2010; *Briggs et al.*, 2010], and the associated beams of high energy electrons [*Dwyer et al.*, 2008; *Cohen et al.*, 2010a] and positrons [*Briggs et al.*, 2011], are intense, short bursts of energetic radiation associated with thunderstorms. They are produced by brehmsstralung from the relativistic runaway electron avalanche process [*Gurevich et al.*, 1992; *Dwyer*, 2003], in which strong electric fields can via acceleration and repeated ionization convert a seed population of relativistic electrons into a high energy electron beam with exponentially increasing numbers of electrons. While it was originally thought that this acceleration might take place above thunderstorms immediately following high charge transfer lightning strokes [e.g., *Taranenko and Roussel-Dupré*, 1996], later measurements of TGF spectra [*Dwyer and Smith*, 2005] and charge transfer in associated lightning discharges [*Cummer et al.*, 2005] constrain the process to thunderstorm altitudes.

[3] The connection between TGFs and thunderstorms [*Fishman et al.*, 1994] and individual lightning discharges [*Inan et al.*, 1996] has been closely examined for clues to the underlying details, as there are a variety of possible source regions and processes [*Dwyer*, 2008; *Carlson et al.*, 2009]. The general connection between TGFs and some form of lightning discharge on a time scale of several milliseconds has been verified [*Cummer et al.*, 2005; *Stanley et al.*, 2006; *Inan et al.*, 2006; *Shao et al.*, 2010; *Cohen et al.*, 2010b], but more precision is not possible with measurements from the RHESSI satellite [*Grefenstette et al.*, 2009]. TGF-associated discharges have been shown to be in-cloud (IC) [*Stanley et al.*, 2006], during the early stages of IC flash development [*Shao et al.*, 2010], and during the initial upward IC leader development [*Lu et al.*, 2010].

[4] The microsecond-level time precision of the GBM instrument on the Fermi satellite [*Briggs et al.*, 2010] enables exploration of the lightning-TGF relationship on finer time scales. GBM measurements combined with World-Wide Lightning Location Network data have shown that the time of peak gamma-ray counts and some form of lightning discharge or fast charge motion occur within several tens of microseconds for at least ~30% of TGFs [*Connaughton et al.*, 2010]. Further identifying and quantifying these associated lightning processes, and establishing their precise temporal relationship to TGF production, is the goal of this work.

[5] Here we analyze the broadband radio signals in association with 2 GBM-detected TGFs. In both cases associated lightning was independently geolocated about 500 km from the radio sensor. The combination of event geolocation, high time resolution and absolute accuracy for both the radio and gamma-ray measurements provides a new view into the association of fast lightning processes with the gamma-ray generation, and also appears to show a distinct radio signature associated with the gamma-ray generation itself.

2. Data and Measurement Details

[6] The two TGFs reported here were measured by the Gamma-ray Burst Monitor (GBM) instrument on the Fermi Gamma-ray Space Telescope [*Briggs et al.*, 2010]. GBM has fourteen scintillation detectors of two types to cover the energy range of 8 keV to 40 MeV. Photons interact in the scintillator crystals and deposit some or all of their energy, resulting in "counts". The telemetry reports the energy of each count and the time to 2 μs resolution with an absolute accuracy of several microseconds via synchronization to GPS [*Briggs et al.*, 2010] that has been validated in-orbit by comparison to the Fermi Large Area Telescope (LAT) with cosmic ray showers [*Briggs et al.*, 2010]. The timing of the LAT has been validated to better than 1 μs [*Abdo*, 2009]. In order to maximize the signal, the gamma-ray light curves in this paper sum the counts from all fourteen detectors of both types. Deadtime correction [*Briggs et al.*, 2010] is not yet available for mixed-detector data, but its implications

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for this work are modest and discussed below. Analytical fits to the binned gamma-ray counts are used in our analysis. Some TGFs are symmetric and well fit with a Gaussian function, while other pulses had faster rise times than fall times and are better fit with a log-normal function [*Briggs et al.*, 2010].

[7] The timing and timescales of the associated lightning processes are observed from continuous recordings from an orthogonal pair of low frequency (LF) magnetic field coils that are sensitive from roughly 1 kHz to 300 kHz and that have a response that is almost linearly proportional to frequency up to 200 kHz, i.e. they are approximately *dB*/*dt* sensors. These coils are installed at the Florida Institute of Technology in Melbourne, FL (28.062° N, −80.624° E). The sampling clock is a 1 MHz GPS-synchronized signal. The absolute time accuracy of the LF recordings was tested using microsecond-level National Lightning Detection Network (NLDN) data and was found to be better than ±2 microseconds. Data from an identical system near Duke University were also used to independently confirm the geolocations and timing of the events of interest.

[8] Signals were recorded from three TGFs for which the source lightning was NLDN-located within 1000 km of the FIT sensors so that the direct and ionospherically-reflected signals can easily be separated. One of these is omitted from this analysis because the NLDN geolocation was uncertain to more than ±10 km, which results in a significant timing uncertainty, and the LF signal was saturated, which prevents detailed processing. The other two were reliably located by NLDN, and are analyzed in detail.

[9] The accuracy and uncertainty in event times and locations are critically important in our analysis. We present all times with a precision of 1 μs and state any uncertainties in these times. Similarly, we present all distances with a precision of 100 meters, which is 0.33 μs at the speed of light. Although Compton scattering can cause significant arrival time delays when the horizontal distance between the spacecraft and the TGF source is large [*Østgaard et al.*, 2008; *Grefenstette et al.*, 2008], for the TGFs presented in this paper, Monte Carlo simulations show that Compton scattering produces delays of only a few microseconds. The absolute timing uncertainty from the measurements and the gamma-ray propagation speed are significantly smaller than the time alignment uncertainties that result from event location uncertainties and thus do not affect the conclusions of this work.

3. Time-Correlated TGF and Lightning Measurements

[10] Figure 1 shows the geography of the sensors, the two observed TGFs, and the associated NLDN lightning locations. In the analysis we time-align the radio and gamma-ray measurements by propagating all signals at the speed of light back to the assumed source location. Based on previous analysis of TGF spectra [*Dwyer and Smith*, 2005], we assume a minimum possible source altitude of 10 km. A maximum reasonable source altitude is derived for each storm from the infrared satellite images and radar measurements of the TGF-producing storm, and in each case a safe upper bound is 16 km. Consequently the gamma-ray source altitude assumed for the time calculations is 13 km, and the time uncertainties associated with the uncertain TGF source altitudes and lightning locations are discussed in detail.

3.1. TGF on September 5, 2010

[11] GBM detected a TGF by an on-orbit trigger on September 5, 2010. The time of peak gamma-ray counts at the spacecraft computed from a gaussian fit was 02:37:08.070547 UT ±3 μs. The Fermi satellite was at 557.0 km altitude over the geographic footprint of 25.05° N, −78.88° E.

[12] Associated with this TGF was an NLDN-reported ±22.7 kA discharge with a source time of 02:37:08.068093 UT at a location of 24.0294° N, −78.3051° E. This discharge had a 50% geolocation error ellipse with semi-major (pointed nearly N-S) and -minor axes of 2.0 and 0.5 km, respectively. This places the discharge a horizontal distance of 127.4 km from the Fermi footprint and 504.3 km from the LF sensors in Florida.

[13] This discharge preceded the TGF by approximately 570 μs. The LF data (Figure 2 reveals another discharge not reported by NLDN that was nearly simultaneous to the TGF. Comparing the time difference for the Duke and FIT sensors for these two discharges (one geolocated and one not) shows that any location difference between them produced at most 2 μs of relative time difference. This is comparable or smaller than the NLDN geolocation uncertainty for the first discharge, and thus we assume the same location and uncertainty for the TGF-associated discharge.

[14] For the geometry of this event, the horizontal location uncertainty from the NLDN geolocation corresponds to ±6 μs of absolute time uncertainty in the LF data. Combining the 13 ± 3.0 km source altitude uncertainty and the horizontal position uncertainty from the NLDN data gives a TGF timing uncertainty of ±11 μs. This uncertainty is dominated by the source altitude uncertainty, while the LF timing uncertainty is dominated by horizontal location uncertainty. They are thus uncorrelated and, in the worst case, could add, giving a maximum possible time alignment uncertainty of ±17 μs from the assumed alignment shown in Figure 2.

[15] Figure 2 (middle) shows the relative timing of the TGF and lightning-radiated LF signal in a 5 ms window. We interpret the sequence of fast pulses between 66.5 and 67.0 as the initiation of an intracloud (IC) lightning flash, which is also consistent with the lack of any significant activity in the 100 ms preceding this sequence (see Figure 2, top). The association of this TGF with the first few milliseconds of an IC flash is consistent with previous reports [*Lu et al.*, 2010; *Shao et al.*, 2010].

[16] Over the 4 ms following the inferred IC flash initiation, there is a sequence of at least three separate strong and fast discharge-like processes. Only one of these was NLDN-reported, and this one occurs 0.57 ms before the TGF. However, one of these discharge-like processes is in close time association with the TGF [*Connaughton et al.*, 2010].

[17] Figure 2 (bottom) shows a detailed view over a 300 μs time window centered on the TGF. The gamma-ray count rate (arbitrary linear units) is shown in 10 μs bins and the Gaussian fit to the binned data. The directly-recorded LF signal of the azimuthal magnetic field (also arbitrary linear units) shows two closely spaced fast pulses in association with the TGF. The pulse polarity indicates the upward motion of negative charge, consistent with all previously

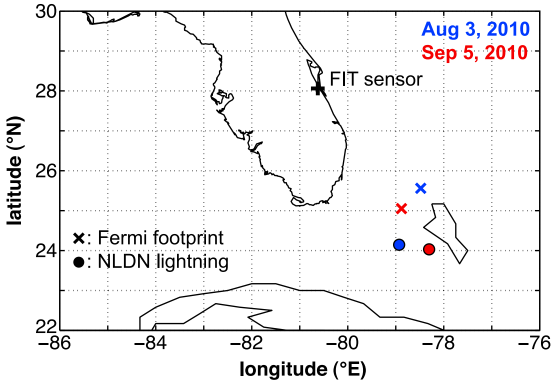

Figure 1. Map showing the location of the LF sensors and, for both events, the footprint of the Fermi satellite at the time of TGF detection and the location of the associated NLDN lightning discharge.

reported TGF-associated signals [*Cummer et al.*, 2005; *Lu et al.*, 2011]. Note that the two pulses near 770 μs are ionospheric reflections, as can be determined from the observed reflected pulse pairs and comparison with waveforms of other discharges in this sequence.

[18] The direct sensor signal is close to the time derivative of B, and at this distance and frequency range (>10 kHz) the magnetic field is dominated by the radiation field and thus essentially proportional to the time derivative of the source current $i(t)$. Consequently we also show in Figure 2 the twice time-integrated LF signal that is approximately proportional to $i(t)$. Note that because the sensor response is not exactly $\partial B/\partial t$, the integrated signal exhibits some undershoot at the end of the TGF that does not reflect the actual source current variation.

[19] Several elements of the TGF-lightning relationship are clear. The gamma-ray counts begin to rise about 40 μs before a pair of fast processes, and the TGF initiation itself is not linked to any significant fast process, even allowing for the maximum possible 17 μs error. The fast processes occur during the rise and are close to the peak, but they lack a precise relationship to the TGF as they occur after the TGF begins and clearly before it ends.

[20] The two fast pulses occur during a slower variation evident in the integrated signal. The measured gamma-ray signal, particularly as a Gaussian fit, and the twice time-integrated radio signal track each other very closely, suggesting a direct connection between the gamma-ray production and the source current of the observed LF signal. The fit TGF peak and the peak of the integrated LF signal occur within just 3 μs of each other, and the ~60 μs rise and fall times are also in good agreement. Correction of the instrumental undershoot in the LF signal and the deadtime

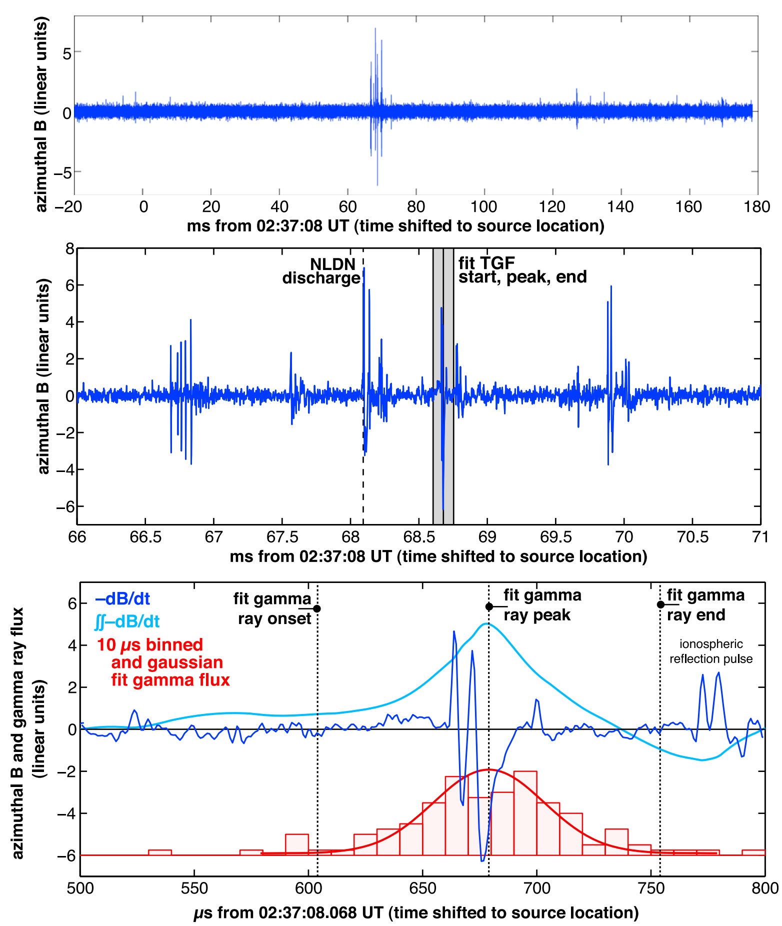

Figure 2. Data summary for TGF on September 5, 2010. (top) 200 ms of LF data around the TGF time. (middle) 5 ms of LF data showing the NLDN-reported discharge and the TGF start, peak, and end time. (bottom) 300 μs of data showing the original and twice-integrated LF data, and the binned and fit TGF gamma-ray count rate.

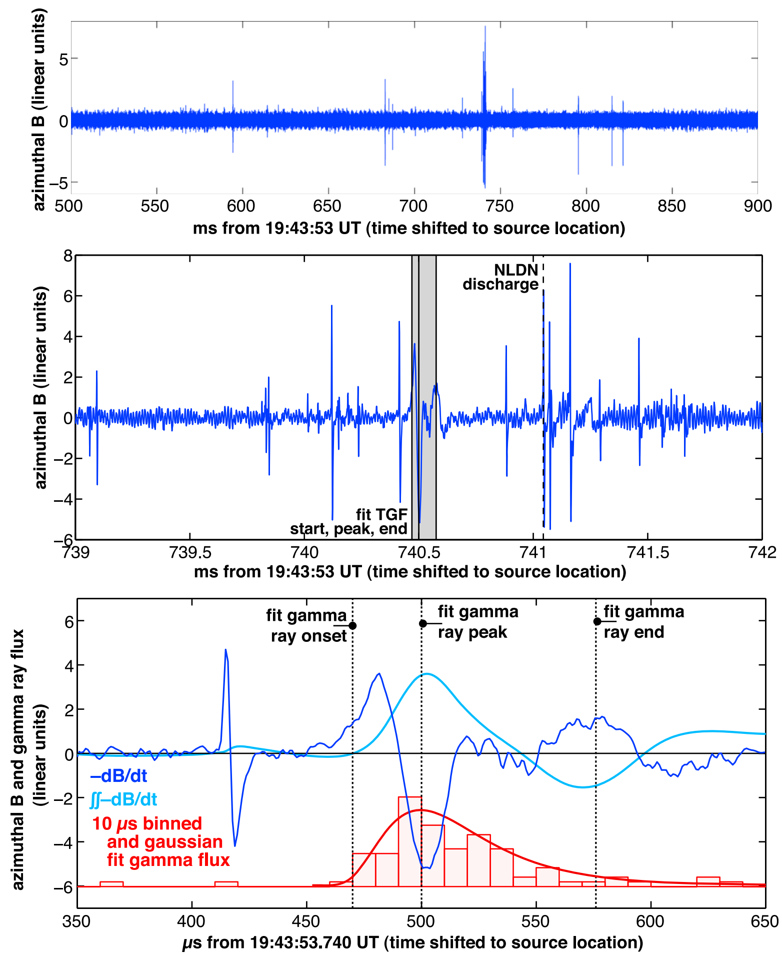

Figure 3. Data summary for TGF on August 3, 2010. (top) 400 ms of LF data around the TGF time. (middle) 3 ms of LF data showing the NLDN-reported discharge and the TGF start, peak, and end time. (bottom) 300 μs of data showing the original and twice-integrated LF data, and the binned and fit TGF gamma-ray count rate.

in the gamma-ray signal, which would result in a more peaked signal, would likely improve the agreement further. The maximum possible ±17 μs time uncertainty in this alignment originating from source location uncertainty does not alter the basic time relationship of the two signals.

[21] For this TGF, there is a lightning source current that has essentially the same time variation of the gamma-ray count rate. The discharges ~0.5 ms before and ~1 ms after the TGF contain similar source pulses that are not associated with any detected gamma rays, although these other pulses are less than half the magnitude of the one associated with the TGF.

3.2. TGF on August 3, 2010

[22] A TGF on August 3, 2010 was identified in the GBM ground-search procedure [*Briggs and the GBM TGF Team*, 2010]. The time of peak gamma-ray count rate at the spacecraft computed from a log-normal fit was 19:43:53.742393 UT ±21 μs (note that the individual gamma-ray arrival times are more precise than this). The Fermi satellite was at 554.3 km altitude over the geographic footprint of 25.56° N, −78.48° E.

[23] Associated with this TGF was an NLDN-reported ±14.2 kA discharge with a source time of 19:43:53.741044 UT at a location of 24.1471° N, −78.9296° E. This discharge had a 50% geolocation error ellipse had semi-major (pointed nearly N-S) and -minor axes of 2.0 and 0.4 km, respectively. This places the discharge a horizontal distance of 163.4 km from the Fermi footprint and 466.7 km from the LF sensors in Florida. For the geometry of this event, the horizontal location uncertainty from the NLDN geolocation again corresponds to ±6 μs of absolute time uncertainty on the LF data. Assuming a 13 ± 3.0 km source altitude gives a gamma-ray source time uncertainty of ±12 μs. This uncertainty is dominated by altitude uncertainty, while the LF timing uncertainty is dominated by horizontal location uncertainty. They are thus uncorrelated, giving a worst-case time alignment uncertainty of ±18 μs from the assumed alignment shown in Figure 3.

[24] Figure 3 (middle) shows the relative timing of the TGF and lightning-radiated LF signal in a 3 ms window. Again the TGF occurred during a ~5 ms burst of strong LF activity. All other pulses in the surrounding 100 ms (see Figure 3, top) arrive from different directions and are thus not associated with the again isolated TGF-associated LF activity.

[25] As in the previous event, there is a sequence of separate (roughly 10 in this case) strong and fast discharge-like processes that occur in a several-ms time window around the TGF. Only one of these was NLDN-reported,

and this one occurs about 0.5 ms after the TGF. But there is a fast discharge-like processes in close time association with the TGF [*Connaughton et al.*, 2010].

[26] Figure 3 (bottom) shows a detailed view of the TGF-lightning relationship over a 300 μs time window centered on the TGF. The gamma-ray count rate (arbitrary linear units) is shown in 10 μs bins and as the log-normal fit to the binned data. The raw LF azimuthal magnetic field (also arbitrary linear units) shows 2 discrete pulses around the TGF time. The first is a fast, isolated pulse that occurs 50 μs before the onset of the gamma-ray counts, and there are no comparable fast process during the TGF itself. Recall that the September 5 event showed two fast pulses during the TGF and none at or prior to onset. Together these events suggest that the fast processes are not clearly associated with any specific stage of the TGF.

[27] The second pulse is significantly slower and is the only pulse in the 3 ms window that lacks a fast onset. Its onset is essentially simultaneous with the TGF onset, and after integration twice in time, we again see that this slower pulse is produced by a source current that follows very closely the time variation of the gamma-ray count rate (again the undershoot at the end is an instrumental effect and the gamma-ray signal is not corrected for deadtime). The time alignment of the peaks is within a few μs, as in the previous event. This is further and compelling evidence that this component of the signal is electric current directly associated with the TGF generation.

4. Summary and Conclusions

[28] In this work, we analyzed the continuous broadband low-frequency radio signals measured at relatively close range (~500 km) in association with 2 GBM-detected TGFs to improve our understanding of the TGF-lightning temporal relationship. The combination of high time resolution and absolute timing accuracy better than several μs for the radio and gamma-ray measurements provides a detailed view into the lightning processes associated with the gamma-ray production. The primary time uncertainty in aligning the lightning signals and gamma-ray measurements results from the uncertain gamma-ray production altitude. After also including lightning geolocation uncertainty, for these events the maximum alignment uncertainty was ±18 μs. This degree of uncertainty does not affect the results presented here, and it will be difficult to improve this without knowing the gamma-ray production altitude to km-or-better accuracy.

[29] These two TGFs are associated with a relatively isolated several-ms period in the lightning flash development that includes multiple discrete and fast discharge-like processes. In both events the TGF was associated with a specific discharge that was neither the first nor the last in the sequence nor was detected by the NLDN, although other discharges in the sequence were detected. This highlights the complexity of the discharge sequence associated with at least some TGFs, and it should be noted that the lack of a network-reported discharge in close time association with a TGF does not imply the absence of such a discharge.

[30] In both events lightning discharge events were associated with the TGFs within several tens of μs, as shown in previous work [*Connaughton et al.*, 2010], but the association is not closer than that. In one case an isolated process occurred 50 μs before the gamma-ray generation began, and in the other a pair of fast processes separated by 10 μs occurred 50 μs after the gamma-ray generation began but before the peak. Neither event contained a detectable fast process at either the beginning or end of the TGF. This variability suggests that there may not be a repeatable connection between these fast processes and TGF generation.

[31] However, the data do show a strong temporal connection between the gamma-ray count rate and a slower process (~50–100 μs rise and fall) in the LF data. In both cases the source current waveform of this slower process very closely follows the timing (within several μs) and shape of the gamma-ray count rate. In one case this slower pulse is unique around the TGF time but in the other it is not. Whether the underlying charge motion is in a lightning process that creates the electric field driving the runaway electron avalanche, or is radiation produced directly from the gamma-ray production is difficult to determine, but the temporal relationship indicates that it is linked to the TGF generation. More events and further analysis is needed to determine whether this connection is found in all TGFs, how this signal is connected to the even slower ms-scale pulses consistently seen with TGFs [*Lu et al.*, 2010, 2011], and to use this signal to probe the internal physics of TGF generation, but it is a step that improves our understanding of the phenomenon.

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