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Key Points:
- Simultaneous gamma-ray and multiband radio measurements provide a more complete picture of the TGF generation processes
- The TGF-generating process is closely associated with strong and nonimpulsive VHF emissions
- The production of all three observed TGFs was accompanied by active lightning streamer zone dynamics

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Very High Frequency Radio Emissions Associated With the Production of Terrestrial Gamma-Ray Flashes

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Abstract Recent studies of the close association between terrestrial gamma-ray flashes (TGFs) production and simultaneous lightning processes have shown that many TGFs are produced during the initial leader of intracloud flashes and that some low-frequency (LF) radio emissions may directly come from TGF itself. Measurements of any simultaneous very high frequency (VHF) radio emissions would give important insight into any lightning leader dynamics that are associated with TGF generation, and thus, such measurements are needed. Here we report on coordinated observations of TGFs detected simultaneously by Fermi Gamma-ray Burst Monitor, two VHF lightning mapping arrays, and Duke ground-based LF radio sensors to investigate more on the close association between TGFs and LF and VHF radio emissions. Three TGFs are analyzed here and confirm previous findings on the close association between TGF generation and lightning processes and, for the first time, provide time-aligned measurements of the VHF radio signature within a few tens of microseconds of TGF generation. Strong VHF emissions were observed essentially simultaneously with two TGFs and within a few tens of microseconds of a third TGF. Equally importantly, the VHF measurement details indicate that the TGF-associated emissions are nonimpulsive and extended in time. We conclude that the TGF-producing process is at least sometimes closely associated with strong VHF emissions, and thus, there may be a link between the generation of TGFs and active lightning streamer dynamics.

Plain Language Summary Terrestrial gamma ray flashes (TGFs) are one of the highest-energy natural photon emissions generated during thunderstorms. Many insights into the physical mechanism of TGFs were revealed by the coordinated observations of TGFs by ground-based radio sensors. Here we presented observations of TGFs detected simultaneously by Fermi Gamma-ray Burst Monitor, two very high frequency (VHF) lightning mapping arrays, and Duke ground-based low-frequency (LF) radio sensors. This is the first time that the temporal relationship between TGFs and VHF emissions is examined with such high precision. The three rather different signatures of these LF signals highlight the complexity and differences from event to event of LF radio emissions associated with TGFs. Meanwhile, the VHF signature within a few tens of microseconds of TGFs was investigated and suggested that the TGF-producing process at least sometimes also radiates brightly at VHF. More importantly, VHF emissions associated with TGFs have some surprisingly consistent features, namely, relatively high power, nonimpulsive, and probably extended source emissions.

1. Introduction

Terrestrial gamma-ray flashes (TGFs) are one of the highest-energy natural photon emissions generated during thunderstorms, with photon energies commonly exceeding 1 MeV. They were first identified and remain primarily detected by space-based gamma-ray photon detectors boarded on the satellites, such as Burst and Transient Source Experiment on the Compton Gamma Ray Observatory (Fishman et al., 1994), Reuven Ramaty High Energy Solar Spectroscopic Imager (Smith et al., 2005), Gamma-ray Burst Monitor (GBM) on Fermi Gamma-ray Space Telescope (Briggs et al., 2010), and Astrorivelatore Gamma a Immagini Leggero (Marisaldi et al., 2010). The connection between TGF production and lightning processes has been investigated in depth by coordinated observations using ground-based very low frequency/low-frequency (VLF/LF, 3–300 kHz) radio measurements and TGFs detected by the above mentioned space-based detectors

(Cohen et al., 2006; Connaughton et al., 2010; Cummer et al., 2005; Inan et al., 1996, 2006; Lu et al., 2010; Shao et al., 2010; Stanley et al., 2006) and also, in one case, by a very high frequency (VHF) lightning mapping array (LMA) (Lu et al., 2011). Collectively, these and more recent results (Cummer et al., 2015) have shown that most and maybe all TGFs are generated near the midpoint of the ascent of initial intracloud (IC) upward negative leaders.

One remarkable signature of TGFs is their close association with LF radio emissions (Connaughton et al., 2013; Cummer et al., 2011, 2014). The amplitude and time scale of these emissions are generally consistent with calculations of the electric current from the TGF generation process itself (Dwyer & Cummer, 2013), indicating that some of the associated VLF/LF radio emissions may come from the TGF itself. Interestingly, some of the most energetic of these TGF-associated events may be a unique signature of TGF production (Lyu et al., 2016) and may thus enable the detection of some TGFs from a ground radio signature alone. Regardless of the precise origin of these LF radio emissions, they confirm that substantial current and net charge motion occurs near the generation time of many TGFs.

Further insight into this lightning-TGF relationship will be helpful in untangling the essential physics of TGF production. One important open question here is what the VHF radio emissions tell us about the dynamics of leader-associated streamer zones around the time of TGF generation. LMAs are an effective tool to map the VHF emissions during lightning processes (Rison et al., 1999). A previous report on the TGF-generating lightning leader observed by LMA showed that the gamma-ray photons were observed during the initial development of an IC flash (Lu et al., 2011), but the signature of VHF emission associated with TGF itself was still unclear due to timing uncertainty in the data. The main goal of this work is to investigate more on the radio emission processes associated with TGF production, especially the VHF emission during TGF, and thus improve our understanding on TGF physics.

Here we report three new examples of simultaneous measurements of TGFs by Fermi GBM, and lightning radio emissions from LMAs and Duke LF magnetic field sensors. In the one case with clear source mapping, the LMA data show that the TGF is produced during the initial leader ascent, as expected. The other two do not contain enough LMA data points to identify the flash structure. But in all three cases, a high-power VHF source is detected within at most several tens of microseconds of the TGF itself. Interestingly, the LF radio emissions from these events are different: one TGF was associated with a slow and isolated LF pulse (Cummer et al., 2011), one was associated with an energetic in-cloud pulse (EIP) (Lyu et al., 2015, 2016) with a National Lightning Detection Network (NLDN) reported peak current of 441 kA, and the third TGF was associated with indistinct LF emissions. These observations show that the TGF-generating process not only produces strong LF radio emissions but appears to produce strong VHF as well.

These strong TGF-associated VHF emissions have one other consistent and unusual feature. They are poorly located in space by the LMA system compared to the other VHF sources around the same time, despite being higher amplitude than those other sources. As discussed below, this is a signature of those VHF sources being fundamentally nonimpulsive, noisy, and extended in time. Collectively, these measurements indicate that active and extended-in-time (and probably space as well) leader and streamer expansion, thought to be the source of lightning VHF emissions, occurs close in time to the TGF generation process. And these VHF emissions are similar even in cases where the LF radio emissions associated with the TGF are rather different in character.

2. Instruments and Data

In this study, coordinated measurements from four GPS-synchronized instruments were investigated: (1) GBM on Fermi, which has a nearly circular orbit with an inclination of 25.6° and detects TGFs efficiently within a horizontal range of ~500 km (Briggs et al., 2010, 2013); (2) two VHF LMAs (Rison et al., 1999; Thomas et al., 2004) deployed at Kennedy Space Center in Florida and Houston in Texas (HSTN LMA), which can detect and locate VHF emissions from lightning flashes up to the range of ~300 km; (3) NLDN (Cummins et al., 1998; Cummins & Murphy, 2009); and (4) four LF magnetic field sensors (Lu et al., 2013) deployed at Duke Forest in NC (Duke), Florida Institute of Technology in Florida (FIT), University of Mississippi in Mississippi (Miss), and the Arecibo Observatory in Puerto Rico. The LF radio signals were recorded by two orthogonal LF magnetic field measuring coils having frequency response proportional to frequency from ~1 to ~100 kHz (dB/dt), and flat frequency response (B) from ~100 kHz up to 300 kHz, with sampling rate of 1 Ms/s. The LF data from

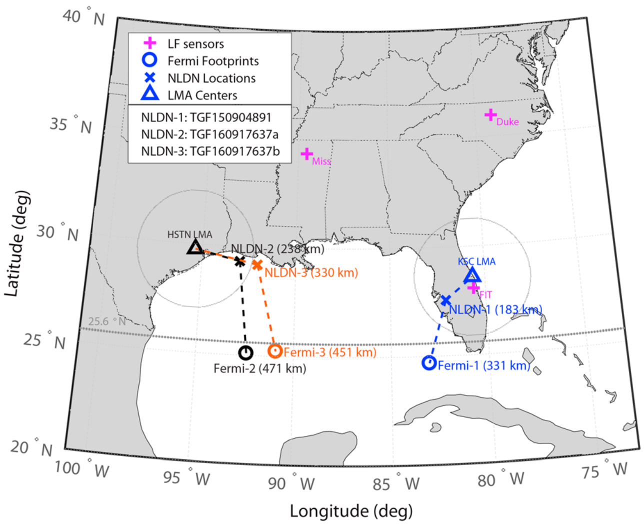

Figure 1. The geolocations of Fermi at the times of the terrestrial gamma-ray flashes (TGFs) and of the National Lightning Detection Network (NLDN) events, lightning mapping array (LMA) centers, and three low-frequency (LF) sensors. The gray circle marks the 200 km range from the LMA centers, while the dotted line at latitude 25.6°N indicates the Fermi orbital inclination. The triangles mark the locations of the Kennedy Space Center in Florida (KSC) and Houston in Texas (HSTN) LMAs. The NLDN locations of the lightning associated with TGFs are marked by crosses, while the footprints of Fermi at the times of TGF detection are shown by the circles with same color of the NLDN locations. The distances of the LMAs and the Fermi footprints from each NLDN location are shown by the numbers in the brackets. The three magenta crosses mark the three locations of the LF sensors. Note that the Arecibo Observatory in Puerto Rico LF sensor is not illustrated in this figure.

these Duke sensors were widely used in the studies on TGFs (e.g., Cummer et al., 2011, 2015) and transient luminous events (e.g., Lu et al., 2013), as well as EIPs (Lyu et al., 2015, 2016).

The three TGFs analyzed here were identified by the off-line search of the gamma-ray photon data detected by GBM, with one TGF that occurred on 4 September 2015 (catalog name of TGF150904891), and another two that occurred on 17 September 2016 (TGF160917637a and TGF160917637b). Lightning events reported by NLDN were examined to find the location of the TGF-associated lightning. The NLDN locations of the TGF-associated events were used as the ground source location of the TGFs to shift both gamma-ray photons and LF signals back to the TGF source. For each TGF, the LF signals from at least three different sensors were examined to find the TGF-associated signals. Figure 1 shows the geolocation of the LMA centers, three of the four LF sensors, Fermi footprints, and NLDN events associating the three TGFs, respectively.

An important element of the time association of different signals is the time uncertainty of the data sets. In the following analysis, the times of LF signals, VHF sources, and gamma-ray photons were shifted to the presumed TGF source location for direct comparison, and the main source of time uncertainty originates in the location uncertainty of TGF source. For the ground-level LF radio signals and VHF sources, the main timing uncertainty originates primarily in the horizontal location uncertainty of the source because this distance is large compared to the source altitude. In this study, the horizontal location of the TGFs is assumed to be the NLDN location of the lightning events that are close to the TGF time. For the three TGFs analyzed here, the three associated events were reported by NLDN with 50% geolocation error ellipse with semimajor and semiminor axis of (0.3, 0.2) km, (0.7, 0.2) km, and (0.2, 0.1) km, respectively. This horizontal location uncertainty corresponds to a time uncertainty of ±1 μs, ±2 μs, and ±1 μs, which is also the main time uncertainty of the LF radio signals when shifting the LF signals back to the NLDN location.

In contrast, the source altitude plays a key role in the timing uncertainty of the gamma-ray photons detected by Fermi GBM. Unfortunately, no reliable source altitude information can be obtained from the data recorded for these three TGFs. As reported by the previous studies, TGFs were closely linked to in-cloud initial leaders (Cummer et al., 2011, 2014; Lu et al., 2010; Shao et al., 2010; Stanley et al., 2006) and usually generated at the midpoint of the upward negative leader (Cummer et al., 2015). The TGF source altitude was constrained by the altitudes of the two main charge layers (Cummer et al., 2015; Lu et al., 2010), which agrees well with the LMA observation in this study. A source altitude of 12 km is assumed for all three TGFs, with a source altitude uncertainty of ±2 km. This source altitude uncertainty corresponds to a gamma-ray time uncertainty of ±7 μs. Note that LMA also reported the time and location of the TGF-associated VHF sources. However, the TGF-associated VHF sources were unreliably located despite being relatively high-power signals. This implies that they are nonimpulsive, radio frequency-noisy signals. The location error is amplified by being at relatively large distances from the LMA networks, but other LMA sources around the time of the TGFs were in good agreement with the NLDN and therefore accurately located, as seen in the following figures. These proximate LMA sources provide a valuable check on the NLDN locations. A time correction is thus applied to the specific LMA sources associated with the TGFs by shifting its LMA reported time to the TGF source location determined by the NLDN location and source altitude of 12 km. Note that time dispersion due to photon interaction with the atmosphere, such as Compton Scattering (Celestin & Pasko, 2012), could cause a spread of the arrival times for low-energy photons at the satellites. However, for the gamma rays with energy above ~1 MeV that are unlikely to have scattered, this effect is not a significant contributor comparing to the source location uncertainty, and it was not considered in this study.

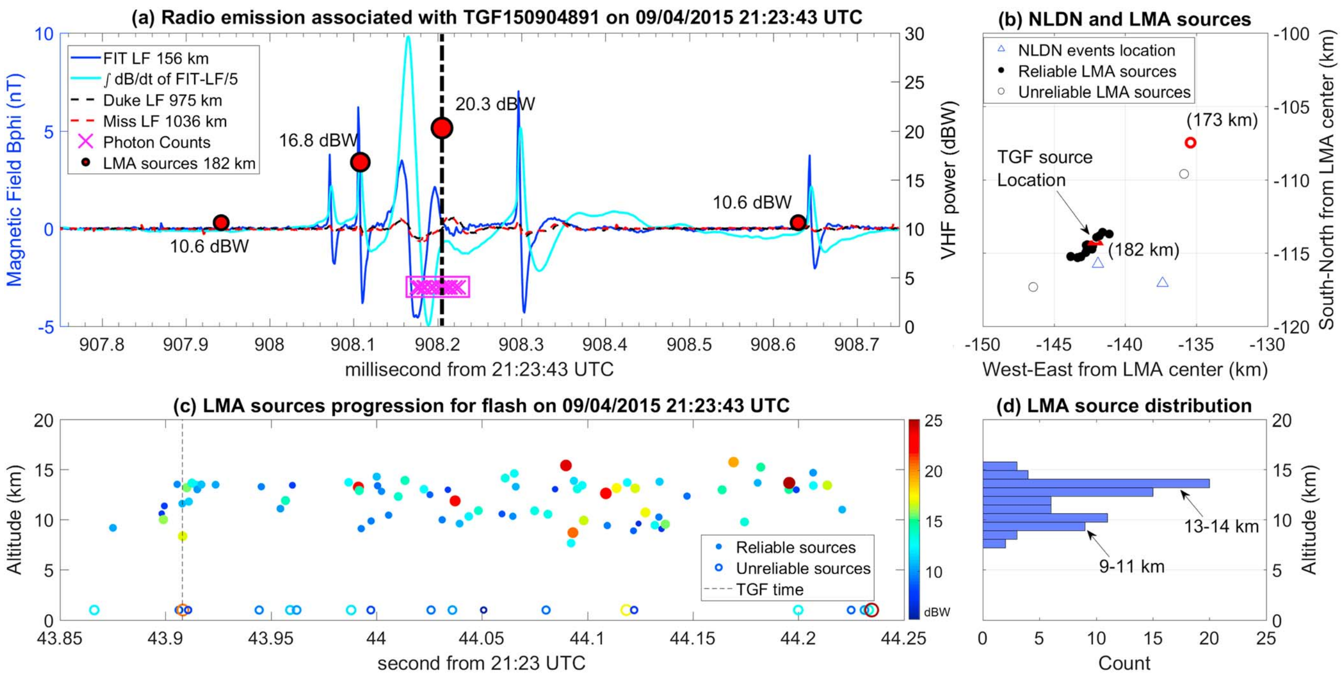

Figure 2. The coordinated measurements of TGF150904891 by Fermi Gamma-ray Burst Monitor, low-frequency (LF) sensors, Kennedy Space Center in Florida (KSC) lightning mapping array (LMA), and National Lightning Detection Network (NLDN). (a) The LF radio signals from station Florida Institute of Technology in Florida (FIT), Duke Forest in NC (Duke), and University of Mississippi in Mississippi (Miss); the LMA sources within 1 ms of the terrestrial gamma-ray flash (TGF); and the time-integrated FIT LF data. The times of the LF signals and the Fermi gamma-ray photons were retrieved by shifting them back to the NLDN location with a source height of 12 km. The times of the LMA sources are marked by the red dots with black edge. The black dash-dot vertical line marks the 20.3 dBW LMA source. (b) The NLDN locations during this lightning flash (triangles) and the LMA sources (chi-square less than 2.0) within 20 ms (circles) of the TGF. The red triangle and red circle mark the NLDN and LMA source location at the time close to TGF. The horizontal range of the sources to the KSC LMA center is shown by the numbers in the brackets. (c) The progression of LMA sources (chi-square less than 2.0) during the 400 ms of the TGF-producing flash. The color and size of the LMA symbols illustrate the power of the sources. The solid dots show the LMA sources within 5 km of the NLDN location and source altitudes less than 17 km (reliable sources), while the empty circles show the LMA sources with large location errors (unreliable sources). (d) The altitude distribution of the reliable LMA sources in (c). Two peaks at 9–11 km and 13–14 km indicate the altitudes of two main charge layers.

3. TGF150904891

TGF150904891 was recorded on 4 September 2015, at 21:23:43 UTC. Figure 2 shows the Fermi photon counts time, the LMA mapped sources, and the LF radio signals from FIT, Duke, and Miss, respectively. Three events with peak current of 12 kA, 32 kA, and 11 kA were reported by NLDN within 1 ms of the TGF time, and the one with smallest location error was chosen to be the assumed ground location of this TGF. It placed the TGF source at 183 km from the LMA center and 331 km from the Fermi footprint. No accurate source height of this TGF can be retrieved. As shown by the vertical distribution of the LMA sources (Rison et al., 1999) in Figure 2d, the two main charge layers were elevated at 9–11 km and 13–14 km. As discussed in the previous section, for this TGF, a time uncertainty was estimated to be ±1 μs for the LF signals and ±7 μs for the gamma-ray photons after shifting them back to the presumed TGF source.

Figure 2a shows the first five evident LF pulses in a 1 ms window of the IC initial leaders recorded by LF sensor at FIT which is 156 km from this flash, and the LF signals from the two LF sensors at Duke and Miss. Four bipolar pulses were measured with pulse duration of 15–20 μs, which were typical LF pulses during the initial leaders of ICs. However, there is one distinct slower pulse observed among the normal leader pulses, with time scale of ~80 μs. The gamma-ray photons were observed within ~20 μs of the start of this slow pulse. The close association between the slow pulse and gamma-ray photons is indicated by their good timing alignment. This is well consistent with the previous reports on the relationship between this kind of distinct slow pulse and TGF (Cummer et al., 2011), which suggests that this kind of radio emission may come directly from the TGF itself, rather than other lightning processes, and thus provides further evidence that substantial electric current and net charge motion can occur at the time of TGF generation.

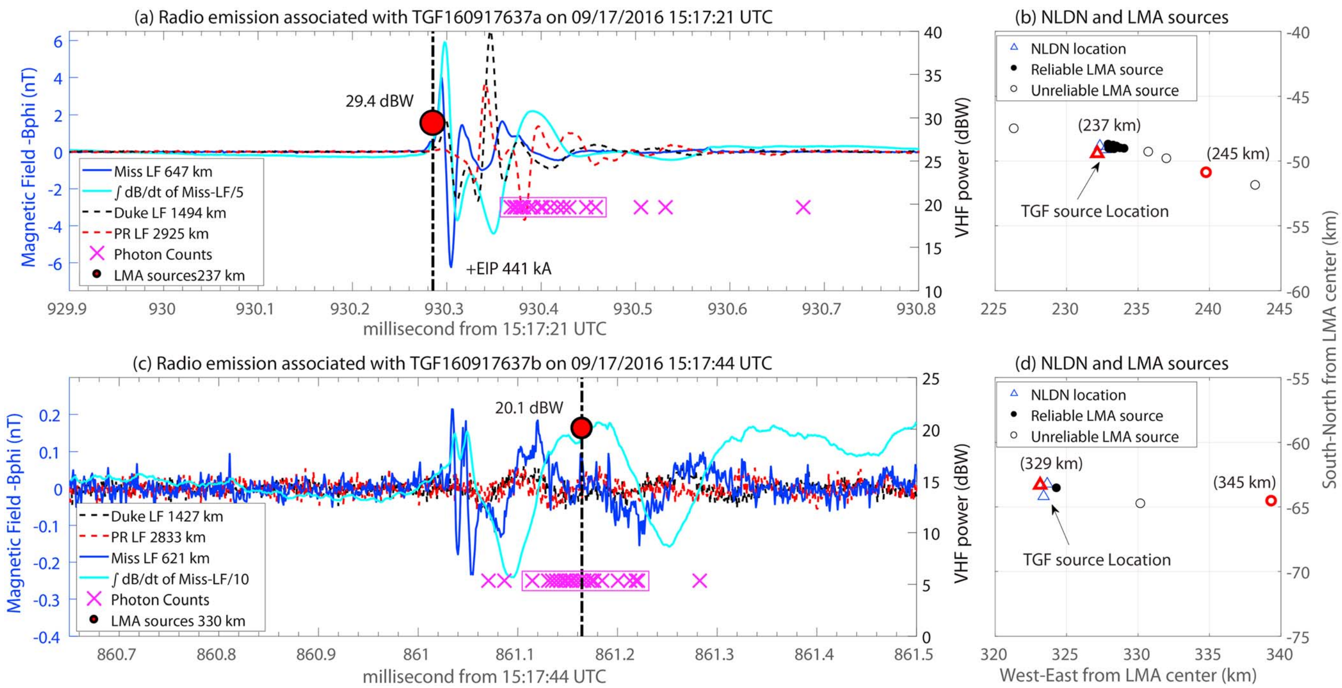

Figure 3. The coordinated measurements of TGF160917637a and TGF160917637b by Fermi Gamma-ray Burst Monitor (GBM), low-frequency (LF) sensors, Kennedy Space Center in Florida (KSC) lightning mapping array (LMA), and National Lightning Detection Network (NLDN). Both terrestrial gamma-ray flashes (TGFs) occurred on 17 September 2016, with a time gap of ~23 s. All the symbols and waveforms have the same meanings as in Figures 2a and 2b.

Twenty LMA sources were mapped during the initial 20 ms of this IC flash, with more than 80% of them being located within 5 km of the NLDN location of the TGF-associated event, as illustrated in Figure 2b. Four LMA sources during the 1 ms window of TGF150904891 were reported, with source powers of 10.6 dBW, 16.8 dBW, 20.3 dBW, and 10.6 dBW. However, the LMA source with the strongest VHF power of 20.3 dBW was noticeably mislocated relative to the other LMA sources, being located ~9 km radially closer to the LMA network than the other sources (red circle in Figure 2b). This is almost certainly due to the nonimpulsive nature of the VHF emissions during the general 80 μs processing window. As found in the study of narrow bipolar events (NBEs) by Rison et al. (2016), incorrectly located strong LMA events are good indicators of the source being nonimpulsive and more continuously radiating, such that the different mapping stations detect slightly different peaks in the waveform envelope. When shifted to the correct location, the event occurred 25 μs earlier than initially indicated, making it closely associated with the TGF photons and the slow LF pulse. In Figure 2a, the time of the 20.3 dBW source was corrected and was marked by the black dash-dot vertical line. After timing correction, the 20.3 dBW LMA source, which was the strongest LMA source during the initial leader, was observed directly during the time of TGF150904891, even considering the ±7 μs time uncertainty of the gamma-ray photons. This shows that nonimpulsive and strong VHF emissions are at least sometimes produced during TGF generation process.

4. TGF160917637a and TGF160917637b

TGF160917637a and TGF160917637b were detected during storms on 17 September 2016, with a time interval of ~23 s, and were generated from two different thunderstorm cells separated by about 90 km.

During the flash associated with TGF160917637a, NLDN reported three events with peak currents of 6 kA, 441 kA, and 7 kA during a 3 ms interval of the initial IC leader. It is interesting to note that the temporally closest event associated with this TGF was a positive EIP (+EIP) with an NLDN peak current of 441 kA, which occurred within ~80 μs of the TGF, as illustrated in Figure 3a. The recently identified +EIPs are a type of strong radio signals that occurred during the initial upward negative leader of some IC flashes (Lyu et al., 2015, 2016). They are strong VLF/LF radio signals with time scale of ~50 μs and very high NLDN-reported peak currents (above 150 kA). It has been found that +EIPs and TGFs are closely linked, which creates the possibility of detecting TGFs with distant radio sensors (Lyu et al., 2016). The new example here provides further evidence on the connection between +EIPs and TGFs. The strong LF emission and high peak current of the +EIP and close association between +EIP and TGF also show that there is substantial current motion associated with the TGF generation (Cummer et al., 2014).

The NLDN reports placed the TGF source at 238 km from the HSTN LMA center and 471 km from the Fermi footprint. No charge layer distribution or altitude of the TGF source can be obtained from the LMA reports. As discussed in section 2, for this TGF, a time uncertainty was estimated at ±2 μs for the LF signals and ±7 μs for the gamma-ray photons when shifting them back to the TGF source.

From the range of 238 km, LMA reported nine sources with chi-square less than 2.0 in the first 20 ms of this TGF-generating IC flash. Five of the nine sources were radially located, including the source with the strongest VHF source power (29.4 dBW). This strongest VHF source was also the source most closely associated time-wise with the TGF event. As illustrated in Figure 3b, NLDN events and the majority of LMA sources were clustered in a small area (3 km × 2 km). Similar to the first case, a time adjustment of 9 μs was applied to this LMA source by shifting its LMA location to the assumed TGF source location. The corrected time of the LMA source was illustrated in Figure 3a and marked by the black dash-dot vertical line. As shown in Figure 3a, the +EIP and the 29.4 dBW VHF source lined well with each other, and they both were within ~70 μs of the gamma-ray photons. Note that at the range of ~240 km, this 29.4 dBW VHF source was the first and the highest power VHF source mapped by LMA during the 20 ms of the IC initial leaders. It is indicated that +EIP-TGF process not only produces strong LF signals but also radiates brightly at VHF band, while the +EIP and strong VHF emission occurred within ~70 μs of the gamma-ray photon burst of TGF160917637a. However, this TGF-associated VHF source was poorly located despite being the strongest VHF signal in the flash, again indicating an atypically nonimpulsive and extended-in-time VHF signal in close association with the TGF.

During the flash associated with TGF160917637b, a total of 11 events was reported by NLDN within ~500 ms. One event with peak current of 17 kA was reported by NLDN within 1 ms of the TGF160917637b. This placed TGF160917637b at 330 km from the HSTN LMA center and 451 km from the Fermi footprint. As discussed in section 2, a time uncertainty was estimated at ±1 μs for the LF signals the LMA source and ±7 μs for the gamma-ray photons when shifting them back to the TGF source.

Two fast leader-like pulses were observed within ~80 μs window of TGF160917637b. At the range of 330 km from HSTN LMA center, one VHF source with the power of 20.1 dBW (chi-square is 2.2) was reported within ~10 μs of the TGF. Again, the LMA source having the greatest VHF source power (20.1 dBW) and closest in time to the TGF was substantially mislocated, by 16 km in range, as seen in Figure 3d. When applying the NLDN location and a source altitude of 12 km to the VHF source, the time of the LMA source was corrected to be 53 μs after the LMA reported time. This placed the 20.1 dBW VHF source directly at the time of the TGF observation, even considering the time uncertainty of gamma-ray photon, LF signals, and LMA source. Again, although the 20.1 dBW VHF source was not the highest power source during the life time of this thunderstorm, it was the only source and the strongest source that detected during this TGF-generating IC leader.

This final case, despite only having a single VHF detection, agrees well with the two other cases in this study. All three show the close association between the LF radio pulse, the strong VHF emission, and TGF gamma-ray photons. This consistent association, despite the rather different character of the LF radio emissions, implies that strong lightning leader and streamer zone activity may be an essential component of the TGF generation process. Moreover, these VHF emissions are different from those produced by ascending in-cloud leaders in that they are unusually nonimpulsive, suggesting a strongly emitting VHF source region that is extended in both time and space. VHF emissions of the same character are seen in association with fast positive breakdown at the onset of some lightning flashes (Rison et al., 2016). However, these TGF-associated VHF emissions are different in that they do not occur at the very onset of the flash but instead after the leader has extended a few kilometers in length.

5. Summary and Discussion

With timing uncertainties of at most 7 μs (mostly due to the source location uncertainty) across all the measurements, the close association between three TGFs and multiband radio emissions (Cohen et al., 2006; Connaughton et al., 2010; Cummer et al., 2005, 2011, 2014; Inan et al., 1996, 2006; Lu et al., 2010; Shao et al., 2010; Stanley et al., 2006) was further investigated. The radio measurements included LF and, for the first time with high relative time precision, VHF radio emissions. The results here jointly show that the TGF-generating process is associated with not only LF radio emissions but also strong VHF.

These measurements confirm previous findings on the connection between TGFs and LF radio signals. Clear LF radio emissions were observed within several tens of microseconds for all three TGFs in this study. However, the details of the LF signatures are different in the three events. TGF150904891 was associated with a slow, smooth, and isolated LF pulse (Cummer et al., 2011; Dwyer & Cummer, 2013) that occurred at essentially the same time as the TGF. This pulse is distinct from the rest of the lightning leader pulses produced by the ascending leader, and it remains plausible that it is produced by the TGF generation process itself. TGF160917637a was preceded by an extremely high NLDN peak current (>400 kA) +EIP (Lyu et al., 2015, 2016) by several tens of microseconds. This is further evidence that all +EIPs are also TGFs (Lyu et al., 2016) and of the very large electric current that is sometimes in association with TGF generation (Cummer et al., 2014). Lastly, for TGF160917637b, modest amplitude LF emissions were observed, including two fast pulses several tens of microseconds ahead of the TGF and less distinct, overlapping slower signals closer in time to the TGF.

The three rather different signatures of these LF signals highlight the complexity and differences from event to event of LF radio emissions associated with TGFs. But it should be pointed out that either isolated slow LF pulses, like the one associated with the first TGF and that reported by Cummer et al. (2011), or +EIPs like the second one and those reported by Lyu et al. (2016), might be a unique signature of TGF production that can be measured by radio sensors. The clear LF radio emissions associated with TGFs also show that considerable charge and current motion are involved in the generation of at least some TGFs, which can be measured by distant ground-based sensors.

The LMA mapping of the lightning flash that produced TGF150904891 provides a picture consistent with the previous understanding of the source location and context within the development of the lightning flash of TGFs (Cummer et al., 2014, 2015; Lu et al., 2010; Shao et al., 2010; Stanley et al., 2006). Specifically, these measurements further confirm that TGFs often occur between the two main charge layers inside a thunderstorm and are generated at approximately the midpoint of the development of initial IC upward leaders (Cummer et al., 2015).

And, for the first time, the VHF emissions associated with TGFs have been examined with time precision on the order of 10 μs. It should be noted here that for LMA general processing, only the strongest events in successive 80 μs windows are recorded and processed (Thomas et al., 2004). This does not mean that there were not any other VHF emissions within that 80 μs processing window, as can be seen from the numerous VHF sources mapped by broadband VHF interferometer (Stock et al., 2014). Nevertheless, we find a basically identical VHF signature for all three events despite the differences of the LF signatures. In each case, there are significant VHF emissions very close to or simultaneous in time with the TGF. Moreover, the TGF-associated VHF emissions are the strongest VHF emission during each of the IC leaders, although the power of the VHF sources was not exceptional. For TGF150904891 and TGF160917637b, the strongest sources during that initial leaders were observed directly during the gamma-ray photon burst of the TGF. For TGF160917637a, strong VHF source was reported simultaneously with the LF radio signal of a +EIP, which is considered to be a unique signature of the some TGFs (Lyu et al., 2016), and both the +EIP and the strong VHF source occurred within a few tens of microseconds of the TGF. We recognize that all three TGFs were located at large distance to the LMA centers, so only a few VHF sources were reported during the initial leader processes. However, despite the limited number of VHF sources detected by LMA during these events, it is remarkable that for all three the strongest VHF source during the overall IC initial leaders was that associated with the TGF.

The TGF-associated VHF emissions have one additional distinguishing characteristic, namely, that they are poorly located by the LMA processing despite being strong signals. Past work (e.g., Rison et al., 2016) has shown that this is characteristic of VHF emissions that are not impulsive but instead extended in time and noisy, causing different LMA sensors to detect different peak times in the waveforms. This implies that the process that radiates the TGF-associated VHF emissions is itself extended in time and thus probably space as well and more extended than typical VHF emission regions during leader development that are well localized by LMAs. Precisely what this means is not clear at the moment, but it does provide insight into unusual lightning and streamer dynamics that are associated with TGF generation. It is important to emphasize that while poor LMA localization is typical of NBEs and the associated fast positive breakdown (Rison et al., 2016), these TGF-associated VHF emissions do not occur at flash onset and are thus not NBEs nor the type of fast positive breakdown reported by Rison et al. (2016).

IC initial upward leaders typically start at the top of the main negative charge region in the thunderstorm and propagate upward for several to several tens of milliseconds. During this ascent they emit discrete bursts of VHF radiation. VHF emissions from lightning are thought to originate from the tip of the virgin air breakdown and thus reflect the development of the lightning process (Rison et al., 1999; Shao & Krehbiel, 1996). It has been found that TGF-generating leaders (Cummer et al., 2015), TGF-generating storms (Chronis et al., 2016), and the overall VHF power of the IC leaders in this study are ordinary in many ways. However, the TGF-generating leaders are relatively long, fast and possibly accelerating as they ascend, which suggests that strong electric fields are involved in the process (Cummer et al., 2015). Furthermore, theoretically, either the leader-seeded model (Celestin et al., 2012; Pasko, 2014) or feedback-driven relativistic runaway electron avalanche model (Dwyer, 2012; Liu & Dwyer, 2013) of TGF production requires the existence of strong but potentially transient local electric fields during the TGF production. All these findings suggest the possibility of producing strong discharge processes during some TGF-producing leaders, which is exactly consistent with the observation of the strongest VHF emission during the TGF-generating leader. Despite the variable features of the three TGF-generating leaders here, the consistent observation of the strongest (but poorly localized) VHF sources during the TGF generation window indicates that energetic leader or streamer activity, extended in time and space, is at least sometimes involved in TGF production.

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