Coincident observations of lightning by the FORTE photodiode detector, the New Mexico Tech Lightning Mapping Array and the NLDN during STEPS

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[1] Opportunities for observation of lightning simultaneously from space and ground are relatively rare. One such opportunity for "ground truth" occurred during the STEPS field program. On 25 June, 2000 the FORTE Satellite passed over a storm that was also observed by a VHF Lightning Mapping Array (LMA). Of the 190 flashes mapped during the 2 minute 45 second pass, 26 had associated satellite optical data, and 3 of these were coincident with the only NLDN ground-strike locations in the storm during that time. The maximum height, horizontal extent and duration of flashes detected optically tended to be greater than for those flashes not optically detected. Results in this paper, a companion paper and other published papers suggest that at least under some circumstances, CG flashes are relatively more likely than intra-cloud (IC) flashes to be observed by an optical sensor in orbit. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3346 Meteorology and Atmospheric Dynamics: Planetary meteorology (5445, 5739); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Noble, C. M. M., W. H. Beasley, S. E. Postawko, and T. E. L. Light (2004), Coincident observations of lightning by the FORTE photodiode detector, the New Mexico Tech Lightning Mapping Array and the NLDN during STEPS, *Geophys. Res. Lett.*, *31*, L07106, doi:10.1029/2003GL018989.

1. Introduction

[2] Optical signals from lightning discharges, observed by satellites, can be used as indicators of deep moist convective processes on a global scale, on Earth [*Turman*, 1978]; on other planets [*Ingersoll et al.*, 2000]; for model initializations [*Chang et al.*, 1999], convective parameterizations [*Christian and Latham*, 1998; *Tapia et al.*, 1998], and global climate studies [*Price and Rind*, 1994; *Reeve and Toumi*, 1999; *Williams et al.*, 2000]. Satellite data are especially promising for use in remote areas where ground-based data may be difficult to obtain. Therefore, it is important to understand how the optical signals relate to the physical properties of the lightning discharges and storms that produce them. In this paper we investigate differences between lightning flashes detected by the FORTE satellite Photodiode Detector (PDD) and lightning flashes not detected by the PDD. To accomplish this, we use "ground truth" data from a VHF Lightning Mapping Array (LMA), operated by the New Mexico Institute of Mining and Technology (NMT), and lightning ground-strike data from the National Lightning Detection Network (NLDN), operated by Vaisala, Inc.

2. Observing Systems

[3] The FORTE satellite, in orbit at approximately 825 km altitude, employs a visible-light (0.4 μm − 1.1 μm) silicon photodiode (PDD), with sensitivity better than 10^{-5} Wm^{-2}, similar to the PBE optical detector on the DMSP satellite in 1977 [*Turman*, 1978]. Data from the PBE coincident with ground-based rf observations of lightning are discussed in a companion paper [*Beasley and Edgar*, 2004]. The PDD field of view covers an area roughly 1200 km in diameter at the surface of the Earth. Each PDD record is 1.92 ms long, with 15 μs time resolution and trigger times known to within 1 μs.

[4] The LMA records the time of arrival of impulsive VHF radiation at multiple stations. The differences in time of arrival are processed to locate the sources of radiation. Location errors are typically ±100 m over the network. Errors increase with distance, especially in the determination of the height of radiation sources, such that the mapping becomes two dimensional at long ranges. The NMT LMA and its operation are described by *Rison et al.* [1999] and *Krehbiel et al.* [2000]. The LMA deployed for STEPS (the Severe Thunderstorm Electrification and Precipitation Study) consisted of 13 stations within a four-county area in northwest Kansas and eastern Colorado (http://lightning.nmt.edu/nmt_lms/steps_2000/index.html).

[5] The NLDN provides the time of occurrence, latitude, longitude, polarity, and other physical characteristics of cloud-to-ground lightning flashes in the continental US. The principles of operation and characteristics of the system are described by *Cummins et al.* [1998].

3. Case Study

[6] On 25 June, 2000, for a period of approximately 2 minutes 45 seconds, coincident lightning data were collected by the FORTE PDD and the LMA in STEPS. The ground-track of the satellite is shown as a solid line in Figure 1, with asterisks to indicate the sub-satellite locations

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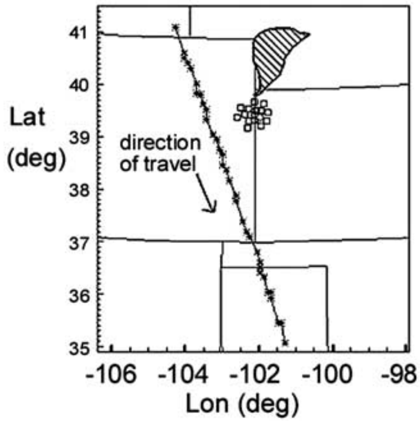

Figure 1. Summary of PDD and LMA data, June 25 2000 ~ 7:50:00–7:52:40 UT.

at the times of PDD triggers. The slight wobble in the ground track is an artifact of the data processing. The LMA stations are shown as small squares. There were 63 optical triggers, with estimated peak power from about 1.6×10^9 W to 2.4×10^{10} W, in the middle of the range of peak optical powers recorded since FORTE was launched [*Kirkland et al.*, 2001]. The shaded region in Figure 1 shows where VHF source locations were recorded by the LMA during a ten-minute period beginning at 07:50:00 UT. The lightning mapped by the LMA occurred about 120 km from the center of the array. At this distance, for a typical VHF source at height of 10 km, the error in height is ±0.7 km, in range, ±0.7 km, and in azimuth, ±0.6 km.

4. Analysis and Results

[7] The term "flash" is sometimes used imprecisely in the literature. For comparison with other work it is important to be clear about the meaning of the term as used in this study. For the coincidence time period, approximately 190 separate flashes were identified in the LMA data by careful visual inspection of the time series of VHF source locations. Groups of source locations were separated in time if the time between two successive points exceeded 0.2 seconds. These groups were further separated if the distance between groups of sources exceeded 1 km. Flash durations were from about 0.2 s to about 1.6 s. This definition of a flash could give results that are statistically different from results obtained using a definition based on electric-field observations or sferics.

[8] For comparison with LMA data, PDD trigger times were corrected for propagation delay to the spacecraft. First, the average location of VHF source points for the entire coincident data window was used for the correction. PDD trigger times were then corrected again using the average VHF source location for the coincident flash in each case. Of the 63 PDD triggers, 41 were coincident with 26 flashes identified in the LMA data, with one to five optical signals per flash. All but three of the coincident events had VHF source locations within ±2 ms (the criterion used by *Kirkland et al.* [2001] to compare PDD triggers with NLDN-located ground flashes). The remaining three were within ±20 ms of the PDD trigger time. Also, all but the latter three had VHF sources occurring either within the 1.92 ms PDD data window or within 500 μs (the time resolution of the LMA data) of the edge of the PDD data window. None of the non-coincident events had VHF sources occurring within ±20 ms of a PDD event time. These PDD triggers were likely from a storm in the Texas panhandle within the PDD field of view, or possibly from positively charged channels, which do not radiate VHF well. Archived NCDC records show that there were no other storms in the field of view during this time. It is possible that the three events with weaker (±20 ms) correlations were caused by IC activity occurring elsewhere within the PDD field of view. We have verified that these events and the other non-coincident PDD events are not coincident with NLDN-located CG flashes outside of the LMA coverage.

[9] Model studies [*Light et al.*, 2001] have shown that observed peak intensity of light from a discharge within a cloud can vary by more than an order of magnitude, depending on the location of the discharge within the cloud with respect to the point at which the observation is made. It is reasonable to expect that lightning flashes with greater energy and flashes that occur close to the edge or top of a cloud are more likely to be detected by the PDD. We chose three measurable physical characteristics as indicators of the position and energetics of each flash: maximum height, spatial extent, and duration of VHF source locations. The spatial extent of each flash was estimated from its north-south and east-west extents. We used this method to simplify and automate the estimation process. For sake of brevity, we do not show the distributions of spatial extent. Shown in Figure 2 are distributions of maximum height of VHF source locations within each flash for the 26 flashes that were detected by both the LMA and the PDD and for the 164 flashes that were detected by the LMA only. Distributions of durations are shown in Figure 3. We used appropriate statistical tests to verify our visual impressions in each case that the distributions were significantly different [*Noble*, 2001]. We also examined the height of maximum rate of occurrence of VHF source locations and found that the mean and shape of these distributions were not significantly different for those flashes that were detected by the PDD and those that were not.

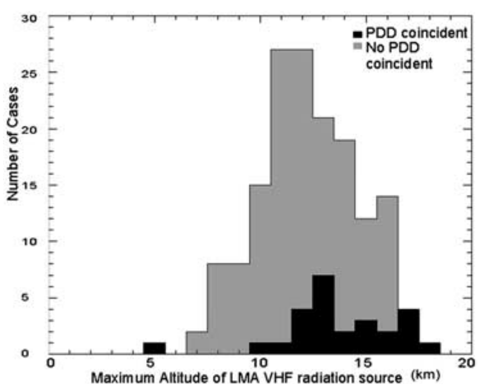

Figure 2. Maximum heights of VHF radiation sources for flashes detected by the PDD and flashes that were not detected by the PDD.

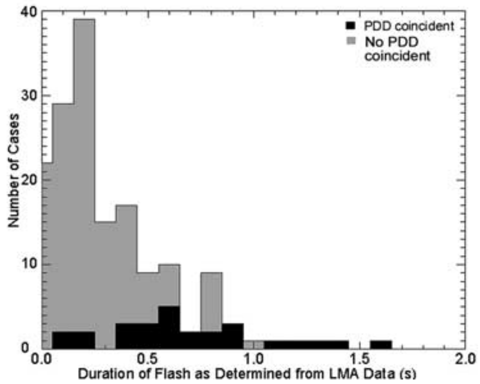

Figure 3. Durations of flashes mapped by the LMA that were detected by the PDD and that were not detected by the PDD.

[10] Finally, we compared PDD trigger times with the occurrence of VHF source locations as a function of height as shown in Figures 4a and 4b. Diamonds (◇) represent PDD optical triggers and plus signs (+) show the altitude of VHF source locations. In Figure 4a, the occurrence of CG flashes as determined by the NLDN is shown with an x for each of two +CG flashses and a Δ for one −CG flash. These were the only NLDN-located ground flashes that occurred in the storm of interest during the satellite pass. In the preceding 17 minutes, there were 8 +CG and 5 −CG flashes and in the succeeding 14 minutes, 5 +CG and 1 −CG flashes located by the NLDN in the storm. Of the 22 NLDN located CG flashes in the 34 minute period, 15 were +CG and 7 were −CG, the same 2:1 ratio as during the satellite pass. The ratio of IC to CG flashes was high in this storm, as it was typically in the storms observed during STEPS (http://lightning.nmt.edu/nmt_lms/steps_2000/index.html).

5. Discussion and Conclusions

[11] From Figures 2 and 3, we conclude that VHF source locations in flashes that were detected optically from space by the PDD tended to be higher in the storm and to have longer durations than the VHF source locations in flashes that were not detected by the PDD. Horizontal extent was also greater for coincident flashes. However, there is no apparent direct correlation between the height of individual VHF radiation sources detected by the LMA and the occurrence of PDD triggers. The data in Figures 4a and 4b show that PDD optical detections occurred sometimes, but not always, when there were numerous VHF sources at 10 km altitude and above, sometimes when there were numerous VHF sources at low altitudes, and sometimes when there were very few VHF sources at any altitude. This is consistent with the conclusion by *Light et al.* [2001] that the intensity of light from a discharge depends strongly on its location within a cloud. It is reasonable to expect that discharges higher in the cloud are, more often than not, closer to the cloud boundary, but it is plausible that energetic discharges lower in the cloud could also be observable from space and that less energetic discharges high in the cloud might not be observed from space. These results are also consistent with the possibility that the physical processes that produce significant VHF radiation and the physical processes that produce significant emissions of visible light may sometimes occur concurrently and sometimes not.

[12] Most of the discharges in the 25 June 2000 storm were IC flashes with "inverted polarity" [*Krehbiel et al.*, 2000], and there were roughly twice as many +CG as −CG. In the VHF data, inverted polarity flashes tend to begin at an altitude of 9 or 10 km and develop downward, presumably as negatively charged channels. Normal polarity IC flashes [*Thomas et al.*, 2000] tend to begin at a height of 5–6 km and develop upward. Storms with predominantly inverted IC discharges have a positive charge layer at midlevels and a negative charge layer in the upper part of the storm (http://lightning.nmt.edu/nmt_lms/steps_2000/index.html). Positive leaders are not detected as well by VHF systems as negative leaders [*Mazur et al.*, 1997]. It is conceivable that positively charged discharge channels propagating upward from a positive charge region might have emitted visible light, but little VHF radiation. This might account for some

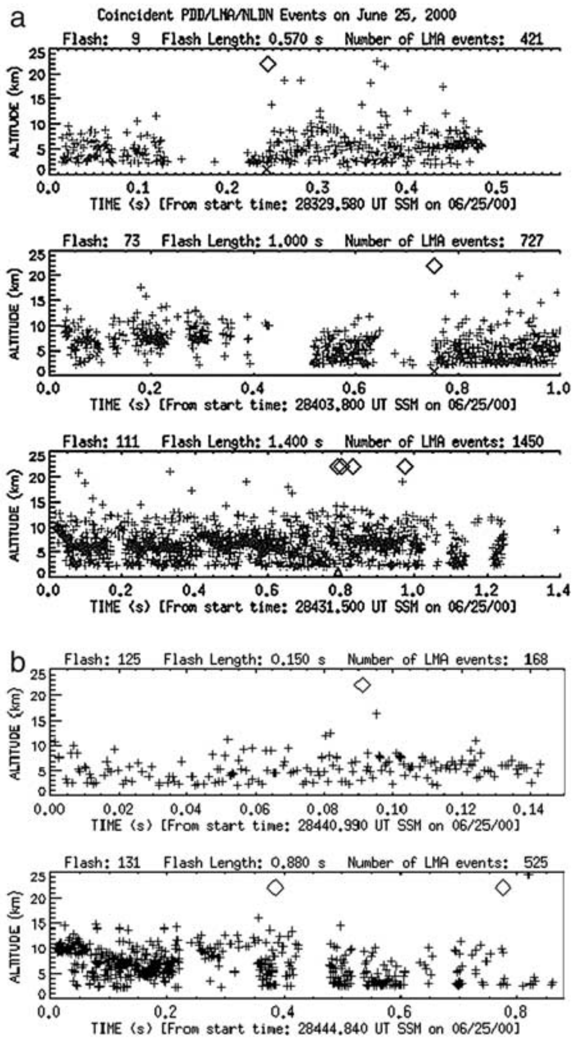

Figure 4. Altitude (km) vs. time (s) plots of VHF radiation sources (+), with times of PDD triggers (◇), (a) showing times of 3 coincident NLDN ground-strikes (x for +CG, Δ for −CG) and (b) PDD triggers for VHF sources at various heights.

of the 22 optical events for which there were no coincident VHF source locations. It should be noted also that the 500 μs time resolution of the LMA data used for this work is relatively coarse. Many points could have been missed.

[13] Many PDD triggers occurred part way through or toward the end of a flash mapped by the LMA. This can be seen in Figure 4a and Figure 4b. Similar behavior was seen in data from the Lightning Imaging Sensor on the NASA/TRMM Satellite [*Thomas et al.*, 2000]. Note in Figure 4a that each of three ground strikes located by the NLDN during the FORTE pass (the only CG flashes during that time) is followed within about a millisecond by a PDD trigger. This is consistent with the observation by *Suszcynsky et al.* [2000] that the PDD often detects light from flashes that make a connection to ground, as that process moves upward into the cloud. It is also consistent with the observation reported in the companion paper [*Beasley and Edgar*, 2004] that 7 out of 8 located ground flashes had coincident optical events observed from space. Return strokes in CG flashes generally have the largest currents and luminosity of all lightning processes and CG flashes frequently have extensive channels reaching high in a storm cloud [*Mazur et al.*, 1997]. These features could make the optical emissions more likely to be observable from space. In some cases [*Thomas et al.*, 2000] in which VHF sources associated with CG flashes were confined to altitudes below 7 km, the flashes were not detected optically from space.

[14] In a case study of a squall-line storm for a period of 215 seconds (comparable with the conditions for observations reported here and in the companion paper) *Kirkland et al.* [2001] found that only about 34% of 178 PDD triggers were coincident with CG flashes located by the NLDN. In other words, 66% of PDD triggers were coincident with IC flashes. The detection efficiency of optical sensors in orbit may be greater for CG flashes, as we suggest, but if there are far more IC flashes in a storm, as is often the case, the number of IC flashes detected could exceed the number of CG flashes detected. More cases with coincident PDD, LMA and NLDN data, and cases in which the variations in electric field of IC flashes with geometry known from LMA data need to be identified in the STEPS and other data sets and analyzed in order to clarify the significance of connections to ground.

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