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An Update on the Performance Characteristics of the NLDN

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***Abstract*—We have estimated the NLDN performance characteristics using data for 388 negative return strokes and 185 kiloampere-scale superimposed pulses in 92 flashes triggered during 2004–2013 at Camp Blanding, Florida. The flash and stroke detection efficiencies were 94% and 75%, respectively. The superimposed pulse detection efficiency was 6% (for peak currents ≥1 kA) and 32% (for peak currents ≥5 kA). The NLDN misclassified 3% of return strokes and 18% of superimposed pulses as cloud discharges. The median location error for return strokes was 309 m. The median absolute current estimation error for return strokes was 14%. It appears that the systematic and random components of current estimation error were -6% and 22%, respectively. The median absolute event-time mismatch for return strokes was 2.7 μs. In addition, we examined the year-to-year variation in performance characteristics of the NLDN.**

Keywords—lightning, lightning detection, lightning locating system, National Lightning Detection Network (NLDN), rocket-triggered lightning

I. Introduction

The U.S. National Lightning Detection Network (NLDN) has been providing lightning data for the contiguous United States since 1989. Upgrades to the network were made in 1994–1995 [Cummins et al., 1998], 2003–2004 [Cummins and Murphy, 2009], 2010–2012 [Nag et al., 2013a], and in April–August 2013 [Nag et al., 2013b]. During the most recent network-wide upgrades, the first step (implemented in 2010) was the introduction of propagation corrections (to account for ground conductivity and topography of terrain over which the lightning electromagnetic waves propagate) for the analog IMPACT sensors. The second step involved a steady replacement of all older IMPACT sensors with fully-digital LS7001 sensors. The sensors in and around the Florida region were replaced by early May 2011. However, the propagation corrections developed for IMPACT sensors were not well-suited for LS7001 sensors, the problem which was rectified in February 2012. In the final step (implemented between April and August 2013), the LS7001 sensors were upgraded to LS7002 sensors to improve sensitivity for better detection of low amplitude lightning events (primarily cloud pulses). Details of the upgrades to both the sensor and associated algorithm are given by Cummins et al. [2010, 2012] and Honma et al. [2013].

Jerauld et al. [2005], Nag et al. [2011], and Mallick et al. [2014] used rocket-triggered lightning data, acquired at Camp Blanding, Florida, to study the performance of the NLDN for the periods of 2001–2003, 2004–2009, and 2004–2012, respectively.

In 2001–2003 [Jerauld et al., 2005], 37 flashes containing 159 return strokes were triggered at Camp Blanding. The NLDN flash and stroke detection efficiencies were 84% and 60%, respectively. The median location error was 600 m. The median value of absolute peak current estimation error was 20%. The sample size for evaluation of errors in peak current estimates was 70.

In 2004–2009 [Nag et al., 2011], 37 flashes containing 139 return strokes were triggered at Camp Blanding. The NLDN flash and stroke detection efficiencies were 92% and 76%, respectively. The median location error was 308 m. The median value of absolute peak current estimation error was 13%. The sample size for evaluation of errors in peak current estimates was 96. Nag et al. [2011] interpreted their results as an improvement in performance characteristics of the NLDN due to its upgrade which was completed in 2004.

Mallick et al. [2014] evaluated more detailed performance characteristics of the NLDN based on data for 80 flashes triggered at Camp Blanding during 2004–2012. The data included 326 return strokes and 173 kiloampere-scale superimposed pulses (initial continuous current pulses and M-components). The flash and stroke detection efficiencies were

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94% and 75%, respectively. The detection efficiency for superimposed pulses was 5% for peak currents ≥1 kA and 32% for peak currents ≥5 kA. The NLDN misclassified 4% of the return strokes as cloud (IC) discharges. For return strokes, the median location error was 334 m and the median value of absolute peak current estimation error was 14%. The sample size for evaluation of errors in peak current estimates was 222.

In this paper, we extend the study of Mallick et al. [2014] to additionally include 62 strokes and 12 kiloampere-scale superimposed pulses in 12 flashes triggered at Camp Blanding in 2013. The overall data set for ten years (2004–2013) includes 388 strokes and 185 superimposed pulses in 92 flashes. The average number of strokes per flash was 4.3. Year-to-year variation in the performance characteristics is also examined.

Results of evaluation, based on rocket-triggered lightning data, are applicable only to subsequent return strokes in natural downward lightning (or to natural lightning flashes without first strokes in the case of flash detection efficiency). In triggered lightning, the first stroke is replaced by the initial-stage processes, while the subsequent strokes are similar to those in natural lightning [e.g., Rakov and Uman, 2003].

II. Data and Methodology

During 2004–2013, a total of 92 flashes (90 flashes containing both the initial stage and leader/return stroke sequences and 2 flashes composed of the initial stage only) were triggered at Camp Blanding (CB) using the rocket-and-wire technique. There were a total of 388 negative return strokes and 185 kiloampere-scale (≥1 kA) superimposed pulses (SIP). Rockets were launched from three different launchers. The positions of the launchers are known to within a few meters. The channel-base current was measured by resistive shunts with a bandwidth of 0 to at least 3 MHz (typically 8 MHz). Fiber optic links were used to transmit the signals from the sensors to digitizing oscilloscopes. The directly-measured current peaks may contain errors up to 10% or so [Jerauld et al., 2005], but for the purpose of this study they are assumed to be the absolute ground-truth.

The following NLDN performance characteristics were determined: (a) flash and return-stroke detection efficiencies, (b) superimposed pulse detection efficiency, (c) percentage of misclassified events, (d) location error, (e) peak current estimation error, and (f) event-time mismatch. Evaluation of the NLDN performance characteristics based on independent, ground-truth observations (particularly errors in locations and peak current estimates) can be viewed as a kind of calibration of the network.

Camp Blanding and NLDN events were correlated using GPS time stamps. The detection efficiency (DE) values were computed as the ratios of the numbers of NLDN-detected events and all triggered-lightning events recorded at Camp Blanding. Since all the triggered-lightning return strokes and superimposed pulses examined here were negative cloud-to-ground events (–CG), the percentage of misclassified events is the number of NLDN-detected events that were reported as not –CGs, expressed in percent of the total number of NLDN-detected events. For a given event, the distance between the location of rocket launcher or the lightning ground attachment point (used as ground-truth) and the location reported by the NLDN is defined as the location error (LE). The errors in NLDN-reported peak currents were computed using the equation $\Delta I = I_{NLDN} - I_{CB}$, where I_{NLDN} is the NLDN-reported peak current and I_{CB} is the peak value of current waveform directly measured at Camp Blanding. The current error is expressed in percent of I_{CB}. The event-time mismatch was computed as $\Delta t = t_{NLDN} - t_{CB}$, where t_{NLDN} is the NLDN-reported time for an event and t_{CB} is the precise (within 1 μs) GPS time of the event recorded at Camp Blanding. The event time reported by the NLDN is one of the outputs of the NLDN locating algorithm and corresponds to the beginning of field pulses generated by that event [Cummins et al., 1998], whereas the GPS timestamp recorded at Camp Blanding corresponds to the time when the channel-base current exceeded the preset threshold or the luminosity of the lightning channel became strong enough to trigger two optical detectors viewing the research site from opposite corners.

Of the 388 strokes recorded at Camp Blanding in 2004–2013, directly measured currents were available for 351 strokes. The NLDN detected 292 strokes (directly measured currents were available for 268). In addition, the NLDN detected 11 superimposed pulses. The "classical" return strokes are generally preceded by essentially zero-current (below 1–2 A or less) intervals and superimposed pulses (SIP) are riding either on the initial-stage current (ICC pulses) or on continuing currents (M-components) following return-stroke pulses. Fig. 1 shows the peak current histograms for all return strokes and superimposed pulses recorded at Camp Blanding during 2004–2013. For return-stroke peak currents, the geometric mean (GM) was 11.8 kA, median was 11.8 kA, maximum was 44.6 kA, and minimum was 2.0 kA. For peak currents of superimposed pulses, the GM was 2.3 kA, median was 1.9 kA, maximum was 19.9 kA, and minimum was 1.0 kA (the selected cut-off level). Table I gives the statistics of peak current for return strokes in different years.

III. Results and Discussion

A. Flash and Stroke Detection Efficiencies

In 2004–2013, the NLDN flash detection efficiency was 94% and the stroke detection efficiency was 75%. Both detection efficiency values are higher than those reported for 2001–2003 by Jerauld et al. [2005] and are consistent with those reported for 2004–2009 by Nag et al. [2011] and for 2004–2012 by Mallick et al. [2014].

Fig. 2 shows the NLDN stroke detection efficiency as a function of peak current directly measured at Camp Blanding. The total number of NLDN-reported strokes for which peak currents were measured at Camp Blanding was 268. The stroke detection efficiency was 100% for peak currents above 25 kA and decreased to 55% for strokes in the 5 to 10 kA range. None of the sixteen strokes with peak currents ≤5kA was detected by the NLDN, which is in agreement with the results of Jerauld et al. [2005], Nag et al. [2011], and Mallick et al. [2014].

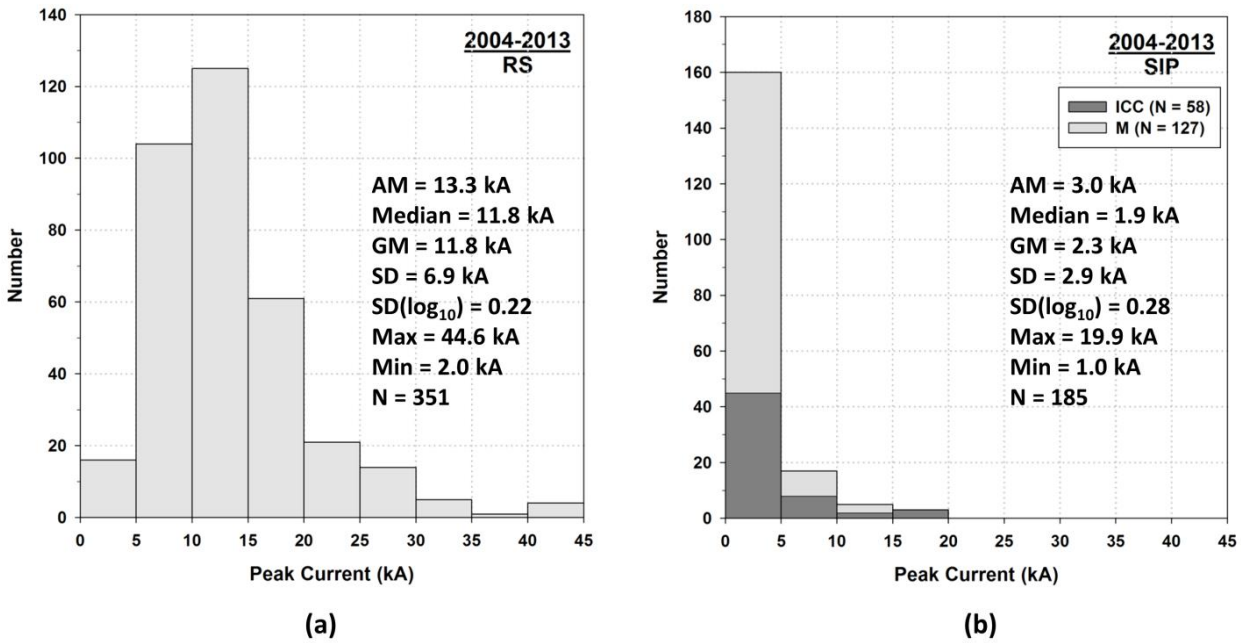

Fig. 1. Histograms of peak currents directly measured at Camp Blanding during 2004–2013 for (a) return strokes and (b) kiloampere-scale superimposed pulses, both detected and not detected by the NLDN. Statistics given are the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), standard deviation of the $\log_{10}$ of the parameter (SD($\log_{10}$I)), maximum value (Max), and minimum value (Min). N is the sample size.

TABLE I. STATISTICS OF PEAK CURRENT DIRECTLY MEASURED AT CAMP BLANDING FOR RETURN DTROKES IN DIFFERENT YEARS FROM 2004 TO 2013

	2004	2005	2007	2008	2009	2010	2011	2012	2013	2004–2013
Median (kA)	8.2	16.6	28.1	12.1	12.1	11.8	10.4	11.7	12.5	11.8
GM (kA)	8.3	14.7	22.8	11.8	13.1	11.4	10.3	11.2	12.9	11.8
Maximum (kA)	17.0	41.0	44.5	23.4	44.6	43.2	31.8	31.1	38.1	44.6
Minimum (kA)	3.4	6.1	11.7	4.3	2.8	3.5	2.0	3.0	5.5	2.0
Sample Size	13	13	2	33	59	40	38	92	61	351

B. Superimposed Pulse Detection Efficiency

In 2004–2013, the NLDN detected 11 out of 185 kiloampere-scale superimposed pulses, of which 7 were ICC pulses and 4 were M-components. The NLDN detection efficiency for superimposed pulses with peaks ≥1 kA was 6% and that for pulses with peaks ≥5 kA was 32% (see Table II). The SIP detection efficiency values are consistent with those reported for 2004–2012 by Mallick et al. [2014].

Table III gives the average number of reporting NLDN sensors for different peak current ranges for both return strokes and kiloampere-scale superimposed pulses. The number of reporting sensors ranged from 2 to 16. The mean number of reporting sensors was 6. As expected, there is a general trend for strokes with higher peak currents to be detected by a larger number of NLDN sensors.

C. Percentage of Misclassified Events

In 2004–2013, 10 (3%) out of 292 return strokes and 2 (18%) out of 11 superimposed pulses detected by the NLDN were misclassified as cloud (IC) discharges. For 2004–2012, Mallick et al. [2014] reported the percentage of misclassified return strokes to be 4% (N = 245). None of the 9 superimposed pulses was misclassified.

D. Location Error

Fig. 3 shows spatial distribution of locations for the NLDN-detected return strokes. The origin of coordinates corresponds to the actual stroke location that was known to within a few meters, so that the horizontal and vertical axes correspond to the east-west (east being positive) and north-south (north being positive) location error components, respectively. The arithmetic mean (AM) and median north-south location errors were 37 m and −100 m, respectively, while the AM and median east-west location errors were −203 m and −195 m, respectively.

Fig. 4 shows the histogram of NLDN location errors for return strokes. The median location error was 309 m, with the largest error being 8 km. About 90% (264 out of 292) of strokes had location error ≤1 km. The median location error for 2004–2013 is lower than that reported for 2001–2003 (600 m) by Jerauld et al. [2005], is comparable with that reported for 2004–2009 (308 m) by Nag et al. [2011], and is slightly lower

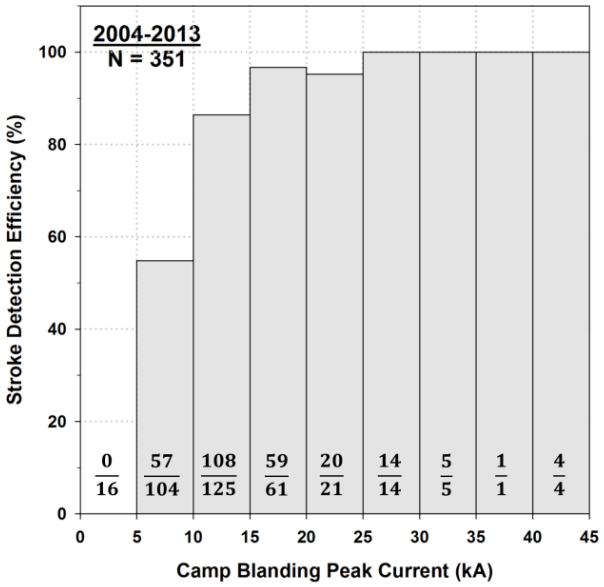

Fig. 2. NLDN detection efficiency for 351 return strokes as a function of peak current directly measured at Camp Blanding during 2004–2013. For each peak current range (bin size of 5 kA), the ratio given inside the column indicates the number of strokes detected by the NLDN (numerator) and the number of strokes recorded at Camp Blanding (denominator) for that peak current range.

than that reported for 2004–2012 (340 m) by Mallick et al. [2014].

Fig. 5 shows the NLDN location error plotted versus peak current directly measured at Camp Blanding for return strokes. 25 out of 28 return strokes with location errors >1 km correspond to strokes with peak currents ≤15 kA. The largest location error of 8 km occurred for a stroke (in a flash triggered in 2012) having peak current of 9.7 kA.

Fig. 6 shows the NLDN location error plotted versus the number of reporting NLDN sensors for return strokes. As expected, the location error tends to decrease as the number of reporting sensors increases.

For 11 superimposed pulses detected by the NLDN, the median location error was 795 m, with the largest error being 4.7 km (for an M-component in a flash triggered in 2011 and having peak current of 8.9 kA).

E. Peak Current Estimation Error

Fig. 7 shows a scatter plot of the NLDN-reported peak current versus peak current directly measured at Camp Blanding for return strokes. The red broken-line diagonal (slope = 1) in this figure is the locus of the points for which the NLDN-reported peak current and the directly-measured peak current are equal. For all 268 NLDN-reported strokes with directly measured currents, the GM of Camp Blanding peak current was 13.7 kA versus 12.5 kA for NLDN-reported peak currents. The AM value of the ratio I_{CB}/I_{NLDN} for 2004–2013 was 1.1. A greater than 1 ratio indicates that the NLDN tends to underestimate the peak current (by about 10%, on average). The best fit to the data (green solid line) is also shown in Fig. 7.

TABLE II. SUMMARY OF KILOAMPERE-SCALE SUPERIMPOSED PULSES RECORDED AT CAMP BLANDING DURING 2004–2013 ALONG WITH THE NLDN DETECTION EFFICIENCIES FOR TWO SELECTION CRITERIA (≥1 KA AND ≥5 KA)

	ICC Pulses			M-Components			SIPs (ICC + M)		
	CB	NLDN	DE	CB	NLDN	DE	CB	NLDN	DE
≥1 kA	58	7	12%	127	4	3%	185	11	6%
≥5 kA	13	6	46%	12	2	17%	25	8	32%

CB – recorded at Camp Blanding
NLDN – detected by the NLDN
DE – NLDN detection efficiency

TABLE III. ARITHMETIC MEAN, MINIMUM, AND MAXIMUM NUMBER OF REPORTING NLDN SENSORS FOR DIFFERENT PEAK CURRENT RANGES FOR BOTH RETURN STROKES AND KILOAMPERE-SCALE SUPERIMPOSED PULSES RECORDED AT CAMP BLANDING DURING 2004–2013

Peak Current Range (kA)	Number of Reporting NLDN Sensors			Sample Size
	Arithmetic Mean	Minimum	Maximum	
0 – 5	4	3	4	3
5 – 10	3	2	6	60
10 – 15	5	2	10	110
15 – 20	7	2	12	62
20 – 25	9	5	11	20
25 – 30	9	5	16	14
30 – 35	9	4	11	5
35 – 40	-	9	9	1
40 – 45	12	9	14	4
0 – 45	6	2	16	279

All events in the 0–5 kA range are SIPs.

Fig. 8a shows a histogram of signed values of NLDN peak current estimation error as a percentage of Camp Blanding peak current. The AM and median values of ΔI% were −6.2% and −6.0%, respectively. Since the distribution appears to be close to normal, the mean value and the standard deviation of ΔI% can be interpreted as systematic (–6%) and random (22%) error components.

Fig. 8b shows a histogram of the unsigned (absolute) values of NLDN peak current estimation error as a percentage of Camp Blanding peak current. For absolute values of ΔI%, the AM and median values were 17% and 14%, respectively. The maximum current estimation error of 127% corresponds to a return stroke (in a flash triggered in 2008) having peak current of 11.2 kA. The median absolute current estimation error for 2004–2013 is lower than that reported for 2001–2003 (20%) by Jerauld et al. [2005] and is comparable to that reported for 2004–2009 (13%) by Nag et al. [2011] and for 2004–2012 (14%) by Mallick et al. [2014].

For 11 superimposed pulses detected by the NLDN, the median value of |ΔI|% was 28%, with the largest error being 84% (for an M-component in a flash triggered in 2013 and having peak current of 3.7 kA).

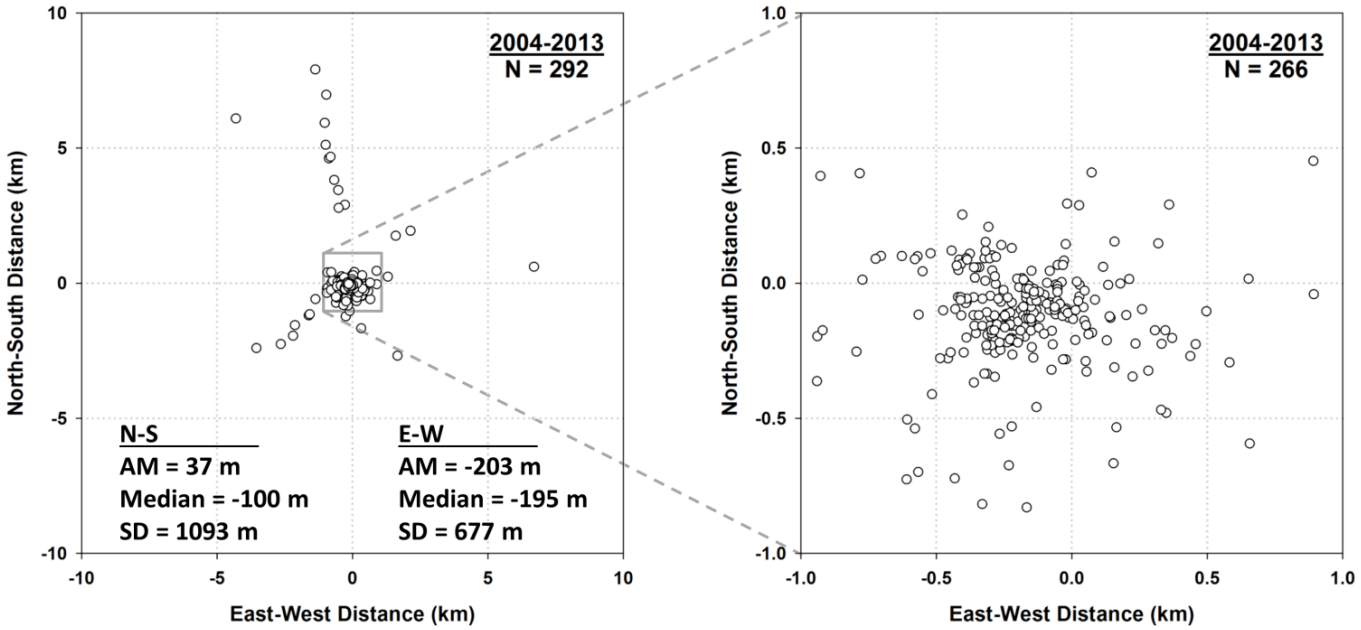

Fig. 3. Plot of NLDN-reported stroke locations for 2004–2013. The origin of coordinates corresponds to the actual stroke location. The horizontal axis corresponds to the east-west component of the location error, with positive values corresponding to east. The vertical axis corresponds to the north-south component of the location error, with positive values corresponding to north. Statistics given are arithmetic mean (AM), median, and standard deviation (SD). N is the sample size.

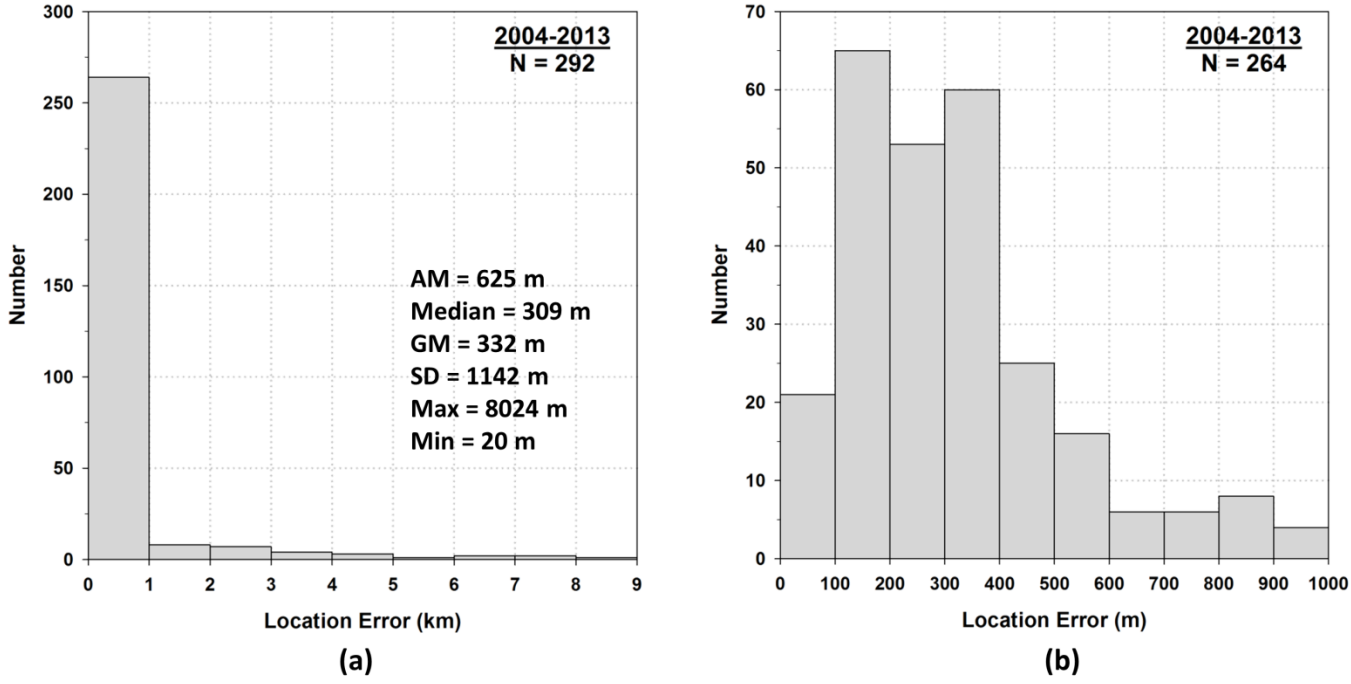

Fig. 4. Histograms of NLDN location errors for (a) all 292 return strokes and (b) 264 return strokes with location errors ≤1 km for 2004–2013. Statistics given are the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), maximum value (Max), and minimum value (Min). N is the sample size.

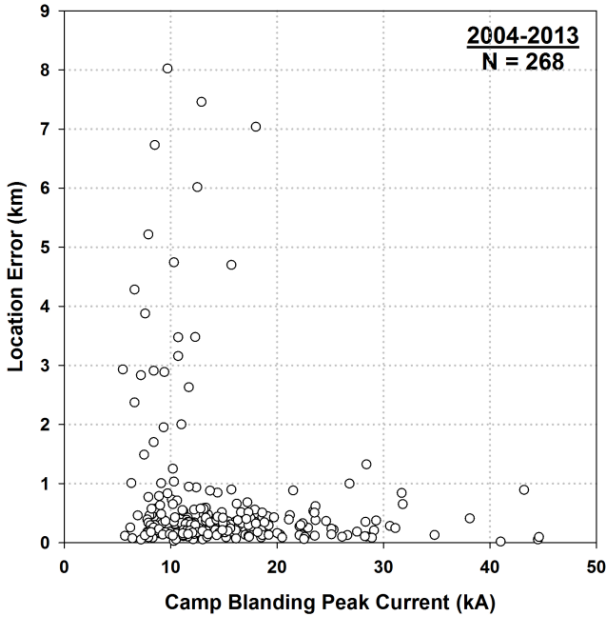

Fig. 5. NLDN location error versus peak current directly measured at Camp Blanding for return strokes (2004–2013).

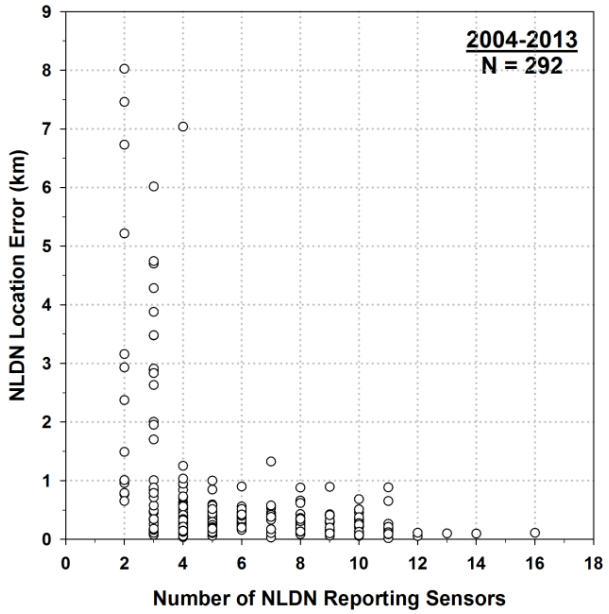

Fig. 6. NLDN location error versus number of reporting NLDN sensors for return strokes (2004–2013).

F. Event-Time Mismatch

Fig. 9a shows a histogram for the signed values of event-time mismatch (Δt) for return strokes. The AM and median values of Δt were 0.1 μs and 2.0 μs, respectively.

Fig. 9b shows a histogram for the absolute values of event-time mismatch (|Δt|) for return strokes. The AM and median values of |Δt| were 3.5 μs and 2.7 μs, respectively. The maximum value of |Δt| was 23 μs and corresponds to a return stroke (in a flash triggered in 2012) having peak current of 9.7 kA. This stroke is also characterized by the largest location error of 8 km. The median absolute event-time mismatch for 2004–2013 is comparable with that reported for 2004–2012 (2.8 μs) by Mallick et al. [2014].

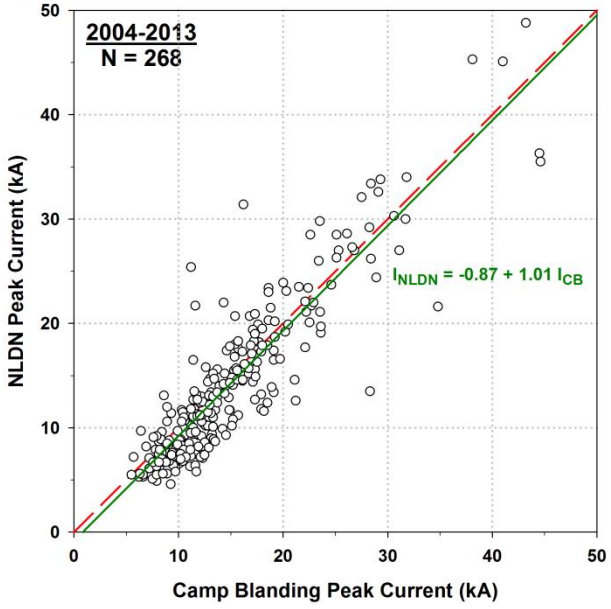

Fig. 7. NLDN-reported peak current versus peak current directly measured at Camp Blanding for 268 return strokes (2004–2013). The green solid line, I_{NLDN} = -0.87 + 1.01×I_{CB}, is the best (least squares) fit to the data, while the red broken line represents the ideal situation when I_{NLDN} = I_{CB}.

Fig. 10 shows the absolute event-time mismatches versus the number of reporting NLDN sensors for return strokes. The majority of events with event-time mismatches >7 μs were reported by 2 to 4 sensors.

Fig. 11 shows the NLDN location error versus the absolute event-time mismatch for return strokes. Different colors are used to identify strokes for different years. The vertical broken line corresponds to |Δt| = 7 μs. As expected, there is a trend for location error to increase with increasing the event-time mismatch. In fact, when the mismatch is >7 μs and 3 data points (with location errors ≤1 km) are ignored, there is strong positive correlation between event-time mismatch and location error. These 12 return strokes with large event-time mismatches and large location errors occurred in flashes triggered in 2011 (3 strokes) and 2012 (9 strokes).

Out of 11 superimposed pulses detected by the NLDN, precise GPS timestamps were available for only 5. The median value of event-time mismatch was 3 μs, with the maximum value being 14 μs. The largest event-time mismatch corresponds to an M-component (in a flash triggered in 2011) and having peak current of 8.9 kA. This M-component is also characterized by the largest location error of 4.7 km reported for superimposed pulses.

G. Comparison of NLDN Performance Characteristics for Different Time Periods

In this section, we compare the NLDN performance characteristics for different years from 2004 to 2013. Table IV gives the NLDN performance characteristics for return strokes

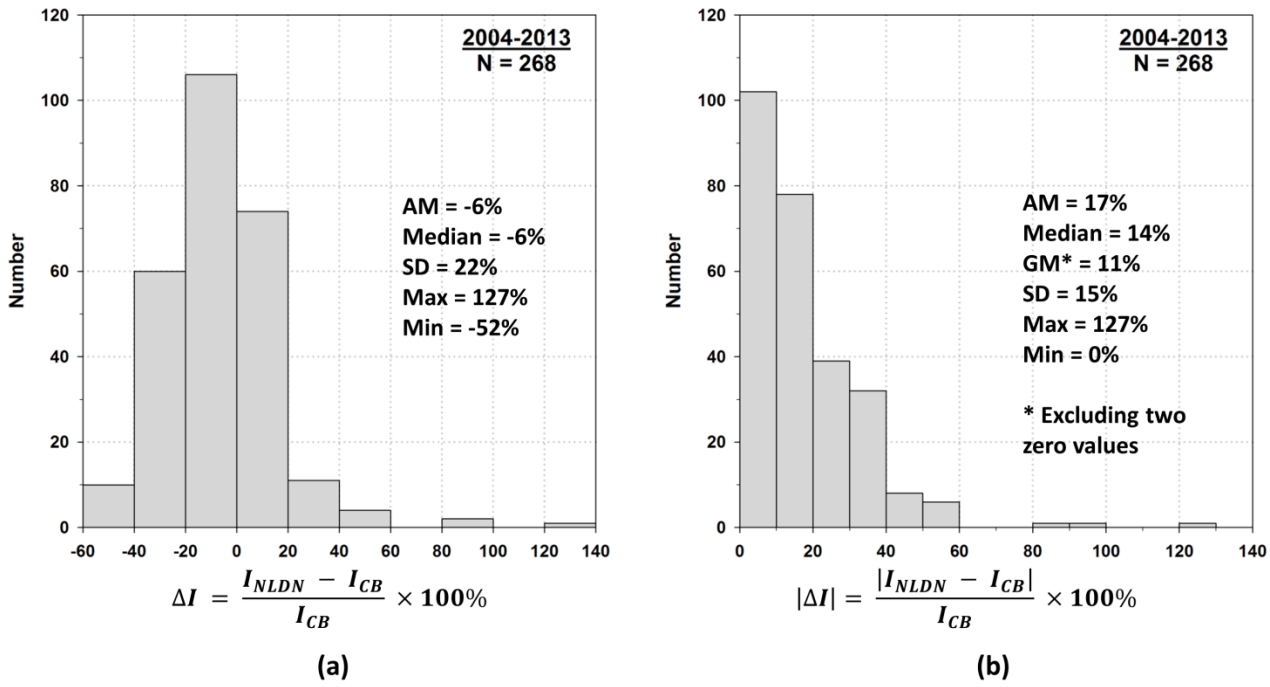

Fig. 8. Histograms of (a) signed and (b) absolute NLDN peak current estimation errors, given as a percentage of the directly measured Camp Blanding current ($\Delta I\% = 100\Delta I/I_{CB}$, where $\Delta I = I_{NLDN} - I_{CB}$) for return strokes (2004–2013). Statistics given are the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), maximum value (Max), and minimum value (Min). N is the sample size.

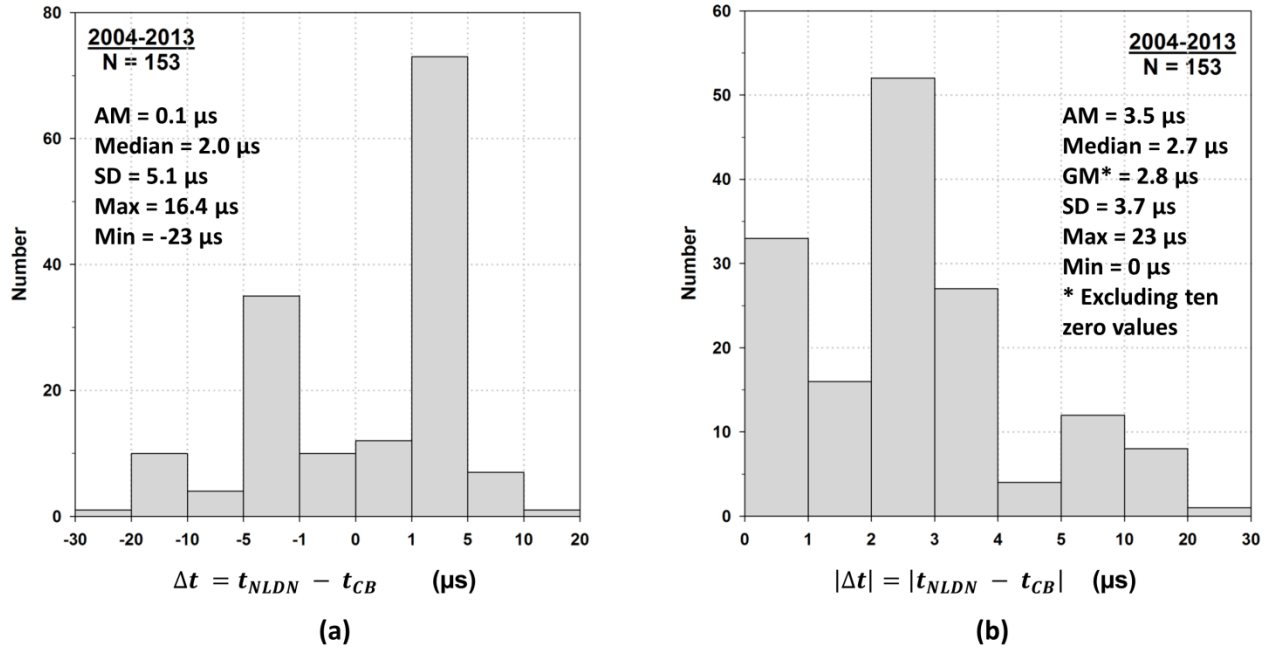

Fig. 9. Histogram of (a) signed and (b) absolute event-time mismatches ($\Delta t = t_{NLDN} - t_{CB}$) for 153 return strokes recorded at Camp Blanding (2004–2013). Statistics given are the arithmetic mean (AM), median, geometric mean (GM), standard deviation (SD), maximum value (Max), and minimum value (Min). N is the sample size.

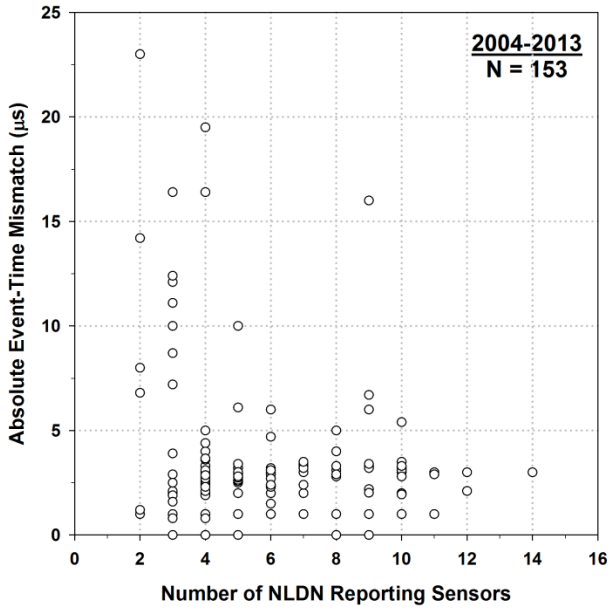

Fig. 10. Absolute event-time mismatch versus the number of reporting NLDN sensors for 153 return strokes recorded at Camp Blanding during 2004–2013.

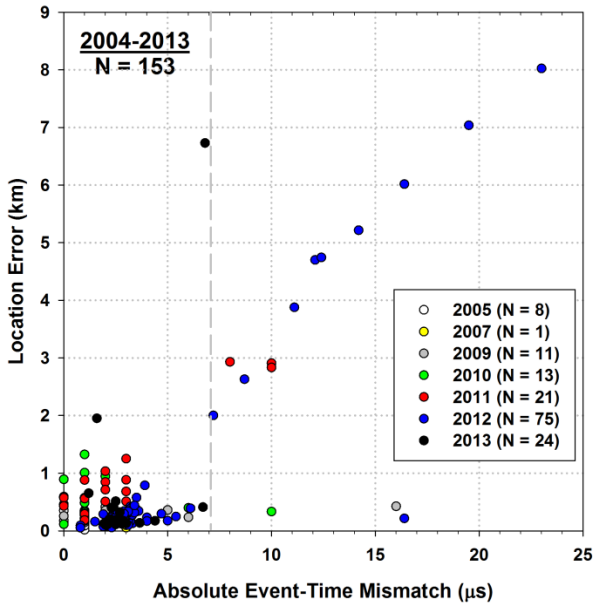

Fig. 11. NLDN location error versus absolute event-time mismatch for 153 return strokes recorded at Camp Blanding during 2004–2013. Different colors are used for different years. There were no flashes triggered in 2006. Precise GPS timestamp were not available at Camp Blanding for any of the strokes in 2008. The vertical broken line corresponds to $|\Delta t| = 7$ μs.

in different years. From Table IV, we can observe the following. The flash detection efficiency was 94% to 100% for all years, except for 2005, when it was 63%. Starting with 2008, the stroke detection efficiency was higher than 75%, except for 2011, when it was 61%. Starting with 2008, the median location error was less than 400 m, except for 2011, when it was 652 m. With that exception, there appears to be a decreasing trend. Starting with 2008, the median absolute current estimation error was 15% or less.

Table V gives the NLDN performance characteristics for the four periods, 2001–2003 [Jerauld et al., 2005], 2004–2009 [Nag et al., 2011], 2004–2012 [Mallick et al., 2014], and 2004–2013 (present study).

IV. Summary

The NLDN performance characteristics in the Florida region, estimated using 2004–2013 rocket-triggered lightning data, were as follows:

- The flash and stroke detection efficiencies were 94% and 75%, respectively.
- The superimposed pulse detection efficiency was 6% (for peak currents ≥1 kA) and 32% (for peak currents ≥5 kA).
- 3% of NLDN-detected strokes and 18% of the NLDN-detected superimposed pulses were misclassified as cloud discharges.
- The median location error for return strokes was 309 m.
- The median absolute current estimation error for return strokes was 14%.
- The median absolute event-time mismatch for return strokes was 2.7 μs.

TABLE IV. Comparison of the Performance Characteristics of the NLDN for Return Strokes in Different Years from 2004 to 2013

		2004	2005	2007	2008	2009	2010	2011	2012	2013	2004–2013
Number of Flashes (with Return Strokes)		3	8	1	7	17	12	11	19	12	90
Number of Strokes		13	13	2	37	72	50	38	101	62	388
Flash Detection Efficiency (%)		100	63	100	100	94	100	100	95	100	94
Stroke Detection Efficiency (%)		69	62	50	81	79	80	61	76	76	75
Location Error (m)	**Median**	135	242	55	362	326	381	652	258	173	309
	Maximum	477	416	55	3477	4283	1327	3481	8024	7458	8024
Absolute Current Estimation Error (%)	**Median**	14	29	18	9	14	15	13	15	15	14
	Maximum	34	35	18	127	52	35	42	87	54	127

There was no lightning triggered at Camp Blanding in 2006.

TABLE V. COMPARISON OF THE PERFORMANCE CHARACTERISTICS OF THE NLDN FOR 2001–2003 [JERAULD ET AL., 2005], 2004–2009 [NAG ET AL., 2011], 2004–2012 [MALLICK ET AL., 2014], AND 2004–2013 (PRESENT STUDY)

Reference	**Jerauld et al. [2005]** [a]	**Nag et al. [2011]** [a]	**Mallick et al. [2014]**	**Present Study**
Time Period	2001–2003	2004–2009	2004–2012	2004–2013
Flash Detection Efficiency	84% (N = 37)	92% (N = 37)	94% (N = 78)	94% (N = 90)
Stroke Detection Efficiency	60% (N = 159)	76% (N = 139)	75% (N = 326)	75% (N = 388)
Superimposed Pulse Detection Efficiency	-	-	5% (N = 173)	6% (N = 185)
Percentage of Misclassified Strokes	-	-	4% (N = 245)	3% (N = 292)
Median Location Error	600 m (N = 95)	308 m (N = 105)	334 m (N = 245)	309 m (N = 292)
Median Absolute Current Estimation Error	20% (N = 70)	13% (N = 96)	14% (N = 222)	14% (N = 268)
Median Absolute Event-Time Mismatch	-	-	2.8 μs (N = 134)	2.7 μs (N = 153)

[a] Samples of Jerauld et al. [2005] and Nag et al. [2011] contained both return strokes and large superimposed pulses. The exact number of the latter in either of the samples is unknown, but believed to be small.

The year-to-year variation in performance characteristics can be summarized as follows:

- The flash detection efficiency was 94% to 100% for all years, except for 2005, when it was 63%.
- Starting with 2008, the stroke detection efficiency was higher than 75%, except for 2011, when it was 61%.
- Starting with 2008, the median location error was less than 400 m, except for 2011, when it was 652 m. With that exception, there appears to be a decreasing trend.
- Starting with 2008, the median absolute current estimation error was 15% or less.

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