Simultaneous observations of optical lightning and terrestrial gamma ray flash from space

N. Østgaard,[1,2] T. Gjesteland,[1,2] B. E. Carlson,[1,2,3] A. B. Collier,[4,5] S. A. Cummer,[6] G. Lu,[6] and H. J. Christian[7]

Received 26 February 2013; revised 26 February 2013; accepted 11 April 2013; published 30 May 2013.

[1] We present the very first simultaneous detection from space of a terrestrial gamma ray flash (TGF) and the optical signal from lightning. By fortuitous coincidence, two independent satellites passed less than 300 km from the thunderstorm system that produced a TGF that lasted 70 μs. Together with two independent measurements of radio emissions, we have an unprecedented coverage of the event. We find that the TGF was produced deep in the thundercloud at the initial stage of an intracloud (IC) lightning before the leader reached the cloud top and extended horizontally. A strong radio pulse was produced by the TGF itself. This is the first time the sequence of radio pulses, TGF, and optical emissions in an IC lightning flash has been identified.
Citation: Østgaard, N., T. Gjesteland, B. E. Carlson, A. B. Collier, S. A. Cummer, G. Lu, and H. J. Christian (2013), Simultaneous observations of optical lightning and terrestrial gamma ray flash from space, *Geophys. Res. Lett.*, *40*, 2423–2426, doi:10.1002/grl.50466.

1. Introduction

[2] Terrestrial gamma ray flashes (TGFs), typically lasting 300-400 μs [*Gjesteland et al.*, 2010; *Fishman et al.*, 2011a; *Grefenstette et al.*, 2009], are the most energetic natural photon phenomenon on Earth (>40 MeV) [*Marisaldi et al.*, 2010]. When first discovered [*Fishman et al.*, 1994], they were believed to be produced at high altitudes and related to sprites. With new observations [*Cummer et al.*, 2005; *Dwyer and Smith*, 2005] and new analyses [*Østgaard et al.*, 2008; *Gjesteland et al.*, 2010], it is now established that their production altitude is <20 km and probably below the tropopause. Recent studies strongly suggest that TGFs occur during the initial phase of a normal polarity intracloud (IC) lightning flash, bringing negative charges upward [*Stanley et al.*, 2006; *Shao et al.*, 2010; *Lu et al.*, 2010; *Cummer et al.*, 2011]. By applying a new and more sophisticated search algorithm to the data obtained by Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), more than twice as many TGFs than previously reported have been identified [*Gjesteland et al.*, 2012a], mostly weaker TGFs, increasing the probability to have supporting data to address the relation between TGFs and lightning. Here we report the very first simultaneous observations from space of a TGF and the corresponding optical lightning signal. By fortuitous coincidence, two independent satellites passed less than 300 km from the thunderstorm system that produced a TGF that lasted 70 μs. In addition, we have two independent measurements of radio signals from the event, giving us unique coverage of the sequence of events related to the TGF.

2. Results

[3] On 27 October 2006 at 04:56:03 UT, RHESSI and the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) flew over the same thunderstorm that had developed over Lake Maracaibo in northern Venezuela. The site is known for its frequent and powerful lightning flashes, Catatumbo lightning. Simultaneously, the two satellites observed a weak TGF and the optical signals from a lightning discharge (Figure 1). Very low frequency (VLF) radio emissions produced by the same thunderstorm were recorded by both sensors near Duke University and by the World Wide Lightning Location Network (WWLLN). LIS, with a detection efficiency of more than 85% [*Christian et al.*, 2003], provides a precise location and time history of the optical emissions. WWLLN, which had a lightning (IC and cloud-to-ground) detection efficiency of 2.3% in 2006 [*Abarca et al.*, 2010], confirms the location of the source. The continuous VLF signal from the Duke sensors provides the detailed sequence of the radio emissions. Having both the TGF and the optical signals and two independent measurements of VLF signals, the two latter with temporal accuracy of ∼20 μs (Duke) and ∼45 μs (WWLLN), gives us a unique opportunity, even with the RHESSI and LIS time uncertainties (0.4 ms and 0.2 ms, respectively), to untangle the sequence of events in this lightning activity that produced the TGF. By comparing the WWLLN matches with the new RHESSI TGFs and correcting the RHESSI TGF times for the light travel time from WWLLN times at the source to the satellite, *Gjesteland et al.* [2012b] showed that there is a systematic lag of the RHESSI clock by 1.9 ms with an uncertainty (σ) of 0.4 ms.

[4] Within a 12 s window, LIS detected lightning activity from three different convective cells about 30 km apart (marked with #1, #2, and #3 in Figure 2b). The lightning started in the convective cell with the coldest cloud

[1]Birkeland Centre for Space Science, University of Bergen, Bergen, Norway.
[2]Department of Physics and Technology, University of Bergen, Bergen, Norway.
[3]Physics and Astronomy Department, Carthage College, Kenosha, Wisconsin, USA.
[4]SANSA Space Science, Hermanus, South Africa.
[5]School of Physics, University of KwaZulu-Natal, Durban, South Africa.
[6]Electrical and Computer Engineering Department, Duke University, Durham, North Carolina, USA.
[7]Earth System Science Center, The University of Alabama in Huntsville, Huntsville, Alabama, USA.

Corresponding author: N. Østgaard, Department of Physics and Technology, Allegt. 55, N-5007, Norway. (Nikolai.Ostgaard@ift.uib.no)

0094-8276/13/10.1002/grl.50466

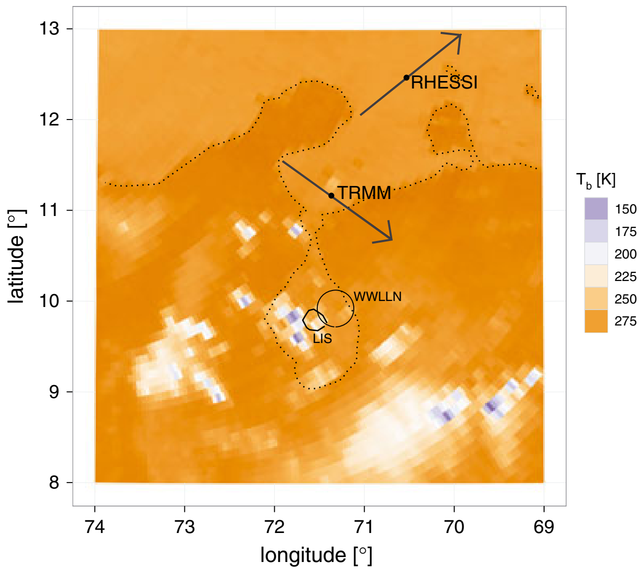

Figure 1. Map showing the geometry of the observation of the TGF measured simultaneously by RHESSI, TRMM/LIS, and WWLLN. The dotted line is the coastline of northern Venezuela including Lake Maracaibo. The color scale shows brightness temperature measured by the TRMM Microwave Imager (TMI), with cold regions indicating high cloud tops over active convective cells. TRMM and RHESSI trajectories are marked along segments of their eastward orbits and their positions when the TGF occurred with dots. The stroke related to the TGF observation was detected by the LIS from a cell top of about 200 K that corresponds to an altitude of ~16 km. A WWLLN signal was recorded from the same cell. The location of the coincident brightness measured by LIS is outlined, and the inferred location of the WWLLN stroke is marked with a dot surrounded by a thin circle with 15 km radius representing typical errors in WWLLN geolocation.

top (Figure 2b, #1) with relatively strong optical signatures (Figure 2a) and then moved to convective cell #2 (Figure 2b) also with a high cloud top, about 200 K, corresponding to ~16 *km*. The optical emissions from this cell were observed for about 330 ms (Figures 2b–2i) and developed as one would expect for an IC discharge: during the initial stage, a leader formed deep in the thundercloud (Figure 2b) then propagated upward before extending horizontally when it reached the cloud top (Figure 2c) [*Shao and Krehbiel*, 1996; *Thomas et al.*, 2000]. The TGF and the VLF signals were observed during the first detected optical emissions in cell #2 (Figure 2b).

[5] Figure 3a shows the optical signals detected by LIS in the interval ±6 s relative to the TGF observed by RHESSI. Six radio signals were detected by WWLLN during that interval and one of them is simultaneously with the TGF. The TGF detected by RHESSI is a weak one with only 10 counts (Figure 3b). For the exact timing of the events, we refer to Figure 3c and Table 1. All times, except for WWLLN, have been shifted back to the source location determined by LIS, by subtracting the propagation time to RHESSI 618 km away as well as the systematic lag of the RHESSI clock by 1.9 ms, LIS 412 km away, and Duke 3010 km away. The WWLLN time is shifted back to source location determined by the five WWLLN stations several thousand kilometers away, giving a total timing and location uncertainty of 45 μs and 15 km, respectively. To determine the time of the first optical emissions detected by LIS, we notice the following: In the first 2 ms integration window (Figure 2B), three pixels are weakly illuminated while the same three pixels are among the brightest in the next 1.5 ms window. This indicates that the optical pulse was split between the two frames, with only 25% of the energy in the first frame. Considering a typical rise time of the pulse of about 150 μs, we therefore believe the first optical signal started at 04:56:03.08062 UT. For a temporal analysis, we consider the following: First, Duke recorded a weak VLF signal (*a* in Figure 3c) at 04:56:03.07624 UT that could signify the initiation of the streamer/leader formation.

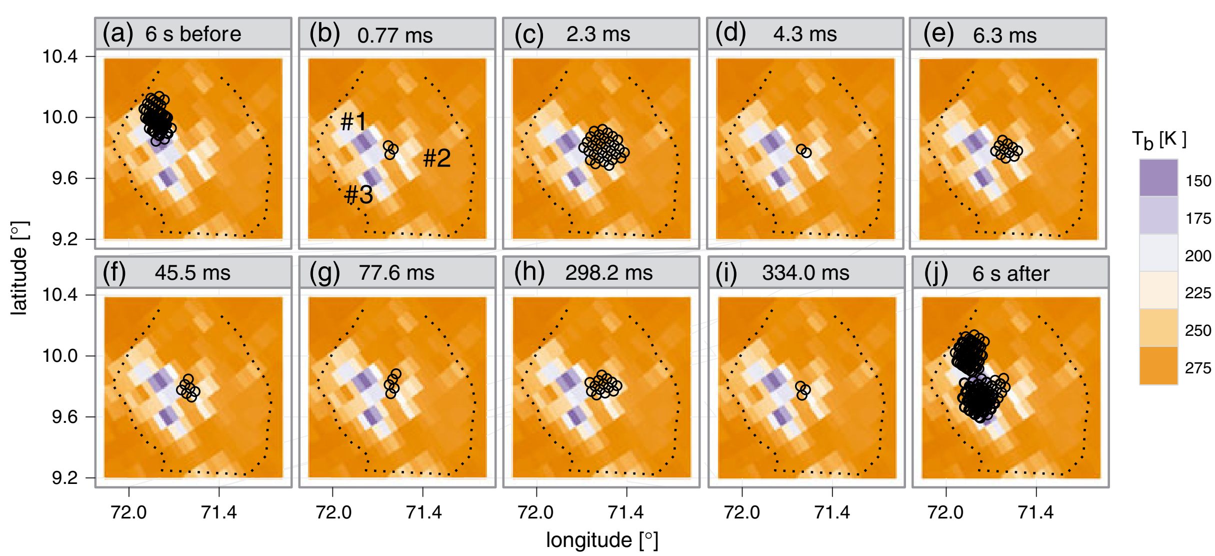

Figure 2. Each panel shows the LIS events at a given time. (a and j) All the events 6 s prior to Figure 2b and after Figure 2i. Figure 2b shows the stroke closest in time to the TGF and #1, #2, and #3 mark the three convective cells. (b–i) Integration time varying between 1.5 ms and 2.1 ms, and the times are the end of the integration interval relative to 04:56:03.00 UT.

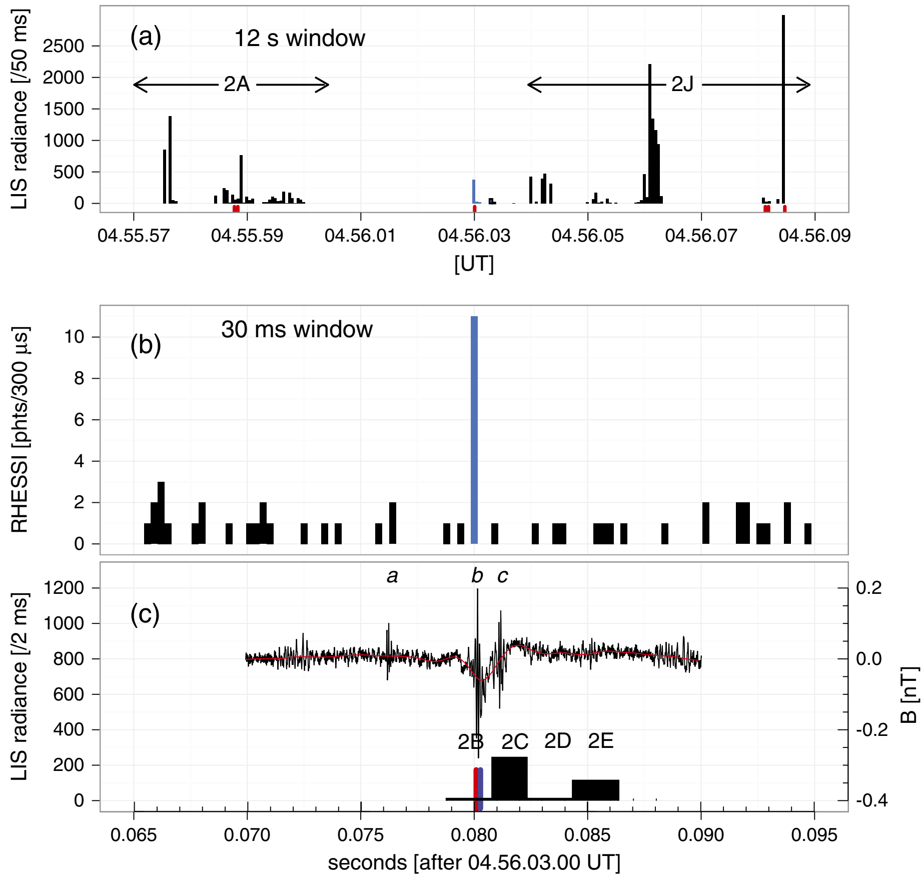

Figure 3. (a) Lightning activity as measured by LIS radiance (μJ/sr/m^2/μs) summed over 50 ms bins during a 12 s window centered on the event. The red bars are the WWLLN events. (b) The RHESSI count rate (300 μs bins). (c) The LIS radiance (μJ/sr/m^2/μs) summed over 2 ms bins (black histograms) for a 30 ms window centered on the TGF event (blue bar), with WWLLN marked with red bar. The Duke VLF signals are shown in black overlaid with a smoothed red line to show the slow pulse. References to the images in Figure 2 are indicated in Figures 3a and 3c.

Then, two distinct VLF radio pulses were recorded (*b* and *c* in Figure 3c) by Duke while the automated algorithm by WWLLN triggered on and geolocated the first one (pulse *b* is recorded by Duke and WWLLN simultaneously, within 50 μs). LIS detected the first optical signal about 0.50 ms (nominal time) after pulse *b* (Duke and WWLLN), and the peak of the optical signal (Figure 2c and 2C in Figure 3c) was almost simultaneously with radio pulse *c*. These observations are consistent with a leader forming deep in the thundercloud propagating upward to become optically visible by LIS when it reaches about 12–15 km [*Thomas et al.*, 2000]. Assuming typical values of leader upward propagation speed for the initial stage of an IC flash of 1.5–3 10^5 m/s [*Shao and Krehbiel*, 1996; *Behnke et al.*, 2005], a time difference of 4.4 ms (between VLF pulse *a* and LIS) implies that the leader traveled 650–1300 m before it became detectable by LIS and 900–1800 m (after 6 ms) before it extended horizontally in the positive charge layer at the cloud top (Figure 2c).

[6] Using the nominal detection time by RHESSI, the TGF was recorded simultaneously with the VLF pulse *b* (within 100 μs). Even with the uncertainty of RHESSI timing of 0.4 ms, these observations definitely show that the TGF was produced during the initial stage of the IC discharge (Figure 2). The TGF reported here is part of the new distribution identified by a new algorithm applied to the RHESSI data [*Gjesteland et al.*, 2012a] and is weaker and shorter than the TGFs previously reported. As the TGF

Table 1. Nominal Times of Events[a]

Observed Events	Time at Source [s after 04:56:03.00]	Uncertainty (ms)	Platform	Relative to LIS (ms)	Relative to RHESSI (ms)
Fast VLF pulse *a*	0.07624	0.020	Duke	–4.4	–4.0
Fast VLF pulse *b*	0.08012	0.020	Duke	–0.50	–0.10
	0.08016	0.045	WWLLN	–0.46	–0.060
TGF	0.08022	0.4	RHESSI	–0.40	-
Fast VLF pulse *c*	0.08116	0.020	Duke	+0.54	+0.94
Optical emissions	0.08062	0.2	LIS	-	+0.40

[a]At source location determined by LIS, except WWLLN time, which is at source location determined by WWLLN.

is observed within a nadir angle <30°, this could be a truly weak TGF and not just attenuated by absorption and Compton scattering [*Østgaard et al.*, 2008; *Gjesteland et al.*, 2011]. However, it is more likely that the TGF was produced just a few kilometers lower than average in the thundercloud. The charge moment derived from the Duke signal of 48 C km is about average for lightning that have been related to TGFs [*Cummer et al.*, 2005] and supports such a lower production altitude.

[7] Even though the timing coincidence between RHESSI TGF and VLF pulse *b* indicates that the VLF pulse *b* is produced by the TGF [*Cummer et al.*, 2011; *Dwyer*, 2012] and not by the bright optical signal detected by LIS 0.5 ms later, the uncertainty of RHESSI and LIS timing (0.4 ms and 0.2 ms, respectively) prevents us from drawing such a conclusion based on the relative timing only. However, there are additional factors that indicate that this is indeed the case. First, the observed TGF had a short duration of 70 μs (t_{FWHM}) from which a current moment of 13 kA km can be estimated [*Dwyer*, 2012, equation (24)]. This is comparable to the current moment derived from the Duke signal of 24 *kA km*. Second, in 2006 WWLLN had a detection efficiency of only 1.8% of IC lightning increasing to 4.8% in 2009 [*Abarca et al.*, 2010]. For the new RHESSI TGFs, the match rate with WLLNN is as high as 12.4% in 2006, and for the short TGFs detected by Fermi, the match rate is more than 40% for TGFs with $t_{\mathrm{FWHM}} < 160\mu\mathrm{s}$ increasing to >50% for $t_{\mathrm{FWHM}} < 120\mu\mathrm{s}$ in 2008–2011 [*Connaughton et al.*, 2012]. (For comparison with t_{50} in Figure 2 by *Connaughton and et al.* [2012], the conversion is $t_{\mathrm{FWHM}} = 2\sqrt{2\ln 2}\,\sigma = 2.35 \times 0.74\, t_{50}$.) The fact that WWLLN did detect the VLF emissions (pulse *b*) coincident with the short TGF and not the one coinciding with the optical emissions (pulse *c*) is consistent with the factor of ~10 times larger detection efficiency of TGFs than of ICs and supports our conclusion that the VLF pulse *b* was produced by the TGF itself.

3. Summary

[8] We have reported the very first simultaneous observations of a TGF and the corresponding optical lightning signal observed from space. With the support of two independent measurements of radio signals from the event, we have a unique coverage of the sequence of events related to the TGF. Our observations show that this weak and short TGF (70 μs) was produced deep in the thundercloud at the initial stage of a normal polarity IC lightning propagating upward before the leader reached the cloud top and extended horizontally. A strong radio pulse that was detected and geolocated coincidentally with the TGF was most likely produced by the TGF itself. This is the first time the sequence of radio pulses, TGF, and optical emissions in an IC lightning flash has been identified.

[9] **Acknowledgments.** This study was supported by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n. 320839 and the Research Council of Norway under contracts 197638/V30, 208028/F50, and 216872/F50. We thank the RHESSI team and D. M. Smith for the use of RHESSI raw data and software. The LIS/OTD Lower Level Data and LIS/ODT software were provided by the LIS/OTD Science Team (Principal Investigator Hugh J. Christian). We thank the institutions contributing to WWLLN (http://wwlln.net/). The Duke University component of this work was supported by the NSF Physical and Dynamical Meteorology Program.

[10] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Abarca, S. F., K. L. Corbosiero, and T. J. G. Jr (2010), An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth, *J. Geophys. Res.*, *115*, D18206, doi:10.1029/2009JD013411.

Behnke, S. A., R. J. Thomas, P. R. Krehbiel, and W. Rison (2005), Initial leader velocities during intracloud lightning: Possible evidence for a runaway breakdown effect, *J. Geophys. Res.*, *110*, D10207, doi:10.1029/2004JD005312.

Christian, H. J., et al. (2003), Global frequency and distribution of lightning as observed from space by the optical transient detector, *J. Geophys. Res.*, *108*, 4005, doi:10.1029/2002JD002347.

Connaughton, V., et al. (2012), Radio signals from electron beams in terrestrial gamma-ray flashes, *J. Geophys. Res.*, doi:10.1029/2012JA018288.

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.

Cummer, S. A., G. Lu, M. S. Briggs, V. Connaughton, S. Xiong, G. J. Fishman, and J. R. Dwyer (2011), The lightning-TGF relationship on microsecond timescales, *Geophys. Res. Lett.*, *38*, L14810, doi:10.1029/2011GL048099.

Dwyer, J. R. (2012), The relativistic feedback discharge model of terrestrial gamma ray flashes, *J. Geophys. Res.*, *117*, A02308, doi:10.1029/2011JA017160.

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.

Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *164*, 1313.

Fishman, G. J., et al. (2011a), Temporal properties of the terrestrial gamma-ray flashes from the Gamma-Ray Burst Monitor on the Fermi Observatory, *J. Geophys. Res.*, *116*, A07304, doi:10.1029/2010JA016084.

Gjesteland, T., N. Østgaard, J. Stadsnes, P. H. Connell, and G. J. Fishman (2010), Effects of deadtime losses on terrestrial gamma ray flash measurements done by the Burst And Transient Source Experiment, *J. Geophys. Res.*, *115*, A00E21, doi:10.1029/2009JA014754.

Gjesteland, T., N. Østgaard, A. B. Collier, B. E. Carlson, M. B. Cohen, and N. G. Lehtinen (2011), Confining the angular distribution of terrestrial gamma-ray flash emission, *J. Geophys. Res.*, *116*, A11313, doi:10.1029/2011JA016716.

Gjesteland, T., N. Østgaard, A. B. Collier, B. E. Carlson, C. Eyles, and D. M. Smith (2012a), A new method reveals more TGFs in RHESSI data, *Geophys. Res. Lett.*, *39*, L05102, doi:10.1029/2012GL050899.

Gjesteland, T., N. Østgaard, R. S. Hansen, B. E. Carlson, and A. B. Collier (2012b), Analysis of the recent RHESSI TGFs, *AGU Fall Meeting, AE33A-0364,* San Francisco.

Grefenstette, B. W., D. M. Smith, B. J. Hazelton, and L. I. Lopez (2009), First RHESSI terestrial gamma ray flash catalog, *J. Geophys. Res.*, *114*, A02314, doi:10.1029/2008JA013721.

Lu, G., et al. (2010), Lightning mapping observation of a terrestrial gamma-ray flash, *Geophys. Res. Lett.*, *37*, L11806, doi:10.1029/2010GL043494.

Marisaldi, M., et al. (2010), Detection of terrestrial gamma ray flashes up to 40 MeV by the AGILE satellite, *J. Geophys. Res.*, *107*, A00E13, doi:10.1029/2009JA014502.

Østgaard, N., T. Gjesteland, J. Stadsnes, P. H. Connell, and B. Carlson (2008), Production altitude and time delays of the terrestrial gamma flashes: Revisiting the Burst and Transient Source Experiment spectra, *J. Geophys. Res.*, *113*, A02307, doi:10.1029/2007JA012618.

Shao, X. M., and P. R. Krehbiel (1996), The spatial and temporal development of intracloud lightning, *J. Geophys. Res.*, *101*, 26,641–26,668, doi:10.1029/96JD01803.

Shao, X. M., T. Hamlin, and D. M. Smith (2010), A closer examination of terrestrial gamma-ray flash-related lightning processes, *J. Geophys. Res.*, *115*, A00E30, doi:10.1029/2009JA014835.

Stanley, M. A., X. M. Shao, D. M. Smith, L. I. Lopez, M. B. Pongratz, J. D. Harlin, M. Stock, and A. Regan (2006), A link between terrestrial gamma-ray flashes and intracloud lightning discharges, *Geophys. Res. Lett.*, *33*, L06803, doi:10.1029/2005GL025537.

Thomas, R. J., P. R. Krehbiel, W. Rison, T. Hamlin, D. J. Boccippio, S. J. Goodman, and H. J. Christian (2000), Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma, *Geophys. Res. Lett.*, *27*, 1703–1706, doi:10.1029/1999GL010845.