Measurements and implications of the relationship between lightning and terrestrial gamma ray flashes

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[1] We report observations and analysis of 30 kHz radio emissions (sferics) from lightning discharges associated with 26 terrestrial gamma ray flashes (TGFs) recorded by the RHESSI satellite over the Caribbean and Americas, between 1500 and 4000 km away from the magnetic field sensors located at Duke University. Thirteen of the TGFs are found to occur within −3/+1 ms of lightning discharges of positive polarity from the direction of the RHESSI subsatellite point, strongly indicating that the TGFs are linked to these discharges. The event timing and sferic direction finding reveals that the discharges occur within a ~300 km radius circle around the RHESSI subsatellite point. Although the positive polarity of all 13 discharges is consistent with runaway breakdown, the lightning charge moment changes are approximately two orders of magnitude smaller than present high altitude runaway breakdown theory predicts. Implications of these measurements are discussed. **Citation:** Cummer, S. A., Y. Zhai, W. Hu, D. M. Smith, L. I. Lopez, and M. A. Stanley (2005), Measurements and implications of the relationship between lightning and terrestrial gamma ray flashes, *Geophys. Res. Lett.*, *32*, L08811, doi:10.1029/2005GL022778.

1. Introduction

[2] Following the discovery of short bursts of gamma rays originating from Earth, called terrestrial gamma ray flashes (TGFs) [*Fishman et al.*, 1994], an analysis of distant low frequency magnetic field measurements during two TGFs [*Inan et al.*, 1996] confirmed the presence of lightning below the satellite around the time of both events. In one of the two cases a statistically significant connection was found to an individual lightning stroke that moved positive charge downward. This charge motion produces a downward electric field above the thundercloud that, if sufficiently large, can generate runaway breakdown [*Gurevich et al.*, 1992] which is thought to be the most likely TGF production mechanism [*Lehtinen et al.*, 1999, and references therein]. The lightning charge moment change required to generate the observed TGFs has been estimated to be around 6000 C km [*Lehtinen et al.*, 2001], which is well above the ~500 C km charge moment changes observed in most sprite-associated lightning strokes [*Hu et al.*, 2002]. However, charge moment change has not yet been measured in TGF-associated lightning; in fact, the entire TGF-lightning relationship has been analyzed for only a few events, and little is known with any certainty.

[3] Using TGF observations from the RHESSI satellite [*Smith et al.*, 2005] and ground-based measurements of the very low frequency (VLF, 3–30 kHz) and lower frequency radio signals radiated by lightning, we quantify the lightning-TGF relationship and constrain the possible source mechanisms. We address three issues: TGF correlation with individual lightning strokes, the implications of event timing analysis, and the charge moment change and related high altitude electric field produced by the observed lightning strokes.

[4] In the summer of 2004 the vector horizontal magnetic field was measured continuously at Duke University (35.975°N, −79.100°E) with two pairs of magnetic induction coils that cover 50 Hz to 30 kHz and <0.1 Hz to 400 Hz. The dominant signal in these fields are the short (typically a few ms) discrete impulses called sferics that are radiated by lightning strokes. A sferic can reveal the time of and direction to the originating stroke [*Orville*, 1991], the polarity of the stroke, and the current and charge transfer characteristics of the stroke [*Cummer and Inan*, 2000]. From a comparison with U.S. National Lightning Detection Network (NLDN) data, our systems have absolute timing accuracy and precision of ~20 μsec and direction finding error standard deviation of ±2° after removal of systematic errors. These uncertainties play a role in the analysis in Section 2.

[5] We limit our analysis to the subset of RHESSI TGFs detected over the Americas and the Caribbean when both of our sensor pairs were operating in a continuous mode. This enables us to determine with certainty whether a lightning stroke occurred at a given time without having an implicit amplitude threshold, and the relatively short propagation distances (most are less than 4000 km) ensure that even small lightning strokes are detectable and reduce the uncertainty in the current and charge transfer estimates below. A total of 26 TGFs met these constraints.

2. TGF-Lightning Correlation

[6] A ±0.5 s window around each TGF time was searched for the closest (in time) lightning stroke from any direction that has sufficient ELF energy to identify its

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polarity. After accounting for the speed of light propagation delay in the gamma rays (1.7 ms, assuming they originate at 50 km altitude [*Lehtinen et al.*, 1999] and propagate upward to the satellite at 550–600 km altitude) and sferics, we find that 13 of the 26 TGFs occur within −3/+1 ms of individual lightning strokes that originate within 10° of the RHESSI subsatellite point (11 of them are within 6°) and whose polarity can be unambiguously determined from our data. The precise event timing is not sensitive to the assumed 50 km TGF source altitude; ±30 km altitude changes correspond to TGF time changes of only ±0.1 ms.

[7] Figure 1 shows one of the strongest examples of this correlation. The top panel shows 0.5 s of VLF-ELF magnetic field data around the time of a TGF recorded by RHESSI on 22 October 2004, 04:33:32.234 UT. The magnetic field component shown is the azimuthal component assuming a coordinate system origin at the RHESSI subsatellite point at 15.09°N, −84.85°E (2390 km from the sensors). There is a clear sferic at almost exactly the same time as the TGF, as well as some much smaller signals distributed throughout the period. The lower panel shows the 10 ms around the lightning and TGF times, where the speed of light propagation times of the gamma rays and sferic have been subtracted, assuming that both originate at the subsatellite point. In this case the TGF occurs 1.7 ms *before* the lightning stroke. The detailed event timing and implications are analyzed in more detail in Section 3.

[8] The downward initial polarity in B_ϕ of the filtered ELF waveform unambiguously implies that the stroke contains net downward motion of positive charge as would occur in a positive cloud-to-ground (+CG) lightning stroke. The polarity of the lightning strokes in all 13 correlated events are of this polarity. This is significant because the anticipated mechanism for TGF generation is runaway breakdown above the thunderstorm, which requires a downward electric field that would only be produced by lightning of this polarity.

[9] The average rate of distinguishable sferics arriving at Duke from a ±10° window during these 13 events is 4.0 per second. The probability of a sferic randomly occurring in a 4 ms window around a TGF time is thus 0.016. From this, the probability of randomly finding 13 or more −3/+1 ms time correlations in 26 trials is extremely small (3.8×10^{-17}). We conclude that these 13 TGFs were produced by a mechanism that is connected to the observed lightning strokes.

[10] Two of the remaining 13 events could not be analyzed because lightning strokes from other directions arrived within a few ms of the TGF time. In 6 cases, very weak sferics occur within −3/+1 ms of the TGF whose polarity could not be determined. For the remaining 5 TGFs there were no distinguishable sferics originating from within 20° of the RHESSI footprint in the entire 1 s interval examined. The background noise and typical 3000–4000 km range of these events bounds any vertical charge moment change at the time of these 11 TGFs as less than 5 C km. The data from our lower frequency coils show that very slow (tens of ms and longer) but strong vertical currents that sometimes occur in connection with sprite-producing lightning [*Cummer and Füllekrug*, 2001] did not occur in these cases. The 5 TGFs not connected to lightning were not distinctly different from those that were clearly connected to a lightning stroke. In fact, one of these is among the strongest and longest TGFs observed by RHESSI.

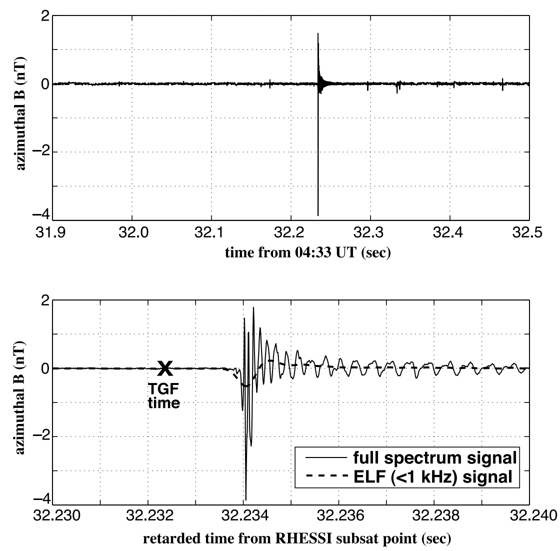

Figure 1. A lightning-TGF correlation example from 22 October 2004, 04:33:32.234 UT. (top) One-half second of VLF-ELF data showing a clear large sferic near the TGF time. (bottom) The precise timing relationship of the lightning and TGF.

3. Detailed Timing and Direction Analysis

[11] We now examine the event timing and direction-finding to define the connection to individual lightning processes and bound the distance between the source lightning and TGFs. After subtraction of speed of light delays, the distribution of time delays from the lightning stroke to the recorded TGF time has a maximum of 0.7 ms, a minimum of −3.0 ms, a mean of −1.24 ms, and a standard deviation of 0.97 ms. Note that the predominantly negative time delays mean that the TGFs occurred on average 1.24 ms *before* the lightning stroke, assuming that the lightning strokes all occurred at the RHESSI subsatellite point.

[12] While the VLF-ELF data timing accuracy and precision are both in the tens of μs, the TGF event times are currently thought to be accurate to ±1 ms. In light of this there are 3 possible explanations of the unexpectedly early TGFs. The 1.24 ms time advance could be a consistent RHESSI timing offset, and the TGFs actually occur just after the observed lightning strokes. This time advance would also occur if the lightning is always ~400 km radially more distant from our sensors than the RHESSI subsatellite point. This seems unlikely given the varying geographic locations of the 13 analyzed TGFs. This would also displace the lightning location consistently to the south of the TGF, which is opposite the direction expected for gamma rays produced runaway electron beams tied to Earth's magnetic field. Lastly, it remains possible that the TGFs are produced by a process associated with the development of the observed lightning strokes but that actually occurs ~1 ms before the stroke itself. Runaway

breakdown initiation by a pre-discharge process is not inconsistent with the small charge moment changes in the associated lightning discharges (see Section 4) and the apparent lack of any associated discharge in some cases.

[13] Subtracting the mean of this delay distribution, the lightning strokes are tightly clustered (almost all ±1 ms) around the TGF times. This is distinctly different than typical lightning-to-sprite delay times which vary from one to hundreds of ms [*Lyons*, 1996]. This implies that TGF initiation is linked to processes that occur within at most a few ms of the lightning stroke, and the observed TGFs are not produced by the slow charge transfers often responsible for sprites.

[14] The ±1 ms spread of lightning times bounds the possible offsets between the lightning and TGF detection point. Assuming no RHESSI timing uncertainties implies that the lightning location is radially displaced from the subsatellite point by approximately ±300 km. Any contribution to this spread from RHESSI timing uncertainties would make this radial displacement even smaller. The lack of skew of the timing distribution towards longer delays (which would happen if the lightning were consistently north of the TGF) appears inconsistent with a TGF offset to the south of the lightning due to magnetic field effects on a runaway electron beam.

[15] Similarly, the differences between the arrival directions of the lightning signals and the direction to the subsatellite point bound the azimuthal spatial offsets. The difference between the directions to the lightning strokes and the subsatellite point has a 2.8° mean and a 4.0° standard deviation. When projected along the distance from Duke to the subsatellite point of each event (typically 2000–4000 km), this ±4.0° corresponds to an azimuthal displacement of ±200 km. Although the direction finding capability of our system is not as precise as the system timing, this azimuthal displacement is consistent with the ±300 km radial displacement determined by the event time distribution.

[16] We conclude that, for these 13 events, the lightning strokes occurred within a circle of radius approximately 300 km centered at the RHESSI subsatellite point. Consequently, the gamma ray beams do not appear to especially wide, but they may not be as tightly beamed as calculations [*Lehtinen et al.*, 1999] have suggested (15° = 130 km diameter at RHESSI altitudes).

4. Measurements of Correlated Lightning Strokes

[17] Lightning vertical current moment and charge moment change can be measured from distant VLF-ELF signals [*Cummer and Inan*, 2000]. Many lightning strokes have been analyzed in this way from similar distances [e.g., *Cummer and Lyons*, 2005], and based on unpublished initial comparisons of this data set with other measurements and techniques, we estimate a worst-case absolute error of −33%/+50% in the charge moment changes measured by this technique.

[18] For the 13 strokes analyzed, we find a maximum impulse charge moment change ($i\Delta M_q$, defined as occurring in the first 2 ms of the discharge) of 107 C km, a minimum of 11 C km, and an average of 49 C km. All of these lightning strokes appear impulsive (charge transfer within

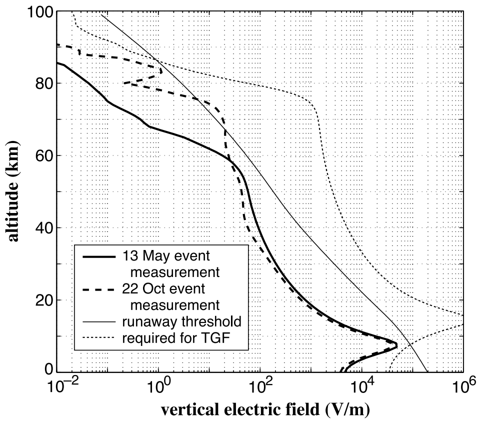

Figure 2. A model-based computation of the vertical electric field directly above the lightning discharge for the two biggest TGF-associated strokes and for the theoretical prediction of *Lehtinen et al.* [2001] based on runaway breakdown. For perspective the runaway breakdown threshold is also shown.

2 ms) and there is no evidence of continuing current in our lower frequency data. And even if there were small, undetected continuing currents, the timing analysis above indicates that they would not play a role in the generation of the observed TGFs.

[19] These $i\Delta M_q$s are 50–500 times smaller than the ~6000 C km needed by model calculations to generate observable TGFs via high altitude runaway breakdown [*Lehtinen et al.*, 2001]. In fact, they are 5–50 times smaller than those that typically produce sprites in the U.S. High Plains [*Cummer and Lyons*, 2005]. To quantify this discrepancy with runaway theory expectations, we used the measured current moment waveforms measured for the 2 biggest TGF-associated lightning strokes as the CG current input in a full wave model of lightning-generated fields in the ionosphere [*Cummer*, 2000] to estimate the vertical electric field above the cloud immediately following the measured lightning strokes. These two TGFs were recorded on 13 May 2004, 13:49:47.202 and 22 October 2004, 04:33:32.234 UT and were relatively close to Duke (1662 and 2390 km). The $i\Delta M_q$s in each stroke were 130 C km and 107 C km, respectively. The 13 May TGF-associated stroke was recorded by our system in triggered mode and was thus not included in the overall statistical analysis. It was, however, the largest TGF-associated $i\Delta M_q$ we have observed and we thus include it here as an upper bound.

[20] For these two cases, Figure 2 shows the modeled vertical electric field profile directly above the lightning stroke 2 ms after the stroke onset when all of the charge has been transferred to ground. For comparison, we used the same model to compute the electric field profile following a 450 C charge transfer from 15 km altitude that *Lehtinen et al.* [2001] found would produce the expected gamma ray flux according to runaway theory. While the *Lehtinen et al.* [2001] stroke produces electric fields 8–10 times above the runaway threshold (which is required to produce the required electron avalanche), the measured lightning strokes produce fields that are two orders of magnitude smaller. We

assume point discharges in all simulations; a more realistically distributed charge would only reduce the high altitude fields. An IC discharge with the same $i\Delta M_q$ would also produce smaller electric fields [*Pasko et al.*, 1997].

[21] In light of these measurements, it is difficult to imagine how fields on the order of a few kV/m at altitudes between 30 and 50 km required by the post-discharge runaway model could be present. At 30 km and 50 km altitudes the dielectric relaxation times are roughly 800 ms and 80 ms, respectively [*Pasko et al.*, 1997]. Although post-discharge fields persist weakly for durations longer than these [*Baginski et al.*, 1988], strong fields produced by external charge motion will decay on approximately these time scales. Consequently, only lower altitude charge motion that occur on the order of the 1 s or faster can produce strong electric fields at these altitudes. Any vertical charge motion of the required magnitude (thousands of C km) and the required time scales ($\sim$1 s or less) would have been detected easily by our low frequency sensors [*Cummer and Füllekrug*, 2001], and no such signature was seen. Although comparable horizontal charge motion (many hundreds of C) over many tens of km could produce the required fields and would not be detectable by our sensors, we know of no reports of this degree of horizontal charge transfer that does not involve some vertical charge motion inside the cloud or to ground.

[22] The small charge transfers observed could generate runaway breakdown if the runaway avalanche is generated closer to the altitude of the charge motion. One possibility is that runaway breakdown is generated at altitudes lower than 30 km by more localized electric fields connected to the observed lightning strokes and/or associated in-cloud processes. This notion is also supported by the prevalence of TGF observations at low latitutdes [*Smith et al.*, 2005], where a largely horizontal background magnetic field will inhibit runaway breakdown above approximately 35 km altitude [*Lehtinen et al.*, 1999]. Thus a scenario consistent with the data is that the observed lightning discharges (perhaps along with a specific thunderstorm charge distribution) create strong fields in or just above the thundercloud, which in turn generate a runaway electron avalanche and a TGF at altitudes below 35 km. Note that the runaway electron beam may not escape the atmosphere because the horizontal background magnetic field stops the runaway process at higher altitudes. Given that TGFs may originate just before the modest observed lightning strokes, it is possible that a weakly radiating in-cloud process produces the TGF, and the observed lightning strokes follow as an effect and are not a cause of the TGFs.

[23] Another possibility not as consistent with the prevalence of TGFs at low latitude is that an upward charge injection from the thundercloud generates high fields at high altitudes with less net charge motion. Such upward charge motion is not inconceivable in light of the existence of upward streamers like blue jets [*Wescott et al.*, 1995] or gigantic jets [*Pasko et al.*, 2002] that originate at cloud top altitudes.

5. Conclusions

[24] In 13 of 26 TGF events analyzed, lightning-generated sferics are seen within $-3/+1$ ms of the TGF time. All of the sferics arrive within 10° of the direction from the sensor to the RHESSI subsatellite point, and all of these signals are radiated by current that moves positive charge downwards as in a +CG. We conclude that these 13 TGFs are linked to a process that radiates at VLF like a modest +CG lightning return stroke. Although the TGFs are tightly linked in time to the lightning strokes, we cannot presently determine whether the TGFs originate either before or after the discharge. Most of the remaining 13 TGFs are correlated with lightning strokes too small to determine their polarity or with no lightning stroke at all. Based on an analysis of precise timing and direction finding, we find that the TGFs associated with clear lightning discharges are detected when the RHESSI footprint is within approximately 300 km of the discharge.

[25] Measured lightning charge moment changes in these strokes are 50–500 times smaller than what runaway theory predicts is needed for electric fields between 30 and 50 km altitude to generate a TGF [*Lehtinen et al.*, 2001]. This indicates that the region of runaway breakdown is closer in altitude to the region of charge motion, and two specific possibilities were discussed. In light of past measurements of lightning charge moment changes of many thousands of C km [*Stanley et al.*, 2000; *Cummer and Füllekrug*, 2001], it is still possible that some TGFs are generated by high altitude runaway breakdown as originally conceived [*Roussel-Dupré and Gurevich*, 1996]. But runaway breakdown produced by a large lightning charge moment change is not responsible for the 26 TGFs analyzed here.

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