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HOUSTON LDAR II NETWORK: AN EVALUATION OF LDAR DERIVED FLASH EXTENT WITH TRADITIONAL NALDN METRICS IN SUMMERTIME SOUTHEAST TEXAS THUNDERSTORMS

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Abstract: A comparison of flash parameters from the North American Lightning Detection Network is made with data obtained from the Houston LDAR II network. This work focuses on relating the number of strokes in a flash (multiplicity) of lightning with the spatial extent and mean altitude of three dimensional lightning as mapped by the LDAR network. It is shown that increasing multiplicities over the range two through ten exhibit, on average, a higher flash extent with higher multiplicities. Single-stroke flashes appear to deviate from this generalization. Higher order multiplicity was also found to suggest lower mean lightning source heights. Finally, there appears to be a correlation between high peak currents and increasing flash extent.

1. INTRODUCTION AND MOTIVATION\

Since the late 1980s, a National Lightning Detection Network (NLDN) for detecting cloud-to-ground strokes has been in place (Cummins et al, 1998). More recently, technology has allowed the use of Very High Frequency (VHF) radio frequency to detect individual energy sources within the flash. One such network is deployed, in the Houston area and is run by the Department of Atmospheric Sciences at Texas A&M University. The Houston network is formally known as the Houston Lightning Detection and Ranging (LDAR) network. The sensors and central server are manufactured by Vaisala.

By mapping the three dimensional information provided by the VHF network and combining the information with cloud-to-ground data, insight into the volumetric characteristics of total lightning becomes possible.

No significant study has been conducted which compares cloud-to-ground data and VHF sources. This thesis aims to fill that gap and provide a comparison for observations using NLDN and the Houston LDAR network. Although the two networks intend to capture uniquely different information, temporal and spatial synchronization facilitates comparison between the two networks.

Immediately, many questions come to mind regarding this comparison. How does the flash extent and altitude compare to multiplicity, the number of strokes per flash. What interactions may exist with the peak current of the flash and flash extent or average height? Are there tendencies for changes through the life of a given thunderstorm? What can be inferred from these observations and what further use of these data might be worthwhile to pursue?

2. THE NORTH AMERICAN LIGHTNING DETECTION NETWORK

Late in the 1970s, data began to be collected on cloud to ground lightning discharges with the deployments of a number of networked lightning sensors in the Western United States and Alaska to aid in forest fire mitigation. This network was comprised of low frequency loop antennas in an orthogonal configuration plus an electric field antenna to obtain unambiguous azimuthal information with an accuracy of two degrees or better (Krider et al, 1980). Shortly thereafter, other networks were established in the United States. In the northeastern United States, a network, with an operations control center at the State University of New York at Albany, was initiated in the spring of 1982. By late 1983, ten sensors were deployed with coverage roughly extending from North Carolina to extreme southern Quebec (Orville et al, 1983). Additionally, a mid-western network, with four sensors, was operated by the National Severe Storms laboratory in Oklahoma (Mach et al, 1986).

Figure 1: Today's NLDN consisting of 113 lightning sensors locations across the continental US (Grogin.)

By 1989, all three networks were expanded and merged into the National Lightning Detection Network (NLDN) providing coverage for the contiguous United. The system was upgraded in 1994 through 1995 with roughly half the sensors incorporating time-of-arrival and magnetic direction finders known as improved accuracy from combined technology (IMPACT) sensors. After the upgrade, the network included 106 sensors with an average baseline near 300 km. (Cummins et al, 1998). In 2004, all sensors were upgraded to more sensitive IMPACT-ESP units and additional sensors were added to the network (Biagi et al, 2004). Today, the network covers the United States (113 sensors) and much of Canada (87 sensors) and is known as the North American Lightning Detection Network (NALDN).

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Post-processed archive NLDN data are received monthly at Texas A&M and provide raw stroke data which includes geolocation information, stroke current (including polarity) and nanosecond-resolution timing. Using geolocation and timing information, flash multiplicity is derived. With the addition of peak current, these data provide four useful metrics to describe the characteristics of C-G lightning (Biagi, et al, 2007).

3. THE LIGHTNING DETECTION AND RANGING NETWORK

While NLDN data provide insight to cloud-to-ground flashes, lightning also exhibits a volumetric distribution in thunderstorms that cannot be mapped by low frequency (1 kHz to 1 MHz) systems. However, VHF systems are able to obtain details about the structure of lightning flashes by measuring radio frequency burst on the order of a few microseconds (Mazur et al, 1997). By using multiple, geographically spaced, receivers, the location of the pulse origin may be found using Time Difference of Arrival (TDOA) methods assuming line of sight propagation at the speed of light through the atmosphere. While errors due to change in velocity of propagation are possible, primarily induced by the variation of vertical gradients in moisture (Freeman, 1987), these errors, especially in the domain on the order of 100 km, will be small.

The Department of Atmospheric Sciences at Texas A&M University has deployed a network of twelve TDOA lightning detection and ranging (LDAR) sensors in the Houston area. The network is centered at 29.79 N, 95.31 W. These sensors are arranged, manufactured by Vaisala, in an outward spiral with average baseline of 25 km between sensors and an average network radius of 75km. Figure 1 provides an overview of the sensor locations throughout the Houston area.

Each sensor has a power supply, a Linux mini-computer, an antenna, GPS receiver for synchronization and a radio receiver. The receiver, based on testing with RF equipment has a nominal bandwidth of 6 MHz. and employs an amplitude detector. The sensor detects up to 10,000 transients per second. However, under quiescent conditions, the sensor is adjusted for 5 to 10 % detected amplitude (500-1000) transients (from noise in the receiver) for optimal sensitivity.

The Frequency of operation and radio frequency gain is remotely adjustable. The Houston network has operated on a total of three RF frequencies during its lifespan. The original deployment operated near 69 MHz, a vacant television channel in the immediate area. However, the occurrence of troposphere propagation enhancement along the Gulf Coast, the radio frequency noise floor often rises substantially during the night due to the reception of distant television stations. E-layer “skip” propagation also contributes to an increased noise level especially during active solar conditions. Paging transmitters in the Houston area above 70 MHz further negatively impacted the system.

Figure 2. LDAR sensor at the Williams Airport in far north Houston

To counteract the interference faced by operating within the VHF-TV band, a move was made to 113 MHz in the normally quiet aeronautical navigation band. Unfortunately, strong noise transients were observed at several locations on this band. The source of the transients was never identified, but the decision was made to try a lower frequency band as it was not known how well the sensors would perform at higher frequencies.

In March 2007, a move to 40 MHz was made and this band has proven to be the most stable, from a noise level perspective. Additionally, a substantive improvement in distant source detection was realized with this change. For the first time, sources as distant as the Dallas/Fort Worth area were detected.

The Houston network provides a three dimensional perspective of each detected source with geolocation, timestamp, and signal strength information. A large flash may be comprised of hundreds of sources thus revealing the structure of the flash as well as flash extent. The method of mathematically deriving each source's position is described in Thomas et al, (2004) and Koshak et al, (1996).

By plotting the detected sources on a map, the internal structure of lightning flashes are revealed in the horizontal and vertical. From these data, horizontal and volumetric extent and average source height are determined.

By combining NLDN cloud-to-ground data and LDAR VHF source data, total lightning characteristics can be established. While the LDAR network detects intra-cloud flashes, the analysis of intra-cloud flashes is outside the scope of this study.

4. PURPOSE AND METHODOLOGY

Each month Vaisala sends NLDN data that have been post-processed and are of a higher accuracy than the real-time NLDN feed. LDAR data are also collected in real time in a decimated (lossy) format. However, every few months, the disk drives located within the sensor, are collected and all flash data are reprocessed using the complete non-decimated data.

Once data are in a usable form, the NLDN data serves as the key for comparison. A box defined as the region with upper left coordinate of (30.3N,95.77W) and lower right coordinate of (29.3N,94.77W) was defined to geographically select cloud-to-ground flashes for analysis. This area constitutes the peak performance region for the Houston LDAR network. Spatially large flashes (over 75km in length) have been observed in the network. As it is desirable to not artificially limit flash extent calculations, a secondary box for LDAR data bound by the upper left coordinate of (31.8N,97.27W) and lower right coordinate of (27.8N,93.27W) served as the domain for LDAR sources.

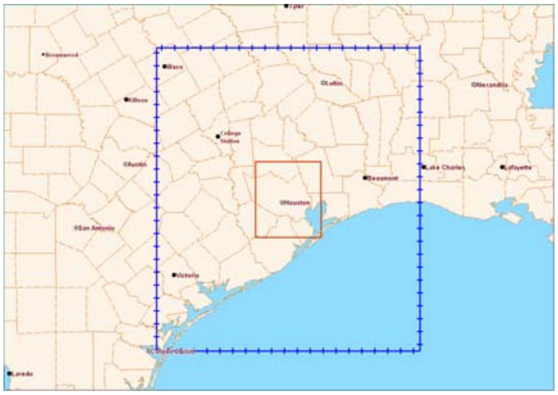

Figure 3. Map of CG domain (red box) and LDAR source boundary (blue hashed box).

To tie both sets of data, each NLDN flash within the NLDN domain was then characterized as to its polarity, multiplicity, peak current, location, and time. For the purposes of this study, each stroke analyzed must be within 10km, and within one second of the previous, to count as a flash with multiplicity greater than one. Cases where multiple flashes break the constraints within the NLDN domain were rejected. In turn, the LDAR data were then parsed to find sources matching the spatially and temporally related LDAR data. If none were found, the lack of VHF sources was noted for detection efficiency calculations. Two possibilities exist: Cloud-to-ground flashes occurred without creating any VHF sources or, more likely, cloud-to-ground flashes occurred that were too weak to detect with the LDAR network. The data from NLDN and LDAR were analyzed graphically on a flash-by-flash basis to determine the following: contiguous volumetric extent in VHF source data, coincident placement of the NLDN and LDAR flash, and contamination from other flashes, such as associated, or sympathetic, lightning (Mazur, 1982) within the LDAR domain. If a unique flash was not obvious in the data, the entire flash was rejected.

To obtain a metric for flash extent, a geographic 200 by 200 bin horizontal grid system was developed over the LDAR domain. This grid resulted in a North / South height of 2.22 km and East / West width of 1.93 km at grid center resulting in an area of roughly 2.1 km^2. In the vertical, the atmosphere was cut into layers of 1000m from 0 to 20 km. These grids are hereafter referred to horizontal bins and volumetric bins. When a VHF source was detected in a bin, that bin was marked as active and the analysis of additional sources continued. When the LDAR entire flash period was parsed, the resulting active bins indicated the volumetric extent for comparison.

The temporal domain for LDAR flashes was 2 seconds on either side of a cloud-to-ground flash. This value was selected as certain flashes (especially “anvil crawlers”) tend to have long life spans and the intent is to not artificially reduce the flash extent by limiting the maximum time of the flash. While comprehensive data regarding the duration of VHF source events were not available, two seconds was chosen as a reasonable limit based on previous visual lightning observations. Height information was extracted from LDAR data and the average height of all detected VHF sources, for each flash, was obtained.

Unfortunately, the complexity surrounding temporal and spatial patterns of lightning results in characteristics that are not trivially solved with computer algorithms. While some automation may be possible, such an exercise exceeds the scope of this work. Therefore, manual analysis of each flash was performed to ensure an accurate representation of total lightning characteristics.

The analysis of flashes with multiplicities greater than ten is hampered by the low occurrence of such flashes. To make some use of the acquired data, flashes exhibiting multiplicity greater than 10 were aggregated into a category known as “10+.”

In southeast Texas, the ratio of positive to negative flashes typically runs near 10% annually with higher positive rates during the winter (Orville et al, 2002). Statistics were collected on positive and hybrid (positive first, then negative and negative first, then positive) flashes and then compared with the more common negative-only flashes.

The LDAR system appears to operate optimally at a frequency of 40 MHz. The study was therefore performed exclusively with 40 MHz. data collected after March 2007. Data were collected with typically 10 to 12 sensors providing input to VHF source solutions depending on maintenance issues at each site. As thunderstorms in March through May occur most frequently as part of mesoscale convective systems, with large expanses of intense lightning data, this period of time is not optimal for capturing single flash events. In order to help mitigate the effects of storm environment, a number of storm days were examined. The period used in this study (May-July 2007) provided an extended wet period caused by a weakness between the virtually stationary Bermuda and Southwestern US highs, several days provided useful data. Synoptic forcing was quite weak during much of the period. However, most storms were not isolated spatially within the domain. This lack of spatial diversity leads to a higher percentage of unusable flashes.

5. RESULTS

As a sanity check on the dataset, average multiplicity, peak currents, percent positive were compared with the findings of Steiger et al, 2002. Values were found to be within reasonable range of the annualized averages obtained previously taking into consideration the time period of this study.

A total of 1407 flashes were analyzed as part of this study with comparisons of each of the five variables under investigation. Figure 2 provides the number of events sampled with varying degrees of multiplicity.

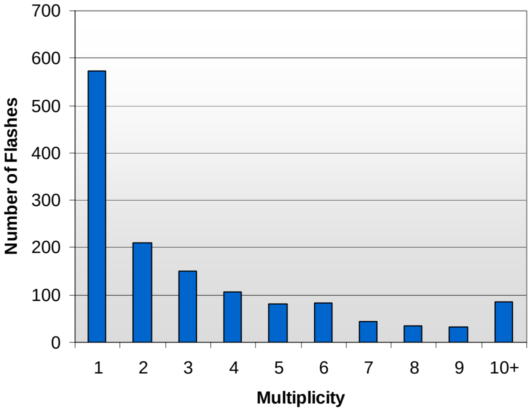

Figure 4. Histogram of multiplicity in flashes analyzed in this study.

576 one stroke flashes were collected along with a total of 831 multi-stroke flashes exhibiting a mean multiplicity of 3.3. A pseudo-exponential decay in events vs. multiplicity is evident in the graph. All flashes with multiplicity of 10 or greater were aggregated into a single category: "10+."

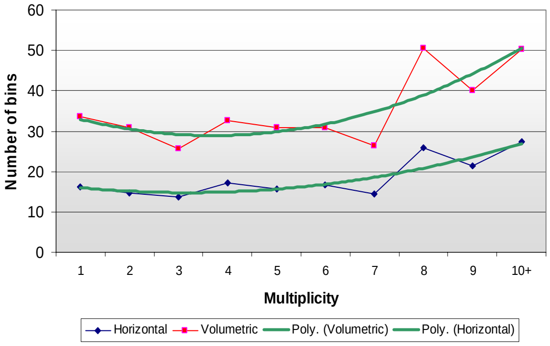

Figure 5. Multiplicity vs. number of bins containing VHF sources. The red dashed line indicates volumetric bins. The blue solid line indicates horizontal grids. Two second-order polynomial trend lines are provided corresponding to each curve above in green.

Figure 5 depicts the number of 2km by 2km grid squares in which VHF sources were detected by the LDAR network. Also depicted is the volumetric flash extent via the cubic system broken into 1000m vertical layers. Thus, the volumetric bins indicate the number of 2km by 2km by 1000m "cubes" in which VHF sources were detected. These two metrics are the basis for flash extent comparisons.

Comparing the average, non-weighted, height of all VHF sources detected by the LDAR network with multiplicity reveals a generally decreasing altitude with increasing multiplicity as depicted in figure 6. A green second order polynomial trend line has been added to the graph to obtain a general trend. While deviation was generally limited to +/- 500m on flashes with multiplicity greater than two, single stroke flashes exhibited the maximum average height.

A general trend of increasing flash extent with multiplicity is observed. However, in both this study and an informal previous study conducted by the author, flashes with a multiplicity of 1 also tend to exhibit a slightly higher flash extent.

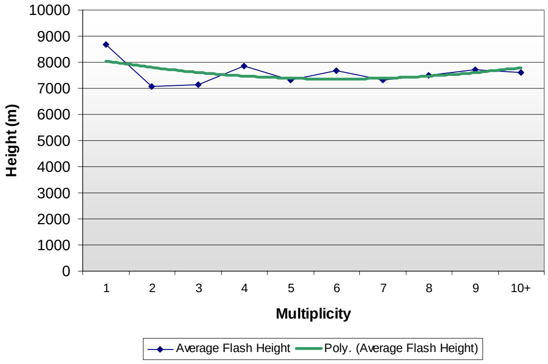

Figure 6. Multiplicity versus the average altitude of all VHF sources detected. A linear trend line is indicated by the dashed black line

The comparative analysis data of flash extent with peak current was marked with significantly higher variability as evidenced in Figures 7 and 8. Yet, there is a nearly linear relationship between these two parameters after smoothing suggesting that an increase of peak flash extent (in 2D and 3D) comes with an increase in peak current.

When comparing mean height and peak flash current, trends suggest a decreasing average height of detected VHF sources with increasing peak current. Once again, the variance of height was high. Note that there were no flashes with peak current absolute values of less than 4.1kA in the dataset of valid flashes. Also, Vaisala has filtered all positive flashes with median peak currents of less than 15kA as these were determined to largely be comprised of intracloud only flashes. This limit was based on initial work by Wacker et al, 1999 recommending a 10kA lower threshold for discriminating between intra-cloud and cloud to ground flashes. This was later modified to 15kA after subsequent Vaisala

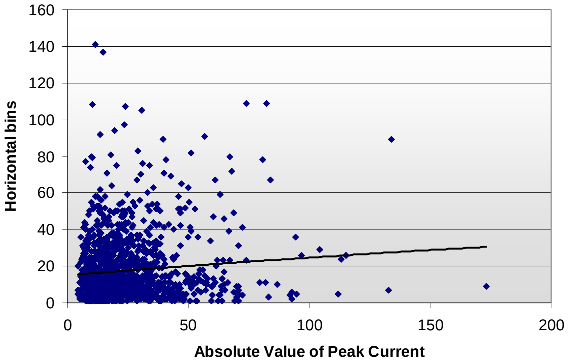

Figure 7. Scatter plot of the number of average number horizontal bins with VHF sources vs. current. The green line indicates a second-order polynomial trend line.

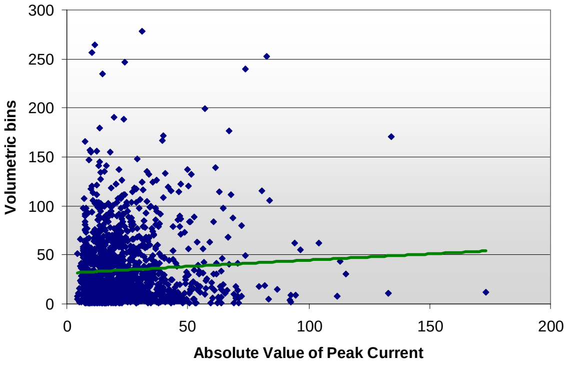

Figure 8. Scatter plot of the number of average number volumetric bins with VHF sources vs. current. The green line indicates a second-order polynomial trend line.

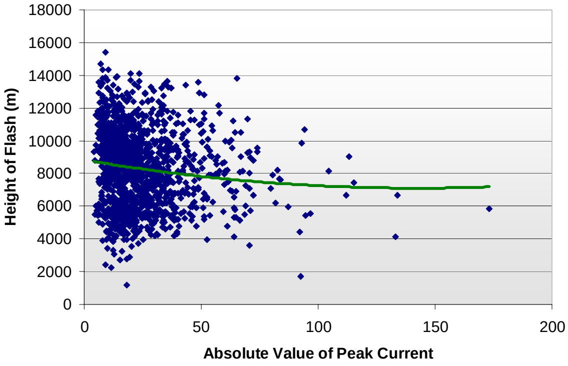

Figure 9. Scatter plot of mean height of VHF sources vs. peak current. The solid green line indicates a second-order polynomial trend.

analysis. Analysis of archived data indicates that our NLDN datasets do not include positive flashes less than 15 kA after March 2006.

Finally, an analysis comparing the flash extent and mean height of positive, hybrid, and negative flashes is offered. Fifty-eight, or about 4% of flashes exhibited one or more positive strokes. Of these, thirty were single stroke positive flashes. Remarkably little difference was observed between flashes of differing polarity.

All Flashes		
	Avg Hgt (m)	**StdDev (m)**
Negative average height	8,284	2,325
Positive average height	8,657	2,665
Single positive average height	9,414	2,798
Bipolar average height	7,689	2,172
Positive first bipolar avg. height	7,216	2,217
Negative first bipolar avg. height	8,201	2,092
Multiplicity=1 flashes		
	Avg Hgt (m)	**StdDev (m)**
Negative average height	9141	2249
Positive average height	11103	2665
	Horz Bins	**StdDev**
Negative horizontal extent	17.0	17.5
Positive horizontal extent	18.4	16.6
	Vol Bins	**StdDev**
Negative volumetric extent	35.3	38.0
Positive volumetric extent	34.6	31.3

Table 1. A comparison of negative, positive and positive flash characteristics.

The sample set of this dataset is small, yet fairly good alignment is evident. Once again, single flashes show the highest average height. Bipolar flashes tended to be lower than average. Examining single stroke flashes alone, positive flashes averaged higher with approximately the same flash extent as their negative counterparts.

VHF source detection efficiency was evaluated by assuming that the NLDN detected flashes are ground truth for the occurrence of cloud-to-ground lightning. Two ranges of efficiency were evaluated. The first range was a circle from 0 to 30 km from the network center. The second range extended from 30 to 60 km from the network center. The Houston LDAR network exhibited a detection of 99.6% within 30 km and 96.8% in the outer ring compared to the NLDN dataset. While hundreds of intracloud flashes were detected by the LDAR network that where not detected by the NLDN (as expected), intracloud evaluations were outside the scope of this study. Nevertheless, the two networks complement each other and share a common key for analysis.

Thunderstorm characteristics also change somewhat depending on the maturity of the storm. Qualitatively, in the early period of a storm's lifetime, flash extents tend to be lower in altitude and exhibit limited flash extents. This is due to the confined nature of the storm. As the storm matures, average height and flash extents increase with the addition of mass especially at anvil levels.

6. DISCUSSION AND CONCLUSIONS

From the data presented in Figure 5, there appears to be a well-defined trend of increasing flash extent with an increase in multiplicity. That is, at least in multiplicities greater than two. A marked increase was noted with single stroke flashes as opposed to multi-stroke counterparts. The reason behind this anomaly, as compared to the trend, is not clear although a lack of competition with other strokes could play a factor. NLDN data show that increasing multiplicity yields a higher median negative current value (Orville et al, 2002) which suggests that perhaps a larger flash extent is needed to supply charge for higher peak current flashes. Horizontal and volumetric trends align quite well with horizontal flash extend increasing more rapidly with increasing multiplicity. This is attributed to more flash extent in the anvil region which is vertically thin.

The average VHF source height with multiplicity data once again shows a maximum with single stroke flashes in figure 6. Multi-stroke flashes trend slightly downward with increasing multiplicity. This may suggest that single stroke flashes are characterized by a more vertical structure where others tend to "fan out".

It seems plausible that larger amplitudes of current would require a larger flash extent and this assertion is supported in figures 7 and 8. While a great deal of variability exists on an individual flash basis, a statistically significant trend is revealed. Confidence is a bit lower in flashes above 100kA due to a small sample set, but there were no indications that a reversal of the overall trend would occur with additional high-amplitude flashes.

It is interesting to note the relationship between figures 6 and 9 both trending similarly in height from left to right. Both datasets start near 9,000 meters with low multiplicity/peak current and then trend to between 7,000 and 8,000 meters suggesting that multiplicity, peak current, and heights are closely related with a large sample set.

Comparing positive, hybrid, and negative flashes yielded results suggesting that little difference exists in the flash extent or heights of such events. The outlier appears to be the lower average height of positive-only (multi-stroke) events and positive-first hybrid flashes. Negative flash and negative-first hybrid flash average heights were in agreement. Along with the findings of the entire dataset, single stroke positive flashes also tend to yield increased average heights. Nonetheless, it is important to ensure perspective with these results as only a small sample set of data provided information for positive and hybrid events.

Detection efficiencies, while seemingly quite high by comparing with NLDN data, are less than what is truly possible with an LDAR network. Great care was taken with site selection to mitigate radio-frequency noise problems. However, Houston is characterized by an elevated radio noise floor. Contributing to this noisy environment are electrical distribution systems, impacts from two-way and paging systems, close proximity of mass media broadcast transmitters at some sites, automobile ignition systems, nearby and many others. Additionally sporadic distant sources of radio frequency contamination occur due to ionospheric enhancements. With a quieter environment, the detection efficiency would likely approach 100%. Larger flash extents are possible with increased network sensitivity, but changes in trends found herein are not expected.

Overall, the findings of this study match well with theoretical expectations with the exception of the elevated heights and flash extent of single-stroke events. Since single-stroke flashes are very common, accounting for over forty percent of the dataset examined here, it is difficult to theorize that special microphysical process exists for just these events. Nevertheless, single-flash events and intra-cloud discharges are two areas of worthwhile study enabled by LDAR networks.

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