Evaluation of U.S. National Lightning Detection Network performance characteristics using rocket-triggered lightning data acquired in 2004–2009

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Received 23 August 2010; revised 25 October 2010; accepted 4 November 2010; published 27 January 2011.

[1] We evaluated performance characteristics of the U.S. National Lightning Detection Network (NLDN) using rocket-triggered lightning data acquired in 2004–2009 at Camp Blanding, Florida. A total of 37 negative flashes that contained leader/return stroke sequences (a total of 139) were triggered during these years. For all the return strokes, locations of channel terminations on the ground were known exactly, and for 122 of them currents were measured directly using noninductive shunts. The NLDN recorded 105 Camp Blanding strokes in 34 flashes. The resultant flash and stroke detection efficiencies were 92% and 76%, respectively. The median absolute location error was 308 m. The median NLDN-estimated peak current error was −6.1%, while the median absolute value of current estimation error was 13%. Strokes in "classical" triggered flashes are similar to regular subsequent strokes (following previously formed channels) in natural lightning, and hence the results presented here are applicable only to regular negative subsequent strokes in natural lightning. The flash detection efficiency reported here is expected to be an underestimate of the true value for natural negative lightning flashes, since first strokes typically have larger peak currents than subsequent ones.

Citation: Nag, A., et al. (2011), Evaluation of U.S. National Lightning Detection Network performance characteristics using rocket-triggered lightning data acquired in 2004–2009, *J. Geophys. Res.*, *116*, D02123, doi:10.1029/2010JD014929.

1. Introduction

[2] The U.S. National Lightning Detection Network (NLDN) has been providing real-time, continental-scale lightning data since 1989. The most recent network-wide NLDN upgrade, which was completed in 2004, is described by *Cummins et al.* [2006] and *Cummins and Murphy* [2009]. The latter work also gives an overview of lightning-locating systems in general. Prior to the upgrade, the NLDN consisted of 106 sensors, including 63 Lightning Positioning and Tracking System Version III (LPATS III) sensors, which provided only time of arrival information, and 43 Improved Accuracy Through Combined Technology (IMPACT) sensors, which provided both time of arrival and azimuth information. During the upgrade, all sensors in the NLDN were replaced with IMPACT-Enhanced Sensitivity and Performance (IMPACT-ESP) sensors, which have improved analog front-end circuitry, higher speed processor, and configurable waveform criteria. The total number of sensors is currently 114. The thresholds of the sensors before and after the 2004 upgrade are the same. A map showing the locations of 15 NLDN sensors in and around the Florida region is found in Figure 1.

[3] *Jerauld et al.* [2005] examined the performance characteristics of the NLDN for the 2001–2003 period using rocket-triggered lightning data acquired at Camp Blanding, Florida. Note that 2003 was essentially a postupgrade year for the Florida region. The NLDN field propagation model, which is part of the NLDN field-to-current conversion procedure, was modified on 1 July 2004 to provide a better match with Camp Blanding ground-truth data used in the evaluation performed by *Jerauld et al.* [2005]. In the present study, we use new rocket-triggered lightning data obtained at Camp Blanding during the years 2004–2009. The evaluation results are representative of the portion of the NLDN covering the Florida region (see Figure 1), whose performance characteristics are not expected to be superior to those of other parts of the network.

2. Data and Methodology

[4] During the summers of 2004–2009, a total of 55 negative flashes were triggered at the Camp Blanding facility of the International Center for Lightning Research and Testing.

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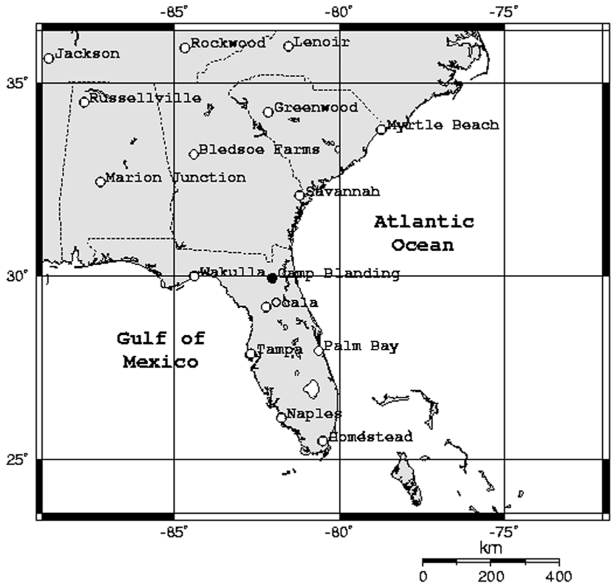


Figure 1. Map showing the locations of 15 U.S. National Lightning Detection Network (NLDN) sensors in and around the Florida region as of late 2003. The approximate location of Camp Blanding is also shown. The current network configuration is essentially the same as shown here, except for the additional sensor in the Bahamas installed in mid-2006.

Of these 55, 37 flashes contained a total of 139 leader/return stroke sequences and 18 flashes consisted of the initial stage (upward positive leader and initial continuous current) only. A summary of the flashes and strokes recorded at Camp Blanding during the 5 years (there was no lightning triggering in 2006) is given in Table 1. In all years, an 11 m tower launcher was used, while in 2005 an 8 m mobile launcher was used in addition to the tower launcher. The position of each launcher is known within a few meters. Lightning current was directly measured at the base of either launcher with a current measuring resistor (noninductive shunt). Different shunts were used in different years, but in all cases the bandwidth of the shunt was from DC to at least 8 MHz. Lightning currents were transmitted to Yokogawa and LeCroy digitizing oscilloscopes via fiber-optic links. The Yokogawa oscilloscopes sampled at 2 MHz (−3 dB low-pass filtered at 500 kHz) or 10 MHz (−3 dB low-pass filtered at 3 MHz) and the LeCroy oscilloscopes sampled at 20 MHz (−3 dB filtered at 5 MHz), 100 MHz (−3 dB filtered at 20 MHz), or 250 MHz (−3 dB filtered at 20 MHz). Peak currents measured using Yokogawa and LeCroy oscilloscopes are in very good agreement [*Jerauld et al.*, 2005]. The fiber-optic transmitters and other electronics associated with the current measurements were placed in shielded steel enclosures. Care was taken to account for the variation in gain of the fiber-optic links by measuring calibration signals before and after each storm. The uncertainty of the calibration of the current measuring system is estimated to be at most about 10%.

[5] Of the 37 triggered flashes considered here, 2 flashes (containing 11 strokes) were triggered before 1 July 2004 (when the NLDN field propagation model was modified) and 35 flashes (containing 128 strokes) were triggered after that date. Note that the propagation model modification does not affect flash or stroke detection efficiency, nor does it influence location errors.

[6] The following NLDN performance characteristics were determined: (1) flash detection efficiency, (2) stroke detection efficiency, (3) location errors, and (4) errors in peak current estimates. Camp Blanding and NLDN events were correlated using GPS (Global Positioning System) time stamps. Once correlated strokes were identified, detection efficiency values were computed as ratios of the numbers of NLDN-detected events and all triggered-lightning events.

[7] Location accuracy was evaluated for all strokes reported by the NLDN, including those for which no peak currents were obtained. The location of the rocket launcher (known within a few meters) was taken as the accurate ground strike point (except in the case of one altitude trigger, when the ground strike point was approximately 100 m from the launcher), and that position was compared with the NLDN-reported location. For a given stroke, the distance between these two locations was defined to be the stroke location error.

[8] Peak values of return-stroke current waveforms directly measured at Camp Blanding were used as the ground-truth in estimating errors in NLDN-reported peak currents. The errors were computed using the following equation: $\Delta I = I_{\rm NLDN} - I_{\rm CB}$.

[9] Of the 139 strokes in 37 flashes triggered over the 5 years, directly measured currents were available for 122 strokes in 35 flashes. The peak current histogram for all strokes recorded during 2004–2009 is given in Figure 2. This histogram includes both strokes detected by the NLDN and those that were not. The geometric mean (GM) and median peak currents are both 12 kA, and the minimum and maximum peak currents are 2.9 kA and 45 kA, respectively.

3. Results and Discussion

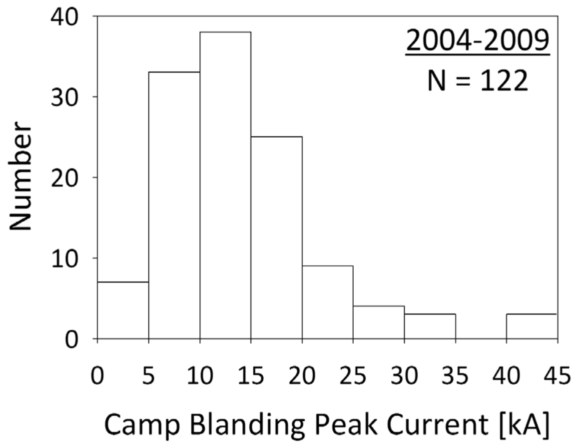
3.1. Flash and Stroke Detection Efficiencies

[10] Table 1 summarizes the NLDN flash and stroke detection efficiencies for 2004–2009. For all flashes triggered during this period, the flash detection efficiency was 92% (34 of 37), which is better than the 84% reported by *Jerauld*

Table 1. Summary of Flashes Triggered at Camp Blanding During 2004–2009 Along With the NLDN Flash and Stroke Detection Efficiencies[a]

Time Period	Number of Flashes With Return Strokes	Number of NLDN Detected Flashes	NLDN Flash Detection Efficiency	Number of Strokes	Number of NLDN Detected Strokes	NLDN Stroke Detection Efficiency
2004–2009[b]	37	34	92%	139	105	76%
2001–2003 [*Jerauld et al.*, 2005]	37	31	84%	159	95	60%

[a]Similar information is also given for 2001–2003 [*Jerauld et al.*, 2005]. NLDN, U.S. National Lightning Detection Network.
[b]There was no lightning triggering in 2006.



Testing Period	2004–2009	2001–2003 [*Jerauld et al.*, 2005]
AM, kA	14	15
SD, kA	7.9	7.4
GM, kA	12	13
Median, kA	12	~13
SD($\log_{10}$I)	0.23	0.20
Min, kA	2.9	2.9
Max, kA	45	43
N	122	122

Figure 2. Histogram of Camp Blanding return-stroke peak currents, *I*, for 2004–2009. Statistics given are the arithmetic mean (AM), standard deviation (SD), geometric mean (GM), median, standard deviation of the $\log_{10}$ of the parameter (SD($\log_{10} I$)), minimum value (Min), and maximum value (Max) for 2004–2009 (present study) and 2001–2003 [*Jerauld et al.*, 2005].

et al. [2005] for 2001–2003. Note that all strokes in "classical" triggered flashes are similar to subsequent strokes in natural lightning, and hence the flash detection efficiency reported here is expected to be an underestimate of the true value for natural negative lightning flashes, since first strokes typically have larger peak currents than subsequent ones. The stroke detection efficiency was 76% (105 of 139) versus 60% reported by *Jerauld et al.* [2005]. The average stroke multiplicity for 2004–2009 (defined as the total number of strokes divided by the number of flashes with return strokes triggered at Camp Blanding) was 3.8 versus 4.3 for 2001–2003.

[11] Figure 3 gives the NLDN stroke detection efficiency as a function of peak current measured at Camp Blanding (the total number of strokes in this case is 122). The stroke detection efficiency is 100% for 19 strokes above 20 kA and decreases to 61% for strokes in the 5 to 10 kA range. None of the seven strokes with peak currents less than or equal to 5 kA was detected by the NLDN. Similarly, for the 2001–2003 data set examined by *Jerauld et al.* [2005], all six strokes having peak currents less than 5 kA were missed by the NLDN.

3.2. Location Accuracy

[12] Figure 4 shows a spatial distribution of locations for the 105 NLDN-detected strokes in 34 flashes triggered at Camp Blanding during 2004–2009. The origin (marked X at the center of the plot in Figure 4) corresponds to the actual strike 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 are −133 m and −84 m, respectively, while the AM and median east-west location errors are −237 m and −211 m, respectively.

[13] Figure 5 shows the histogram of NLDN absolute stroke location errors for the 105 strokes shown in Figure 4. The median absolute location error was 308 m, with the largest error being 4.2 km. This is better than a median absolute location error of 600 m and a maximum of 11 km reported by *Jerauld et al.* [2005] for 95 Camp Blanding strokes located by the NLDN in 2001–2003. Figure 6 shows the NLDN absolute location error plotted versus the peak current measured at Camp Blanding. Five of six location errors >1.5 km correspond to strokes with peak currents <10 kA, and one corresponds to a peak current of 11 kA. Figure 7 shows the NLDN absolute location error plotted versus the number of NLDN reporting sensors. The number of reporting sensors ranges from 2 to 14. The largest location error tends to decrease as the number of reporting sensors increases.

[14] The NLDN 50% error ellipse, calculated for each stroke location, is defined as a confidence region for which there is a 50% probability that the actual stroke location lies

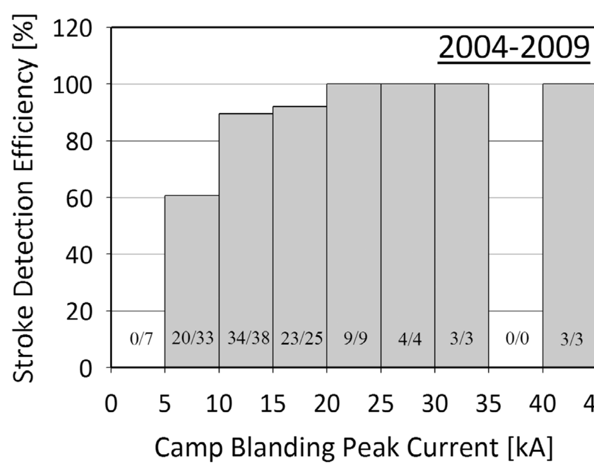
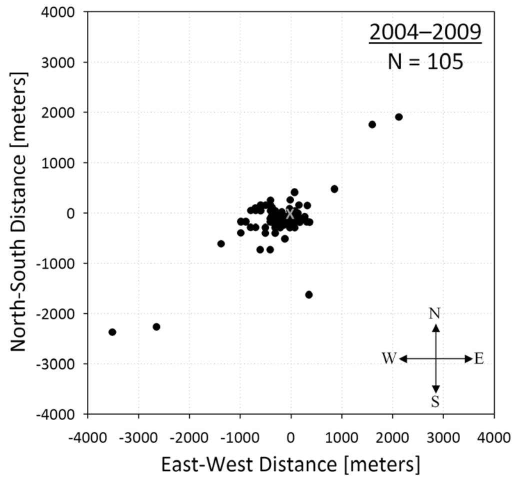


Figure 3. NLDN stroke detection efficiency as a function of peak current measured at Camp Blanding. For each peak current range (bin size of 5 kA), the ratio given inside the column indicates the number of strokes detected by the NLDN (numerator) and the number of strokes recorded at Camp Blanding (denominator) for that peak current range. The total number of strokes whose currents were measured at Camp Blanding is 122, of which 96 (79%) were detected by the NLDN.



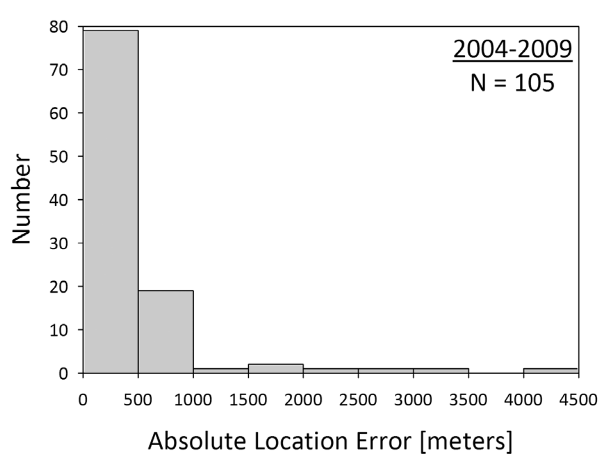
N-S and E-W Components of Location Error

Testing Period		2004 –2009	2001–2003 [Jerauld et al., 2005]
N-S	AM, m	-133	860
	SD, m	472	2340
	Median, m	-84	60
E-W	AM, m	-237	-460
	SD, m	586	520
	Median, m	-211	-400
N		105	95

Figure 4. Plot of NLDN-reported stroke locations for 105 strokes in 34 flashes triggered during 2004–2009 at Camp Blanding. The origin (indicated by the cross) corresponds to the actual stroke location (lightning triggering 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), for each location error component for 2004–2009. The same statistics are also given for 2001–2003 [*Jerauld et al.*, 2005].

within the area circumscribed by the ellipse, with the center of the ellipse being the most probable (reported) stroke location. The semimajor axis of the 50% ellipse is usually viewed as the median (50%) location error. Corresponding error ellipses for any probability level (e.g., 90%) can be derived by multiplying the semimajor and semiminor axes of the 50% ellipse by an appropriate scaling factor [*Vaisala Inc.*, 2004]. The two-dimensional Gaussian distribution of errors in latitude and longitude is based on the assumption that the random errors in sensor time and angle measurements are uncorrelated and their distributions are approximately Gaussian [*Cummins et al.*, 1998]. Strokes located within a group of several sensors typically have relatively small, nearly circular error ellipses, whereas strokes detected by only two or three sensors typically have very large, elongated ellipses. A stroke detected by only two sensors, when that stroke is located near the line joining the two sensors (base line), typically has an elongated ellipse whose major axis is along the baseline. Figure 8 shows the NLDN 50% semimajor axis lengths plotted versus peak current measured at Camp Blanding. A semimajor axis length of <1 km was reported for the majority of strokes (80 of 96). The largest semimajor axis length was 7.6 km for a stroke having a peak current of 14.7 kA.

[15] Figure 9 shows the NLDN absolute location error plotted versus NLDN 50% semimajor axis length. Strokes having absolute location errors <1 km are typically associated with a semimajor axis length of <1 km. The slanted solid line (slope = 1) in Figure 9 is the locus of points for which the NLDN 50% semimajor axis length and corresponding location error are equal; that is, it represents the boundary of the 50% error ellipse. If the error ellipses are



Testing Period	2004–2009	2001–2003 [*Jerauld et al.*, 2005]
AM, m	489	1470
SD, m	632	2130
GM, m	321	680
Median, m	308	600
Min, m	23	40
Max, m	4239	11000
N	105	95

Figure 5. Histogram of the NLDN absolute location errors. Corresponding statistics are given for both 2004–2009 (present study) and 2001–2003 [*Jerauld et al.*, 2005].

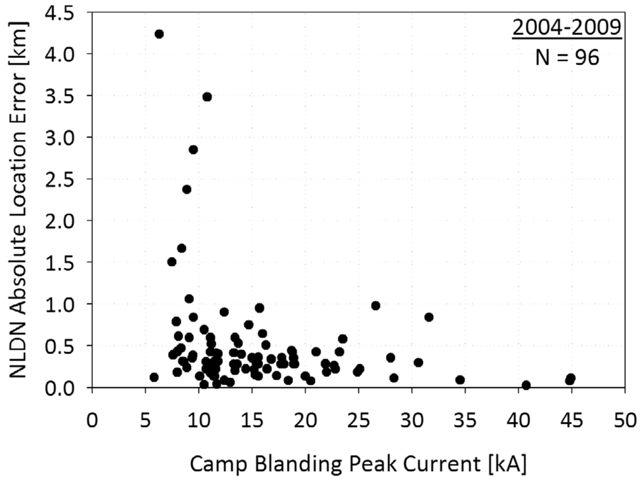


Figure 6. NLDN absolute location error versus Camp Blanding peak current.

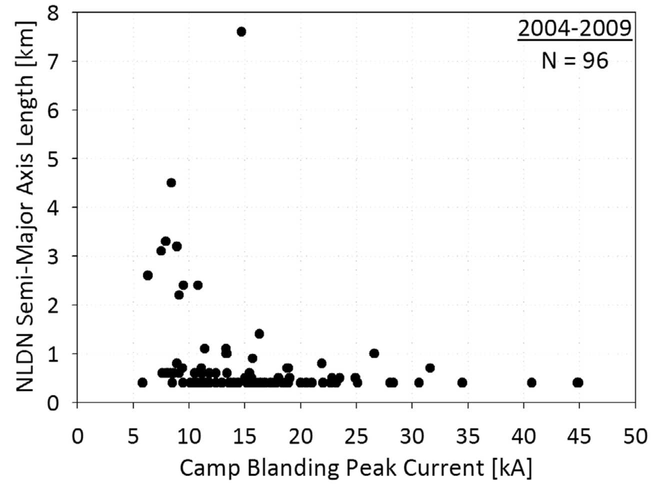


Figure 8. NLDN 50% error ellipse semimajor axis length versus Camp Blanding peak current.

assumed to be nearly circular, then data points below this line correspond to strokes with ground-truth locations enclosed by the 50% error ellipse and data points above it to ground-truth locations outside the 50% error ellipse. Data points below the dashed line (slope = 1.82) in Figure 9 correspond to strokes with ground-truth locations enclosed by the 90% error ellipse (assumed to be nearly circular). It follows from Figure 9 that 87 (83%) of 105 strokes had ground-truth locations enclosed by the 50% error ellipse, which means that most location errors in 2004–2009 were lower than predicted by the 50% NLDN error ellipse. These results suggest that the 50% ellipse semimajor axis is a conservative estimate of the NLDN median location error, at least for negative subsequent strokes in north-central Florida. Further, all 105 strokes had ground-truth locations enclosed by the 90% error ellipse (assumed to be nearly circular). It is worth noting that the 11 events with the semimajor axis lengths >2 km (see Figure 9) actually have elongated (not nearly circular) error ellipses. However, a more detailed analysis shows that this does not change the conclusions drawn from the analysis based on nearly circular error ellipse assumption and presented above. Interestingly, the event with the largest 50% ellipse semimajor axis length

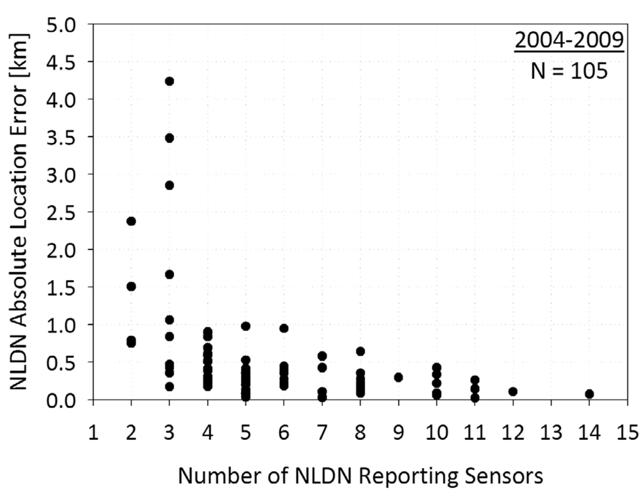


Figure 7. NLDN absolute location error versus the number of reporting NLDN sensors.

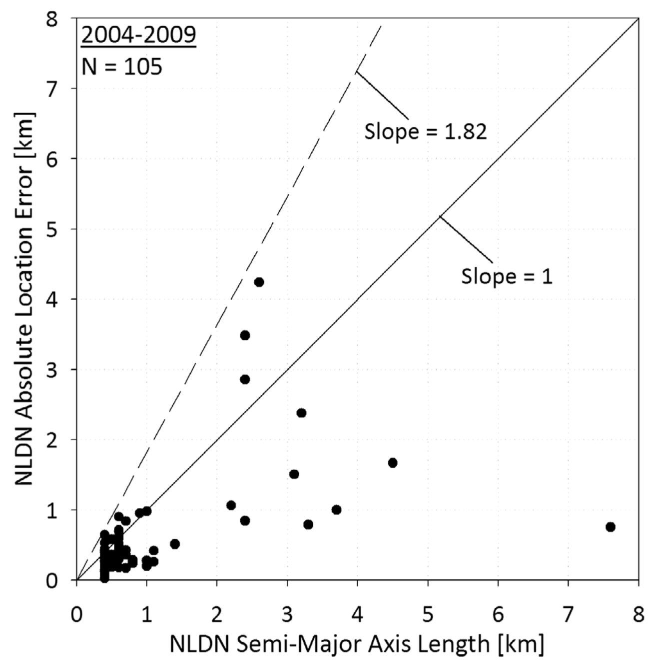


Figure 9. NLDN absolute location error plotted versus NLDN 50% error ellipse semimajor axis length. The slanted solid line (slope = 1) is the locus of points for which the NLDN 50% semimajor axis length and corresponding location error are equal. If the error ellipses are assumed to be nearly circular, then points below this line correspond to strokes with ground-truth locations enclosed by the 50% error ellipse and strokes above are outside the 50% error ellipse. Points below the dashed line (slope = 1.82) correspond to strokes with ground-truth locations enclosed by the 90% error ellipse (assumed to be nearly circular).

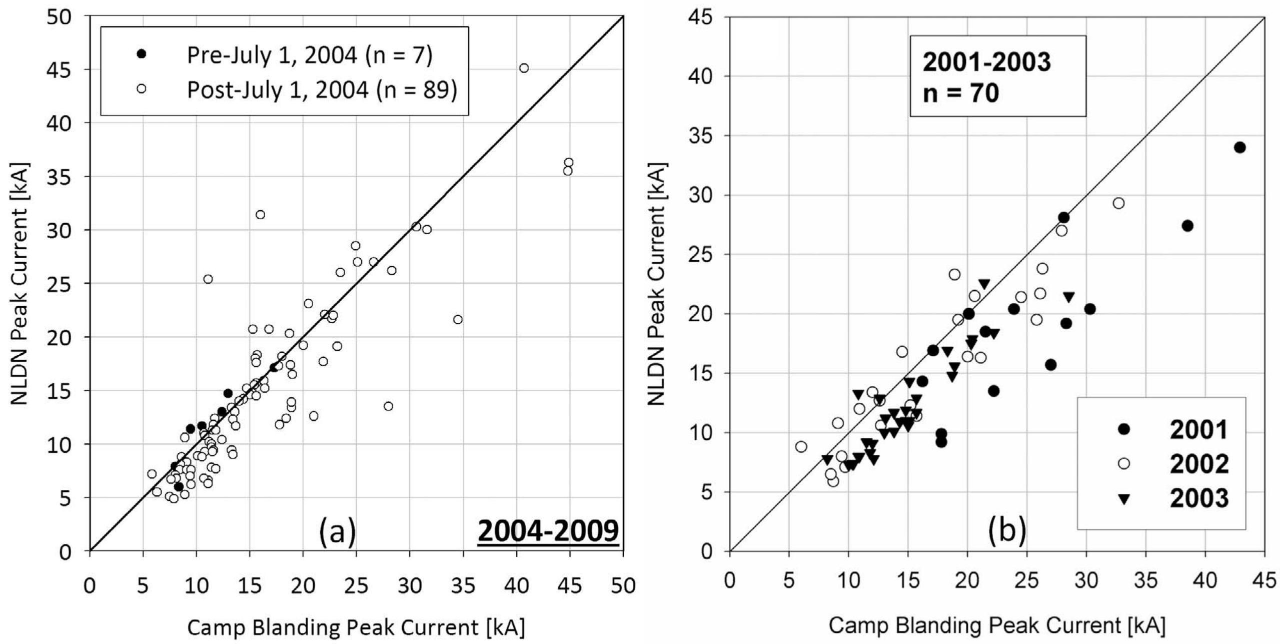
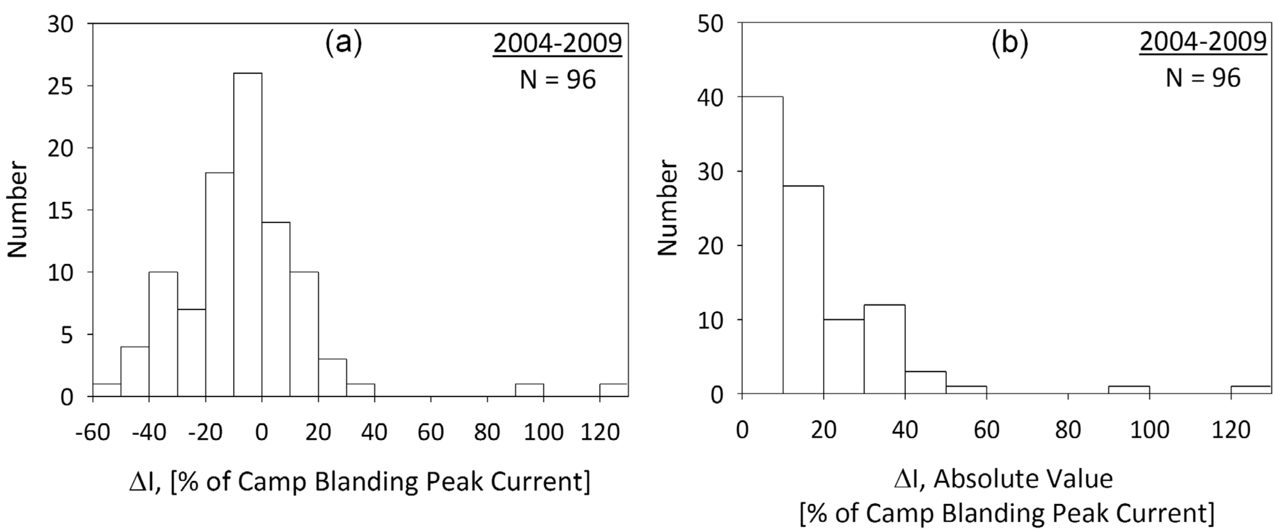


Figure 10. NLDN-reported peak current versus peak current directly measured at Camp Blanding for (a) 2004–2009 (present study) and (b) 2001–2003 [*Jerauld et al.*, 2005].



Testing Period	2004–2009	2001–2003 [*Jerauld et al.*, 2005]
AM	-6.4%	-15%
SD	25%	17%
Median	-6.1%	-18%
Min	-52%	~ -50%
Max	129%	~ 50%
N	96	70

Testing Period	2004–2009	2001–2003 [*Jerauld et al.*, 2005]
AM	17%	20%
SD	19%	11%
Median	13%	20%
Min	0%	0%
Max	129%	~ 50%
N	96	70

Figure 11. 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 $\Delta I = I_{NLDN} - I_{CB}$). Corresponding statistics for 2004–2009 (present study) and 2001–2003 [*Jerauld et al.*, 2005] are given below each histogram.

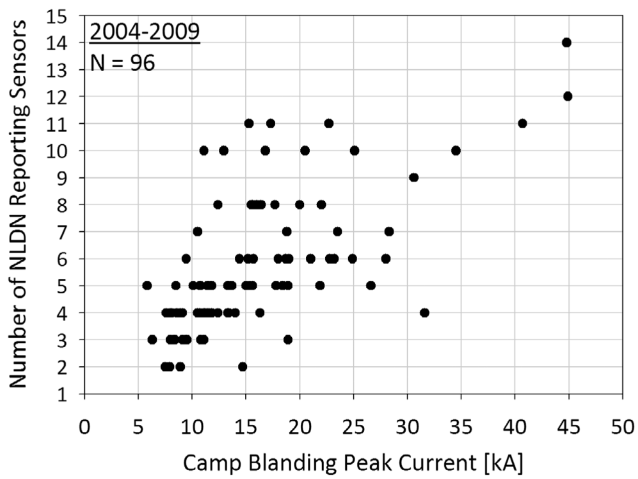


Figure 12. Number of reporting NLDN sensors versus Camp Blanding peak current for 96 strokes detected by the NLDN.

(7.6 km) had a relatively small absolute location error (753 m). This event was unremarkable in all other respects.

3.3. Peak Current Estimates

[16] The NLDN-estimated peak current versus peak current measured directly at Camp Blanding for 2004–2009 is plotted in Figure 10a. For all 96 strokes, the GM Camp Blanding peak current is 14 kA versus 13 kA for NLDN-estimated peak currents. In Figure 10a, the slanted solid line (slope = 1) is the locus of the points for which the NLDN peak currents and the Camp Blanding peak currents are equal. Of the 11 strokes in flashes triggered before 1 July 2004 (when the NLDN field propagation model was modified), 7 were detected by the NLDN, and of the 128 strokes in flashes triggered after that date, 89 were detected by the NLDN. For both time periods, there is a strong positive linear relationship between the NLDN-estimated and directly measured peak currents. The AM values of the ratio I_{CB}/I_{NLDN} are 1.0 and 1.1 for the data acquired prior to and after 1 July 2004, respectively. For all data combined, the AM ratio is 1.1. This is to be compared to the AM I_{CB}/I_{NLDN} ratio of 1.2 found for 2001–2003 by *Jerauld et al.* [2005] (see Figure 10b). The ratio >1 indicates that the NLDN tends to underestimate the peak current (by about 10% in 2004–2009 versus 20% in 2001–2003). One possible reason for the apparent improvement is the different NLDN field propagation model implemented on 1 July 2004.

[17] Figures 11a and 11b show the histograms for the signed and absolute values, respectively, of NLDN peak current estimation errors as a percentage of Camp Blanding peak current ($\Delta I\% = 100\Delta I/I_{CB}$, where $\Delta I = I_{NLDN} - I_{CB}$). The AM and median values of $\Delta I\%$ for 2004–2009 are −6.4% and −6.1%, respectively, which are considerably lower (in absolute value) than the corresponding values of −15% and −18% reported for 2001–2003 by *Jerauld et al.* [2005].

[18] For absolute value of $\Delta I\%$ (see Figure 11b), the AM and median values in the present study are 17% and 13%, respectively. *Jerauld et al.* [2005] reported both the AM and median absolute error to be 20% for 2001–2003. As shown in Figure 11b, the errors never exceeded 129% in absolute value (60% if two outliers are excluded) for 2004–2009 versus 50% for 2001–2003.

[19] The number of NLDN reporting sensors is plotted against Camp Blanding peak current for 96 strokes in Figure 12. As expected, strokes with higher peak currents tend to be detected by a larger number of NLDN sensors. The average number of reporting sensors for different peak current ranges is given in Table 2. For the 20–30 kA range, the average number of reporting sensors was seven.

4. Summary

[20] We evaluated the performance characteristics of the NLDN using as the ground-truth rocket-triggered lightning data acquired in 2004–2009 at Camp Blanding, Florida. The evaluation results are representative of the portion of the NLDN covering the Florida region (see Figure 1), whose performance characteristics are not expected to be superior to those of other parts of the network. A total of 37 negative flashes containing leader/return stroke sequences (strokes) were triggered at Camp Blanding during these years. The total number of strokes was 139. The NLDN recorded 105 Camp Blanding strokes in 34 flashes. The resulting flash and stroke detection efficiencies were 92% and 76%, respectively. The median absolute location error was 308 m, and the largest error was 4.2 km. The median absolute value of current estimation error was 13%. The current estimation errors never exceeded 129% in absolute value (60% if two outliers are excluded).

[21] The flash and stroke detection efficiencies found for 2004–2009 are higher than those reported for 2001–2003 by *Jerauld et al.* [2005]. The median location error and median absolute error in peak current estimates are both lower for 2004–2009 than for 2001–2003.

[22] Strokes in "classical" triggered flashes are similar to regular subsequent strokes (i.e., followed previously formed channels) in natural lightning, and hence the results presented here are applicable only to regular negative subsequent strokes in natural lightning. The flash detection efficiency reported here is expected to be an underestimate of the true value for natural negative lightning flashes, since first strokes typically have larger peak currents than subsequent ones.

Table 2. Average Number of Reporting NLDN Sensors for Different Peak Current Ranges

	Peak Current Range (kA)					
	5–10	10–20	20–30	30–40	40–50	5–50 (Entire Range)
Average number of reporting NLDN sensors	4	6	7	8	12	6
Sample size	20	57	13	3	3	96

[23] **Acknowledgments.** This research was supported in part by National Science Foundation grants ATM-0346164 and ATM-0852869 and by the Defense Advanced Research Projects Agency (DARPA).

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