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Enhanced cloud lightning performance of the U.S. National Lightning Detection Network™ following the 2013 upgrade*

Martin J. Murphy, Amitabh Nag, John A. Cramer, and Alburt E. Pifer
Vaisala Inc., Louisville, Colorado, USA

***Abstract*— In spring and summer 2013, Vaisala upgraded all sensors in the U.S. National Lightning Detection Network™ (NLDN™) to the new LS7002 sensor. This improved sensor has enhanced sensitivity to cloud discharges, including the ability to process multiple pulses in cloud discharge pulse trains, or "bursts", and to send that information back to the central processor. To accompany the new sensor development, we also deployed new localization algorithms, one of which properly handles inter-pulse time intervals within pulse bursts and is capable of determining the positions of multiple pulses within bursts. These improvements are expected to improve the cloud flash detection efficiency of the NLDN as well as the spatial resolution of cloud flashes. During the summer and fall of 2013, data from some small thunderstorms were processed using the improved algorithms, and the results were compared to high-resolution VHF lightning mapping data from two Lightning Mapping Arrays. The objectives of this analysis were to determine the extent to which the anticipated improvements in cloud flash detection efficiency have been realized and to determine where there may be room for additional improvements.**

Keywords—cloud lightning, NLDN, validation

I. INTRODUCTION

During the first half of 2013, Vaisala deployed the new LS7002 sensor to all sites in the U.S. National Lightning Detection Network (NLDN). A broader discussion of the 2013 NLDN upgrade is given in the companion paper at this conference by Nag et al. Among the new features of the LS7002 is the capability to process multiple pulses within pulse trains generated by cloud discharges and to send that information to the central processor. In order to handle that information, the central processor, the Vaisala TLP100, was also upgraded to include a new geolocation algorithm that specifically handles the inter-pulse time intervals within pulse trains, or "bursts", and can determine the positions of multiple pulses.

The pulse train processing of the upgraded NLDN is the focus of this paper. Specifically, four primary questions of interest have been addressed through recent analysis: Do the improvements in cloud discharge (hereafter, "IC") pulse processing lead to increased total flash detection efficiency? Do pulse trains occur preferentially at a particular point in the lifecycle of flashes? Do the improvements in IC pulse processing lead to any degree of spatial mapping capability? And finally, what further improvements are needed in our IC processing capabilities?

II. METHODS

Reference data sets were provided by two Lightning Mapping Arrays (LMAs; see Thomas et al. 2004) operated in the U.S. states of Kansas and Colorado during 2013. Fig. 1 shows the areas of highest-resolution coverage of the two LMAs. As described by Murphy et al. (2013a), LMA data typically include noise, primarily sources that were geolocated using data from only 6 LMA stations. The LMA data were filtered by an essentially identical procedure to that described by Murphy et al. (2013a) over São Paulo, Brazil, including the outright removal of sources detected at very low altitudes, mainly below local ground, and more than about 2.5 km above the tropopause. In the cases studied here, from early August to early October, 2013, the tropopause altitude was typically 14 – 15 km MSL at most. Figures 2a and 2b show the Kansas LMA data from 2 August, 2013, between 10:00 – 12:00 UTC, before and after filtering, with color indicating time in 5-minute increments. The small, isolated storm within 100 km of the center of the LMA was the target of study on this date. The filtered image, Fig. 2b, shows that essentially all of the noisy sources that were originally located within 100 km, but came from more distant storms, were eliminated by the filtering process.

The flash detection efficiency of the NLDN was determined relative to the number of LMA flashes. That number was determined by passing the filtered source data

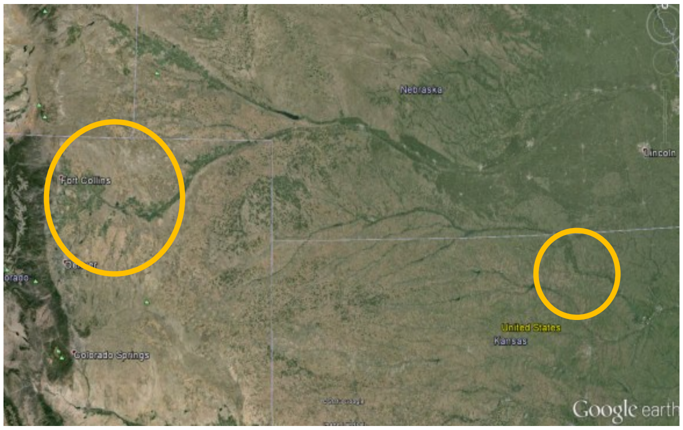

Fig. 1 Regions of optimal coverage of the two LMAs used in this study

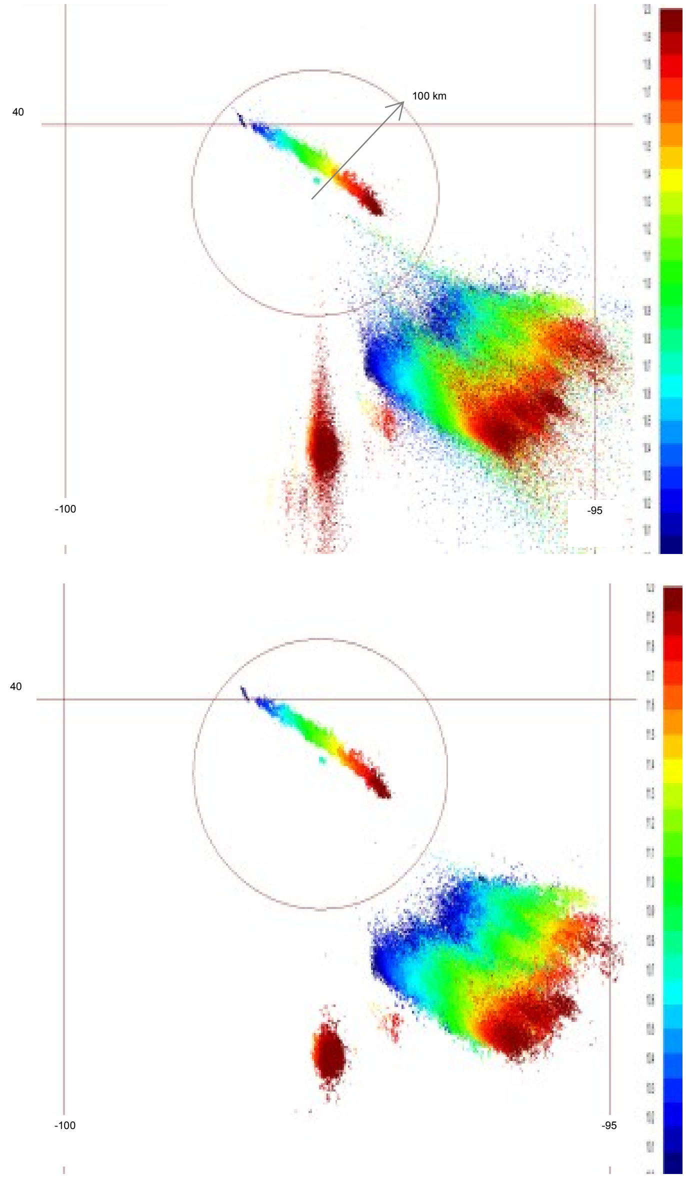

Fig. 2 Original and filtered LMA data on 2 Aug. 2013, 10:00 - 12:00 UTC, in the Kansas LMA, color-coded by time. The circle shows a 100-km radius around the center of the LMA. The two longitude lines are at -100 and -95 degrees, and the single latitude line is at 40 degrees.

through the source-to-flash grouping algorithm of Lojou and Cummins (2005). To avoid the complications in flash grouping and counting associated with high flash-rate storms, we selected only storms with total flash rates at or below 20 flashes per minute as determined by a manual count. Despite this restriction, we also found that it was necessary to remove flashes that ended up with fewer than 5 LMA sources from the data set. That is a complication that may or may not be totally justifiable, given that Rison et al (2013) observed a number of cases of very small discharges, but we have been careful to select storms with discrete lightning flashes that appear to satisfy our choice of a 5-source minimum.

During the summer and autumn of 2013, the sensor data from the upgraded NLDN were delivered in two different formats: the pre-upgrade format, in which the pulse train information was absent, and the post-upgrade format that includes pulse train information. These two data sets were reprocessed using the pre- and post-upgrade geolocation algorithms, respectively. This approach allowed us to determine the relative improvement in cloud lightning performance of the NLDN as a result of the pulse train processing.

It is important to note that, in the context of this study, “detection efficiency” is defined as the fraction of LMA flashes having at least one cloud discharge (IC) pulse observed by the NLDN. It is not the objective of this study to validate the cloud-to-ground (CG) lightning performance of the NLDN, which has already been extensively validated elsewhere (e.g. Nag et al. 2011, Biagi et al. 2007). We have, however, begun to investigate possible differences in IC performance between flashes that do contain return strokes (referred to below as “hybrid flashes”) and those that do not (referred to as “cloud flashes”). The NLDN CG stroke data was used to segregate these two categories of flashes.

The time of occurrence of pulse trains within flashes was determined by calculating the difference between the first LMA source in each flash and the start of the pulse train as observed by the NLDN. Only cases where the NLDN observed and geolocated at least three pulses within 2 ms were considered.

III. RESULTS

A. Detection efficiency and detection efficiency improvements

Table 1 shows the flash detection efficiency of NLDN based on IC data only from five case studies over the two LMAs. The results are broken down by hybrid flashes, those containing at least one CG stroke, and pure cloud flashes. In all cases, over half of the hybrid flashes had at least one IC discharge that was geolocated by the upgraded NLDN. The percentages of cloud flashes that were detected by NLDN was somewhat lower. Preliminarily, it appears that lower IC detection efficiency may occur in an area that extends from central Colorado toward the northeast and is probably due simply to somewhat longer sensor baselines, although this issue is still under investigation.

TABLE I. DETECTION EFFICIENCIES

Date / LMA	Hybrid flashes		Cloud flashes	
	LMA flashes	*NLDN IC (DE %)*	*LMA flashes*	*NLDN IC (DE %)*
2013-08-02 / Kansas	31	24 (77)	76	44 (58)
2013-08-03 / Kansas	23	17 (74)	82	45 (55)
2013-09-10 / Colorado	130	79 (61)	562	263 (47)
2013-09-16 / Colorado	56	36 (64)	673	280 (42)
2013-10-04 / Colorado	37	22 (59)	190	56 (30)

Table 2 shows the relative change in the percentage of all LMA flashes having one or more NLDN IC pulses just as a result of the inclusion of pulse train processing. In almost all cases, the result is an increase, although the substantial case-to-case variations and the 16 September case appear to be due to some loss of data in the new format, an issue that has been remedied through a new software release. In the interpretation of these numbers, it is important to note that the 2013 upgrade includes a sensor hardware change that allows an increase in overall sensor sensitivity of 1.33 relative to the pre-2013 sensors. Because all of the cases in this study come from 2013, that increase in sensitivity is not reflected in Table 2. Rather, only the relative change due to pulse train processing is included here. The overall increase in total lightning detection efficiency of the NLDN relative to the pre-2013 state is still under investigation.

B. Occurrence of pulse trains within the life cycles of flashes

Fig. 3 shows the distribution of the time difference between the first LMA source and the start times of pulse trains having at least three geolocated pulses within 2 ms. The vast majority, about 95%, of these pulse trains occur within 10 ms of the flash start time as indicated by the LMA, indicating that preliminary breakdown is a favored process in the production of such pulse trains. Note that the percentage here, 95%, differs from the preliminary value given by Murphy et al. (2013b), 84%, due to additional analysis of position accuracy issues. Given that short-duration pulse trains with short inter-pulse intervals are characteristic of the preliminary breakdown in negative CG flashes, rather than cloud flashes (see, e.g., sections 4.3 and 9.6 of Rakov and Uman, 2003), Murphy et al. (2013b) noted that the sample might be biased toward negative CG flashes by the requirement of at least three geolocated pulses within 2 ms. However, we find that 39% of the flashes in this set have CG strokes, which only suggests a modest bias toward CGs, given the IC-CG ratios typical of high-plains thunderstorms.

TABLE II. RELATIVE CHANGE IN DETECTION EFFICIENCY AS A RESULT OF PULSE TRAIN PROCESSING

Date	LMA	LMA flashes	relative change in IC DE (%)
2013-08-02	Kansas	107	+15.4
2013-08-03	Kansas	105	+5.0
2013-08-09	Colorado	1463	+7.9
2013-09-10	Colorado	692	+9.8
2013-09-13	Colorado	107	+9.5
2013-09-16	Colorado	729	–4.0
2013-09-18/19	Colorado	169	+27.4
2013-09-23	Colorado	352	+1.5
2013-09-27	Colorado	45	+5.8
2013-10-04	Colorado	227	+5.5
TOTAL		**3996**	**+5.5**

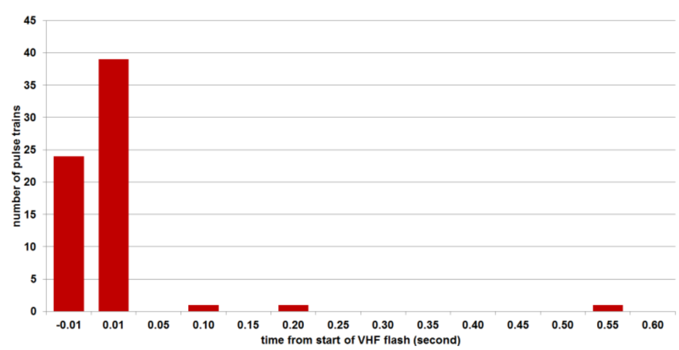

Fig. 3. Distribution of the time difference between the start of LMA flashes and the first pulse in a train with multiple geolocations.

The observation that pulse trains tend to occur mostly during preliminary breakdown leads to the possibility of defining the location accuracy of cloud lightning activity in a meaningful way: We calculate the position error between the first or second geolocated pulse in a train that occurs at preliminary breakdown and the first VHF source detected by the LMA. Fig. 4 shows the distribution of that position error in 63 pulse trains that had multiple geolocated pulses and occurred at the beginning of their respective flashes. The median value of this position error is 1.5 km. The original distribution of these position errors presented by Murphy et al. (2013b) had a lower median, 1.0 km, with 119 pulse trains, but it also had a substantial tail that suggested further investigation. In this study, we have studied many of the questionable positions from the original set in detail and have discovered that our original processing was likely too loose in two respects: initial time alignment of pulses and acceptance of sensors that are likely too distant to be contributors to low-amplitude IC pulses. Figures 3 and 4 here were made after

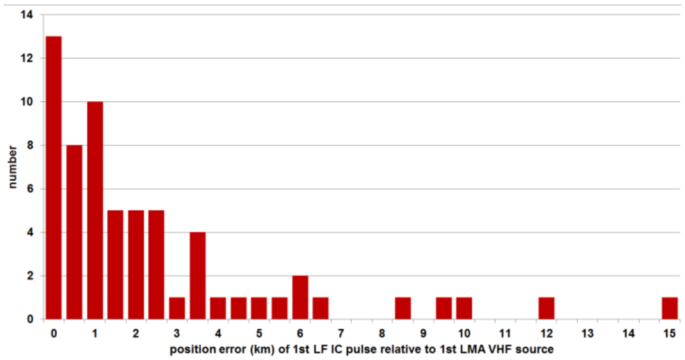

Fig. 4. Distribution of position errors between the first LMA sources and first pulses in pulse trains occurring at preliminary breakdown

reprocessing the data sets with additional restrictions. In the course of the reanalysis, we also noted that the first pulse in trains with at least 3 geolocations can differ somewhat in position from later pulses. Primarily, this appears to be due to position quality, where the first pulse may only have 2-3 contributing sensors, and therefore, poorer location accuracy. While compiling Fig. 4, when we could clearly identify one of these pulses, we used the second pulse in the train rather than the first. This substitution was made in 5 of the 63 pulse trains in Fig. 4 (8%).

C. Spatial mapping of flashes

Figures 5a and 6a show flashes processed using the pre-upgrade data format and algorithms, and their companion Figures 5b and 6b show the same flashes processed using the post-upgrade data format and corresponding geolocation algorithms. In all of these figures, the small dots are the LMA sources and the larger symbols are the NLDN IC pulse positions. The color scale represents time, going from dark purple at the flash start to red at the flash end. Typical flash durations are about 0.5 sec. These examples show clear increases in the spatial extents depicted by the NLDN within these flashes. However, there are also a number of flashes where no additional spatial extent is depicted by the post-upgrade algorithms, only an increase in the number of geolocated pulses. It is important to bear in mind that the pulse trains themselves have durations of typically a few milliseconds or less, and thus, they are not expected to provide any substantial spatial mapping on their own. Rather, any spatial mapping should result from the combination of the increased sensor sensitivity together with pulse trains, occasionally more than one per flash. That said, in the examples in Figures 5b and 6b, the spatial extent is provided by the pulse train positions. The largest distance across the pulse train is only 4.0 km in Fig. 5b and 4.2 km in Fig. 6b. These are comparable to the sizes of the LMA flashes but still greater than suggested by the error ellipses of the pulse positions. Further detailed assessment is warranted.

When we occasionally observe some degree of spatial mapping from pulse trains alone, it seems to result mainly from pulses with only 2-3 contributing sensors, and therefore, relatively large random position errors. In the cases analyzed to date, we have observed as many as 12 NLDN IC pulses in a single flash. Among flashes having at least one NLDN IC pulse, the average number of geolocated pulses per flash is 2.1, and 49% of flashes have more than just one geolocated pulse.

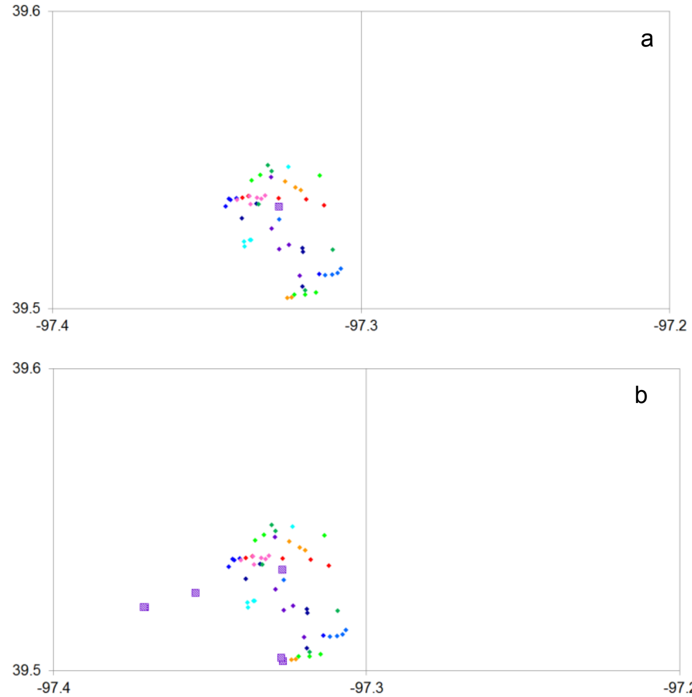

Fig. 5 Flash at 11:37:01 UT on 2013-08-02 in Kansas. Axes show latitude, longitude. Small dots are LMA sources, color-coded by time in 10 colors (purple to red). Larger squares are NLDN IC discharges. (a) without pulse train processing, (b) with pulse train processing

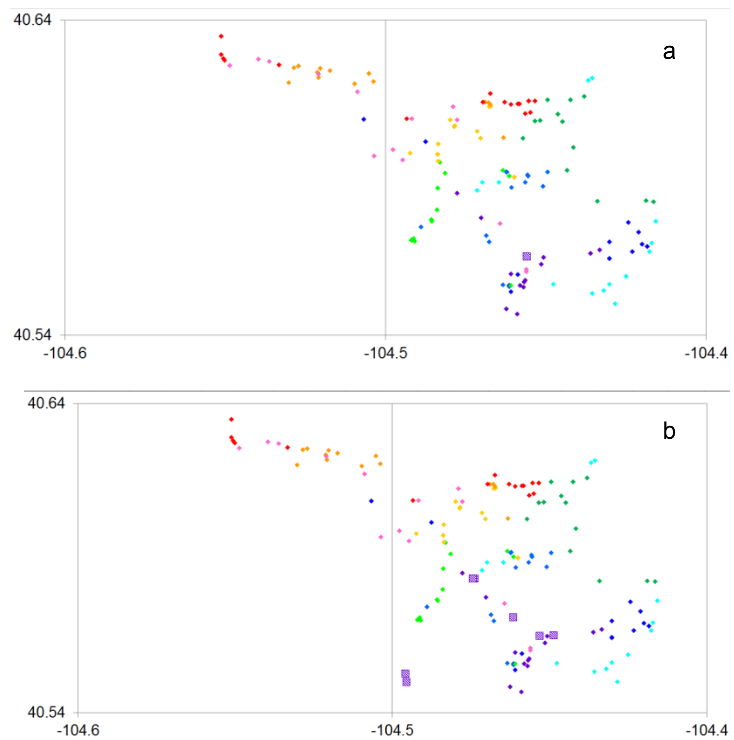

Fig. 6 Flash at 01:09:59 UT on 2013-09-23 in Colorado. Axes show latitude, longitude. Small dots are LMA sources, color-coded by time in 10 colors (purple to red). Larger squares are NLDN IC discharges. (a) without pulse train processing, (b) with pulse train processing

IV. Conclusions and Future Work to Improve IC Processing

This study has shown that the upgraded NLDN is capable of detecting as much as 45-63% of all lightning flashes with at least one IC pulse, and that some degree of flash spatial mapping is obtained in some flashes. However, some outstanding issues remain to be addressed. First, we noted a possible spatial inhomogeneity in IC detection efficiency over Colorado. Further analysis over that LMA will be combined with analysis using VHF lightning mapping data from other parts of the U.S. to clarify if the issue is truly regional or was primarily an artifact associated with the loss of some of the newer-format sensor data. The preliminary location accuracy analysis by Murphy et al. (2013b) showed some outliers from the pulse train processing. This now appears to be due mostly to the manner in which the data were originally processed, but there is still some scatter due in part to the number of contributing sensors. Additional scrutiny of the random position error is warranted, and it may eventually turn out to be advantageous to utilize existing algorithms in the TLP100 that are capable of filtering outliers.

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