Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma

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Abstract. 3-dimensional lightning mapping observations obtained in central Oklahoma by the New Mexico Tech Lightning Mapping Array (LMA) have been compared with optical observations of the discharges from space obtained by NASA's Lightning Imaging Sensor (LIS). Excellent spatial and temporal correlations were obtained between the two sets of observations. All lightning discharges seen by LIS were mapped by the LMA. Most of the detected optical events were associated with lightning channels that extended into the upper part of the storm. Cloud-to-ground discharges that were confined to mid- and lower-altitudes were less well detected than intracloud discharges, and tended to be detected late in the discharge. Intracloud discharges were readily detected by LIS as soon as they extended into the upper part of the storm, and often extensively illuminated the cloud at the end or part way through the discharge. The extensive illumination was impulsive in nature and was also seen at the end of some cloud-to-ground discharges.

Introduction

A deployable, 3-dimensional lightning mapping system, called the Lightning Mapping Array (LMA), has been developed at New Mexico Tech and was initially operated in central Oklahoma during June 1998 and subsequently in New Mexico [*Rison et al.*, 1999]. Each LMA station measures the arrival time of impulsive VHF events during successive 100 μs time intervals and the system is typically able to locate several hundred to a few thousand sources per lightning discharge (the term discharge is used to refer to an entire lightning event). A number of interesting storms were observed by the mapping system in Oklahoma, including several supercell storms, a tornadic storm, and multi-cellular storm systems [*Krehbiel et al.*, 2000].

One Oklahoma storm on the evening of June 10-11 was observed by NASA's Lightning Imaging Sensor (LIS) on board the TRMM spacecraft [*Christian et al.*, 1992]. The LIS images are obtained every 2 ms, with individual pixels in its 600 km x 600 km total field of view corresponding to a 4 km x 4 km area at the ground directly below the satellite, increasing in size to 7 km on a side at the edges of the field of view. The overpass occurred at 06:18 UTC, about an hour after local midnight as a group of convective storms passed over the southeastern stations of the LMA. During the 90 second period of the overpass, 128 lightning discharges were detected by the LMA, which determined their spatial and temporal development inside the cloud. The LIS detected light from the top of the cloud during 108 of the discharges. LIS did not detect any discharges not mapped by the LMA. During this period the National Lightning Detection Network (NLDN) detected a total of 128 strokes to ground from 32 of the discharges.

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Observations

Figure 1 shows an overview of the lightning activity detected by the LMA during a 30 second time interval when the satellite was passing directly overhead. Several discharges occurred every second within the extensive storm system. Over 29,000 VHF radiation events were located by the LMA during the time interval of the figure. The rectangular contours show the outline of luminosity detected by the LIS during the same time interval. A total of 7500 pixel illuminations covered the electrically active part of the storm in Figure 1. The best spatial agreement was obtained after shifting the LIS locations north by 6 km (about one pixel). Similar spatial offsets have been seen in comparing LIS observations with mapping data from the Lightning Detection and Ranging system at Kennedy Space Center.

Figure 2 shows an expanded view of two seconds of observations. Two lightning discharges occurred during this time; an intracloud (IC) discharge and a cloud-to-ground (CG) discharge. Both discharges were detected by the LIS. The IC discharge occurred first and is seen at the beginning of the height versus time plot in panel 2*b*. Light was detected as soon as the discharge reached the upper level; this was typical of most of the IC discharges observed by the two systems. The CG discharge started at 16.58 s in panel 2*b* and began with two strokes to ground, both detected by NLDN, but not by LIS. Instead, the LIS detected multiple pixel illuminations two times late in the discharge, with the first detection corresponding to the final stroke detected by NLDN.

Figure 3 shows observations during a 4 second time interval containing three IC and three CG discharges. Optical illumination was detected from each of the IC discharges but from none of the CG discharges. This is best seen in the plan view of panel *e*, where illumination contours surround the three ICs but not the CGs. The difference was

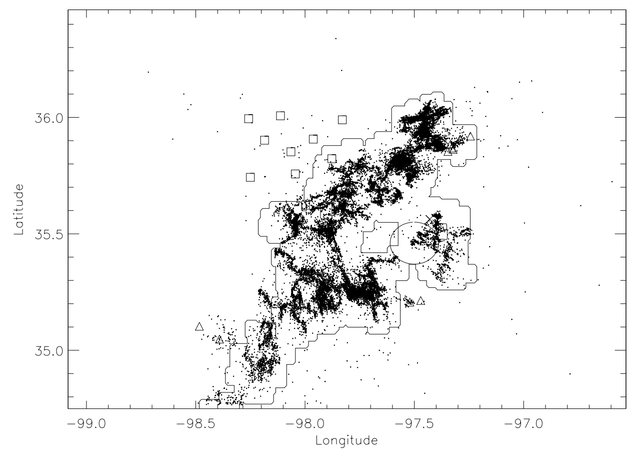

Figure 1. Overview of the storm, showing the correlation between LMA-detected lightning activity (dots) and the LIS-detected cloud illumination (rectangular contour lines). Individual LMA stations are denoted by squares and occupied an area about 60 km in diameter. The map covers an area about 200 km on a side; the Oklahoma City area is indicated by the circle near the center of the map. The storm is the same as shown in Figure 1 of *Krehbiel et al.* [2000].

that the channels of the IC discharges extended up to 12-15 km altitude msl, whereas the CG sources were confined below 7 km altitude. The CG discharges overlapped in time with the IC discharges and are best distinguished in the vertical cross-sections of panels 3*c* and 3*f*. Two of the three CG discharges were relatively small, which would decrease their optical detectability. The CG discharge of Figure 2 was not detected until it had developed extensively within the cloud.

To determine how well LIS detected low-altitude lightning, we identified a total of 27 discharges that were confined below 7 km, similar to those in Figures 2 and 3. Of the 27, four were detected by LIS. Examination of the raw LIS data showed that an additional five discharges were also detected optically but were removed by a filtering algorithm used to distinguish between lightning and noise events. Improved filter algorithms currently under development would have detected these discharges. The NLDN located CG strokes from 16 of the 27 low-altitude discharges.

Figure 4 shows detailed results for an intracloud discharge. The discharge had a typical bilevel structure, in agreement with the observations of *Shao and Krehbiel* [1996], who correlated the lower and upper levels with the main negative and upper positive charge regions of the storm. The discharge began with upward breakdown between the two levels; luminosity was first detected 41 ms later after the breakdown had reached the upper level at about 11-12 km altitude. Virtually all of the subsequent luminosity was associated with renewed breakdown into the upper level and with extension of the upper level channels, but not with continued activity in the lower level. The strongest light emissions occurred during the last half of the discharge, when the LIS data showed that many pixels were impulsively illuminated over the entire region mapped by the LMA. These emissions were undoubtedly associated with impulsive high-current events, termed K-changes in electric field measurements. K-events occur along the entire extent of the channels in the later stages of IC discharges (e.g.. *Shao and Krehbiel* [1996]), and are very bright optically. The final, fast upward breakdown at 27.98 s is typical of the initiating streamer of a K-change, and was immediately followed by strong luminosity. The previous strong luminosity events were likely to have also been produced by K-events not detected by the LMA. (The LMA typically detects only a few points during K-events because of its 100 μs time resolution.) Weaker K-events are known to occur early in a flash and may have produced the initial luminosity pulses.

Figure 5 shows observations of a complex, hybrid IC-CG discharge of 2 s duration. It began as a normal CG discharge and produced a series of negative polarity strokes to ground, as indicated by NLDN. For the first 0.7 seconds the discharge was confined below 7 km altitude and produced insufficient luminosity at the top of the cloud to be detected by LIS (panel 5*b*). At about 49.2 seconds in panel 5*b*, the discharge developed upward in the cloud. Two pixels were illuminated

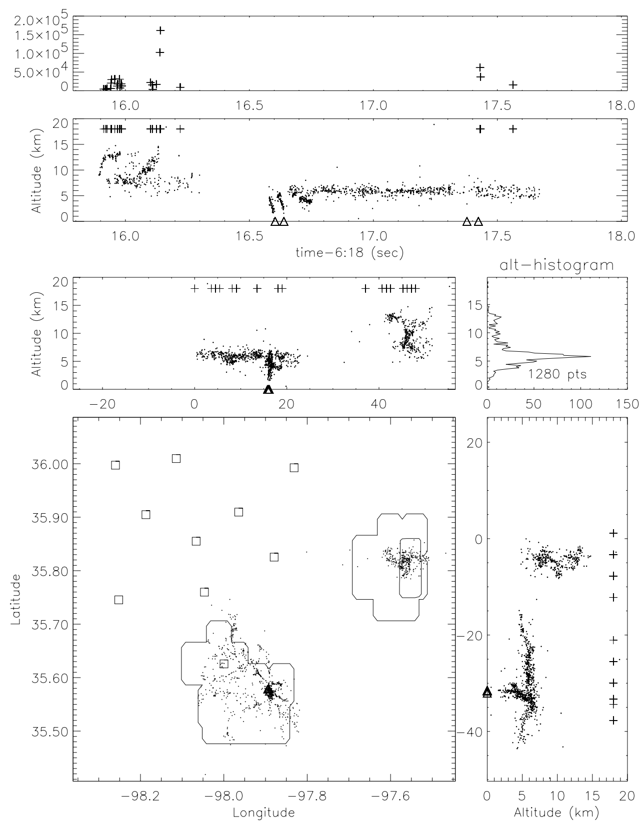

Figure 2. Observations for an intracloud and cloud-to-ground discharge that were detected by LIS. Panel *e* is a plan view as in Figure 1. The interior rectangular contour in panel *e* indicates twice the optical intensity of the outer contour. Panel *a* shows LIS measurements of the light intensity versus time (μJ ster^{-1}m$^{-2}\mu$m^{-1}) integrated over 2 ms time intervals. Panel *b* shows the height of the LMA events versus time. Panels *c* and *f* show vertical projections of the LMA data as viewed from the south and west, respectively, with distance in kilometers. The + symbols above the LMA data in panels *b*, *c*, and *f* show the times and locations of the optical events detected by LIS. Shown along the abscissa of these panels are the locations and times of negative (△) and positive (×) cloud-to-ground strokes located by the National Lightning Detection Network. Panel *d* shows the height distribution and number of radiation sources located by the LMA during this period.

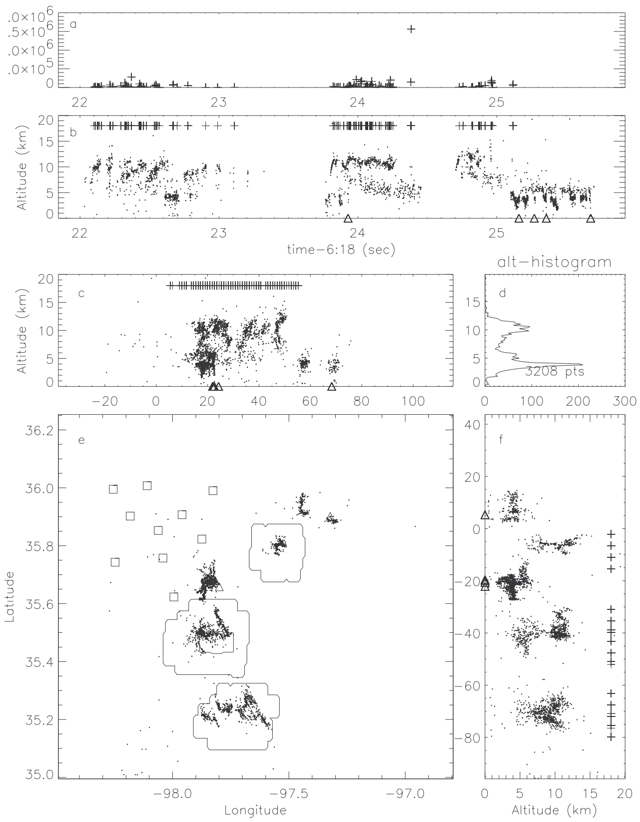

Figure 3. Four seconds of observations showing three intracloud and three cloud-to-ground discharges, in the same format as Figure 2.

above the active region 10 ms before the beginning of the upward activity; additional luminosity was detected when this activity reached the upper part of the cloud. The optical activity intensified during the more vigorous upward breakdown around 49.5 s and then became impulsive in the final stages of the discharge. The final optical event was by far the most energetic and simultaneously illuminated most of the LIS pixels over the discharge region. The strong and impulsive nature of the luminosity indicates that it was produced by a K-event; the final K-events are often the most energetic of a lightning discharge. The discharge continued at low altitude for another 0.4 s but produced no detected luminosity.

Of the 128 discharges observed during the LIS overpass, 101 produced breakdown above 7 km altitude. These discharges usually extended up 10 km altitude or higher. LIS detected light from 99 of the 101 high-altitude discharges; the two discharges missed by LIS produced a small number of LMA points in a localized region. Eight of the LIS detections were found only in the raw data. We identified 26 discharges in the LMA data that were similar to the hybrid discharge of Figure 5 in that they had activity at high altitude and appeared to go to ground; LIS detected all 26 (one was found only in the raw data) and the NLDN located CG strokes for 11.

The vertical cross-sections and the histogram of Figure 5 show a third level of activity at about 4 km altitude, just below the negative charge at 6 km altitude. Such a tri-level structure is a common feature of the LMA observations both in Oklahoma and New Mexico (e.g., [*Krehbiel et al.*, 2000]). The third level appears to be associated with lower positive charge in the storm, and is well illustrated in the Figure 5 observations.

Summary and Discussion

The results of this study show that discharges which extended into the upper part of the cloud were well detected by the satellite-based Lightning Imaging Sensor. Discharges confined below 7 km altitude were less well detected. The brightest optical events tended to occur at the end of intracloud discharges, when a large number of pixels covering the full horizontal extent of the flash were impulsively illuminated.

CG discharges tended to be detected by a few impulsive optical events toward the end of the discharge. This agrees with the results by *Goodman et al.,* [1988] that the most luminous events of CG discharges were late-stage in-cloud components and subsequent return strokes. Their measurements were obtained from a U2 aircraft flying at 20 km altitude over an extensive multicellular system, similar in extent and depth to the storm of this study. *Goodman et al.* found the optical intensities and energies for IC and CG discharges to be remarkably similar. This would predict that IC and CG discharges would be equally well-detected by satellite, which has not been found in the present study. Rather, vir-

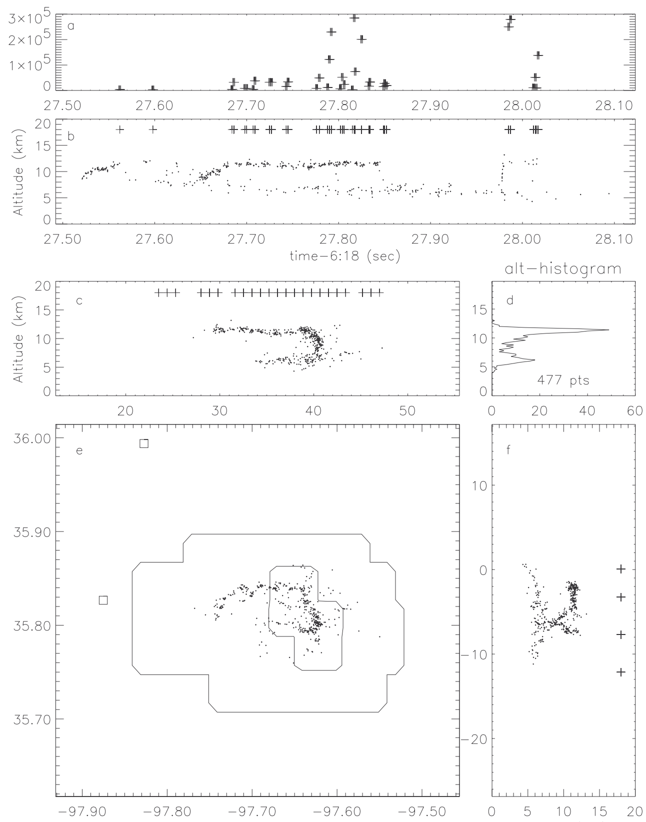

Figure 4. Detailed observations of a bilevel intracloud discharge, showing the association of satellite-detected luminosity with upper level activity. At the time of the overpass the satellite was traveling almost directly from west to east, causing the illuminated pixels to be displaced from each other in the east-west direction (panel *c*) but to lie on top of each other in the north-south vertical cross-section (panel *f*).

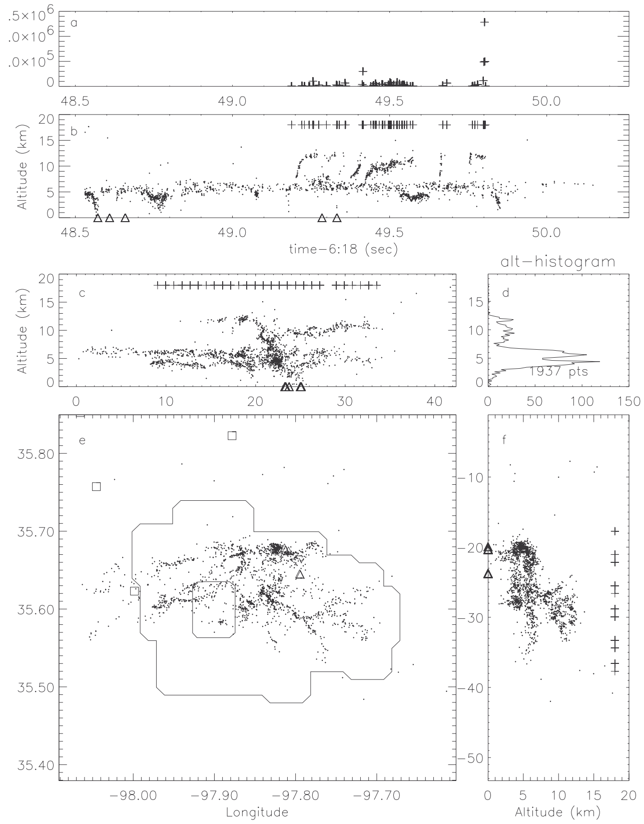

Figure 5. Same as Figure 4, except of a horizontally extensive, hybrid cloud-to-ground and intracloud discharge.

tually all IC discharges having an upper level component were detected by LIS, while about 60% of the estimated CG discharges were detected. Many of the latter were hybrid discharges having high-altitude components.

Optical detection of luminous events inside a cloud is possible since light is scattered many times and escapes with only negligible absorption. The observed difference in detectability for the low- and high-altitude discharges was undoubtedly due to differences in the optical depth between the source and the surrounding cloud surfaces. As shown by *Thomason and Krider* [1982], most of the light escapes to the nearer surfaces; very little of the light originating near one cloud boundary will escape out a distant boundary. This explains why discharges extending into the upper part of the storm were detected with virtually 100% efficiency. The fact that discharges confined to the main negative charge region or below were less well-detected (9 out of 27, or 33%) implies that the negative charge region was closer to the lower cloud surface of the storm than the upper surface. The difference with the results of *Goodman et al.*, [1988] concerning the detectability of low-level discharges is not understood; observations are needed of a greater number of storms to provide more statistically significant information on this issue.

A second-generation version of the LMA is currently being implemented in northern Alabama that will address the above question. The observations will be correlated with detailed radar, electric field, and other measures of the storm and lightning activity to investigate how satellite and ground-based mapping lightning measurements relate to such quantities as the updraft strength, depth of convection, and storm mass fluxes. The luminous events are also indicative of high-temperature, impulsive processes that will be important sources of odd nitrogen compounds at high altitudes in the atmosphere, which in turn are very important to the ozone chemistry [*Coppens et al.*, 1998].

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