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A link between terrestrial gamma-ray flashes and intracloud lightning discharges

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[1] Atmospheric electric field change (sferic) waveforms were detected at Los Alamos Sferic Array stations in association with terrestrial gamma-ray flashes (TGFs). Five TGF sferic waveforms detected at sufficiently close range were all found to be consistent with a positive-polarity intracloud (+IC) discharge process which transported electrons upward. The amplitudes of the events were among the top 5% of IC discharge flashes. Altitudes obtained from ionosphere reflections for two of the closer events were found to be 13.6 km and 11.5 km. These altitudes are lower than expected if one assumes that the sferic was near the source of the gamma-rays. One of the sferics was an energetic narrow bipolar event which occurred near the inferred onset of a flash, suggesting that the preceding TGF may correspond to the actual onset.

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1. Introduction

[2] Gamma-rays originating from Earth, referred to as "terrestrial gamma-ray flashes" (TGFs), were first discovered by the BATSE instrument on the CGRO satellite and attributed to bremsstrahlung from MeV electrons [*Fishman et al.*, 1994]. An analysis of extremely low frequency data around the time of two BATSE TGFs by *Inan et al.* [1996] revealed one TGF which was correlated in time with what appeared to be a positive-polarity cloud-to-ground (+CG) discharge and another event which was not correlated with a sferic but occurred in proximity to an active storm region.

[3] The more recent RHESSI satellite has a greatly improved detection rate [*Smith et al.*, 2005] with >620 probable TGF events detected in over 3 years of operations. Analysis of a subset of RHESSI TGFs by *Cummer et al.* [2005] established a strong relationship between TGFs and lightning and with positive-polarity discharges in particular. Contrary to widespread expectations of a high altitude source, all TGF sferics were found to have insufficient charge moment changes to produce runaway breakdown at 30–50 km altitude [*Cummer et al.*, 2005]. A recent comparison of RHESSI TGF spectra with Monte Carlo simulations of runaway breakdown revealed that the source was likely deeper in the atmosphere at 15–21 km altitude [*Dwyer and Smith*, 2005].

[4] The Los Alamos Sferic Array (LASA) became operational in 1998 with the purpose of locating, classifying, and characterizing lightning discharges [*Smith et al.*, 2002]. Unlike the National Lightning Detection Network (NLDN) [*Cummins et al.*, 1998], LASA stores electric field waveforms for further analysis. Each electric field sensor detects atmospheric radio emissions (sferics) within a frequency band of $\simeq$160 Hz to 500 kHz.

[5] In April 2004, LASA underwent a major software and hardware upgrade which resulted in a very dramatic increase in sensitivity with no dead-time between triggers [*Shao et al.*, 2006]. Eight LASA stations were deployed in northern Florida with another station operated at Los Alamos. In this paper, we report on the analysis of LASA data in relation to currently available RHESSI TGF data for April 1, 2004 through July 24, 2005 and August 1 through November 30, 2005. We focus the analysis only on those TGF events which were sufficiently close to determine the discharge type with particular emphasis on two events for which source altitudes could be readily determined.

2. Analysis

[6] In order to search for coincident TGF events, the data from all available stations was filtered with a ±10 ms window around the expected arrival time of the sferic based on the arrival time of gamma-rays at the satellite. The distance to RHESSI's subsatellite point and its altitude ($\simeq$560 km) were both factored into the calculation of the expected arrival time of a causative sferic. The ±10 ms window is more than sufficient to account for the $\sim$1000 km RHESSI footprint radius as well as time offsets of up to 3 ms as suggested by *Cummer et al.* [2005].

[7] Only those TGFs with a RHESSI subsatellite point within 1100 km of a station are used in this analysis in order to accurately discriminate between intracloud (IC) and CG waveforms. For the data available from April 1, 2004 to November 30, 2005, a total of 8 TGFs met our range filter criteria. Of those, 6 had sferics detected at one or more LASA stations within 10 ms of an expected sferic from the RHESSI TGF. Two of the events on June 18, 2004

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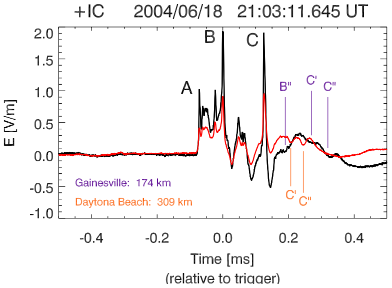

Figure 1. June 18 TGF electric field waveforms at Gainesville (black) and Daytona Beach (red). Some of the ionosphere (C′) and earth-ionosphere (B″, C″) reflections for peaks A–C are readily evident.

and August 11, 2005 were sufficiently close and impulsive that we were able to extract source altitudes.

3. June 18, 2004

[8] The RHESSI satellite was situated over the Gulf of Mexico south of Tallahassee, Florida on June 18, 2004, when it detected a TGF at 21:03:11.6443 UT. Five of the eight Florida stations were operational at the time. Four of them triggered off of a positive-polarity sferic around the time of the TGF. The TGF lightning was centered at 30.373°N, 83.951°W with the onset of the first impulsive sferic at 21:03:11.645038 UT. The geolocation was 128 km north-northeast of the RHESSI subsatellite point. The expected arrival time of electromagnetic radiation at RHESSI in association with the sferic was 2.6 ms after the actual onset of gamma-rays.

[9] Utilizing Florida data for the summer of 2005, we estimate the probability of a random coincidence of a positive-polarity sferic within the ±10 ms TGF search window, within ~200 km of the RHESSI subsatellite point, and with an amplitude matching or exceeding that of the weakest TGF coincidence in this study (see section 5) as roughly 10^{-4}.

3.1. Waveform Characteristics

[10] Figure 1 shows the waveforms detected at two of the four stations. The sign convention we use is such that an upward displacement in the plots corresponds to upward negative charge motion. The presence of multiple fast pulses on the leading edge of the waveform indicates that this was an IC discharge process [*Weidman and Krider*, 1979]. Furthermore, the time required for the electric field to go from 10% to maximum (peak B) was 74 μs. This rise time is much longer than the general criteria of less than ≃10 μs rise-time for CG return stroke waveforms [*Lin et al.*, 1979].

[11] The rise time of the first pulse from 10 percent to maximum was 4.4 μs. Compensating for the underlying slow field change, the full-width half-max (FWHM) of pulses A–C was 3.0 μs, 4.6 μs, and 5.1 μs, respectively. These widths are comparable to the mean 4.7 μs FWHM of narrow bipolar events (NBEs) [*Smith et al.*, 1999]. However, NBEs occur in relative temporal isolation with only minor charge transfer [*Eack*, 2004], while these are clearly clustered in time with a significant slow charge transfer occurring in the same time interval.

[12] Fast pulses with similar durations have been observed during the initial active phase of a flash [*Weidman and Krider*, 1979] as well as during K-changes [*Shao et al.*, 1995] which occur only in the late phase of a flash [*Ogawa and Brook*, 1964]. Unfortunately, we cannot assess when the TGF occurred within a parent flash since the detection efficiency of ICs from the storm was relatively low and many IC sferics would likely have been missed. However, it is interesting to note that there is a small field change at 0.3–0.45 ms prior to the first peak which indicates that there was some preceding charge motion (see Figure 1).

3.2. Horizontal Extent

[13] Pulses A–C were geolocated using the time of arrival of peak power at the various stations [*Shao et al.*, 2006]. The TGF pulses were located in the core of the storm close to the center of NBE activity. Pulses B and C were on either side of Pulse A and both were geolocated within ≃1 km of it along a radial line to the center of our network. We conservatively estimate that the range errors were on the order of ±5 km while the tangential errors were only ±1 km. There were a couple of weaker pulses between A and B which we also geolocated and they too fell along the same radial line and within the radial errors. Thus, it appears that the discharge was reasonably compact with horizontal dimensions of less than 2 km in the tangential direction. However, we cannot preclude a chance alignment along the radial direction with larger discharge dimensions. We also do not know if the weak slow field change preceding the pulses was due to horizontal charge motion in a larger flash.

3.3. Altitude

[14] Impulsive IC events are known to produce ionosphere and earth-ionosphere reflections which can be used to obtain the altitude of the compact source and the ionosphere [*Smith et al.*, 2004]. Pairs of reflected pulses can be seen in Figure 1. Because the relative difference between the propagated distance (time delay) for the direct (ground wave) pulse and reflected pulses decreases with range, the reflected pulses should have arrived sooner after the ground wave at the more distant stations, as was observed.

[15] In order to obtain the altitudes of pulses A and B, the ground waves had to be removed in order to decipher the reflected waves from the ionosphere. We accomplished this by differencing the waveforms between various station pairs after compensating for different range attenuation to the stations as well as removing both the low and higher frequencies with a passband filter of 10–150 kHz. In order to simplify the calculations, we used average ionosphere reflection altitudes and conductivites for each station which

Table 1. Altitudes of TGF Peaks

Date	Peak	Altitude, km	Uncertainty, km	Correlation Coefficient
June 18, 2004	A	14.5	???	0.387
	B	13.6	11.7–15.8	0.651
	C	13.6	11.6–16.2	0.740
August 11, 2005	-	11.5	10.5–12.5	0.674

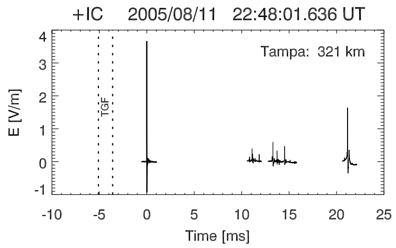

Figure 2. August 11 TGF electric field waveform at Tampa. A large +NBE is preceded by a TGF and is followed milliseconds later by more +IC sferics.

optimized the correlation coefficient between the modeled and observed reflections for roughly 30 NBEs in the 10 minute time period centered on the TGF.

[16] The optimum source altitudes for pulses A–C were obtained by averaging the determinations from all of the unique pairings of the Gainesville, Palatka, and Daytona Beach waveforms. Because the range to the Tampa station was nearly identical to that of Daytona Beach, it was excluded from the comparison. Table 1 shows the optimum altitudes, uncertainties, and average correlation coefficient for each peak. The altitude of peaks B and C appear to be identically at 13.6 km. However, the uncertainties are such that we cannot rule out a vertical displacement between any two peaks of as much as 4 km. It is important to note that the uncertainties in the altitudes may be overestimates, as evidenced by a tighter clustering of +NBE altitudes around the TGF (not shown). Also, the lower average correlation coefficient for pulse A may stem from a systematic error introduced by contamination from incomplete negation of subsequent pulses in the waveform difference.

4. August 11, 2005

[17] On August 11, 2005, RHESSI detected a TGF at 22:48:01.6321 UT while it was nearly over Miami, Florida. A coincident large positive-polarity sferic was detected at all six of the operational Florida stations. The event was geolocated at 25.4484°N, 81.0398°W with a source time of 22:48:01.635371 UT. The event was 117 km west of the RHESSI subsat point and 321 km away from the closest station in Tampa. The expected arrival time of electromagnetic radiation at RHESSI was 5.1 ms after the actual time, which is more than 2 ms outside of the range estimated by [*Cummer et al.*, 2005]. As was noted in section 3, the chance that this was a random coincidence is $<10^{-4}$.

4.1. Waveform Characteristics

[18] The zero-crossing fall time of this waveform from the positive maximum was very fast at 3.1 μs. This is an order of magnitude faster than the $\geq$30 μs criteria for return stroke fall times [*Lin et al.*, 1979] and thus this event is associated with an IC discharge process. Furthermore, the total rise and fall time (5.2 μs) was less than 7 μs and the waveform was isolated within the 1.5 ms trigger length at Tampa, so it was a special form of +IC known as a +NBE [*Smith et al.*, 2004].

[19] The association of a TGF with a large NBE is particularly significant, since such NBEs are in turn often associated with initial strong VHF pulses from IC flashes [*Rison et al.*, 1999; *Jacobson*, 2003]. A recent study of broadband (ULF-LF) electric field data in close proximity to ordinary IC flashes has shown that the initial VHF pulse occurs within 2 ms of flash onset [*Maggio et al.*, 2005], though longer VHF lag times may exist. Furthermore, this NBE was followed several milliseconds later by numerous IC pulses (see Figure 2) consistent with the initial active phase of the flash. Thus, it is likely that this TGF occurred at or near the time of discharge initiation.

[20] It has been theorized that NBEs are a direct manifestation of runaway breakdown at the time of flash onset [see *Gurevich et al.*, 2006, and references therein]. However, the timing does not support a direct connection of the gamma-rays to the NBE. The predicted arrival time of gamma-rays at RHESSI is 5.1 ms after the actual onset and the maximum error in the RHESSI time is conservatively estimated at 4 ms while that of the NBE source time is less than 0.1 ms. Furthermore, the gamma-ray pulse observed by RHESSI was unusual in that it had at least 2 peaks and a relatively long total duration of $\simeq$1.5 ms, which is in stark contrast to the narrow single peak of the NBE.

[21] At the range of the storm, the Tampa station would have detected any events with a range-normalized amplitude of $\geq$0.90 V/m at 100 km (equivalent to a peak current threshold of only 3.7 kA for a CG). Thus, any field changes produced by the TGF must have been below this amplitude or outside of the $\simeq$160 Hz to 500 kHz bandpass of our stations.

4.2. Altitude

[22] The ionosphere and earth-ionosphere reflections were plainly evident in each NBE record collected at the 6 Florida stations. The NBE source height determinations from each station were all within 0.2 km of an 11.5 km average (Table 1). This altitude is significantly lower than the June 18, 2004 TGF sferic altitude and is also lower than an average +NBE altitude of 13 km for predominantly Florida storms [*Smith et al.*, 2004]. An 11.5 km source altitude conflicts with the prediction of a 15–21 km source altitude based on a comparison of modeled spectra with RHESSI average TGF spectra by *Dwyer and Smith* [2005] as well as the association of enhanced TGF detections at lower latitudes with a higher tropopause [*Williams et al.*, 2006]. However, since the gamma-ray source was temporally displaced from the NBE, it may also have been vertically displaced. Also, because both the TGF and IC characteristics were unusual, this event may not typify those

Table 2. Close TGF Overview

Date	t_{rise}, μs	t_{fall}, μs	Event Type	E_{100}, V/m	I_{CG}, kA	TGF ΔT, ms
May 13, 2004	32	23	+IC	12.6	52	−3.4
Jun 18, 2004	74	23	+IC	3.4	14	−2.6
Jul 24, 2004	n/a	n/a	n/a	<22.7	<94	n/a
Aug 07, 2005	n/a	n/a	n/a	<6.0	<25	n/a
Aug 11, 2005	2	3	+IC	13.9	57	−5.1
Aug 22, 2005	23	41	+IC	3.4	14	−1.8
Sep 10, 2005	56	17	+IC	3.7	15	−2.6
Sep 12, 2005	n/a	n/a	n/a	<6.7	<28	n/a

used by *Dwyer and Smith* [2005] to form the average RHESSI spectra.

5. Waveform Summary

[23] Table 2 summarizes the waveform characteristics of all TGF events which had a RHESSI subsat point within 1100 km of an active LASA station. Six of the eight TGF events had waveforms detected at one or more stations within ±10 ms of the expected time. All six waveforms were found to have rise and/or fall times which indicated that they were ICs, contrary to the prediction of a TGF EMP source from a CG return stroke by *Inan and Lehtinen* [2005]. In all cases the waveforms were of positive-polarity (electrons moving upward), consistent with the results of *Cummer et al.* [2005]. However, the August 7, 2005 +IC was only detected at Tampa and the probability of a random coincidence within the ±10 ms window was 41% due to active close storms, so we treat it as a potential missed-detect in our analysis.

[24] Five TGF events were either detected at a sufficient number of LASA stations (3) for a geolocation or, in the case of the May 13, 2004 TGF, was geolocated off of inferred first-hop negative sky-waves detected by NLDN stations at 1040–1860 km range (M. J. Murphy, personal communication, 2005). All geolocations were at or within 130 km of the subsat point and appeared to be randomly oriented about it. However, geolocations up to $\simeq$760 km away from the subsat point have been found for more distant TGFs which were not included in this analysis.

[25] In order to estimate range-normalized peak electric field values, we use the same empirical relationship used by the NLDN with a $r^{-1.13}$ dependency of amplitude on range (r) and an additional small exponential falloff [*Cummins et al.*, 1998]. This relationship is optimised for events at 50–200 km range. We estimate that errors of up to 30% in the range-normalized estimates may be expected for some of the more distant events in Table 2. For the non-detect events, we can only determine an upper limit for the range-normalized amplitude based on our bipolar trigger thresholds and the positions of storms in satellite infrared images within the $\sim$1000 km RHESSI footprint radius. The much lower limit for the 2005 events relative to July 24, 2004 was due to much lower thresholds.

[26] All of the geolocated events were found to have 100 km range-normalized amplitudes of 3.4 V/m or greater. This would correspond to the amplitude produced by a CG return stroke with a peak current of $\geq$14 kA. In order to put this into perspective, a distribution of range-normalized absolute peak electric fields for IC *flashes* was obtained for May through July of 2005 for a region in Florida where LASA sensitivity is greatest (<2 kA for CGs). Based on these results, it is clear that the ICs in Table 2 are energetic since they are all within the upper 5% of the distribution.

[27] Finally, we calculated the RHESSI TGF source onset times relative to that of sferic "onset". In the few cases where there were multiple distinct sferics within the trigger record, the largest amplitude event was used. For the sake of simplicity, an altitude of 15 km was assumed for the gamma-ray source. Varying the altitude up or down by several kilometers would not affect our timing conclusions. In all five cases, the TGFs led the sferics by 1.8–5.1 ms. This may indicate that ambient conditions prior to the sferics was responsible for the gamma-rays, as might be expected if runaway breakdown was initiating flashes [*Gurevich et al.*, 1999]. However, only the August 11, 2005 event was outside of the conservative estimate of 4 ms for the maximum systematic error in RHESSI timing and up to ±1 ms for the random error. Thus, it is possible that most (but not all) TGFs are produced by a discharge process which also produces the observed IC sferics. Indeed, a recent comparison of Swift and RHESSI data for the gamma-ray burst SGR 1806-20 revealed a 3.0 ± 0.3 ms offset which, if Swift timing is correct, would line-up four of the five geolocated TGFs in Table 2 with sferics to within the random timing uncertainty.

[28] **Acknowledgments.** The authors thank our LASA station hosts [see *Shao et al.*, 2006]. The authors are indebted to Alfred Fernandez of LANL who helped setup the array and to Alexander Gurevich and Robert Roussel-Dupre for many insightful comments. This work was performed under the auspices of the United States Department of Energy. This manuscript is dedicated in memory of the late Miley Stanley.

References

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*(D8), 9035–9044.

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.

Dwyer, J. R., and D. M. Smith (2005), A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations, *Geophys. Res. Lett.*, *32*, L22804, doi:10.1029/2005GL023848.

Eack, K. B. (2004), Electrical characteristics of narrow bipolar events, *Geophys. Res. Lett.*, *31*, L20102, doi:10.1029/2004GL021117.

Fishman, J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313–1316.

Gurevich, A. V., K. P. Zybin, and R. A. Roussel-Dupre (1999), Lightning initiation by simultaneous effect of runaway breakdown and cosmic ray showers, *Phys. Lett. A*, *254*, 79–87.

Gurevich, A. V., K. P. Zybin, and Y. V. Medvedev (2006), Amplification and nonlinear modification of runaway breakdown, *Phys. Lett. A*, *349*, 331–339.

Inan, U. S., and N. G. Lehtinen (2005), Production of terrestrial gamma-ray flashes by an electromagnetic pulse from a lightning return stroke, *Geophys. Res. Lett.*, *32*, L19818, doi:10.1029/2005GL023702.

Inan, U. S., S. C. Reising, G. J. Fishman, and J. M. Horack (1996), On the association of terrerstrial gamma-ray bursts with lightning and implications for sprites, *Geophys. Res. Lett.*, *23*(9), 1017–1020.

Jacobson, A. R. (2003), How do the strongest radio pulses from thunderstorms relate to lightning flashes?, *J. Geophys. Res.*, *108*(D24), 4778, doi:10.1029/2003JD003936.

Lin, Y. T., M. A. Uman, J. A. Tiller, R. D. Brantley, W. H. Beasley, E. P. Krider, and C. D. Weidman (1979), Characterization of lightning return stroke electric and magnetic fields from simultaneous two-station measurements, *J. Geophys. Res.*, *84*(C10), 6307–6314.

Maggio, C., L. Coleman, T. Marshall, M. Stolzenburg, M. Stanley, T. Hamlin, P. Krehbiel, W. Rison, and R. Thomas (2005), Lightning-initiation locations as a remote sensing tool of large thunderstorm electric field vectors, *J. Atmos. Oceanic Technol.*, *22*(7), 1059–1068.

Ogawa, T., and M. Brook (1964), The mechanism of the intracloud lightning discharge, *J. Geophys. Res.*, *69*, 5141–5150.

Rison, W., R. J. Thomas, P. R. Krehbiel, T. Hamlin, and J. Harlin (1999), A GPS-based three-dimensional lightning mapping system: Initial observations in central New Mexico, *Geophys. Res. Lett.*, *26*(23), 3573–3576.

Shao, X. M., M. A. Stanley, A. Regan, J. Harlin, and M. Pongratz (2006), Total lightning observations with new and improved Los Alamos Sferic Array (LASA), *J. Atmos. Oceanic Technol.*, in press.

Shao, X. M., P. R. Krehbiel, R. J. Thomas, and W. Rison (1995), Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*(D2), 2749–2783.

Smith, D. A., X. M. Shao, D. N. Holden, C. T. Rhodes, M. Brook, P. R. Krehbiel, M. Stanley, W. Rison, and R. J. Thomas (1999), A distinct class of isolated intracloud lightning discharges and their associated radio emissions, *J. Geophys. Res.*, *104*(D4), 4189–4212.

Smith, D. A., K. B. Eack, J. Harlin, M. J. Heavner, A. R. Jacobson, R. S. Massey, X. M. Shao, and K. C. Wiens (2002), The Los Alamos Sferic Array: A research tool for lightning investigations, *J. Geophys. Res.*, *107*(D13), 4183, doi:10.1029/2001JD000502.

Smith, D. A., M. J. Heavner, A. R. Jacobson, X. M. Shao, R. S. Massey, R. J. Sheldon, and K. C. Wiens (2004), A method for determining intracloud lightning and ionospheric heights from VLF/LF electric field records, *Radio Sci.*, *39*, RS1010, doi:10.1029/2002RS002790.

Smith, D. M., L. I. Lopez, R. P. Lin, and C. P. Barrington-Leigh (2005), Terrestrial gamma-ray flashes observed up to 20 MeV, *Science*, *307*, 1085–1088.

Weidman, C. D., and E. P. Krider (1979), The radiation field wave forms produced by intracloud lightning discharge processes, *J. Geophys. Res.*, *84*, 3159–3164.

Williams, E., et al. (2006), Lightning flashes conducive to the production and escape of gamma radiation to space, *J. Geophys. Res.*, doi:10.1029/2005JD006447, in press.

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