Characteristics of broadband lightning emissions associated with terrestrial gamma ray flashes

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[1] To characterize lightning processes that produce terrestrial gamma ray flashes (TGFs), we have analyzed broadband (<1 Hz to 30 kHz) lightning magnetic fields for TGFs detected by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite in 2004–2009. The majority (96%) of 56 TGF-associated lightning signals contain single or multiple VLF impulses superposed on a slow pulse that reflects a process raising considerable negative charge within 2–6 ms. Some TGF lightning emissions also contain VLF signals that precede any appreciable slow pulse and that we term precursor sferics. The analyses of 9 TGFs related to lightning discharges with location uncertainty <100 km consistently indicate that TGFs are temporally linked to the early portion of the slow process and associated VLF impulses, and not to precursor sferics. The nearly universal presence of a slow pulse suggests that the slow process plays an important role in gamma ray production. In all cases the slow process raises negative charge with a typical mean current moment of +30 kA km. The resulting charge moment change ranges from small values below +10 C km to a maximum of +200 C km, with an average of +64 C km. The current moment waveform extracted from TGF sferics with single or multiple VLF impulses also shows that the slow process initiates shortly before the major TGF-associated fast discharge. These features are generally consistent with the TGF-lightning sequence reported by Lu et al. (2010), suggesting that the majority of RHESSI TGFs are produced during the upward negative leader progression prevalent in normal polarity intracloud flashes.

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1. Introduction

[2] Brief (typically <1 ms) bursts of gamma rays with mean energies of ~2 MeV originating from the Earth's atmosphere, referred to as terrestrial gamma ray flashes (TGFs), have been observed by the Burst and Transient Source Experiment (BATSE) detector [*Fishman et al.*, 1994], the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite [*Smith et al.*, 2005] and other space-borne detectors [*Marisaldi et al.*, 2010; *Briggs et al.*, 2010]. With spectra typically harder than cosmic gamma ray bursts [*Nemiroff et al.*, 1997], TGFs are accepted as a consequence of bremsstrahlung from relativistic runaway electrons (with energies ~20–40 MeV) that impact nuclei of air molecules [*Gurevich et al.*, 1992; *Lehtinen et al.*, 1996; *Dwyer*, 2008]. Energetic electrons and positrons from Compton scattering and pair production of gamma rays can be registered as TGFs as well when they become trapped by the geomagnetic field and run into spacecraft crossing magnetic field lines [*Dwyer et al.*, 2008; *Cohen et al.*, 2010b]. The large number of relativistic electrons required to produce the observed gamma ray dose could be generated from electrons of varying energies that are accelerated in strong electric fields formed either by the thunderstorm charge structure [*Gurevich et al.*, 1992; *Dwyer*, 2008] or by individual lightning processes [*Roussel-Dupré et al.*, 1998; *Inan and Lehtinen*, 2005; *Moss et al.*, 2006; *Dwyer*, 2008; *Carlson et al.*, 2009].

[3] The connection between TGFs and lightning was first revealed by detecting low-frequency atmospheric emissions (sferics) from lightning discharges with timescales <1 ms [*Inan et al.*, 1996]. Examinations of many more TGF-associated sferics typically place the TGF-associated lightning within 300 km of the subsatellite point and gamma ray production in almost all cases occurs within a few ms of a significant lightning discharge [*Cummer et al.*, 2005; *Cohen et al.*, 2006; *Inan et al.*, 2006; *Stanley et al.*, 2006]. Although the further exploration of TGF-lightning relationship is limited by the

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1–2 ms uncertainty in the absolute RHESSI timing [*Grefenstette et al.*, 2009] and the unknown lightning location in many cases, recent measurements from the Gamma-ray Burst Monitor aboard the Fermi Space Telescope [*Briggs et al.*, 2010] show that a significant fraction of TGFs occur within several tens of μs of a lightning discharge [*Connaughton et al.*, 2010].

[4] The modest charge moment changes associated with TGFs constrain the TGF source region to altitudes below 30 km [*Cummer et al.*, 2005]. The analyses comparing simulations with the event averaged TGF spectra further suggest that TGFs originate below 21 km altitude [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007; *Hazelton et al.*, 2009]. Meanwhile, the inferred altitudes of TGF-associated lightning discharges (10 to 17 km) [*Stanley et al.*, 2006; *Shao et al.*, 2010] imply that TGFs emanate from regions inside or near thunderclouds. These findings are qualitatively consistent with models where runaway electrons are produced in the thunderstorm [*Moss et al.*, 2006; *Dwyer*, 2008], and not with earlier models that attribute TGFs to certain mesospheric phenomenon caused by large cloud-to-ground (CG) strokes [*Lehtinen et al.*, 1996, 1999].

[5] Other work has clarified some of the detailed TGF-lightning relationship. The analyses of lightning signals associated with a small number of TGFs indicate that they are related to intracloud (IC) lightning discharges [*Stanley et al.*, 2006; *Shao et al.*, 2010]. *Lu et al.* [2010] showed explicitly with the observation from a Lightning Mapping Array (LMA) that the gamma ray production occurred during the upward negative leader progression early in an IC flash. Detailed analyses of the sequence of TGF-associated sferics [*Shao et al.*, 2010] suggest the same scenario in more occasions. These observations suggest that at least some TGFs are produced in association with negatively charged lightning leaders, a process that can generate energetic radiation observable on the ground [*Moore et al.*, 2001; *Dwyer et al.*, 2003, 2004].

[6] The analyses of over 100 RHESSI TGFs imply that the uncertainty of the relative timing between TGFs and lightning may partly arise from the complexity of TGF-related lightning processes [*Inan et al.*, 2006]. Multiple fast discharges with varying amplitude might occur during the lightning process that yields one burst of gamma rays [*Lu et al.*, 2010; *Cohen et al.*, 2010a]. Each of these discharges could by itself lead to a different interpretation of the TGF-lightning relationship. *Shao et al.* [2010] suggested some of these discharges are probably associated with individual stepping of the negative leader.

[7] Although the relative temporal relationship between TGFs and specific lightning processes remains unclear, previous analyses have identified two salient features of TGF-related lightning signals, i.e., (1) the very low frequency ((VLF) 3–30 kHz) impulse from fast discharges typically with <100 μs duration [*Stanley et al.*, 2006] and (2) the ultralow frequency ((ULF) 300–3000 Hz) pulse from slow processes that produce considerable charge moment changes within a few ms [*Cummer et al.*, 2005; *Lu et al.*, 2010]. The aim of our work is to define the relationship between these distinct processes and associated gamma ray production. We find that essentially all the TGF-associated lightning sferics occur in the presence of a clear ULF pulse from a slow process that causes a modest charge moment change within 2 to 6 ms. It is also found that some TGF sferics contain VLF signals from fast discharges distinctly preceding TGFs. The general lightning sequence follows closely the detailed case study of *Lu et al.* [2010], which in turn suggests that most TGFs are produced in association with the upward negative leader in IC flashes. Although there have been extensive studies of the characteristics, particularly the morphology, of IC flashes [*Bils et al.*, 1988; *Villanueva et al.*, 1994; *Shao and Krehbiel*, 1996], and some of these describe signals similar to those observed in association with TGFs, these studies do not provide insight to differentiate the physical processes behind these different signals. It is unclear how the upward leader progression yields a significant charge transfer within a few ms, which seems to be less understood in comparison with the typical IC flash evolution. We also derive the electrical properties (e.g., peak currents and charge moment changes) and time-resolved current moment of TGF-associated lightning processes, providing fundamental constraints on the modeling of lightning-related bursts of gamma rays.

2. Data and Methods

2.1. Measurements and Data Selection

[8] We analyze the lightning signals associated with TGFs when the RHESSI footprint was within 5000 km of the sferic recording site near Duke University. Two pairs of induction coils are used to record magnetic fields in the 50 Hz to 30 kHz and <1 Hz to 400 Hz bands, sampled at 100 kHz and 2.5 kHz, respectively, providing quantitative information on the vertical charge transfer on a wide range of timescales. Measurements from these sensor pairs are referred to as the VLF and ULF data, respectively, both with absolute timing accuracy better than 50 μs [*Cummer et al.*, 2005].

[9] In a 6 year period of 2004–2009, RHESSI registered about 200 TGFs in the region of our interest, for 78 of which both VLF and ULF data were recorded. The further analysis is focused on lightning signals that exceeded five times the local noise level (0.02 nT in VLF data) and that originated from lightning discharges within ±10 ms of the TGF and with azimuthal displacement <600 km from the subsatellite point. The database of this work is formed by 56 TGFs that meet these criteria, with a ratio (72%) consistent with other analyses that identify even weaker lightning signals [*Inan et al.*, 2006].

2.2. Measurements of Lightning Properties

[10] Electrical properties of TGF-associated lightning processes, such as polarity, peak current and charge moment change, can be deduced from broadband measurements. We define the polarity of the current and (vertical) charge moment change (ΔM_q) of a lightning process that lowers positive charge (or raises negative charge) to be positive. The approach of *Cummer and Inan* [2000] is applied to extract the source current moment waveform. Because the bandwidth of our measurements spans <1 Hz to 30 kHz, the extracted current moments are accurate for timescales from hundreds of ms down to tens of μs. Shorter timescales are not accessible with the data and some features presented in the extracted current moments should be considered as an upper bound on the source duration. In contrast, the overall

charge moment change computed over the discernible duration of a current moment is relatively accurate.

[11] Most lightning detection networks, including the U. S. National Lightning Detection Network (NLDN) [*Cummins et al.*, 1998], determine the lightning peak current from a statistical relationship with peak lightning fields in the tens to hundreds of kHz band. This relationship was usually derived through the measurements with respect to triggered CG strokes and is assumed to be applicable to IC discharges [*Cummins et al.*, 1998]. We have attempted to explore a similar correlation at lower frequencies. The examination of VLF data for over 2000 CG lightning strokes in the range of 200 to 4000 km, without discriminating polarity, indicates that the VLF intensity is statistically correlated with the NLDN-reported current. We assume that the peak values of lightning current and VLF signal satisfy the relationship,

$$B_p = \alpha \cdot I_p / r^\beta \tag{1}$$

where B_p (nT) is the peak VLF signal recorded at distance r (km) from the lightning discharge with a peak current of I_p (kA). Our calculation places the lightning discharge at the subsatellite point unless its location is known from other measurements. The values of α and β depend mainly on ionospheric conditions and thus on local time of day [*Smith et al.*, 2004]. For the nighttime, we find $\alpha \approx 40.6$ and $\beta \approx 1.02$, in comparison with $\alpha \approx 127.06$ and $\beta \approx 1.23$ for the daytime, and $\alpha \approx 70.3$ and $\beta \approx 1.11$ around the day/night terminator. Note that the estimate of α and β is subject to the precise sensor bandwidth and thus applies only to Duke VLF data. The standard deviation between peak currents estimated with this method and reported by the NLDN is about 30%, which is sufficient to provide quantitative information about TGF-related lightning discharges analyzed here. Also, the polarity of peak currents is not deduced from the VLF signal, but the polarity of the associated charge moment change can be unambiguously determined from the ULF data.

2.3. Analysis Example

[12] Figure 1 presents the analysis with the measurements of a TGF on 16 October 2004 when the RHESSI footprint (marked by a plus in Figure 1a) was near the coastline of Mexico. The energies of 18 photons that composed this TGF are plotted in Figure 1b, where the time is corrected by the 1.8 ms offset. These photons illuminated the RHESSI detectors within 0.2 ms, in comparison with the typical background rate of 2 counts per millisecond [*Grefenstette et al.*, 2009].

[13] The VLF and ULF data (Figure 1c) associated with this TGF exhibit a single dominant pulse, which is the most typical TGF lightning signal in our database. For the purpose of clarity, the ULF measurement in this plot and those that follow is multiplied by a factor and then is offset vertically to avoid overlap with the VLF waveform. Note that the slow pulse readily discerned in the ULF data can also be identified by low-pass filtering the VLF data. The ratio between two orthogonal components of the VLF signal oriented in the geographic north-south and east-west directions [*Cummer et al.*, 2005] points the lightning in a direction 6.3 ± 2° off the subsatellite point. The inferred lightning direction points through a heavy infrared cloud region (shown in grey in Figure 1a) centered about 500 km from the RHESSI footprint. We place the TGF-associated lightning discharge at the center of the region where the direction finding overlaps the cloud area. For a lightning discharge at this location (marked by a cross in Figure 1a), we estimate the peak current to be 160 kA, and the total ΔM_q is +57 C km over 2 ms.

[14] With the deduced lightning location we evaluate the temporal TGF-lightning relationship by transforming photon counts over 50 μs bins to the sferic recording location. The gamma ray production and lightning discharge are assumed to be collocated at 15 km altitude above mean sea level (msl), as adopted in the following analyses. After correcting propagation delays, we infer that the burst of gamma rays initiated approximately 0.5 ms before the lightning discharge in association, which occurred at a time deduced from the VLF impulse onset (indicated in Figure 1c).

3. Waveform Features of Broadband TGF Lightning Signals

[15] Previous work has shown that about half of TGF lightning signals consist of multiple VLF impulses, and the remaining contain a single impulse [*Cohen et al.*, 2010a]. *Lu et al.* [2010] identified the distinction between fast discharges and a slow process of 2–3 ms for one TGF. The significance of this slow process is suggested by the fact that the ULF pulse is discerned for 54 out of 56 TGF lightning signals. This section discusses the relationship between the ULF pulse and VLF impulses. Five categories of TGF-associated sferics are identified.

[16] Figure 2a shows a lightning signal that is dominated by a VLF impulse superposed on the ULF pulse. This is referred to as the prototypical TGF-associated sferic, which demonstrates the VLF impulse and ULF pulse in a simplest manner. The lightning signals recorded for 27 out of 56 (48%) TGFs are of this type.

[17] Figures 2b and 2c show two examples of variants to the prototypical TGF sferic. The lightning signal in Figure 2b exhibits two discrete impulses that are both superposed on the ULF pulse. Multiple VLF signals that are all superposed on a slow pulse are shown in sferics associated with 16 out of 56 (29%) TGFs. The lightning emission plotted in Figure 2c also contains two VLF signals, but the first one is clearly isolated and precedes the slow pulse by 3 ms. Lightning signals like this are associated with 7 out of 56 (13%) TGFs. We call the VLF signal prior to the slow ULF pulse the precursor sferic. That precursor sferics are only visible in some TGF lightning signals and that when present they appear to precede the gamma ray production (section 3.1) both suggest that they may not be an essential part of the TGF-producing process.

[18] The TGF lightning signal shown in Figure 2d contains both precursor sferics and multiple VLF impulses during the slow pulse. Sferics associated with 4 out of 56 (7%) TGFs are of this minority type, which exhibits both of the variations shown in Figures 2b and 2c to the prototypical TGF sferic.

[19] Although the classification of TGF lightning signals into a specific category is influenced by the criteria on sferic

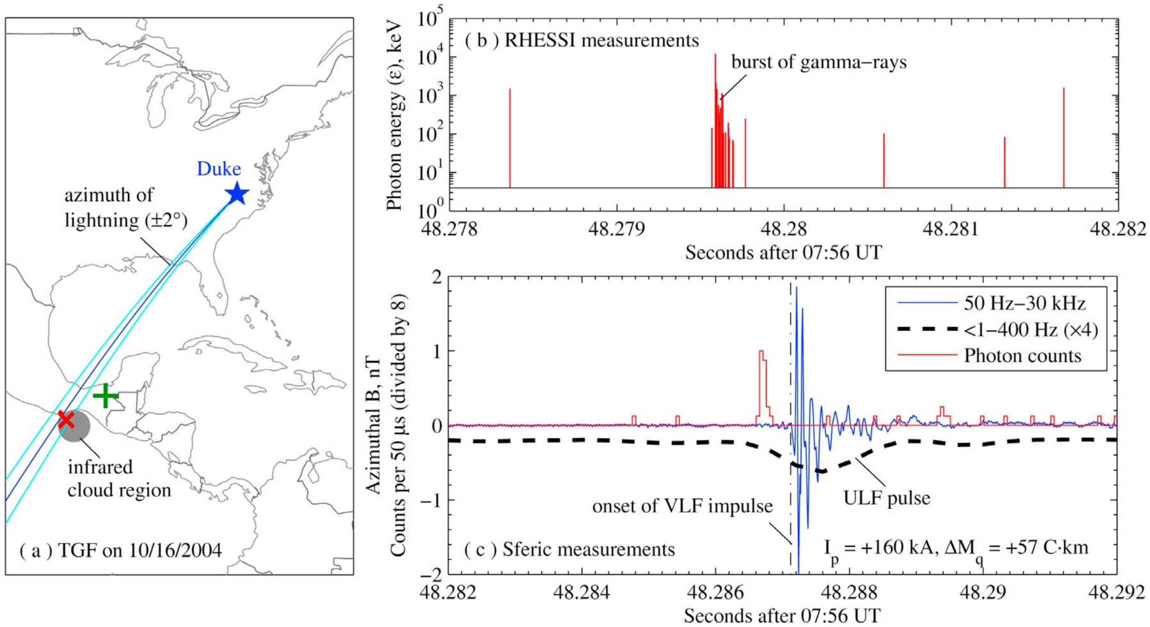

Figure 1. RHESSI observation of a TGF on 16 October 2004 and lightning signals in association recorded near Duke University. (a) The subsatellite point and the inferred lightning location are marked with a green plus and a red cross, respectively. (b) The time history of gamma ray observation by RHESSI is transformed to (c) the sferic recording site. The onset of the VLF impulse is indicated by a dotted-dashed line, which after light travel corrections gives the initiation time of the TGF-associated lightning discharge. The ULF measurement is multiplied and an offset is applied to avoid the overlap with the VLF waveform. The comparison in Figure 1c indicates that the burst of gamma rays initiated shortly (~0.5 ms) before the lightning discharge.

identification, it is apparent that the slow pulse is a consistent feature of the aforementioned four types of TGF sferics. This suggests that most TGFs are associated with a slow process that usually produces a modest charge moment change (>+40 C km on average) [*Cummer et al.*, 2005]. Fast discharges that generate most of the VLF energy usually cause small charge transfers (<+10 C km) due to relatively short durations (<100 μs) and modest peak currents (tens of kA) [*Stanley et al.*, 2006].

[20] Despite the apparent significance of a slow process, sferics associated with 2 out of 56 TGFs lack discernible ULF energy (see an example in Figure 2e). One of these two TGFs was associated with a narrow bipolar event (NBE) [*Shao et al.*, 2010], a special category of IC discharges with short durations (~10 μs) and peak currents comparable to intense CG strokes [*Smith et al.*, 1999]. There are observations showing that NBEs occur simultaneously with the onset of IC flashes [*Rison et al.*, 1999]. To date two RHESSI TGFs are found to be associated with NBEs [*Stanley et al.*, 2006; *Shao et al.*, 2010]; the ULF data indicate that both were related to small charge moment changes (<+10 C km), which complies with the known features of NBEs [*Smith et al.*, 1999; *Eack*, 2004]. We do not analyze this small subset of TGFs further in this work.

[21] To derive further insights into the waveform features, we compare the time history of gamma ray detection with sferic waveforms from lightning discharges located with a small uncertainty (<100 km). Despite the ~1–2 ms RHESSI timing uncertainty, this analysis still shed some light on the TGF-producing processes by minimizing the uncertainty due to unconstrained lightning locations.

3.1. Precursor Sferics Before TGF Production

[22] The TGF-producing IC flash analyzed by *Lu et al.* [2010] generated a precursor sferic, which occurred around the flash onset and apparently preceded the observed gamma ray production during the upward negative leader progression. Figure 3 compares the time history of gamma ray detection with lightning signals for two TGFs that were both linked to lightning discharges detected by the NLDN, of which the location uncertainty is typically <1 km [*Cummins et al.*, 1998]. Both waveforms contain precursor sferics from fast discharges prior to a slow process that produced a ΔM_q of approximately +50 C km within 2 ms.

[23] Figure 3a shows the lightning signal associated with a TGF on 24 September 2006. The NLDN registered the lightning discharge that excited the largest VLF impulse. Our analysis indicates that this discharge occurred around the burst of gamma rays, which is also shown by *Shao et al.* [2010]. The major VLF impulse was preceded by two precursor sferics by 8.5 ms and 2 ms, respectively. Allowing for the ~1–2 ms uncertainty in the RHESSI measurement, the burst of gamma rays is not associated with the first precursor sferic and probably not with the second. Neither precursor sferic contains discernible ULF energy, indicative of negligible charge transfers. Both precursor sferics are likely associated with individual stepping of negative leaders [*Shao et al.*, 2010].

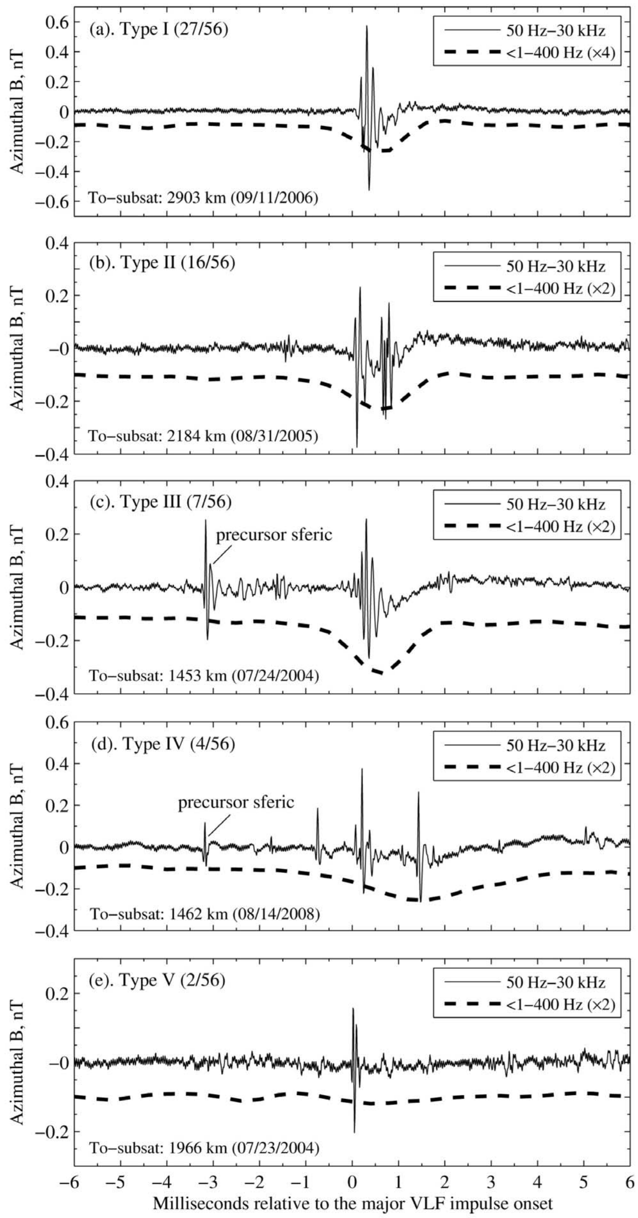

Figure 2. Classification of TGF lightning signals recorded near Duke University: (a) a prototypical TGF sferic that consists of one VLF impulse superposed on the ULF pulse (Type I); (b and c) two variants to the prototypical with multiple VLF impulses during the ULF pulse (Type II) and with a precursor sferic before the ULF pulse (Type III), respectively; (d) the precursor sferic and multiple VLF impulses during the ULF pulse (Type IV); and (e) a lightning signal without a discernible ULF component (Type V). In all plots the ULF data are multiplied and an offset is applied to avoid the overlap with the VLF waveform.

[24] The lightning signal associated with a TGF on 5 October 2009 (Figure 3b) contains a precursor sferic ~5 ms before the main VLF impulse, which was from a positive lightning discharge registered by the NLDN with a 15 kA peak current. The timing analysis indicates that the gamma rays were produced within 0.5 ms after the onset of the main VLF impulse, which actually exhibits the complexity indicative of two fast discharges very close in time (<0.4 ms). Even accounting for the RHESSI timing uncertainty it is apparent the burst of gamma rays was not likely associated with the precursor sferic.

[25] We identify precursor sferics with signal strength five times the local noise for 22% of the database. This ratio is up to 40% if we count sferics with smaller amplitude. Precursor sferics, when present, precede the TGF-associated ULF pulse by 2 to 10 ms, which further suggests that precursor sferics may not play a significant role in TGF production. In most cases, the precursor sferic is small in amplitude, but occasionally its equivalent peak current can be as large as the TGF-associated lightning discharge (see an example in Figure 2c). It is conceivable that relatively strong precursor sferics may affect the timing analysis comparing the first VLF impulse with gamma ray detection [e.g., *Cohen et al.*, 2010a]. The previous work indicative of TGFs occurring 4–8 ms after a lightning discharge might be a consequence of large precursor sferics. Nevertheless, the presence of a discernible slow pulse appears to be the best indicator of TGF-associated lightning processes.

3.2. Multiple VLF Impulses Associated With TGFs

[26] Some TGF sfeics contain multiple VLF impulses over a few ms. The lightning emission associated with a

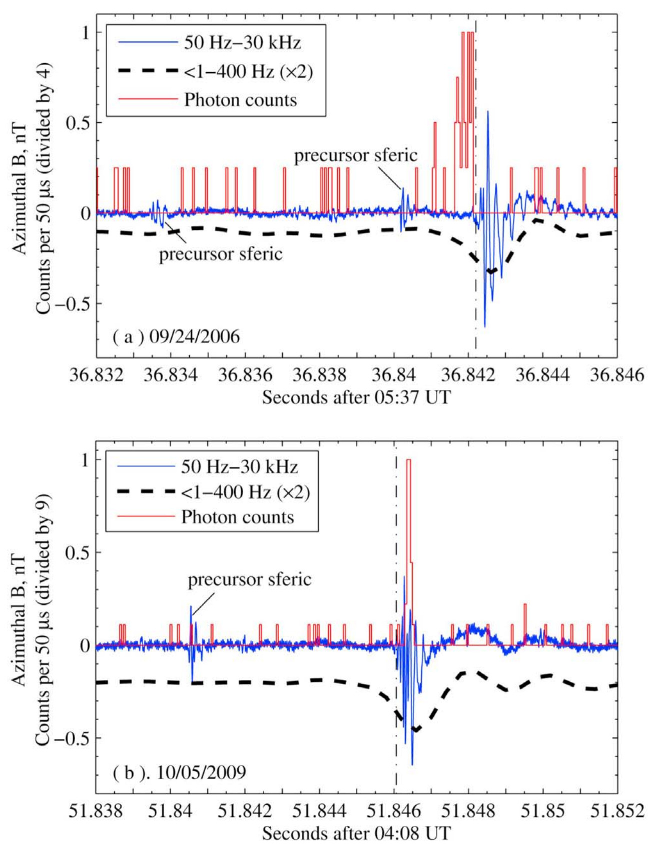

Figure 3. (a and b) TGF lightning signals with precursor sferics. The burst of gamma rays was produced within 0.5 ms of the most significant lightning discharge, which occurred at a time inferred from the onset (indicated by a dotted-dashed line) of the VLF impulse superposed on the ULF pulse.

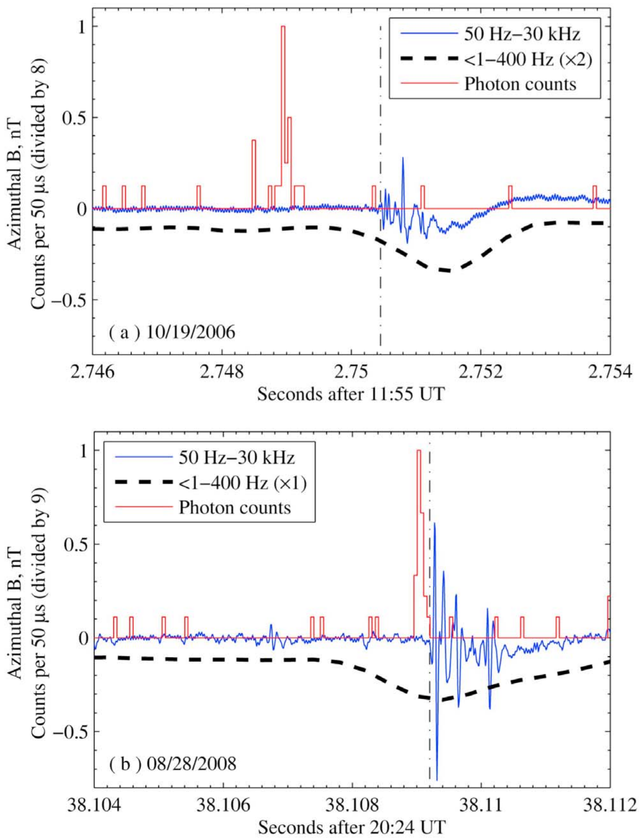

Figure 4. (a and b) TGF lightning signals with multiple VLF impulses during the ULF pulse. Both sferics were associated with one burst of gamma rays that initiated before a sequence of fast discharges. The onset of the first discharge is indicated by a dotted-dashed line.

BATSE TGF consists of three discrete VLF impulses, each of which appears to be related to a burst of gamma rays [*Cohen et al.*, 2006]. This correlation, however, was later shown to be highly variable and the multiplicity of TGF lightning signals is not clearly relevant to gamma ray production [*Cohen et al.*, 2010a].

[27] The observed multiplicity of TGF-associated lightning emissions could be either caused by the precursor sferic, and/or by the occurrence of multiple fast discharges during the slow process. As the analyses above suggest that precursor sferics do not play an essential role in gamma ray production, the multiplicity of TGF sferics is defined here as the number of discrete VLF impulses during the ULF pulse. Here we analyze the link between multiple VLF impulses and gamma ray production.

[28] Figure 4a shows a lightning signal containing VLF impulses from two lightning discharges, with peak currents estimated to be 6 kA and 16 kA, respectively. With an interdischarge interval of 0.5 ms or less, both fast discharges attended the same slow process that caused a ΔM_q of +25 C km within 2 ms. One of these discharges was geolocated by the U. S. Precision Lightning Network (USPLN), which consists of >100 sensors over the continental United States and claims lightning location accuracy comparable to the NLDN. As shown in Figure 4a, this TGF consists of one burst of gamma rays that occurred within 2 ms before the first discharge. Accounting for the RHESSI timing uncertainty, we see that the burst of gamma rays was likely produced early in the slow process, which is consistent with other cases we examined.

[29] Figure 4b shows another TGF associated with multiple strong VLF impulses from three fast discharges. These discharges occurred during a slow process that gave rise to a ΔM_q of +100 C km within 4 ms. All of these discharges appeared to have relatively strong peak currents between 20 and 50 kA, but the associated TGF consisted of only one burst of gamma rays. Although none of these discharges was geolocated, that 40% of the photons detected by RHESSI for this TGF were MeV counts suggests a source within 300 km of the subsatellite point [*Hazelton et al.*, 2009]. The direction finding using VLF data, when combined with infrared satellite images, further constrains the TGF source in an isolated convective core centered about 160 km from the subsatellite point. The timing analysis using the inferred lightning location suggests that the burst of gamma rays initiated approximately 0.3 ms (subject to the RHESSI timing uncertainty) prior to the first fast discharge, similar to the TGF-lightning relationship shown in Figure 3a.

[30] VLF measurements indicate that the multiplicity of TGF sferics ranges between 1 and >5 with an interdischarge interval of ~0.4 to 2 ms. Even smaller intervals are possible but hard to quantify due to the limited bandwidth of measurements. In a small majority of cases (~60%) one fast discharge occurs during the slow process, while the remaining exhibit multiple VLF impulses superposed on the ULF pulse. The slow process with a single fast discharge usually drives a ULF pulse of 2 ms. TGF-associated lightning emissions with multiplicity >2 are usually associated with a relatively long (>2 to 6 ms) ULF pulse, but in nearly all cases only one statistically significant burst of gamma rays was observed. Therefore, the varying multiplicity of VLF impulses during the ULF pulse is more likely inherent to the lightning process itself rather than gamma ray production.

3.3. Revisiting the TGF-Lightning Relationship

[31] By noticing that the TGF-producing processes usually give rise to a distinct ULF pulse, we evaluate the temporal TGF-lightning relationship by focusing on lightning discharges that excite VLF impulses during the ULF pulse. Nine TGFs associated with lightning discharges whose locations are constrained with a relatively small uncertainty (<100 km) are selected for this analysis (Table 1); five of these TGFs have been shown to be associated with IC lightning discharges [*Stanley et al.*, 2006; *Shao et al.*, 2010]. For three TGFs, the lightning locations are deduced by comparing the direction finding (using the VLF data) with infrared satellite imagery. The uncertainty of lightning location obtained with this technique, and that of three TGF-related lightning discharges examined by *Shao et al.* [2010] and *Cohen et al.* [2010a], is <100 km. The remaining three TGFs were associated with lightning discharges detected by the NLDN or the USPLN. In Table 1, the time by which the TGF onset precedes the (first) fast discharge during the slow process is denoted as Δt_d. The presence of small sferics around the onset of some TGF-associated VLF impulses causes 0.1 ms uncertainty in the determination of lightning time.

Table 1. Temporal Relationship Between Bursts of Gamma Rays and Lightning Discharges Located With <100 km Uncertainty for 9 RHESSI TGFs[a]

RHESSI Observation of TGFs				Lightning Location		Distance (km)		
Date	Time (UT)	Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)	To Subsatellite	To Sensor	Δt_d (ms)
16 Oct 2004[b]	07:56:48.2796	17.53	−92.08	15.20	−95.90	483	2849	0.5
22 Aug 2005[b]	12:25:38.4049	34.21	−78.36	33.00	−78.40	135	340	0.2
5 Jun 2006[c]	08:28:51.5514	12.25	−73.83	11.64	−75.67	211	2727	−0.1
11 Sep 2006[d]	04:17:08.4781	17.17	−99.57	16.20	−98.20	185	2899	0.2
17 Sep 2006[c]	09:19:34.8042	12.98	−78.02	11.60	−77.58	160	2714	0.4
24 Sep 2006[e]	05:37:36.8371	28.13	−95.28	29.35	−96.12	158	1752	0.5
19 Oct 2006[f]	11:55:02.7460	30.81	−89.33	31.12	−92.27	282	1333	1.7
28 Aug 2008[b]	20:24:38.1052	21.35	−78.98	20.70	−77.60	160	1704	0.3
5 Oct 2009[e]	04:08:51.8435	33.25	−92.97	30.40	−93.42	320	1468	−0.2

[a]Locations of the subsatellite point and the lightning discharge associated with individual TGFs are given. The distances from lightning to subsatellite points and to the sferic recording site (35.97°N, −79.09°E) are used to calculate Δt_d, giving the time by which the burst of gamma rays initiates prior to the lightning discharge that emits the (first) VLF impulse superposed on the ULF pulse. The TGF time is given as the first 50 μs bin with ≥2 photons.
[b]The lightning location is deduced by comparing the direction finding using the VLF data with infrared cloud images.
[c]The lightning location is reported by *Shao et al.* [2010] using the data from the Los Alamos Sferic Array (LASA).
[d]The lightning location is from *Cohen et al.* [2010a, Figure 2].
[e]The associated lightning discharge is located by the U.S. National Lightning Detection Network (NLDN).
[f]The associated lightning discharge is located by the U.S. Precision Lightning Network (USPLN).

[32] The analyses of 9 TGFs consistently indicate that the TGF occurred within 2 ms of a fast discharge, in agreement with past work related to RHESSI TGFs [*Cummer et al.*, 2005; *Stanley et al.*, 2006; *Inan et al.*, 2006]. The variance in the temporal TGF-lightning relationship, as revealed by previous work, might be a consequence of the ~1–2 ms RHESSI timing uncertainty, or by the inherent nature of the TGF-lightning connection. The observed fact that at least a small fraction of RHESSI TGFs are not associated with appreciable VLF sferics [*Inan et al.*, 2006] implies that an intense lightning discharge is not necessarily involved in gamma ray production. It is also likely the TGF-associated lightning discharge occurs as an effect of gamma ray production [*Cummer et al.*, 2005], which can ionize the air on the way of its propagation [*Dwyer*, 2008] and thus forms a conduit that preconditions fast discharges or subsequent leader progression.

[33] Although the precise relationship between gamma ray production and lightning discharge cannot be determined with these data, the results in Table 1 suggest that TGFs typically occur in association with the ULF-generating slow process. Our analyses suggest that the burst of gamma rays is most likely produced during the early development of the slow process, as shown in the case reported by *Lu et al.* [2010]. In other words, most of the ΔM_q estimated from the ULF pulse is produced after the burst of gamma rays, which is more obvious and not affected by the RHESSI timing uncertainty for those TGFs associated with a relatively long ULF pulse.

4. Relationship Between the Slow Process and Fast Discharges

[34] On the basis of the analyses in section 3, it is apparent the typical TGF-associated lightning signal originates from a slow process attended by one or more fast discharges. The relative timing is important for understanding these processes involved in gamma ray production. In the case analyzed by *Lu et al.* [2010], the slow process began within 1 ms before a sequence of intracloud lightning discharges. In this section, we derive the current moment waveform for two TGF sferics that contain single and multiple VLF impulses (superposed on a ULF pulse), respectively. We find that the slow process consistently begins before the major fast discharge. This feature is distinct from the signals we observe for most +CG strokes, in which these processes begin essentially simultaneously [*Gomes and Cooray*, 1998]. Here we provide further evidence that most TGFs are associated with IC lightning processes.

[35] The following procedures are applied to the TGF lightning signal. A deconvolution method is applied to extract a time-resolved current moment from the ULF pulse and the VLF impulse, respectively [*Cummer and Inan*, 2000], based upon the finite difference time domain model of *Hu and Cummer* [2006]. The results are combined to yield a current moment that generates sferics consistent with both ULF and VLF measurements. This current moment provides further insight into the precise temporal relationship between the slow process and fast discharges. Note that the effective bandwidth of our measurements is <1 Hz to 30 kHz, and source currents within this bandwidth can be uniquely determined. Therefore, the slow variation in the current moment waveform corresponding to the ULF pulse, and thus the charge moment change, are reliably derived. However, there is an uncertainty on the duration of current moment extracted from the VLF impulse imposed by the upper limit of sensor response, and hence the source components above 30 kHz cannot be accurately evaluated. Here we present the broadest current moment to represent a fast discharge. In reality, a narrower pulse of current moment with bigger amplitude still fits the measurements and produces the same charge moment change. This uncertainty is discussed with an example in section 4.1.

4.1. A Single Fast Discharge During the Slow Process

[36] Figure 5 shows the observation of a TGF on 22 August 2005 (at 12:25:38.404 UT) when the subsatellite point was only 207 km from sferic recording site. *Stanley et al.* [2006] classified the lightning discharge related to this TGF as an IC discharge not registered by the NLDN. The comparison with radar observations (the inset in Figure 5a)

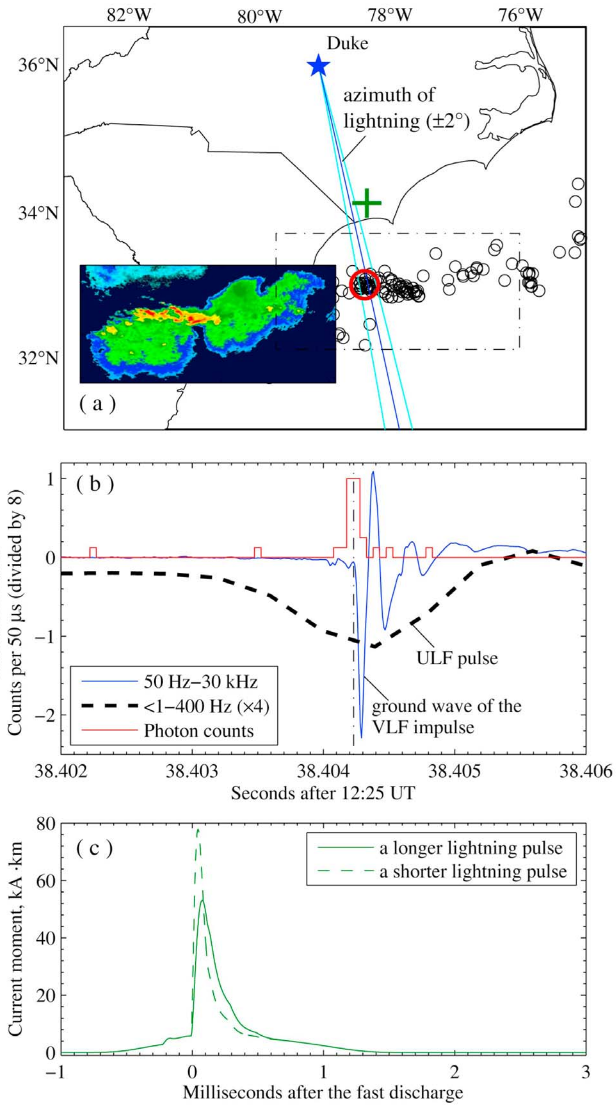

Figure 5. Observations of a TGF on 22 August 2005. (a) The lightning location (at the center of the red circle) is deduced from the direction finding and NLDN recordings of positive events in 10 min around the TGF. The inset in Figure 5a shows the radar echo (1 min after the TGF detection) observed from Wilmington, North Carolina at 2.4° elevation angle. (b) The sferics recorded at 340 km distance show small deflections within 0.3 ms prior to the VLF impulse onset marked by a dotted-dashed line. These variations suggest that the ULF-driving slow process initiated shortly before the fast discharge. The timing analysis indicates that the burst of gamma rays occurred within 0.2 ms of the discharge. (c) Two current moment waveforms that, with different timescales of the fast current pulse, can both reproduce the main features in the measured lightning signals.

around the TGF observation locates this discharge in a thunderstorm that developed high cloud tops (~15 km msl), and in which the NLDN located tens of positive CG and IC lightning discharges between 12:20 and 12:30 UT. Most of these discharges were produced in the convection region that dominated the northern portion of the storm. The direction finding result using the VLF data (Figure 5a) suggests that this discharge was most likely located in a 15 km radius (corresponding to a ±2° direction finding uncertainty) region centered about 130 km from the subsatellite point.

[37] The ULF and VLF measurements for this TGF are plotted in Figure 5b. At 340 km distance, the ground wave dominates the VLF impulse and thus the inferred time of the TGF-associated lightning discharge is accurate to 50 μs. The charge moment change calculated from the ULF pulse is +30 C km. Our analysis indicates that the burst of gamma rays initiated within 0.2 ms of the fast discharge (subject to the RHESSI timing uncertainty), consistent with *Stanley et al.* [2006]. There are some small but distinct variations (with magnitude six times the noise) around the VLF impulse onset, implying the occurrence of weak discharges prior to the major lightning discharge. For half of TGF-associated lightning signals, similar variations with amplitude exceeding the background noise are identified around the onset of the main VLF impulse.

[38] Figure 5c shows the current moment waveform extracted from the ULF and VLF data. The time resolution of fast features present in this current moment is limited by the upper bandwidth (30 kHz) of VLF measurements, and thus the duration of the fast discharge current could be shorter (but not longer). In Figure 5c, we show the discharge current with the longest duration and another current with a shorter duration that both can generate sferics consistent with measurements. Note that the ΔM_q for each case is the same, as constrained by the ULF data, and thus a shorter-duration pulse yields a larger peak current moment. Nevertheless, both current moment waveforms consistent with the measurements show that the slow process initiated ~0.5 ms prior to a fast IC discharge. Therefore, it is very likely the TGF-associated slow process was also intracloud, the same as the case reported by *Lu et al.* [2010] where multiple fast discharges punctuated the slow process. Small deflections around the onset of the VLF impulse are reproduced through the variation in the predischarge slow current.

4.2. Multiple Fast Discharges During the Slow Process

[39] Here we present the analysis of a complicated TGF lightning signal that yields the same characteristics as those derived by *Lu et al.* [2010]. Figure 6 shows the observations of a TGF on 14 August 2008, for which the VLF data (Figure 6a) indicate the occurrence of 7 (or more) fast discharges during an unusual slow process that lasted significantly longer than other cases. The first VLF impulse is identified as a precursor; the subsequent VLF impulses span over a 5 ms interval dominated by a ULF pulse, which was followed by another ULF pulse that also contained a few VLF impulses. The RHESSI data do not show evidence of another statistically significant TGF related to the subsequent ULF pulse (Figure 6b). Although the lightning location is unknown, the relatively high ratio (~20%) of MeV photons suggests a source within 300 km of the subsatellite point [*Hazelton et al.*, 2009]. The direction finding using VLF data points the lightning in a direction that intersects a convective core centered at <100 km distance from the subsatellite point, and the uncertainty of the estimated lightning location is less than 200 km.

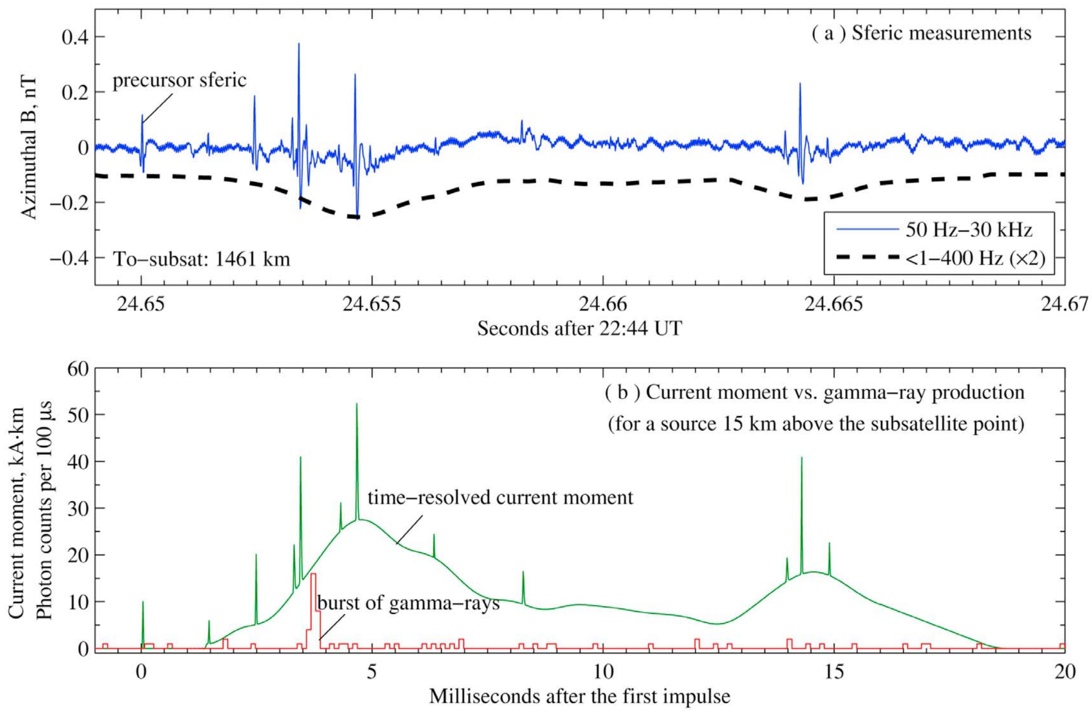

Figure 6. (a) The lightning signal associated with a TGF on 14 August 2008 contains a precursor sferic and multiple VLF impulses superposed on a relatively long slow pulse. (b) The current moment waveform extracted from the sferic data suggests that the single-peak burst of gamma rays was produced during the slow process, which became detectable roughly 1 ms after the precursor discharge.

[40] This TGF consisted of one burst of gamma rays that endured ~0.3 ms. The current moment waveform extracted from the sferic data is plotted in Figure 6b, in comparison with the gamma ray production from a source 15 km above the subsatellite point. Although the precise time of gamma ray production remains uncertain to 1–3 ms, it is apparent that the burst of gamma rays occurred after the precursor discharge. As shown in Figure 6b, the slow process became detectable about 1 ms after the precursor discharge, increased for 3 ms until peaking at +30 kA km, and persisted for another several ms. The deduced current moment indicates that this slow process lasted rather long, and caused a ΔM_q over +100 C km within 6 ms. Therefore, the TGF-lightning relationship and the current moment waveform shown in Figure 6b are both remarkably similar to the TGF produced early in an IC flash [*Lu et al.*, 2010], which is probably the case here.

[41] It should be emphasized that the significant difference in the width of fast pulses in the two analyzed cases is real. The current pulses that produced the VLF impulses in Figure 6a are not wider than 50 μs, but the fast pulse in Figure 5c could be as wide as a few hundred μs. This is another example of the surprising variability seen in the detailed lightning signals associated with generally similar TGFs.

5. Electrical Properties of TGF-Associated Lightning Processes

[42] As a lightning-related phenomenon thought to be rare [*Smith et al.*, 2005], TGFs are likely associated with lightning processes with certain peculiarity. The analyses of quantitative features of TGF sferics may shed some light on TGF-producing processes and provide important bounds for detailed modeling. For a total of 54 TGF lightning signals that were not from NBEs, we computed the peak current of lightning discharges that emit VLF impulses, and the charge moment change mainly caused by the ULF-driving slow process. For lightning signals with multiple VLF impulses superposed on the ULF pulse, the highest peak current is used in the analysis.

[43] Figure 7a shows the histogram of peak currents of 54 TGF-associated lightning discharges that all occurred during the slow process. There are another 22 TGFs related to sferics with magnitude less than five times the background noise, and the associated peak currents are below 10–20 kA (depending on distance). Collectively, the peak currents of TGF-associated lightning discharges range from less than 10 kA to a maximum of 270 kA, with the majority (>85%) below 70 kA. Although it was suggested that TGF-related peak currents over, for example, 100 kA imply the connection between TGFs and +CG strokes [*Cohen et al.*, 2010a], it remains possible that unusual IC flashes can produce lightning discharges of this magnitude. The maximum peak current (270 kA), which is estimated for a case discussed by *Cummer et al.* [2005, Figure 1], is close to the extraordinarily large magnitude (450–700 kA) predicted for positive return strokes to drive mesospheric runaway breakdown through electromagnetic pulses [*Inan and Lehtinen*, 2005]. A closer examination of this case, however, identifies the precursor sferic and also suggests a TGF-associated current moment waveform similar to that shown in Figure 5c

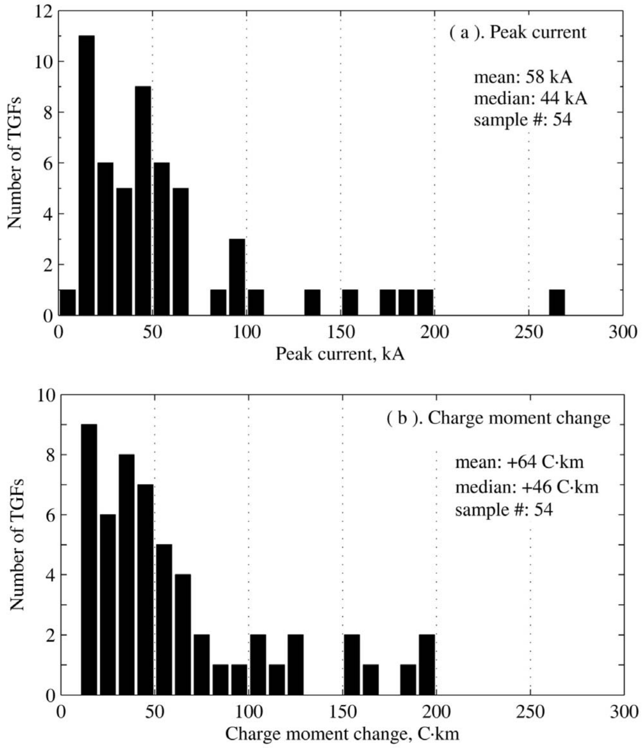

Figure 7. (a) Histograms of peak currents and (b) charge moment changes calculated for 54 TGF-associated lightning signals that contain one or more VLF impulses during a distinct ULF pulse.

for an IC discharge. Although the CG-related mechanism described by *Inan and Lehtinen* [2005] applies to intense IC discharges as well, it is not likely the cause of any TGFs analyzed here. We also noticed all the 11 TGF-associated lightning discharges with estimated peak currents over 70 kA occurred at geographic latitudes below 23°, and none of the 10 TGF lightning discharges at higher latitudes exceeded 60 kA. The chance of this observation is <10% if TGF-related lightning discharges over tropical and high latitudes do not differ significantly in amplitude. Therefore, TGF-associated lightning discharges with relatively high-peak currents seem to be more common in tropical regions.

[44] The histogram of ΔM_q estimated from the ULF pulse associated with 54 TGFs is shown in Figure 7b. The mean and median TGF-associated ΔM_q is +64 C km and +48 C km, respectively, which is in close agreement with the +49 C km average (over 2 ms) reported by *Cummer et al.* [2005] for fewer cases. It should be emphasized that we calculated ΔM_q over the detectable duration of a ULF pulse that usually lasts 2 to 6 ms. We also analyzed another 95 RHESSI TGFs for which only ULF measurements were acquired. ULF pulses with magnitude >5 times the background noise level (~0.005 nT in ULF data) are found for 70 events, and statistics of these ULF pulses are consistent with that derived for 54 TGFs examined with both VLF and ULF data. The remainder are mostly related to small ULF pulses that are hard to quantify, but the associated ΔM_q should be small (<+20 C km). Therefore, all the TGFs in our database are associated with ΔM_q significantly smaller than the typical +350–600 C km threshold producing short-delayed sprites [*Cummer and Lyons*, 2005] and the typical threshold (>+1000 C km) associated with long-delayed sprites [*Li et al.*, 2008]. The maximum TGF-associated ΔM_q we ever measured is +200 C km over 2 ms, which is not sufficient to cause runaway breakdown in the mesosphere, through a mechanism driven by transient strong electric fields of tremendous charge transfers on the order of +1000 C km [*Lehtinen et al.*, 1996, 2001; *Inan*, 2005]. In fact, TGFs usually appear to occur early in the slow process, which means the cumulated charge transfer, if possibly responsible for gamma ray production, is only a fraction of the ΔM_q computed from the ULF pulse.

[45] On the other hand, the typical TGF-associated ΔM_q is unusually large for IC lightning processes. The overall ΔM_q caused by many IC flashes (that last hundreds of ms) is around +100 C km [*Krehbiel*, 1981; *Rakov and Uman*, 2003]. The typical charge moment change and duration of a TGF-related slow process also yield a mean current moment of +30 kA km, which is rather strong for the upward negative leader in IC flashes. The oppositely charged cloud regions tapped by IC flashes are separated by 3–6 km in altitude [*Stolzenburg et al.*, 1998], as observed for a TGF-producing flash [*Lu et al.*, 2010]. This suggests that the mean current of a TGF-related lightning leader over several ms is 5 to 10 kA. Previous analyses of intracloud charge transfer show that negative leaders early in IC flashes usually carry a current <1 kA [*Liu and Krehbiel*, 1985; *Rakov and Uman*, 2003], which implies that the situation suitable for gamma ray production is rare for IC flashes. The observations on ground level indicate that the current of downward negative stepped leaders can increase up to 5 kA prior to return strokes [*Thomson et al.*, 1985].

6. Summary and Conclusions

[46] The main objective of this work is to characterize lightning processes associated with TGFs observed by the RHESSI satellite in 2004–2009. Examinations of broadband (<1 Hz to 30 kHz) magnetic fields recorded for 56 TGFs indicate that almost all (54 out of 56, or ~96%) the TGF-associated lightning signals contain a distinct ULF pulse from a slow process of 2–6 ms duration (and longer than 10 ms in one case). One or more discrete VLF impulses from fast discharges with <100 μs duration are superposed on the ULF pulse, although all the TGFs in our database contained one burst of gamma rays. If the varying multiplicity of VLF impulses is somehow related to gamma ray production, then in the cases we report the additional bursts of gamma rays must be significantly less intense than the primary burst and are indistinguishable from the background noise. A significant fraction (~40%) of TGF-associated ULF pulses are preceded by precursor sferics without discernible charge moments. The analyses of 9 TGFs related to lightning constrained with <100 km location uncertainty suggest that gamma rays are produced early in the slow process, and typically within 1 ms of a significant fast discharge. The precursor sferics are not likely associated with gamma ray production, but they can have large amplitude and cause discrepancies of several ms when one identifies the temporal TGF-lightning relationship. The remaining two TGFs appeared to be associated with a single fast discharge without any appreciable charge moment change, which in

one case was identified as a narrow bipolar event (NBE) [*Shao et al.*, 2010].

[47] The critical finding is that the overall lightning sequence (i.e., precursor discharges and fast discharges during the slow process) observed in nearly all the TGF lightning signals is consistent with the case study of a TGF-producing IC flash observed by the North Alabama LMA [*Lu et al.*, 2010]. This provides evidence that the majority of TGFs are likely produced during the upward negative leader progression, as theoretically addressed by *Moss et al.* [2006] and *Dwyer* [2008].

[48] Time-resolved current moment waveforms derived for two TGFs indicate that, for ULF pulses with single or multiple VLF impulses, the slow process initiated prior to the major TGF-associated lightning discharge. This is unusual for +CG strokes [*Gomes and Cooray*, 1998], but is again similar to the case reported by *Lu et al.* [2010], providing additional evidence that the majority of TGFs are associated with IC discharges [*Williams et al.*, 2006]. Although only a handful of TGF-associated lightning discharges could be classified, all of them were IC [*Stanley et al.*, 2006; *Shao et al.*, 2010]. On the other hand, it is worthwhile to examine the broadband magnetic fields of IC lightning discharges without invoking TGF observations. In particular, it is necessary to establish whether or not an appreciable ULF pulse is common to the initial flash development.

[49] The quantitative analyses of lightning signals associated with 54 TGFs yielded some statistics of the peak current and total charge moment change related to TGFs. The estimated peak currents of TGF-associated lightning discharges vary between small values below 10 kA and a maximum of 270 kA. The majority (>85%) of TGFs are associated with lightning discharges with peak currents less than 70 kA. Interestingly, lightning discharges with peak currents >70 kA were only associated with TGFs observed at latitudes below 23°, namely over tropical storms. All the TGFs in our database were related to positive charge moment changes between <+10 C km and +200 C km, with a mean of +64 C km. The TGF-associated ΔM_q is dominated by the slow process that typically carries a mean current moment of +30 kA km over 2 to 6 ms. Observations of TGFs associated with the largest peak current (270 kA) and the largest charge moment change (+200 C km in 2 ms) warrant further research into thunderstorm and lightning properties that can lead to such extreme values in IC flashes and how these might be linked to gamma ray production.

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