

# Performance of the U.S. NLDN during the Kansas Windfarm2012 and 2013 Field Programs

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**Abstract**— This work presents results of a “before and after upgrade” performance assessment of the NLDN near a wind farm in Kansas. Detection efficiency and type classification (cloud vs. CG) were evaluated using both video observations and qualitative lightning current measurements provided by the wind farm SCADA system. CG stroke location accuracy was assessed using the SCADA data. The results presented here indicate that current NLDN performance near a Kansas wind farm is consistent with Vaisala estimates, in terms of CG flash DE (~95%), stroke location accuracy (median < 150m), cloud flash DE (~39%), and type-classification accuracy (~90%).

**Keywords**—lightning; LLS performance; high-speed video;

## I. INTRODUCTION

During the spring of 2013, the U.S. National Lightning Detection Network (NLDN) underwent an upgrade aimed at improving the detection of in-cloud lightning flashes. This upgrade was completed in the Kansas area (central U.S.) prior to the start of the Kansas Windfarm2013 field program (see Cummins et al., this conference). Prior to the NLDN upgrade, a less-extensive field program was carried out in the same domain during the summer of 2012.

This work provides “before and after upgrade” performance assessment of the NLDN in this Kansas region using both video observations and qualitative lightning current measurements in turbine generator blades reported by the wind farm “Supervisory, Control and Data Acquisition” (SCADA) system. This assessment includes an analyses of NLDN detection efficiency for both cloud and cloud-to-ground (CG) flashes, location accuracy for CG strokes, and accuracy of classification type. Assessment of the relative performance for upward-initiated discharges and downward-attaching discharges are also discussed.

## II. DATA AND METHODS

### A. U.S. National Lightning Detection Network (NLDN)

The U.S. National Lightning Detection Network (NLDN) consists of about 100 ground-based sensors that are owned and operated by Vaisala. These sensors detect the electromagnetic signals from cloud-to-ground (CG) return strokes and cloud pulses in the frequency range of 400 Hz to 400 kHz. Each reported event includes time, location, polarity, peak current, type classification (cloud discharge or CG stroke), and various

data quality parameters. Using the location information, it is possible to determine the azimuth and distance to any reference location. The NLDN dataset for this study was limited to events that were reported within 80 km of the wind farm Operations and Maintenance (O&M) building. This (small) radius was chosen to limit bias towards high peak-current events at greater distances.

### B. Assessment Instrumentation

For this assessment, lightning flashes were observed by two fixed-position conventional speed video cameras (2012 and 2013) and mobile high-speed cameras in 2013. All cameras were equipped with GPS time stamps that were accurate to +/- one image (exposure integration) time. Under some circumstances, information provided by the Kansas Lightning Mapping Array (KSLMA) was used in 2013 to confirm the flash classification (cloud or CG) that was observed on video. The KSLMA was able to report essentially all flashes within 80 km of the central location, and is discussed in several papers presented at this conference. An overview of the observation domain is provided in Fig. 1.

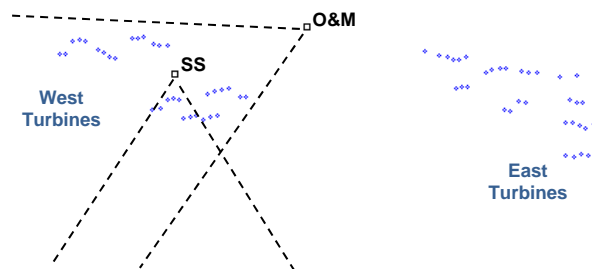


Fig. 1. Windfarm Layout. Turbines are shown as small blue circles. Fixed-location camera fields-of-view for Substation (SS) and Operations-and-Maintenance building (O&M) are shown as black dashed lines.

The conventional speed cameras recorded 30 frames per second. Each video frame was de-interlaced into two separate fields, resulting in 17ms images. Multiple strokes that occur within a 17 ms exposure integration time are not distinguishable on video unless they occur in different channels. The high-speed cameras varied in resolution and frame-rates, but all produced at least 5000 frames-per-second.

### III. RESULTS

The SCADA system provided reports about lightning currents in each turbine generator blade. Although these current values did not correlate well with the peak current values reported by the NLDN, they provided critical indicators of lightning current by identifying specific times that turbine generators experienced “significant” lightning transients.

#### C. Analysis Methods

Detection Efficiency (DE), defined as the percentage of *all* lightning discharges (either CG flashes, CG strokes, or IC flashes, in this work) that were reported by the NLDN, was evaluated using both video observations and SCADA reports.

Each lightning video was evaluated as follows. We first identified the type of the flash. A “definite” cloud-to-ground lightning flash was defined as a flash with visible channel within the field-of-view (FOV) from the cloud to the ground. A flash which had two or more strokes within one second was additionally defined as a multiple stroke CG flash. On the other hand, an intra-cloud lightning (IC) flash was defined as a flash with the discharge regions inside and/or near clouds and without a visible channel to the ground. Flashes that contained luminous fields that could not be defined exactly or were partially out of the FOV were labeled as “unknown”. Some of the unknown flashes were later classified using the KSLMA, as discussed above. It should be noted that in many cases the channels for cloud flashes were obscured by intervening clouds or precipitation. In addition, the zenith angles for distant flashes are low, causing difficulty in determining the flash type. Therefore, many flashes were classified as unknown, but are included in an “overall” flash DE analysis. Since a lightning flash typically lasts less than a second, visible channels that had an interval exceeding one second were considered to be part of two separate flashes.

For each illumination seen on video, the NLDN data were reviewed to see if there were any NLDN reports that occurred within the time period for that field. Time-correlated reports were then evaluated to determine if they were azimuth-consistent with the video observation. A flash that had any consistent NLDN report was considered to be a detected flash. An overall flash DE was computed using all flashes (IC, CG, and unknown). The DE for individual CG strokes was also calculated.

Location accuracy for CG strokes was assessed for in both 2012 and 2013 using 72 “known” CG strikes to turbine blades reported by the SCADA system. The accuracy of the SCADA time stamps were limited to about 5 seconds due to the “polling” nature of the SCADA reports. Additionally, there were a few known cases of “simultaneous” SCADA reports from multiple (more than 2) turbines in close proximity to each other, and we suspect that these are due to modest-current leaders emanating from blades of turbines that were not directly struck. In these cases, the distance to the closest reporting turbine generator was selected as the location error. Finally, it should be noted that most lightning attachments to turbine generators are near the blade tip, so there is an inherent  $\pm 40$  m uncertainty in the actual strike location. These SCADA cases also provide additional information about the detection efficiency of CG flashes and upward flashes.

Results for the 2012-2013 SCADA-reported strikes are discussed first. This is followed by the 2012 and 2013 video analyses, discussed separately.

#### A. Analysis of SCADA Reports

There were a total of 110 SCADA reports in 2012 and 2013. These reports occurred as a result of 85 lightning-related “events”, 67 of which were interpreted as resulting from downward flashes that directly contacted a turbine. Twenty-nine (29) of these occurred in 2012, and 38 occurred in 2013. An event was considered to be detected if an NLDN report occurred during a  $\sim 5$  s uncertainty in the SCADA time-stamp, and if the NLDN report was within 2 km of the reporting turbine generator.

The location difference between the turbine generator and the NLDN reported ground strike location for these 67 events is shown in histogram form Fig. 2. The 2012 counts as a function of distance are the grey bars, and the 2013 counts are the black bars. There is no obvious difference in the results for the two years. The median location difference is 126 m, and the mean location difference is 259 m. No location differences were greater than 1.2 km.

Not all SCADA reports were associated with a nearby NLDN report. Two flashes that were possibly downward-initiated CG’s were not reported, resulting in a 97% DE (67/69) for downward flashes. There were 18 SCADA events (some with reports from multiple turbines) that were likely upward-initiated discharges. Only one of these events was associated with NLDN reports of return strokes. Thus the NLDN detection of return strokes for likely upward flashes was 5.6% (1/18). A few of these upward discharges were observed by our video cameras, and they were generally not “complete flashes.” They exhibited bright leaders that extended a few hundred meters above the turbine, as illustrated in Fig. 3, but did not exhibit long initial continuing currents or produce return strokes. Sixteen of these 18 events (88%) were time-coincident with NLDN reports within 1.1 to 12.5 km of the impacted turbine

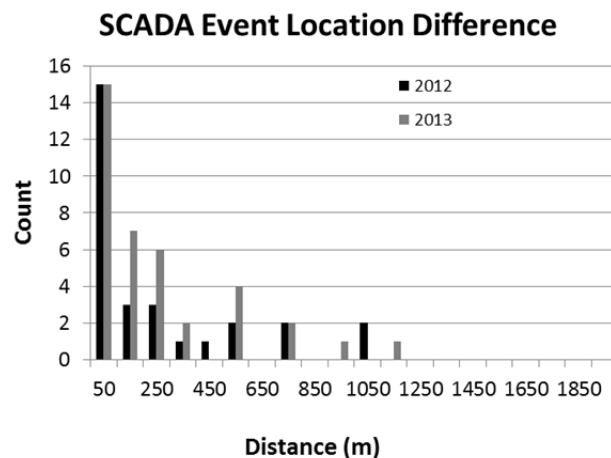


Fig. 2. Location Difference between turbines with SCADA-reported lightning current and the time-correlated NLDN stroke.

Nine of the time-correlated SCADA reports were associated with 7 NLDN events classified as cloud flashes. Four of these SCADA reports occurred at a time when we have no waveform or LMA data to validate the flash type. LMA data and NLDN waveforms were available for the other SCADA reports. Two of them resulted from a single misclassified +CG flash captured on high-speed video, and discussed in detail by Cummins et al. (this conference). The remaining SCADA reports were associated with complex flashes that had extensive horizontal channels over the turbines in questions, with no evidence of CG strokes near the turbines. This analysis indicates that at least one of the 7 NLDN events was misclassified, and that at least three were properly classified as cloud events.



Fig. 3. Example of two upward discharge from turbines that were “triggered” by a nearby high-current cloud-to-ground flash. Some such upward discharges have high-enough currents ( $> \sim 6$  kA) to be reported by the SCADA system.

### B. 2012 Video Analysis

Results for the 2012 video analysis are summarized in Table I below. These results represent video analyses for 9 storm days starting on June 14. Not all strokes within a CG flash could be positively identified on video as CG, so only a subset of the actual strokes is included. The CG stroke DE is 88.5% (468/529) and the CG flash DE is 96.3% (183/190). IC Flash DE (28.6%) is much lower, as expected. The overall “total lightning” flash DE is 78.1%. This value will be somewhat high, since it is likely that the population of unknown flashes is biased towards CG flashes due to their brighter optical emissions when viewed from the ground.

For the 2012 analysis, type classification accuracy (IC vs. CG) was carried out at the level of flashes. If one or more NLDN reports within a flash were classified as CG, then the flash was classified as CG. 94.5% (173/183) of the video-defined CG flashes were correctly classified by the NLDN, and 89.3% (25/28) of the video-defined cloud flashes were correctly classified.

TABLE I. 2012 VIDEO ANALYSIS

Flash Type	2012 Video Analysis		
	No. of Videos	NLDN Reports	DE%
CG Strokes	529	468	88.5
CG Flashes	190	183	96.3
IC Flashes	98	28	28.6
Unknown Flashes	234	142	60.7
<b>Total Flashes</b>	<b>1051</b>	<b>821</b>	<b>78.1</b>

### C. 2013 Video Analysis

Results for the 2013 video analysis are summarized in Table II below. These results represent video analyses for 7 storm days starting on May 28. As in 2012, not all strokes within a CG flash could be positively identified on video as CG, so only a subset of the actual strokes is included. The CG stroke DE is 69.2% (144/208) and the flash DE is 96.1% (99/103). IC Flash DE (32.5%) is again much lower. The overall “total lightning” flash DE is 55.5%.

TABLE II. 2013 VIDEO ANALYSIS

Flash Type	2013 Video Analysis		
	No. of Videos	NLDN Reports	DE%
CG Strokes	208	144	69.2
CG Flashes	103	99	96.1
IC Flashes	328	108	32.9
Unknown Flashes	373	207	55.5
<b>Total Flashes</b>	<b>805</b>	<b>413</b>	<b>51.3</b>

For the 2013 analysis, type classification accuracy (IC vs. CG) was also carried out at the level of flashes. 90.9% (90/99) of the video-defined CG flashes were correctly classified by the NLDN, and 91.6% (98/107) of the video-defined cloud flashes were correctly classified.

Interestingly, the only parameters that show improvement in 2013 are the cloud flash DE (32.5% vs. 28.6%), and the percentage of cloud flashes that are properly classified (91.6% vs. 89.3%). In fact, the CG stroke DE in 2013 was significantly lower in 2013 (69.2% vs. 88.5%) and the improvement of cloud flash DE was lower than expected based on findings for cloud pulse detection improvement between 2010 and 2013 reported by Nag et al, 2013 . These unexpected findings led to an investigation of day-to-day IC flash DE variations among the 7 analysis days. These findings are summarized in table III below.

TABLE III. DAILY IC FLASH DE ANALYSIS

<i>Date</i>	<i>No. of Video Flashes</i>	<i>NLDN Reports</i>	<i>DE%</i>
May 28, 2013	20	10	50.0
<b>May 29, 2013</b>	65	15	<b>23.1</b>
<b>May 30-31, 2013</b>	28	4	<b>14.3</b>
<b>June 4, 2013</b>	6	0	<b>0.0</b>
June 5, 2013	164	59	35.9
June 25, 2013	45	20	44.4
<b>Total Flashes</b>	328	<b>108</b>	<b>32.9</b>
<b>Remove May 29 through June 4</b>	<b>229</b>	<b>89</b>	<b>38.9</b>

It is clear from table that there was an extended period of poor performance starting sometime on May 29 and continuing at least through June 4, with cloud flash DE values between 0.0 and 23.1% (red text). Subsequent discussions with NLDN technical staff disclosed the fact that this exact time period was during a troublesome upgrade of the satellite-based communications system employed by the NLDN, in preparation for the increased communications requirements due to the NLDN upgrade. The practical result was data losses during this time period between the sensors and the master earth stations, modulated by the short-term data rates from individual sensors. Given this scenario, the greatest impact would be on cloud flashes that produce numerous low-amplitude pulses. The next-greatest impact would be on CG flashes with large number of return strokes, thus reducing the stroke DE as indicated by our comparison of Tables I and II. The least impact would be for CG flashes, since there is typically at least one high-current return stroke that would be detected by a large number of sensors.

In order to produce a more-representative post-upgrade cloud flash DE for this region, the cloud flash DE analysis was redone excluding the poorest-performing period between May 29 and June 4. The results are shown in the bottom row of Table III, showing a cloud flash DE of 38.9%.

#### IV. DISCUSSION AND SUMMARY

This work presented results of a “before and after upgrade” performance assessment of the NLDN near a wind farm in Kansas. Detection efficiency and type classification (cloud vs. CG) were evaluated using both video observations and qualitative lightning current measurements provided by the wind farm SCADA system. CG stroke location accuracy was assessed using the SCADA data.

All CG flash DE estimates were consistently high – 97% / 96.3% / 96.1% for SCADA, 2012 video, and 2013 video observation, respectively.

The CG stroke DE and cloud flash DE were negatively impacted in 2013 during a one-week period (4 storms) when

the NLDN satellite communications system was undergoing an upgrade to increase the communications bandwidth. This communications issue is the likely reason for a reduced CG stroke DE in 2013 (69.2%) as compared to 2012 (88.5%), and the unexpectedly small improvement in cloud flash DE (28.6% vs. 32.9%). Exclusion of the compromised time period in 2013 resulted in an estimated cloud flash DE of 39.8% (see Table III). The estimated cloud flash DE in 2012 was somewhat higher than expected (28.6%), and may be the result of the small sample size (98 flashes). Assuming a binomial sample distribution for the DE estimates with  $p=0.5$ , the expected RMS error in the DE estimate is  $\sim\sqrt{0.25/98} = 5\%$ .

There is an apparent discrepancy between the improvement in IC pulse detection (related to CG strokes) reported by Nag et al. 2013, and the modest improvement in IC flash DE between 2012 and 2013 (38.9%/28.6% = 1.36) reported here. There are several factors that could contribute to this difference. First, the factor-of-four improvement in the Central Great Plains reported by Nag et al. was the ratio of “IC” pulses to CG return strokes. This metric does not distinguish between IC pulses associated with CG flashes and those associated with cloud flashes. It also does not address the relative number of IC pulses associated with each flash type (pulses-per-flash). This distinction is important, since Murphy et al. (2014 – this conference) show that IC pulses associated with CG flashes are somewhat easier to detect. This suggests that a meaningful fraction of the additional IC pulses seen in 2013 were not related to IC flashes. The second contributing factor is the time period and analysis domain size. The Nag et al. dataset includes all observations in a 9x9-degree domain for a 30 day period, creating a (statistically) more-reliable dataset. The third factor and final factor is that Nag et al. was comparing 2013 to 2010. It is likely that the IC pulse DE was somewhat higher in 2012 than in 2010, because the many of the older impact sensors were replaced by fully-digital LS7001 sensors in late 2011 and early 2012, in preparation for the transition to LS7002’s in 2013.

Type classification accuracy estimates (cloud vs. CG flashes) were statistically indistinguishable for both years and both types. Classification accuracy varied between 89.3% and 94.5%

The location accuracy estimates obtained using the SCADA observations were also indistinguishable between 2012 and 2013. The 2-year combined median location error (85 observations) was 126 m, with a mean location error of 259 m. No location errors were greater than 1.2 km. Given the 45 m blade diameter for the wind turbines, and the possibility that some of the SCADA reports could have been produced by upward leaders in response to nearby CG strokes, these errors are probably upper bounds on actual location errors. We note that these errors are also somewhat larger than those observed by Cramer et al. (2014, this conference) in 2012-13 for 22 tall towers spread through a large portion of the continental U.S.

The results presented here indicate that current NLDN performance near a Kansas wind farm is consistent with Vaisala estimates, in terms of CG flash DE (~95%), stroke location accuracy (median < 150m), cloud flash DE (~39%), and type-classification accuracy (~90%). Video assessment of

additional storm days in June and July 2013 is required in order to better understand long-term and day-to-day variations in cloud flash DE. Assessment of additional days in 2012 is of interest, in order to reduce the statistical uncertainty in the 2012 cloud flash DE in this region.

#### ACKNOWLEDGMENT

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