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Key Points:

- LIS metrics are defined that describe the overall structure of optical flashes, their energetics, and their evolutions with time
- Extreme optical flashes are observed with an 89 km separation between groups, 234 visible branches, and durations as long as 7.4 s
- The largest footprint area (10,604 km^2) and diameter (162 km) flashes appear to result from scattering of optical energy from radiant groups

Supporting Information:

- Supporting Information 1
- Movie S1
- Movie S2
- Movie S3
- Movie S4
- Movie S5
- Movie S6
- Movie S7
- Movie S8

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The Evolution and Structure of Extreme Optical Lightning Flashes

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Abstract This study documents the composition, morphology, and motion of extreme optical lightning flashes observed by the Lightning Imaging Sensor (LIS). The furthest separation of LIS events (groups) in any flash is 135 km (89 km), the flash with the largest footprint had an illuminated area of 10,604 km^2, and the most dendritic flash has 234 visible branches. The longest-duration convective LIS flash lasted 28 s and is overgrouped and not physical. The longest-duration convective-to-stratiform propagating flash lasted 7.4 s, while the longest-duration entirely stratiform flash lasted 4.3 s. The longest series of nearly consecutive groups in time lasted 242 ms. The most radiant recorded LIS group (i.e., "superbolt") is 735 times more radiant than the average group. Factors that impact these optical measures of flash morphology and evolution are discussed. While it is apparent that LIS can record the horizontal development of the lightning channel in some cases, radiative transfer within the cloud limits the flash extent and level of detail measured from orbit. These analyses nonetheless suggest that lightning imagers such as LIS and Geostationary Lightning Mapper can complement ground-based lightning locating systems for studying physical lightning phenomena across large geospatial domains.

Plain Language Summary The World Meteorological Organization recently accepted new records for the greatest length and duration of a lightning flash. These extreme flashes were observed by Lightning Mapping Array (LMA) networks that use radio emissions to trace the path lightning takes through the cloud. Optical instruments such as the Lightning Imaging Sensor (LIS) measure the evolution of lightning from orbit by recording the light that escapes the top of the cloud. For many flashes, the optical signals reveal similar patterns of development to what is seen by LMAs. Though lightning imagers provide a limited picture of flash structure, their unparalleled global view is valuable for studying lightning phenomena in remote and data sparse regions. This study identifies the most exceptional lightning flashes detected by LIS on the Tropical Rainfall Measuring Mission satellite and examines their optical structure, energetics, and evolutions. The longest optical flashes are shorter than the LMA records but still depict lateral development over a 50–100 km distance. The longest-lasting LIS flashes rival the LMA record at 4–7 s. Notable examples of LIS flashes with radiant optical pulses ("superbolts"), flashes with many visible branches, and flashes that contain clusters of nearly continuous illumination are also identified.

1. Introduction

Lightning imagers are specialized optical instruments that measure changes in cloud radiance caused by lightning activity. Two such instruments have surveyed lightning from low-Earth orbit. The Optical Transient Detector (OTD) flew between 1995 and 2000 aboard the MicroLab-1 satellite at an inclination of 70° and altitude of 735 km (Boccippio et al., 2000). The Lightning Imaging Sensor (LIS: Christian et al., 2000) was subsequently included in the Tropical Rainfall Measuring Mission (TRMM) satellite sensor package. With an inclination of 35°, LIS on TRMM sampled the tropics between December 1997 and June 2015 at an initial altitude of 350 km that was boosted to 403 km in 2001. TRMM offered more than 3 times the temporal coverage of OTD and hosted a diverse collection of meteorological instrumentation that provided coincident measurements of the precipitation structure of the parent thunderstorm. These included a Precipitation Radar (PR), Microwave Imager (TMI), and Visible and Infrared Scanner (VIRS) (Kummerow et al., 1998).

Knowledge of the parent thunderstorm is essential for understanding the appearance of an optical lightning flash because the optical emissions are modified by scattering within the cloud medium (Boccippio et al., 2000; Peterson et al., 2016). This complicates the assessment of trends in the lightning imager data since flashes observed under favorable conditions can appear differently than flashes observed under less favorable conditions. For example, a flash observed at night with a low background radiance would appear larger than the same flash observed during the day. Peterson et al. (2016) discussed scenarios like this using TRMM PR, TMI, and VIRS measurements. Scattering effects are sufficiently pronounced that they can also be noted in videos of thunderstorms taken from the International Space Station (ISS).

The complement of sensors on TRMM make the satellite a powerful platform for comparing the distribution and morphology of optical flashes with the measurable precipitation structure of the parent thunderstorm (Peterson & Liu, 2011, 2013). Optical lightning studies that use different satellites will require a fusion of data from multiple independent platforms to provide the coincident radar and passive microwave view that was available on TRMM. Two new lightning imagers that have recently been launched include a second LIS deployment aboard the International Space Station (ISS; Blakeslee et al., 2014) and the Geostationary Lightning Mapper (GLM) on the Geostationary Operational Environmental Satellite R/16 (Goodman et al., 2013).

Exceptional lightning flashes are particularly relevant following the World Meteorological Organization (WMO) acknowledgement of new records for the longest reported distance and duration covered by lightning. Regional Lightning Mapping Array (LMA) networks (Thomas et al., 2004) observed a 321 km long flash over Oklahoma and a flash over southern France that lasted 7.74 s (Lang et al., 2016). LMA systems map the development of the lightning channel in the very high frequency (VHF) radio band with an exceptional level of detail, but over a limited range of a few hundred kilometers. LMA observations are not available in parts of the world that are known for exceptional lightning, particularly over the open ocean (Hutchins et al., 2013; Orville & Huffines, 2001; Peterson & Liu, 2013). The only measures of flash development and structure in these regions are what can be viewed from orbit.

This study identifies the most exceptional examples of flash structure, energetics and scattering, and evolution in the optical TRMM-LIS data set. LIS measurements are used to quantify the length, the areal extent, the duration, the peak radiance, the number of visible branches, the number of distinct radiant pulses, and the longest interval of nearly continuous illumination in each flash. Exceptional flashes based on these metrics are examined in the context of the coincident cloud measurements provided by TRMM.

2. Data and Methodology

2.1. Definitions of LIS Features

This study uses the LIS science data set hosted by the Global Hydrology Resource Center (GHRC) DAAC. LIS measurements are stored in orbit files that document the properties of lightning features ranging from individual illuminated pixels to entire thunderstorm areas. These features provide a consistent framework that describes the transient optical pulses produced by lightning. LIS features are given a specific nomenclature and set of definitions that are defined in the LIS Algorithm Theoretical Basis Document (Christian et al., 2000; Mach et al., 2007). Individual LIS pixels (4–5 km at center of the field of view) that are illuminated beyond a dynamic background radiance threshold are identified as *events*. Events within the same ~2 ms LIS frame are clustered into features known as *groups* that represent the radiance of the flash at a given instant. Groups that occur within 330 ms and 5.5 km of each other are clustered into *flashes*.

Since there are 2 orders of magnitude that separate a LIS flash feature (330 ms) from a LIS group feature (2 ms), the standard LIS hierarchy often obscures lightning processes that last longer than a group and shorter than a flash. The lateral development of the lightning channel is one example. Peterson et al. (2016) identifies horizontal propagation, which is a phenomenon that occurs over the course of multiple LIS groups but may still only correspond to a portion of a flash. Other examples include strokes (Koshak, 2010) and continuing currents (Bitzer, 2017).

We define a LIS *series* of quasi-subsequent groups feature that exists between the group and flash level to cluster distinct optical pulses that result from some of these phenomena. A typical LIS flash can be described as a collection of temporally isolated groups dispersed throughout the flash duration. Thus, a natural manner of partitioning flashes into smaller features is to distinguish time intervals of continuous illumination. Bitzer and Christian (2015) and Bitzer (2017) use a time continuous group method to calculate the on-orbit frame rate of the LIS instrument and identify continuing current. Using time-adjacent groups to define series

Table 1
LIS Flash, Series, and Group Characteristics in the LIS Feature Database

Parameter name	Defined for: Flashes	Series	Groups
Atomic time (TAI93)	X	X	X
Latitude and longitude	X	X	X
Footprint area	X	X	X
Duration	X	X	
Total radiance	X	X	X
Number of			
Visible branches	X		
Series	X		
Bright series	X		
Groups	X	X	
Events	X	X	X
Maximum separation of			
Groups	X	X	
Events	X	X	X
Propagation factor	X	X	
Elongation factor	X	X	X
Radiance ratio	X	X	X
Maximum group radiance	X	X	
Total series duration	X		
Longest series duration	X		

features becomes problematic when the maximum event energy in each fame is near the threshold for detection, however. In this case, a single frame that does not exceed the background threshold is sufficient to divide a series in two. Since most LIS groups are composed of events that are at maximum within a factor of 2 of the lowest measured radiance, there is a significant potential for series splitting in any given flash.

We thus define series features as a collection of quasi-subsequent groups that may be separated by one or more empty 2 ms frames. The tolerance for the duration of allowed gaps in a series is adjustable depending on the application. We use a tolerance of one empty frame between groups in this initial application of LIS series features. Series are integrated into the LIS hierarchy with a full set of reported properties (footprint area, total radiance, etc.), parent features (flashes, areas), and child features (groups, events). We specifically identify the subset of *bright series* that contain particularly radiant optical pulses. These are defined by calculating the mean and standard deviation of total group radiance for a given flash, and then identifying groups whose radiance exceeds one standard deviation above the mean. A bright series is any series feature that contains at least one of these particularly radiant groups.

Like the LIS flash features, series features may be composed of a single LIS group. A LIS flash always contains at least one series and may contain multiple bright series. The 1-sigma group radiance threshold allows for bright series multiplicity within a flash and scales with its radiant energy regardless of cloud type or time of day. Series features are constructed for all 97,344 orbit files in the LIS science data set, but we do not consider any examples from 2015 out of caution for data quality issues as TRMM was approaching the end of its operational life.

2.2. Definitions of LIS Lightning Characteristics

The characteristics of LIS flashes and their constituent series and groups are collected into a common LIS feature database. The full list of available parameters in this database is shown in Table 1. These include the standard properties reported in the LIS science data set, similar measures for the new series features, and the elongation, propagation, and radiance ratio metrics introduced in Peterson et al. (2016). Elongation is defined as the furthest separation of events in a LIS feature divided by the characteristic diameter of the flash. The flash characteristic diameter is calculated as the distance across a circle with the same area as the reported flash footprint. Propagation is similarly defined as the furthest separation of group centroids (abbreviated group separation) in a LIS feature divided by its characteristic diameter. As in Peterson et al. (2016), a flash, series, or group is considered “elongated” if its elongation factor is greater than 1 and a flash or series is considered “propagating” if its propagation factor is greater than 0.5. Finally, the radiance ratio is defined as the quotient between the maximum event radiance of a flash, series, or group divided by its minimum event radiance.

We also use the geospatial distribution of LIS group centroids to count the number of visible branches in the optical flash. For each group in each flash in the LIS science data set, we draw a line segment between its centroid location and the nearest neighbor preceding group. Repeating this procedure for all groups in the same flash results in a skeleton model of the group-level structure. These models are then decomposed into individual branches that are defined as any line or curved segment that exists between intersection nodes exceeding 5 km in length (~1 LIS pixel).

We also identify particularly radiant LIS groups that may be examples of lightning “superbolts.” Turman (1977) describes superbolts as the most intense optical pulses produced by lightning. These radiant pulses measured by the optical systems on the Vela satellite radiate on the order of 10^{11}–10^{13} W and are over 100 times more intense than typical lightning pulses. The design of LIS and its available science products complicate the classification of superbolts using Turman’s definition. The superbolts identified in the Vela data lasted up to 1 ms and thus could be contained within a single LIS group. As a first-order comparison, we define LIS superbolts as groups with total radiances that exceed the average group radiance by a factor of 100 or greater.

We describe the cloud regions illuminated by optical flashes using the TRMM collocated 1Z09 data set presently hosted at Texas A&M University, Corpus Christi. This data set contains the orbit-level grids of TRMM PR, TMI, and VIRS data. It formed the basis for the construction of the Precipitation Feature (PF) database (Liu et al., 2008) as well as our Illuminated Cloud Feature (ICF) database (Peterson et al., 2016).

2.3. Selection of Extreme Cases

The selection of extreme cases from the LIS feature database described in Table 1 requires a fair amount of intelligence to omit artifacts and platform anomalies that often come to the surface in such analyses. Artifacts range from random noise produced as the satellite passes through the South Atlantic Anomaly to streaks from high-energy particles passing through the detector to "lollipops" caused by data buffer issues that modify the shape of an observed optical flash. These artifact classes are obvious in the event-level data because they take on shapes that are either not physical or incompatible with radiative transfer across the infrared scene (i.e., boxes with square corners). We do not consider cases that are clearly unrelated to lightning (for example, 100 km streaks that are 1–2 pixels wide in clear air regions) and omit flashes that are only exceptional due to the influence of an artifact (for example, a lollipop artifact that doubles the footprint area of one of the largest flashes). Flashes that contain artifacts that do not affect their ranking are still considered.

We also consider the possibility of multiple distinct lightning discharges being grouped into the same LIS flash feature. There may be little distinction between where one flash ends and another begins in intense convection with a high flash rate. Overgrouping is an infrequent source of error that only becomes apparent when examining extreme LIS flash durations and group counts. If the storm is continuously illuminated by subsequent flashes while LIS is overhead, a large fraction of the sensor view time will be clustered into a single flash. While long-lasting overgrouped flashes occur in convection, the longest-lasting flashes measured by LMA systems—for example, the extreme cases in Lang et al. (2016)—often extend into the stratiform region. Thus, our discussion of the longest-lasting LIS flashes will consider separate extreme cases for convective and stratiform flashes.

3. Results

The flash characteristics that are used to identify exceptional cases of optical lightning are grouped into three categories. The first category quantifies the group-level structure of the optical flash. It includes the maximum separation of groups used to measure propagation in Peterson et al. (2016), and the number of visible branches. The second category is related to the energetics of the optical flash and how it interacts with the surrounding cloud region through scattering. It includes the footprint area of the flash, the maximum separation of events, and the maximum group radiance used to identify LIS superbolts. The final category describes the evolution of the flash. It includes the number of bright series in the flash, and the durations of both the flash and its longest-lasting series. The following sections discuss exceptional flashes in terms of structure, first, then energetics and radiative transfer, and finally evolution. With the exception of the flash with the most bright series (Figure 6), animations of the top candidate in each category are also provided in Movies S1–S8 in the supporting information.

3.1. LIS Flashes With the Furthest Separated Groups

The first measure of horizontal flash structure that we consider is the maximum separation of groups in the flash. Peterson et al. (2016) used this metric to differentiate between flashes that propagate horizontally from one part of the storm to another and flashes that repeatedly illuminated the same storm region. As LIS cannot measure the vertical structure of the flashes in question, structural metrics like maximum group separation measure the horizontal component of the three-dimensional development of the lightning channel that is radiant enough and close enough to the top of the cloud to be detectable from orbit.

The longest LIS flash in terms of group separation is depicted in Figure 1. The plan view of LIS events (large pixels) and groups (small pixels) is shown with the TRMM VIRS 10.8 μm infrared brightness temperature (colored pixels) in Figure 1d. The optical flash skeleton (black lines), the extent of PR convective features (dashed lines), and the extent of the 225 K infrared brightness temperature region (dotted lines) are overlaid. The longitude and latitude extent of each LIS group is shown in Figure 1b and Figure 1e, respectively, with

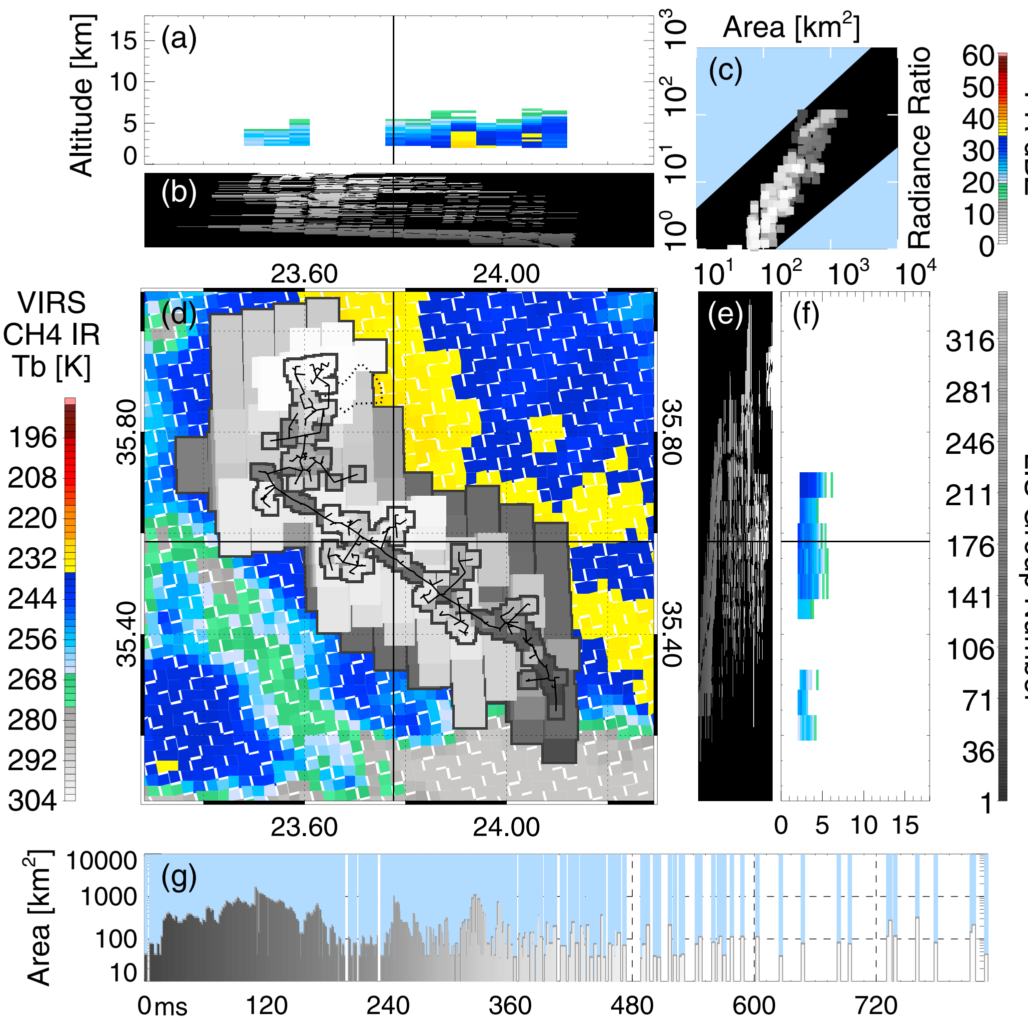

Figure 1. The LIS flash with the largest separation of groups. LIS events (large pixels) and group centroids (small boxes) are coded by LIS group number. (a) PR reflectivity longitude-altitude cross section. (b) Longitude extent of LIS groups. (c) Radiance-area profile of LIS groups in the flash (approximate boundaries from Peterson et al., 2016 shaded blue). (d) Plan view on top of VIRS CH4 10.8 μm brightness temperatures (colored pixels). PR convective features (dashed lines) and VIRS CH4 <225 K regions (dotted lines) are shaded. (e) Latitude extent of LIS groups. (f) PR reflectivity latitude-altitude cross section. (g) Time series of LIS groups (greyscale) and series (blue shaded).

group centroid locations shown as black lines. Similarly, PR reflectivity cross sections through the center of Figure 1d are shown in Figure 1a (longitude) and Figure 1f (latitude). The radiance-area profile of the groups in the flash is shown on the top right in Figure 1c. The approximate boundaries of the flash-level distributions in Peterson et al. (2016) are shaded blue. Finally, the time series of LIS group area is shown in Figure 1f with individual series shaded blue. LIS events and groups in each of these panels are color coded by LIS group number in a common gray color scale across all panels.

This 827 ms stratiform flash over the Mediterranean Sea in the coastal waters off northern Crete was composed of 347 groups and 33 series including 2 bright series. The first group in the flash occurred near the southeast flank of its footprint. Subsequent groups propagated to the northwest (Figures 3b and 3e) in a single series lasting 190 ms (Figure 3g). The overall group-level structure of the flash is 89 km from end to end and contains an estimated 110 branches. The groups in this flash are dispersed throughout the illuminated cloud and the maximum group displacement accounts for 80% of the maximum event separation. The flash contains both groups that have a large footprint area for their radiance ratio along the lower boundary of the radiance-area distribution in Figure 1c and groups that have high radiance ratios for their area along the left boundary of the distribution. An animation of this flash can be found in Movie S1.

Table 2
Top Five LIS Flashes With the Largest Group Separations

Ranking	1	2	3	4	5
Maximum group distance (km)	89.1	87.2	86.8	86.8	84.3
Local time	19:41	4:53	5:40	21:03	21:28
Land/ocean	Ocean	Ocean	Land	Ocean	Land
Area (km^2)	3,637	2,742	2,675	3,336	3,273
Maximum event distance (km)	109	93.9	94.6	109	93
Branch count	110	118	215	108	188
Series count	33	118	148	49	221
Bright series count	2	11	21	7	8
Group count	347	355	650	319	508
Duration (ms)	827	3,110	2,754	1,183	5,048
Longest series (ms)	190	59	72	77	38
Radiance eatio	104	75.2	133	92	104
Maximum group radiance[a]	103	15	35	18	74

[a]As a factor of the mean group radiance.

The top five LIS flashes with the largest group separations are summarized in Table 2. All five flashes had group separations greater than 80 km compared to event separations between 93 and 109 km, more than 100 visible branches, hundreds of groups, and at least one series that lasts several dozen milliseconds and would likely be considered continuing current in Bitzer (2017). Though all five flashes in Table 2 attained radiance ratios greater than 75, only the top case in Figure 1 contained a group with sufficient radiance to be considered a LIS superbolt. All five flashes occurred near dawn or dusk and primarily illuminate stratiform cloud.

Relatively low background radiances compared to midday and the homogeneous layered structure of stratiform regions provide ideal conditions for lightning imagers to resolve the development of the flash over large horizontal distances. Still, the 89 km maximum group separation falls short of the 321 km length of the WMO record largest flash measured by an LMA. Thomas et al. (2000) compared LIS and LMA measurements of the same lightning discharges. They found that LIS measured radiant events associated with cloud pulses in nearly every case where the lightning channel extended into the upper part of the cloud but had notably less skill (~60% detection efficiency) in measuring optical emission from CG discharges that occurred close to the cloud base. Moreover, the optical pulses that were measured by LIS from these CG flashes also tended to occur late in the discharge. Lightning imagers like LIS may not resolve the entire horizontal development of the flash if a significant optical depth of cloud or intervening ice cloud separates the discharge and the sensor. However, the exceptional cases in Table 2 show that these instruments can still map a significant portion of the flash in these cases of expansive stratiform lightning.

3.2. LIS Flashes With the Most Visible Branches

Counting the number of visible branches in the group-level data results in a tie for the most dendritic flash, with 234 distinct branches in each case. The first case was an oceanic stratiform flash over the eastern Mediterranean Sea. It illuminated an area of 2,333 km^2 and was composed of 549 groups and 264 series (including 30 bright series) dispersed throughout its 4.2 s duration. The maximum distance between its groups was 58 km. The second case was a 1,966 km^2 land-based flash over northern India with 450 groups and 129 series (including 27 bright series) over a 1.9 s duration and a 41 km maximum separation between groups.

Given the similar spatial and temporal scales of these flashes, we choose to show the Mediterranean example in Figure 2. As it was an afternoon flash (14:35 local time) with a high background radiance, its illuminated footprint does not extend far beyond its group centroid skeleton in Figure 2d. It propagated generally to the southwest as it evolved with some branches extending southward and others extending westward, producing a triangular feature in its group-level structure. An animation of this flash can be found in Movie S2.

This fantail progression diverging outward from a single point is common in the highly branched LIS flashes in Table 3. All five are stratiform flashes with footprints larger than 1,700 km^2 and group separations of at least 40 km. They all contain 400–500 groups and more than 100 series over the course of 1.9–4.2 s. These cases have extensive lateral extents and a visible dendritic structure consistent with the Glossary of Meteorology

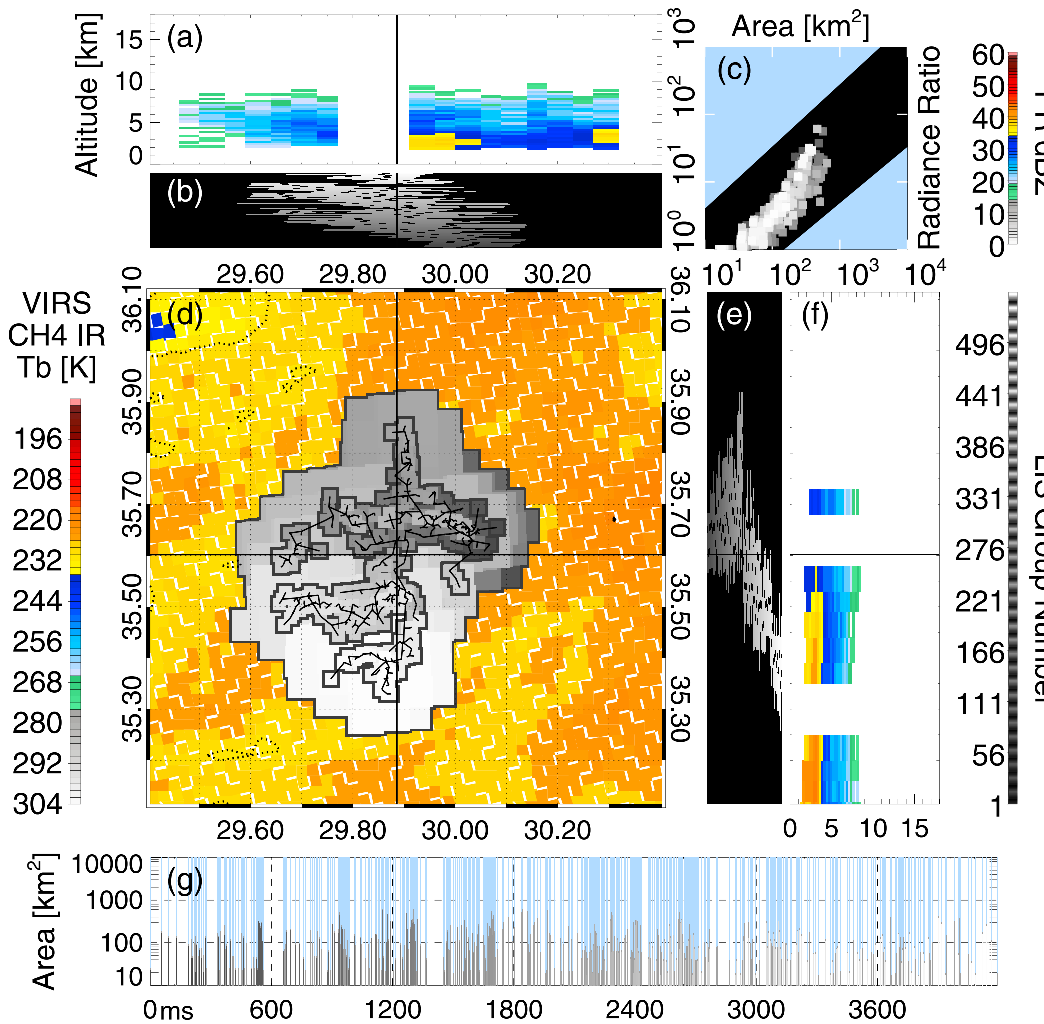

Figure 2. The same as Figure 1 for the LIS flash with the most visible branches.

(American Meteorological Society, 2017) definition of spider lightning. As they are also examples of stratiform lightning embedded within a MCS, there is a high probability that they were positive polarity discharges, but additional data are required for verification.

Table 3
Top Five LIS Flashes With the Most Branches

Ranking	1	1	3	4	5
Branch count	234	234	229	221	220
Local time	14:35	20:16	19:49	20:42	4:37
Land/ocean	Ocean	Land	Land	Ocean	Land
Area (km^2)	2,333	1,966	3,576	1,741	3,260
Maximum event distance (km)	63.1	56.1	66.5	55.5	72.4
Maximum group distance (Km)	58.4	40.9	46.6	41.4	50.0
Series count	264	129	128	122	204
Bright series count	30	27	7	15	6
Group count	549	450	443	509	484
Duration (Ms)	4,195	1,948	2,207	2,174	3,377
Longest series (Ms)	40	24	63	48	54
Radiance ratio	85	43	113	110	114
Maximum group radiance[a]	33	14	124	62	91

[a]As a factor of the mean group radiance.

3.3. LIS Flashes With the Largest Footprint Area

The LIS flash with the largest footprint area is shown in Figure 3. It occurred at 16:17 UTC on 19 October 2009 over the Pacific Ocean near the Philippines. It lasted 934 ms with 29 series (4 bright series), 98 groups, and 58 visible branches. It achieved a high radiance ratio of 114, and its most radiant group was 283 times more luminous than the average LIS group, qualifying it as a LIS superbolt. The flash illuminated an area of 10,604 km^2 that included the convective cloud that initiated the flash and the adjacent boundary cloud regions on either side of the convective feature in Figure 3d. This footprint is illuminated nearly all at once over the course of two groups during a single bright series after 540 ms (Figure 3g). Though this footprint lacks an apparent eccentricity, its 140 km maximum separation of events suggests that it had the potential to illuminate an area 4,800 km^2 larger (15,394 km^2 in total) if the cloud were radially symmetric. An animation of this flash can be found in Movie S3.

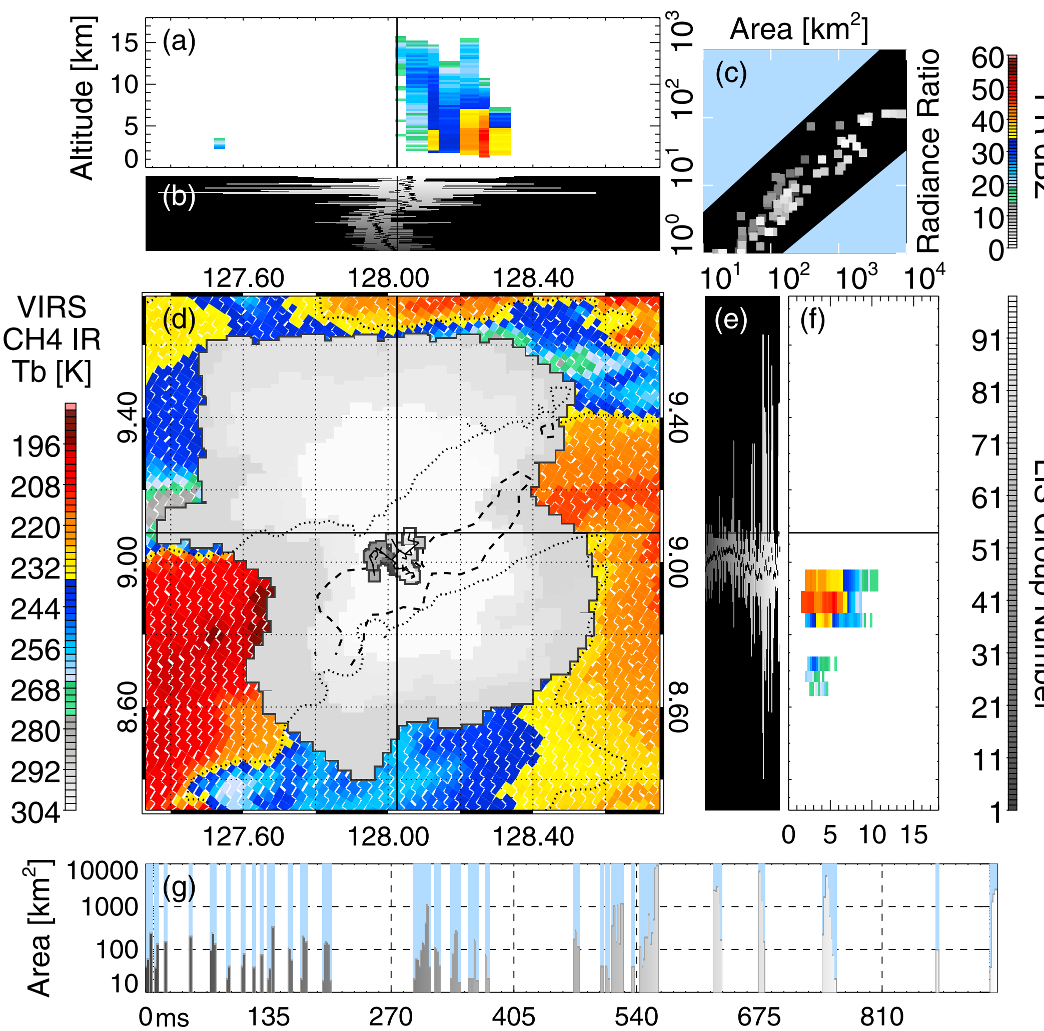

Figure 3. The same as Figure 1 for the LIS flash with the largest footprint area.

The flash footprint denotes the area across which optical energy from the flash interacts with nearby clouds through scattering to produce a strong enough optical signal to be detected by LIS. The group-level structure of the flash is confined to a 17 km wide portion of the 140 km diameter flash footprint along the northern flank of the convective core (Figure 3d). The flash footprint diameter is noticeably diminished parallel to the linear convective feature (dashed line). Moreover, the western flank of the flash warps around the northern 225 K contour while its southeastern flank does not penetrate the colder 225 K region further east. In exceptionally expansive cases like this, the morphology of the footprint has little to do with the scale of the discharge—approximated by the group centroid skeleton—and is instead dictated by how the clouds are distributed across the scene.

The properties of the top five largest LIS flashes by footprint area are summarized in Table 4. All five flashes have maximum event separations that are ~10–20 times greater than their maximum group separations, radiance ratios 114 or higher, and at least one superbolt group. The footprints of these flashes are only exceptional due to a few particularly radiant groups contained within one to four bright series in each case. Each of these flashes also occurs near the boundary of the parent thunderstorm, and thus, peripheral clouds with warmer cloud top temperatures (i.e., lower clouds) account for a large fraction of the flash footprint. Boundary clouds can even comprise a majority of the flash footprint as in Figure 3d. Thus, the most expansive LIS flashes appear to be exceptional due to their energetics and radiative transfer in the cloud rather than the structure of the flash.

Table 4
Top Five LIS Flashes With the Largest Footprint Areas

Ranking	1	2	3	4	5
Area (km^2)	10,604	9,698	9,605	9,270	8,861
Local time	0:49	5:18	19:59	19:30	0:02
Land/ocean	Ocean	Land	Land	Land	Land
Maximum event distance (km)	140	161	143	119	120
Maximum group distance (km)	16.8	8.9	7.0	10.2	9.1
Branch count	58	8	12	28	9
Series count	29	4	6	11	3
Bright series count	4	1	3	4	1
Group count	98	12	19	37	9
Duration (ms)	934	508	451	559	102
Longest Series (ms)	18	7	10	25	7
Radiance ratio	114	135	135	114	130
Maximum group radiance[a]	283	274	172	237	157

[a]As a factor of the mean group radiance.

3.4. LIS Flashes With the Furthest Separated Events

The flash with the greatest separation between events is also the second-largest flash in terms of footprint area from Table 4. This flash was observed on 27 September 2013 at 10:27 UTC over the Buenaventura region of Colombia. The evolution of this optical flash is documented in Figure 4. It consisted of 12 groups organized into four series (one bright series) in 508 ms. Despite a 162 km maximum separation between events, its groups were only separated by 9 km. The illuminated footprint of this flash wrapped around the eastern flank of a concentric anvil cloud from north by northwest to the southeast. As in the previous case, the optical footprint penetrated a shorter distance into the convective core to the southwest than any direction with lower cloud tops (greater infrared brightness temperatures). An animation of this flash can be found in Movie S4.

In total, three flashes from Table 4 are also in the top five in terms of event separation listed in Table 5. As before, these flashes all contain a few highly radiant groups or series that account for their exceptional footprint sizes and maximum event separation distances. None of these flashes contain groups that are separated by a significant fraction of the event

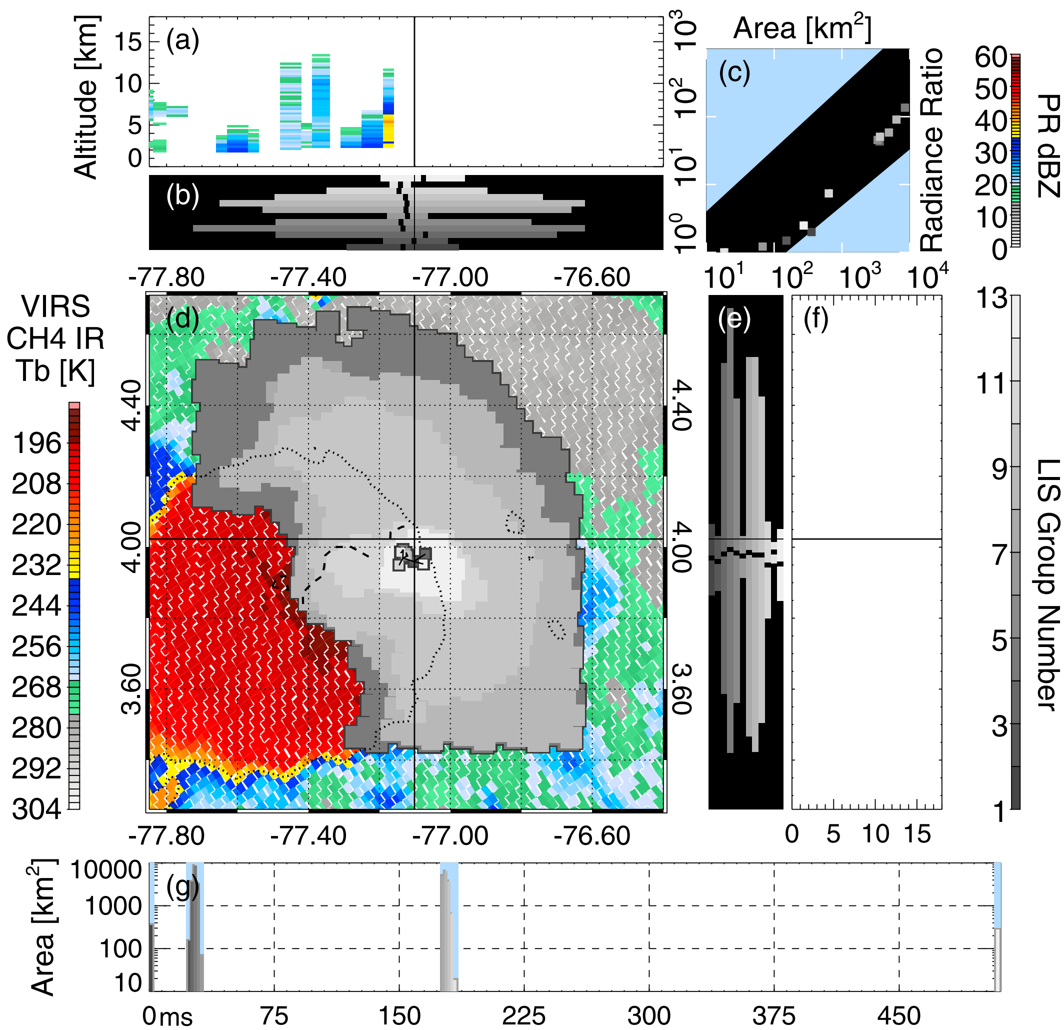

Figure 4. The same as Figure 1 for the LIS flash with the largest separation of events.

Table 5
Top Five LIS Flashes With the Largest Event Separations

Ranking	1	2	3	4	5
Maximum event distance (km)	162	153	143	140	138
Local time	5:18	21:11	19:59	0:49	15:44
Land/ocean	Land	Land	Land	Ocean	Ocean
Area (km^2)	9,698	8,701	9,605	10,604	6,683
Maximum group distance (km)	8.9	4.1	7.0	16.8	11.2
Branch count	8	1	12	58	9
Series count	4	2	6	29	9
Bright series count	1	-----[a]	3	4	1
Group count	12	2	19	98	16
Duration (ms)	508	89	451	934	571
Longest series (ms)	7	0	10	18	9
Radiance ratio	135	135	135	114	112
Maximum group radiance[b]	274	157	172	283	140

[a]Insufficient groups to determine bright series. [b]As a factor of the mean group radiance.

separation. All of the flashes in Table 4 and Table 5 have maximum event separations that exceed their characteristic radii and thus would be considered "elongated" in Peterson et al. (2016). Many large flashes take on such an elongated appearance due to their energetics and radiative transfer in the cloud.

Figure 3 and Figure 4 show two storms—one elongated and one concentric—that both produce large, elongated flashes. In each case, the flash footprint is guided by the precipitation structure of the surrounding cloud regions but does not conform to the geometry of the convective cell that initiated the flash. Instead, the flash footprint advances in the direction of boundary clouds and is blocked in the direction of intense convection. Scattering anomalies (i.e., an embedded convective cell, ice cloud boundary, etc.) in any direction lead to elongated flashes and complex footprints (i.e., Figure 4d) that are difficult to explain in the absence of coincident thunderstorm observations.

It is important to note for the cases in Tables 4 and 5 where the flash footprint grows beyond the anvil cloud that LIS will record transient optical pulses that resemble lightning, regardless of their origin. Solar glint reflecting off the ocean surface, for example, would be scattered by

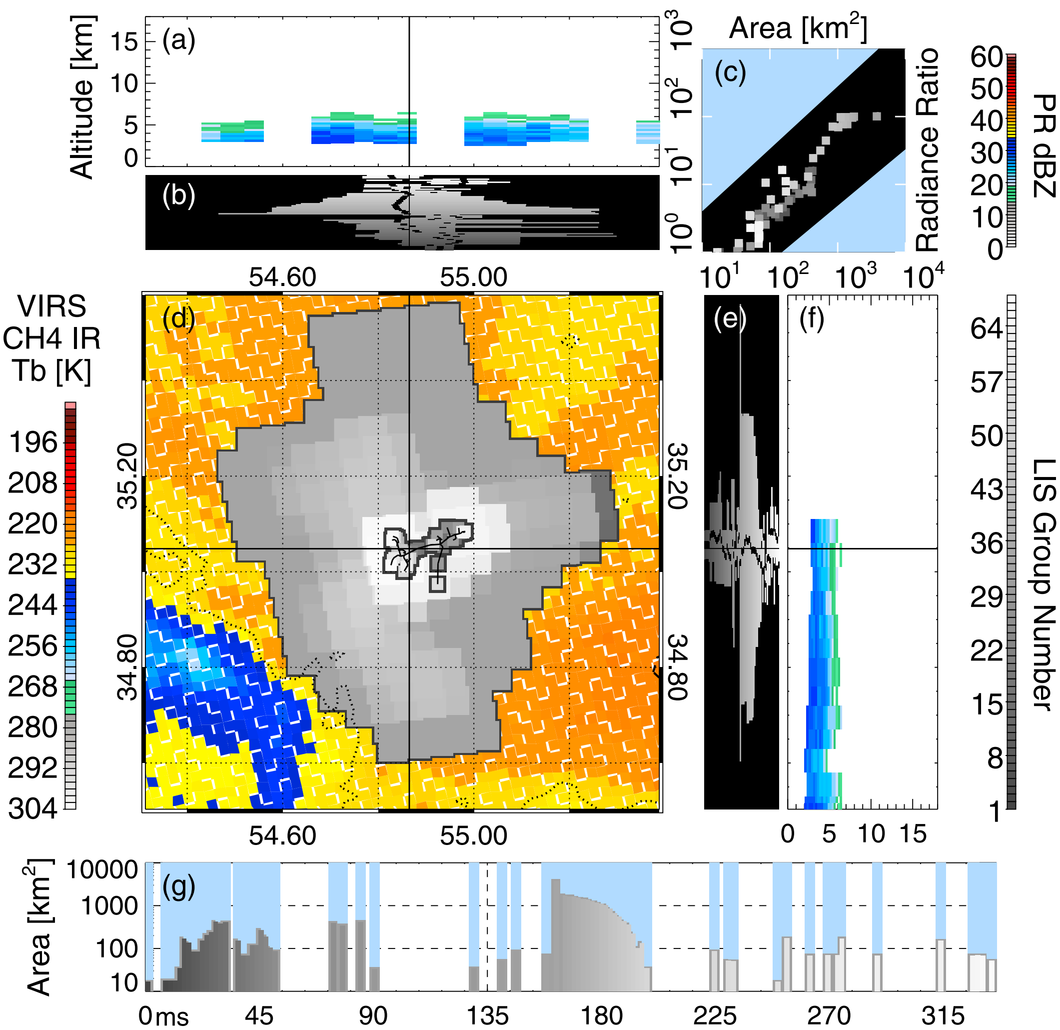

Figure 5. The same as Figure 1 for the LIS flash with the most radiant group.

Table 6
Top Five LIS Flashes With Most Radiant Groups (Superbolts)

Ranking	1	2	3	4	5
Maximum group radiance[a]	765	701	656	622	566
Local time	15:04	15:24	23:05	7:52	17:06
Land/ocean	Land	Land	Land	Land	Land
Area (km^2)	3,984	5,957	7,650	3,544	5,109
Maximum event distance (km)	100	184	114	94.7	111
Maximum group distance (km)	14.0	3.02	27.8	26.5	9.53
Branch count	40	8	69	96	15
Series count	18	4	16	72	7
Bright series count	1	1	2	1	1
Group count	67	8	127	169	18
Duration (ms)	333	102	789	1,301	360
Longest series (ms)	40	7	61	34	18
Radiance ratio	101	82	110	90.6	102

[a]As a factor of the mean group radiance.

the clouds in much the same way as the optical radiance produced by lightning. Glint can be ruled out for most of the flashes in Tables 4 and 5 because they either occur at night or over land. The Buenaventura flash in Figure 4 is the most suspect since it occurred 30 min before sunset and illuminated the eastern flank of the thundercloud, but it is located in an inland forested region far from large bodies of water to reflect sunlight.

3.5. LIS Flashes With the Most Radiant Groups (Superbolts)

The LIS flash with the most radiant group is shown in Figure 5. An animation of this flash can also be found in Movie S5. This 333 ms stratiform flash illuminated an area of 3,984 km^2 and was composed of 67 groups and 18 series. Its sole bright series began with a superbolt group that was 765 times more radiant than average followed by 40 ms of consecutive groups that decreased in radiance and illuminated area with time (Figure 5g). A box-shaped "lollipop" artifact can also be noted in the flash footprint during this bright series.

The top five LIS radiant superbolts are summarized in Table 6. All of these exceptionally radiant flashes take on an elongated shape with events separated by distances greater than 90 km and footprints larger than

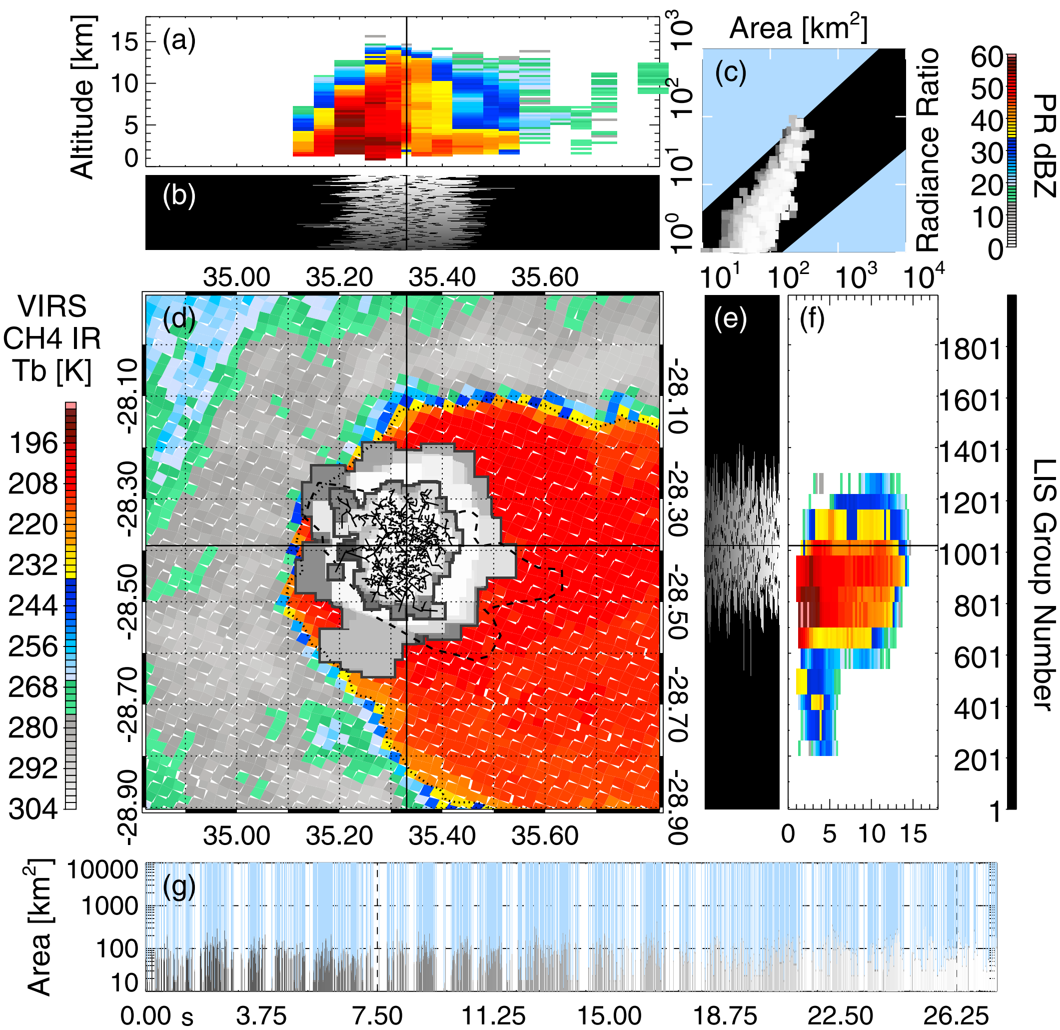

Figure 6. The same as Figure 1 for the LIS flash with the most bright series.

Table 7
Top Five LIS Flashes With Most Bright Series

Ranking	1	2	3	4	5
Bright series count	138	111	80	79	79
Local time	2:15	8:46	2:15	16:34	8:47
Land/ocean	Ocean	Ocean	Ocean	Ocean	Ocean
Area (km^2)	1,236	2,851	1,414	1,736	1,714
Maximum event distance (km)	44.8	79.4	45.9	59.7	44.4
Maximum group distance (km)	31.3	42.1	24.9	53.5	37.9
Series count	1,173	1,176	665	705	533
Group count	2,000	2,000	1,119	984	844
Branch count	630	585	447	344	298
Duration (ms)	27,555	27,384	16,451	21,862	14,251
Longest series (ms)	22	23	18	14	16
Radiance ratio	92	111	92	39	76
Maximum group radiance[a]	15	46	14	13	11

[a]As a factor of the mean group radiance.

3,500 km^2. These flashes lasted between 333 and 1,301 ms and attained radiance ratios above 80. The maximum group radiance is between 566 times and 765 times greater than the average LIS group in each case. Although oceanic and nocturnal flashes tend to be larger and brighter on average, all of the top five superbolts occurred over land and three of the top five occurred during the afternoon. The four flashes within the PR swath are also stratiform flashes, and all cases follow the same pattern of a single radiant group embedded in a 7 to 61 ms bright series whose radiant energy diminishes over time.

There are a few factors involved in the multiple-group series resulting from superbolts that fade with time. They may start with a particularly radiant and/or long-lived optical pulse such as the continuing currents described in Bitzer et al. (2016). Multiple scattering across the expansive flash footprint dilates the optical signal in time, increasing the duration of the series. At the same time, the LIS dynamic background—which operates as a running average (Christian et al., 1989)—changes in response to the long-lived series, reducing its footprint and total radiance with time. Additional analysis of the data, comparison with ground-based measurements, and radiative transfer modeling would be beneficial for explaining the physics of these unique flashes.

3.6. LIS Flashes With the Most Bright Series

The final three metrics relate to the evolution of optical flashes. The LIS flash with the most bright series is depicted in Figure 6. This flash is an obvious example of overgrouping with precisely 2,000 groups entirely contained within the convective core of the parent thunderstorm. All of the lightning activity in the storm during this 27 s window is clustered into a single LIS flash, but we may still be able to extract information about individual optical pulses during this time from the series-level data. A total of 1,173 distinct series are detected including 138 bright series. The average flash has a total of 10 series. If this 10-to-1 ratio holds for high flash rate storms, then we can expect the LIS flash feature in Figure 6 to contain approximately 100 individual lightning flashes and its parent thunderstorm to have a flash rate of over 200 flashes per minute.

The top five flashes by bright series count are summarized in Table 7. All of these flashes are embedded in intense convection with hundreds to thousands of groups over durations of 14 s to 27 s. High bright series counts are particularly responsive to overgrouped LIS flashes because this parameter identifies cases of single flash features with a large number of distinct optical pulses that are produced by subsequent discharges.

Table 8
Longest-Lasting LIS Flashes

Classification	Entirely convective	Convective to stratiform	Entirely stratiform	Top five propagating
Duration (ms)	27,555	7,466	4,318	5,047
Local time	2:15	19:45	6:45	21:38
Land/ocean	Ocean	Ocean	Land	Land
Area (km^2)	1,236	1,866	2,202	3,273
Maximum event distance (km)	44.8	81.9	65.7	93.0
Maximum group distance (km)	31.3	61.1	47.9	84.3
Branch count	630	207	166	188
Series count	1,173	300	189	221
Bright series count	138	37	21	8
Group count	2,000	663	340	508
Longest series (ms)	22	30	17	38
Radiance ratio	91	103	44	103
Maximum group radiance[a]	15	21	23	74

[a]As a factor of the mean group radiance.

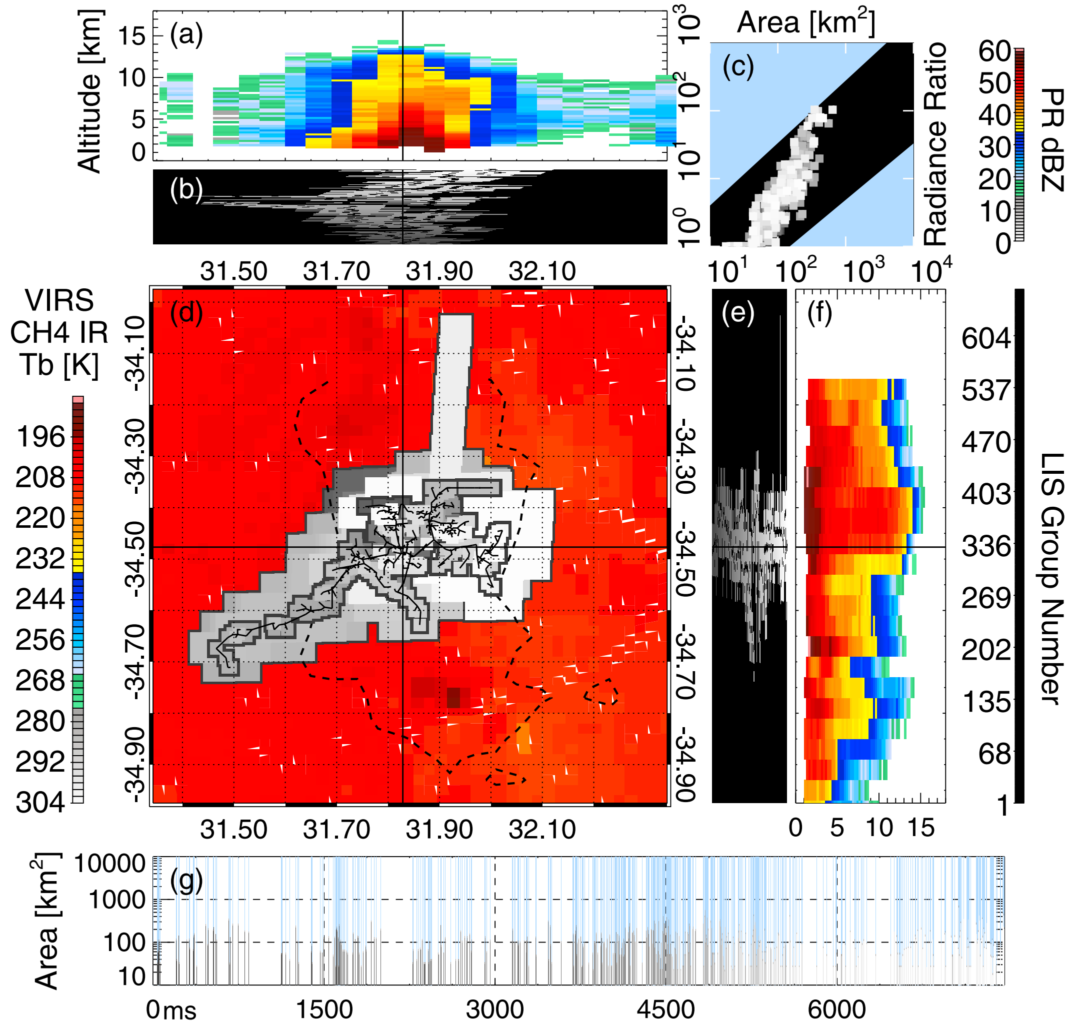

Figure 7. The same as Figure 1 for the longest-lasting convective-to-stratiform propagating LIS flash.

3.7. LIS Flashes With the Longest Durations

The overgrouped cases from the previous section complicate the comparison of LIS and LMA extreme flash durations. While the WMO record longest-lasting flash in Lang et al. (2016) was a stratiform flash over southern France that lasted 7.74 s, the longest-lasting LIS flashes in our database produce regular optical signals over time periods up to 27 s (Figure 6). Rather than comparing the top five longest-lasting LIS flashes as in previous sections, Table 8 summarizes the longest-lasting LIS flash based on cloud type (convective and stratiform) and for only large propagating flashes like the cases in Lang et al. (2016).

The overgrouped case from Figure 6 that lasted 27 s was the longest-lasting entirely convective flash. In contrast, the longest-lasting flash that propagated from the convective core into the stratiform region is shown in Figure 7 and animated in Movie S6. This oceanic flash off the coast of South Africa lasted 7.5 s producing 663 groups and 300 series, 37 of which were bright series. It illuminated a cloud region 1,866 km^2 in size with a maximum separation of groups of 61 km and 207 visible branches in the group-level data. The longest-duration entirely stratiform flash, meanwhile, lasted 4.3 s and illuminated an area of 2,202 km^2. Its evolution and structure are shown in Figure 8 and animated in Movie S7. Its 340 groups and 189 series emanate from a single point and spread laterally as the flash propagates to the southeast in a similar fantail pattern to the cases with the most visible branches from Table 3. The maximum separation of groups is 47.9 km compared to a 65.7 km separation of events. Finally, the

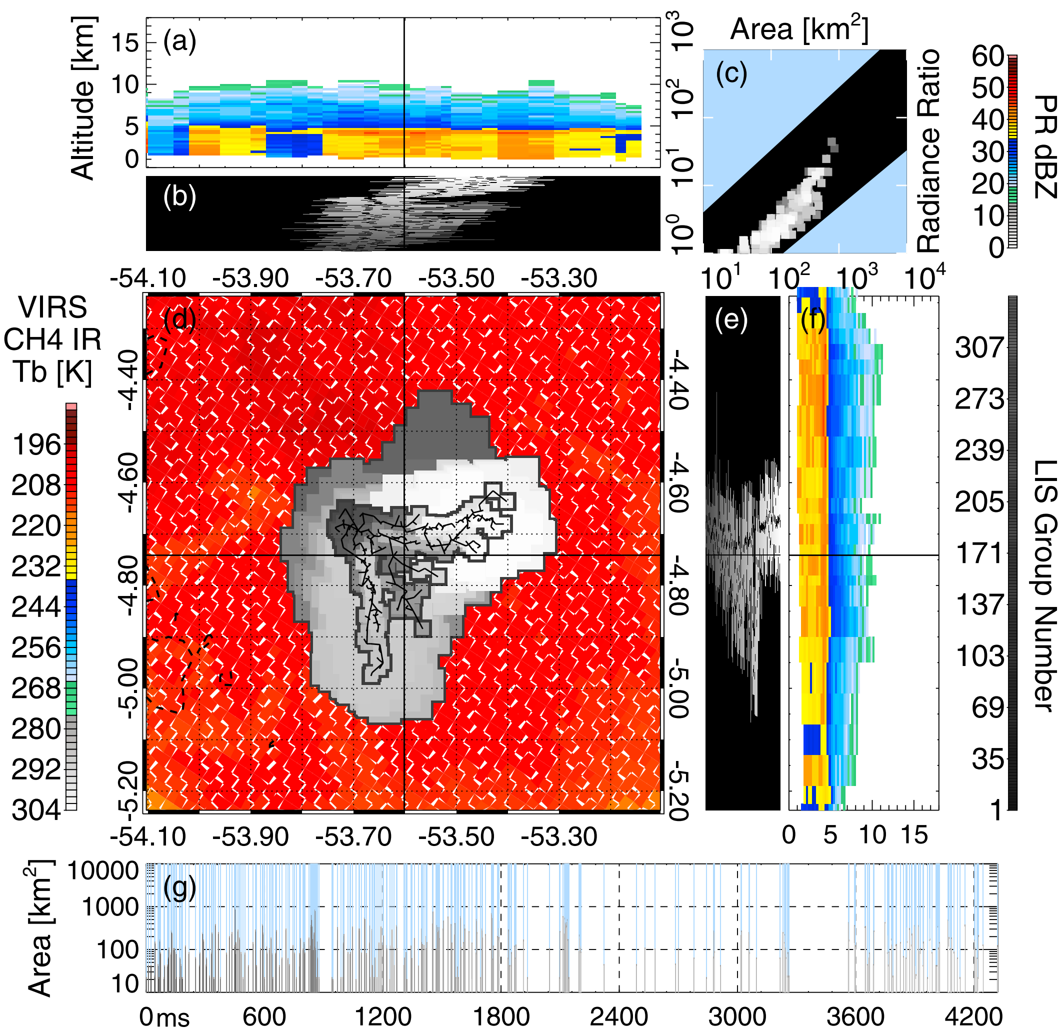

Figure 8. The same as Figure 1 for the longest-lasting entirety stratiform propagating LIS flash.

longest lasting of the top five flashes by maximum group separation (Table 2) lasted 5.0 s and traversed a horizontal distance of 84.3 km between groups.

LIS has recorded exceptional cases of long-lasting lightning that are within 1 s of the WMO record measured by an LMA. Though optical lightning measurements fail to capture the extreme length of LMA flashes, platforms like LIS and GLM can compete with LMAs in recording flashes with exceptional durations.

3.8. LIS Flashes With the Longest Series Duration

The flash with the longest series duration is shown in Figure 9. The first series in the flash lasted 242 ms—a full third of its 659 ms duration—and contained a majority of the groups in the flash. It was followed by another 23 series that lasted a few milliseconds apiece. The flash was observed in the morning hours (6:15 local time) off the eastern shore of South Africa. It began along the rear flank of the convective core of its parent thunderstorm and propagated westward, southward, and eastward into the stratiform region producing 105 branches in the group-level data. An animation of this flash can be found in Movie S8.

The top five flashes in terms of series duration are summarized in Table 9. Each of the five cases is a propagating flash whose maximum group-level structure fills the majority of its observed footprint. Though they each contain at least 100 groups, most of these are clustered into a single series. Each case also only has one to three bright series with none containing particularly bright superbolt groups.

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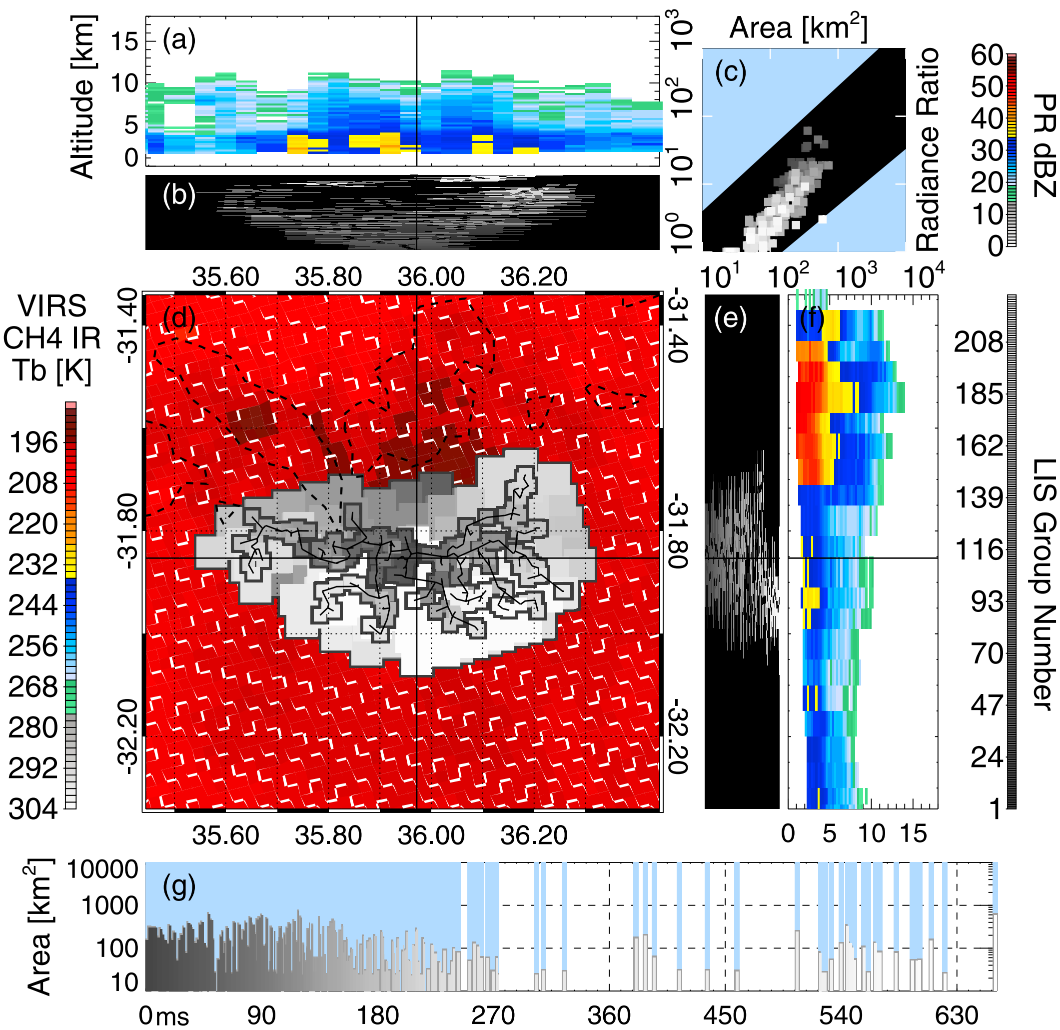

Figure 9. The same as Figure 1 for the LIS flash with the longest-lasting series.

Table 9
Top Five LIS Flashes With the Longest Series Durations

Ranking	1	2	3	4	5
Longest series (ms)	242	242	228	224	220
Local time	6:15	19:44	4:34	2:47	0:54
Land/ocean	Ocean	Ocean	Ocean	Land	Ocean
Area (km^2)	2,199	1,208	1,395	765	1,375
Maximum event distance (km)	67.6	41.3	59.3	31.0	52.0
Maximum group distance (km)	60.4	38.0	52.0	24.4	48.3
Branch count	105	102	122	53	77
Series count	24	24	17	1	10
Bright series count	1	2	3	1	1
Group count	228	237	266	112	158
Duration (ms)	659	662	678	224	703
Radiance ratio	76	114	114	64	108
Maximum group radiance[a]	11	31	31	8	22

[a]As a factor of the mean group radiance.

4. Conclusion

This study documents extreme examples of optical flash structure, energetics and radiative transfer in the cloud, and evolution measured by LIS on the TRMM satellite. In terms of flash structure, the longest LIS flash spans 89 km between groups, and the most dendritic LIS flash contains 234 visible branches. In terms of energetics, the most radiant LIS "superbolt" group is 765 times brighter than a typical group. The size of the largest LIS flash (10,604 km^2) and maximum distance between events in a LIS flash (162 km) are both influenced by the distribution and properties of the surrounding clouds but do not appear to be affected by the group-level structure of the flash.

A "series" feature is defined between the group and flash levels in the LIS hierarchy that clusters subsequent groups. Series features document the evolution of optical LIS flashes on time scales greater than 2 ms and less than the flash duration by distinguishing individual optical pulses produced by lightning. They can also be used to extract flash properties from overgrouped LIS flashes wherein multiple separate discharges in high flash rate storms are combined into a single LIS flash feature. The longest-lasting convective LIS flashes are cases of overgrouping that last up to 27 s in duration. The longest-lasting LIS flash that propagates from the convective core into the stratiform region of the parent thunderstorm lasted 7.5 s, the longest-lasting entirely stratiform flash lasted 4.3 s, and the longest-lasting of the top 5 propagating flash lasted 5 s. The longest-duration LIS series lasted 242 ms.

These metrics demonstrate how LIS measurements can be used to map the horizontal development of individual lightning flashes. LIS on the TRMM satellite was able to measure lightning flashes that propagated roughly one third of the world record for the longest distance for LMA measurements and other flashes whose durations were on the same temporal scale as the world record for the longest-lasting LMA flash. There are limitations to what optical platforms like LIS can resolve—always a two-dimensional composite of a three-dimensional flash structure, and often missing development near the cloud base—but they are still able to provide useful measurements of flash evolution. The key value in using satellite lightning imagers to examine physical lightning phenomena lies in their global coverage. Lightning measurements from LIS, GLM, and future sensors provide a wealth of information on lightning in remote and data sparse regions of the world. This information may prove useful in operations for assessing lightning hazards and other risks posed by thunderstorms.

Acknowledgments

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References

American Meteorological Society (2017). "Spider lightning." Glossary of Meteorology. Retrieved from http://glossary.ametsoc.org/wiki/Spider_lightning

Bitzer, P. M. (2017). Global distribution and properties of continuing current in lightning. *Journal of Geophysical Research: Atmospheres*, *122*, 1033–1041. https://doi.org/10.1002/2016JD025532

Bitzer, P. M., & Christian, H. J. (2015). Timing uncertainty of the lightning imaging sensor. *Journal of Atmospheric and Oceanic Technology*, *32*(3), 453–460. https://doi.org/10.1175/JTECH-D-13-00177.1

Blakeslee, R. J., Christian, H. J., Stewart, M. F., Mach, D. M., Bateman, M., Walker, T. D., … Coker, C. (2014). Lightning Imaging Sensor (LIS) for the International Space Station (ICC): Mission description and science goals. *XV Int. Conf. Atmos. Electricity*. Norman, OK, 15 pp.

Boccippio, D. J., Goodman, S. J., & Heckman, S. (2000). Regional differences in tropical lightning distributions. *Journal of Applied Meteorology*, *39*(12), 2231–2248. https://doi.org/10.1175/1520-0450(2001)040%3C2231:RDITLD%3E2.0.CO;2

Christian, H., Blakeslee, R., & Goodman, S. (1989). The detection of lightning from geostationary orbit. *Journal of Geophysical Research*, *94*(D11), 13,329–13,337. https://doi.org/10.1029/JD094iD11p13329

Christian, H. J., Blakeslee, R. J., Goodman, S. J., & Mach, D. M. (Eds.) (2000). *Algorithm Theoretical Basis Document (ATBD) for the Lightning Imaging Sensor (LIS)*. Alabama. Retrieved from http://eospso.gsfc.nasa.gov/atbd/listables.html: NASA/Marshall Space Flight Center. posted 1 Feb. 2000

Goodman, S. J., Blakeslee, R. J., Koshak, W. J., Mach, D., Bailey, J., Buechler, D., … Stano, G. (2013). The GOES-R geostationary lightning mapper (GLM). *Atmospheric Research-Journal*, *125–126*, 34–49.

Hutchins, M. L., Holzworth, R. H., Virts, K. S., Wallace, J. M., & Heckman, S. (2013). Radiated VLF energy differences of land and oceanic lightning. *Geophysical Research Letters*, *40*, 2390–2394. https://doi.org/10.1002/grl.50406

Koshak, W. J. (2010). Optical characteristics of OTD flashes and the implications for flash-type discrimination. *Journal of Atmospheric and Oceanic Technology*, *27*, 1822–1838.

Kummerow, C., Barnes, W., Kozu, T., Shiue, J., & Simpson, J. (1998). The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology*, *15*(3), 809–817. https://doi.org/10.1175/1520-0426(1998)015%3C0809:TTRMMT%3E2.0.CO;2

Lang, T., Pédeboy, S., Rison, W., Cerveny, R., Montanyà, J., Chauzy, S., … Krahenbuhl, D. (2016). WMO world record lightning extremes: Longest reported flash distance and longest reported flash duration. *Bulletin of the American Meteorological Society*, *98*(6), 1153–1168. https://doi.org/10.1175/BAMS-D-16-0061.1

Liu, C., Zipser, E. J., Cecil, D. J., Nesbitt, S. W., & Sherwood, S. (2008). A cloud and precipitation feature database from 9 years of TRMM observations. *Journal of Applied Meteorology and Climatology*, *47*(10), 2712–2728. https://doi.org/10.1175/2008JAMC1890.1

Mach, D. M., Christian, H. J., Blackeslee, R. J., Boccippio, D. J., Goodman, S. J., & Boeck, W. L. (2007). Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. *Journal of Geophysical Research*, *112*, D09210. https://doi.org/10.1029/2006JD007787

Orville, R. E., & Huffines, G. R. (2001). Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Monthly Weather Review*, *129*(5), 1179–1193. https://doi.org/10.1175/1520-0493(2001)129%3C1179:CTGLIT%3E2.0.CO;2

Peterson, M. J., Deierling, W., Liu, C., Mach, D., & Kalb, C. (2016). The properties of optical lightning flashes and the clouds they illuminate. *Journal of Geophysical Research: Atmospheres*, *122*, 423–442. https://doi.org/10.1002/2016JD025312

Peterson, M. J., & Liu, C. (2011). Global statistics of lightning in anvil and stratiform regions over the tropics and subtropics observed by the Tropical Rainfall Measuring Mission. *Journal of Geophysical Research*, *116*, D23201. https://doi.org/10.1029/2011JD015908

Peterson, M. J., & Liu, C. (2013). Characteristics of lightning flashes with exceptional illuminated areas, durations, and optical powers and surrounding storm properties in the tropics and inner subtropics. *Journal of Geophysical Research: Atmospheres*, *118*, 11,727–11,740. https://doi.org/10.1002/jgrd.50715

Thomas, R., Krehbiel, P. R., Rison, W., Hamlin, T., Boccippio, D. J., Goodman, S. J., & Christian, H. J. (2000). Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma. *Geophysical Research Letters*, *27*(12), 1703–1706. https://doi.org/10.1029/1999GL010845

Thomas, R., Krehbiel, P. R., Rison, W., Hunyady, S. J., Winn, W. P., Hamlin, T., & Harlin, J. (2004). Accuracy of the lightning mapping array. *Journal of Geophysical Research*, *109*, D14207. https://doi.org/10.1029/2004JD004549

Turman, B. N. (1977). Detection of lightning superbolts. *Journal of Geophysical Research*, *82*(18), 2566–2568. https://doi.org/10.1029/JC082i018p02566