GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L02801, doi:10.1029/2009GL041753, 2010

Geolocation of terrestrial gamma-ray flash source lightning

M. B. Cohen,[1] U. S. Inan,[1,2] R. K. Said,[1] and T. Gjestland[3]

Received 12 November 2009; revised 4 December 2009; accepted 15 December 2009; published 22 January 2010.

[1] Terrestrial gamma-ray flashes (TGFs) are impulsive (∼1 ms) but intense sources of gamma-rays associated with lightning activity and typically detected via low orbiting spacecrafts. We present the first catalog of precise (<30 km error) TGF source locations, determined via ground-based detection of ELF/VLF radio atmospherics (or sferics) from lightning discharges, which enables precise geolocation of lightning locations. We present the distribution of source-to-nadir distances, established due to effects of Compton scattering on the escaping photons. We find that TGFs occur in coincidence with the lightning discharge, but with a few ms variance, and that a detectable sferic at long distances is nearly always present. The properties of TGF-associated sferics and their connection to multiple-peak TGFs are highly variable and inconsistent, and are classified into two categories. **Citation:** Cohen, M. B., U. S. Inan, R. K. Said, and T. Gjestland (2010), Geolocation of terrestrial gamma-ray flash source lightning, *Geophys. Res. Lett.*, *37*, L02801, doi:10.1029/2009GL041753.

1. Introduction

[2] It has been nearly two decades since the BATSE instrument aboard the CGRO spacecraft serendipitously made the first observations of terrestrial gamma-ray flashes (TGFs) [*Fishman et al.*, 1994]. TGFs typically last ∼1 ms with gamma-ray spectrum resembling that of bremsstrahlung (i.e., exponential spectrum with ∼7 MeV folding energy) [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007]. Rare TGFs consist of as many as 12 impulses separated by 1–2 ms. TGFs are associated with lightning discharges occurring within a few ms [*Inan et al.*, 1996; *Cummer et al.*, 2005; *Inan et al.*, 2006; *Cohen et al.*, 2006; *Stanley et al.*, 2006].

[3] TGFs are presumed to result from bremsstrahlung from collisions between relativistic electrons (accelerated into an avalanche process by lightning-associated electric fields), and neutral atmospheric molecules. However, the precise circumstances of electron acceleration and avalanche breakdown remains in question. Initially, TGFs were thought to be generated at 50–70 km altitude, resulting from quasi-electrostatic fields [*Lehtinen et al.*, 1999] exceeding the runaway breakdown threshold, but recent analysis suggest that (at least most) TGFs are sourced nearer to the thundercloud, at 15–20 km altitude [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007].

[4] In the absence of direct measurements near the TGF source, some workers [*Ostgaard et al.*, 2008; *Grefenstette et al.*, 2008; *Hazelton et al.*, 2009] have analyzed the spectral content of gamma-rays at the satellite to determine the generation altitude, avalanche multiplication number, photon energy at the source, and photon beam width. Unfortunately, these spectral studies are hampered by the ambiguous location of the TGF source, since the lightning discharge may have occurred directly beneath the spacecraft or some hundreds of km away. The escaping gamma-rays, which may be narrowly beamed or isotropically radiated from the source, travel upward through the atmosphere, undergoing Compton scattering which attenuates the number of photons, alters the spectrum, and spreads the photon beam. Hence, the angle from source to spacecraft significantly impacts the observed spectrum [*Ostgaard et al.*, 2008]. Since a single TGF event may not contain a large number of photons, the spectrum must be derived by averaging many TGFs, but such an ensemble contains an amalgam of events both near to, and far from, the satellite nadir, making interpretation more difficult and ambiguous.

[5] A notable effort to circumvent this limitation is presented by *Hazelton et al.* [2009], who divide TGFs into two groups, one for which a storm occurred within 300 km of the satellite nadir, and one without such storms, using data from the World Wide Lightning Location Network (WWLLN). A softer spectrum is reported from the latter group, attributed to more Compton scattering of gamma-rays escaping the atmosphere toward the satellite. Since the sparse detection efficiency of WWLLN (at best a few percent of cloud-to-ground (CG) lightning discharges) enables only the use of storm locations, rather than TGF-associated lightning locations, further statistical subdivisions of the source locations are not presented.

[6] Both prominent satellite detectors of TGFs to date, CGRO and RHESSI, apparently suffer from the effects of instrumental saturation ('dead time') [*Grefenstette et al.*, 2008], since neither was designed for the purpose of detecting TGFs. RHESSI also suffers from gradual radiation damage, leading to decreasing detection efficiency and knowledge of the spectral response over its lifetime [*Grefenstette et al.*, 2009].

[7] We thus turn our attention to the distribution of distances from TGF source to satellite nadir, which may present an alternative to studying the spectrum received at the satellite. The probability of a TGF event generating sufficient gamma-rays at RHESSIs altitude is a function of the source-to-nadir distance, since the Compton scattering increasingly affects a TGF sourced far away from the satellite nadir.

[8] We utilize ground-based Very Low Frequency (VLF, 3–30 kHz) radio receivers to provide the first catalog of geolocated lightning sources of TGFs. Lightning discharges generate impulsive VLF radio atmospherics (or 'sferics')

[1]STAR Laboratory, Stanford University, Stanford, California, USA.
[2]Koç University, Istanbul, Turkey.
[3]Department of Physics and Technology, University of Bergen, Bergen, Norway.

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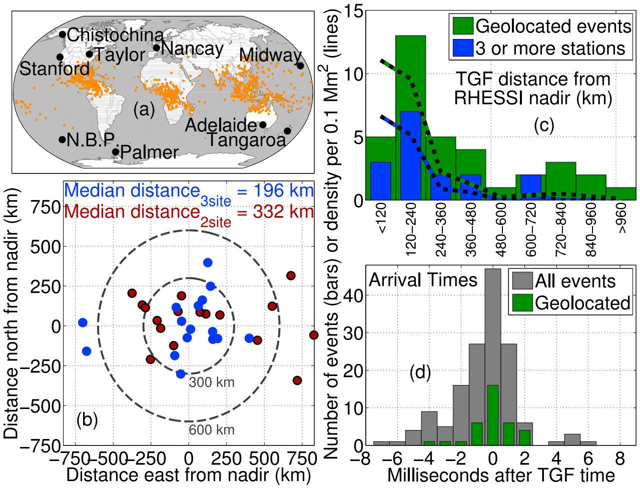

Figure 1. (a) VLF receivers used (black), and locations of all RHESSI-observed TGFs (orange), (b) scatterplot of TGF source locations with respect to RHESSI nadir, separately for 2-site cases (red) and >=3-site cases (blue), (c) distribution of distances from RHESSI nadir to TGF source, (d) distribution of arrival times of VLF sferic with respect to TGF time.

which can be detected at global distances due to efficient (few dB per Mm) attenuation in the Earth-ionosphere waveguide, so that a set of globally spaced receivers can geolocate lightning locations [*Said*, 2009]. Previous studies of TGF-associated radio atmospherics [*Inan et al.*, 1996; *Cummer et al.*, 2005; *Inan et al.*, 2006; *Cohen et al.*, 2006] utilize only one VLF receiver, and therefore cannot accurately determine the lightning location, or have discussed only a few cases [*Stanley et al.*, 2006].

2. Description of Data

[9] VLF data are acquired with the AWESOME receiver, described by *Cohen et al.* [2009], which consists of two orthogonal air-core loop antennas, sampling magnetic field spectral densities as low as a few fT/rt-Hz with 16-bit resolution at 100 kHz, and synchronized to GPS with <100 ns timing error. The receivers utilized in this study are shown with black dots in Figure 1a, along with the location of all TGFs detected by RHESSI through January 2009 in orange dots.

[10] Geolocation of lightning events with VLF data can be done with time-of-arrival (TOA) and/or magnetic direction finding. The precise arrival times of the sferics are determined using a time of group arrival technique, similar to that discussed by *Dowden et al.* [2002], but with an additional bandwidth restriction and phase calculation which takes into account the noise levels and which appears to produce more accurate geolocation results when compared with data from the National Lightning Detection Network (NLDN). Although substantially more accurate techniques have been developed for arrival time determination [*Said*, 2009], these techniques work best at distances below ~6000 km, whereas many of the TGF cases considered here occur as much as 10 Mm from the VLF receivers utilized. The arrival azimuths of sferics are determined using the direction finding technique described by *Burgess* [1993]. Estimates of the error in calculating the arrival times and azimuths of sferics are made using a comparison with NLDN data, which very conservatively suggests an error no worse than 0.05 ms in TOA determination, and 2° in arrival azimuth determination. We examine data in a/*pm*15 ms window from each TGF time. The probability of a sferic occurring by chance within ±15 ms is extremely small [*Inan et al.*, 2006].

[11] Figure 2 shows an example of lightning geolocation for a TGF detected on 11-Sep-2006, when RHESSI was 553 km above the location 17.17°N, 99.57°W, as shown in panel (f). The VLF data are shown from four receivers, in panels (a)–(d), from Palmer Station (PA, 64.77°S, 64.05°W), Taylor University (TA, 40.49°N, 85.51°W), Stanford University (SU, 37.40°N, 122.15°W), and the Nathaniel B Palmer vessel (NP, 50.65°S, 129.59°W). The gamma-ray data from RHESSI are shown in panel (e).

[12] The propagation speeds are assumed to be c for the gamma rays from RHESSI nadir (20 km altitude) to RHESSI (~550 km altitude), and 0.991c for the sferic propagation from RHESSI nadir to the VLF receiver as by *Dowden et al.* [2002]. Accounting for these delays, all four VLF receivers show arrival of a sferic within 1.5 ms of this expected time.

[13] The arrival time differences between the four receivers yield three independent TOA curves as shown in Figure 2g. The red curve shows the locus of points satisfying the observed sferic arrival times for PA and SU, the blue curve for PA and TA, and the purple curve for PA and NP. A minimum squared error point is found, near where these TOA curves meet, which is the calculated location of the TGF source.

[14] In some cases, only two VLF sites recorded the sferic, in which case only one TOA curve is available. For these cases, the arrival azimuth measured at Palmer Station (shown in black) is used to determine the location of the

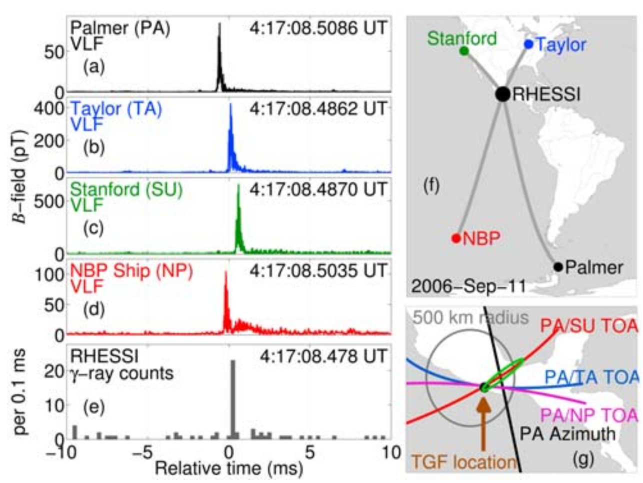

Figure 2. (a)–(d) VLF data at four receivers, corresponding to the arrival time of TGF-associated activity, (e) gamma-ray data from RHESSI, (f) the location of the four VLF receivers, as well as RHESSI, (g) the geolocation technique with time of arrival and arrival azimuth.

TGF along that TOA curve. For instance, if only the PA and SU receivers collected data and observed the TGF-associated sferic, the TGF would be presumed to be at the intersection of the black and red curves.

[15] The location errors for all cases are separately determined with a Monte Carlo calculation assuming gaussian random TOA uncertainty with standard deviations of 0.05 ms, and arrival azimuth uncertainty of 2°. The errors are (separately for each case since it depends on the geometry) characterized as ellipses. For the 2-site cases, the error ellipse is elongated in the direction along the TOA curve since arrival azimuth is inherently less accurate at long range. The green ellipse in Figure 2g shows an example of this error if only PA and SU data were available, requiring the use of arrival azimuth at PA. The error in nadir-source distance can then be calculated from the error ellipse via a Monte Carlo approach, and is typically no larger than 30 km for the 3-site cases, with a few cases being higher due to unfavorable geometry.

[16] VLF data are examined from receivers shown in Figure 1a. However, data are available only serendipitously, as each site recorded on different schedules or periods, however data from Palmer Station are available for nearly all the cases reported here. Furthermore, many TGFs occur in locations such that the sferic associated with the TGF was not detected by at least two receivers. A search of RHESSI TGFs reported through October 2009 yields 36 cases of triangulated lightning locations, 16 of which generate sferics observed by at least three receivers, the rest observed by only two receivers (one of which is Palmer Station).

[17] This particular TGF is also reported by *Hazelton et al.* [2009] as one of four exceptional cases where the TGF occurred far from the RHESSI nadir (371 km), yet included a high-energy photon, which is discussed therein as inconsistent with a narrow, low-altitude gamma-ray source. However, our geolocation results indicates this TGF to have occurred only 185 km from the RHESSI nadir, which would imply that much smaller effects of Compton scattering was present on the observed gamma-rays. The anomalous result of *Hazelton et al.* [2009] may simply have been an erroneous location from the Los Alamos Sferic Array (which is more commonly used for lightning over the continental United States).

[18] Two of the >=3-site cases (05-Oct-2009 and 24-Sep-2006) have been independently geolocated by NLDN, with the Stanford-derived location being <20 km from the NLDN-derived location, supporting the accuracy of the 3-site geolocations presented here. Both NLDN cases indicate positive intracloud strokes. The 2-site geolocations are less accurate due to the azimuth uncertainty, but are nonetheless included since they may be useful statistically.

3. Observations

[19] Figure 1b shows a scatterplot of the location of the 36 TGFs with respect to the RHESSI nadir, separately for cases where sferics were observed at two sites (red), and at three or more sites (blue). The median distance from RHESSI nadir to the TGF location is 196 km for the >=3-site cases, and 332 km for the 2-site cases, the slightly higher median for the latter category likely due to the higher geolocation error.

[20] Figure 1c shows the distribution of source-to-nadir distances, with the more accurate >=3-site cases (blue) shown separately from all cases (green). The distribution of source-to-nadir distances is shown with bars, and the line traces show the occurrence density, i.e., dividing by $1/r$ to account for the increasing area as a function of radius. The occurrence density drops by roughly a factor of 5 by the 240–360 km distance range, indicating that even small (30°) oblique angles to RHESSI (~550 km altitude) significantly impacts the number of escaping gamma-rays, and therefore the probability of detection.

[21] The relative timing of TGFs and their associated radio atmospherics has also been the source of some confusion, with results from the CGRO spacecraft [*Cohen et al.*, 2006] indicating TGFs coming after the sferic, results from RHESSI satellite initially indicating that TGFs may come before the sferic [*Cummer et al.*, 2005], leading to the suggestion of an error in the RHESSI satellite clock [*Inan et al.*, 2006]. A subsequent comparison between RHESSI data and data from the Swift instrument led to a timing correction [*Stanley et al.*, 2006], which is taken into account here.

[22] We thus present the distribution of arrival times in Figure 1d, assuming a sferic propagation path from nadir to receiver. The gray histogram shows the relative sferic arrival times at Palmer Station, Antarctica for 158 cases for which a TGF-associated sferic is observed at Palmer Station. The distribution has a mean of −0.5 ms and a standard deviation of 2.4 ms, in line with past studies after the timing correction [*Cummer et al.*, 2005; *Inan et al.*, 2006; *Cohen et al.*, 2006].

[23] However, this statistical approach includes ~3 ms uncertainty for a given event, owing to the unknown TGF location, and this uncertainty is removed by the geolocation. In the green histogram shown in Figure 1d, therefore, the arrival times are exact, and need not be analyzed statistically. As discussed later, some TGFs consist of multiple sferics, in which cases the earliest sferic is chosen.

[24] The TGF usually occurs within 2 ms before or after the sferic, consist with the conclusion of *Inan et al.* [2006] of at least a 2 ms variance in the relative timing of TGF and sferic arising as a result of the TGF generation processes and their temporal connection to the sferic, which, as evidenced by this 2 ms variation, may not be a direct link. However, the RHESSI clock accuracy remains subject to some ambiguity, so this question may be explored by future missions.

4. TGFs and sferics

[25] *Inan et al.* [2006] present 116 TGF cases for which associated radio atmospherics occur within ±15 ms of the TGF, arriving from the region of RHESSI. *Inan et al.* [2006] also report that a minority (24%) do not have associated radio atmospherics at Palmer Station, Antarctica, even though the receiver there is sensitive to CG lightning flashes as low as 3 kA at a distance of 10 Mm. It is concluded therein that some TGFs may occur in the presence of lightning activity, but not VLF-radiating lightning discharges.

[26] However, revisions to the catalog of TGF events [*Grefenstette et al.*, 2009] resulted in some being reclassified as statistical anomalies, including both of the TGF cases presented in Figure 4 of *Inan et al.* [2006]. There now

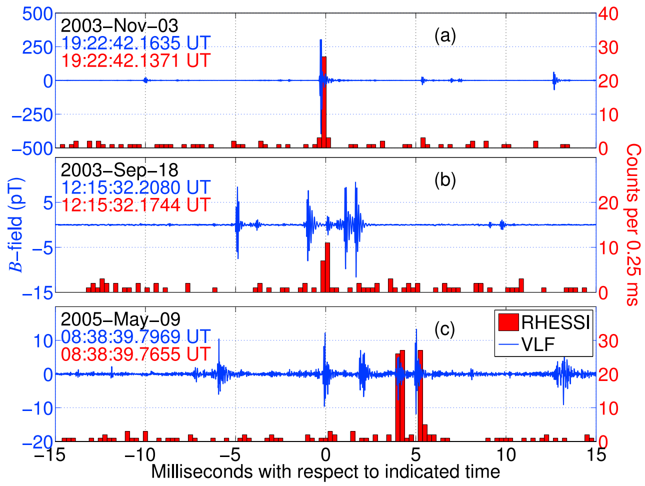

Figure 3. Three examples of VLF sferics (blue) observed at Palmer Station, in association with RHESSI gamma-ray data (red).

remain only a small number of cases (9 out of 158 analyzed) for which an associated radio atmospheric cannot be observed at Palmer Station under the criteria utilized by *Inan et al.* [2006]. These few remaining cases, assuming they are not statistical anomalies, possibly originate alternatively from weak intracloud lightning discharges as opposed to the existence of TGFs without sferics. The very high percentage of TGFs whose radio atmospherics are observable from many Mm away is consistent with the conclusion by *Inan et al.* [2006] that TGFs are often associated with the more powerful lightning activity in a given storm, or may also be associated with narrow bipolar pulses [*Stanley et al.*, 2006] since weak IC lightning activity is not detectable with VLF measurements at very long distances.

[27] The characteristics of TGF-associated sferics are widely disparate, as shown in Figure 3, and are distinguished into at least two categories. Many observed sferics show a single strong impulse, consistent with the signature of a powerful CG lightning discharge. An example of this single-impulse category is shown in the blue trace of Figure 3a, with the corresponding RHESSI gamma-ray data shown with red bars. A second category of TGFs are associated with a train of typically smaller sferics, separated by a few ms, as exemplified in Figure 3b. The first category occurs slightly more often among 158 cases examined.

[28] A small fraction of TGFs consist of multiple peaks separated by 1–2 ms, with one remarkable event reported by CGRO (BATSE trigger 8006 on 01-Mar-2000) consisting of ~12. *Cohen et al.* [2006] report one observation of a triple-peak TGF (BATSE trigger 3925) associated with a triple-peak sferic. However, the connection between sferic peaks and TGF peaks is not one-to-one. Figure 3c shows a dual-peak TGF detected by the RHESSI spacecraft, where the ground VLF recordings show four small sferics between 0 and 5 ms, which are all determined (via direction finding) to have come from the RHESSI nadir direction. The two sferics that appear to correspond to the two TGF peaks are neither the first two nor the strongest two. The inconsistency in the sferic characteristics, as well as the aforementioned timing variance, may indicate that the fields generating the TGF are not directly connected to the fields generating the sferic, though a TGF may nonetheless require the conditions that usually lead to a sferic.

5. Conclusion

[29] We have provided the first catalog of precise TGF locations, based on observations from the RHESSI spacecraft in coordination with ground-based VLF data. The source-to-nadir distances are presented, whose statistical distribution arises as a result of the increasing effects of Compton scattering for increasing horizontal distances from TGF source to RHESSI nadir. Table S1 showing TGF distances for all 36 events discussed here is provided as auxiliary material, along with the distance uncertainty and sferic multiplicity.[1]

[30] We have analyzed the arrival times of the sferic compared to the TGF (after removing the geographic uncertainty). In addition, we have given examples of widely disparate characteristics of TGF-associated sferic waveforms, classified them into two categories, and discussed the inconsistent connection between multiple-peak TGFs and separate VLF impulses.

[31] **Acknowledgments.** This work was supported by NSF grant OPP-0233955 to Stanford University. We thank David Smith and Brian Greffenstette for making RHESSI data available at http://scipp. ucsc.edu/~dsmith/tgflib_public, and for helpful discussions. We thank Brant Carlson for helpful discussions.

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M. B. Cohen, U. S. Inan, and R. K. Said, Electrical Engineering Department, Stanford University, 350 Serra Mall, Rm. 356, Stanford, CA 94305, USA. (mcohen@stanford.edu)

T. Gjestland, Department of Physics and Technology, University of Bergen, Postboks 7803, N-5020 Bergen, Norway.