

THE NLDN PERFORMANCE CHARACTERISTICS: AN UPDATE

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Abstract – The performance characteristics of the U.S. National Lightning Detection Network (NLDN) are evaluated by comparing stroke locations and return-stroke peak currents reported by the NLDN with the corresponding ground truth data for lightning triggered at Camp Blanding, Florida. The flash and stroke detection efficiencies are also estimated. In the previous study for 2004–2009, 37 flashes with 139 return strokes were triggered at Camp Blanding. The NLDN detected 34 flashes with 105 return strokes. The resultant flash detection efficiency was 92% and stroke detection efficiency was 76%. The median location error was 308 m and median absolute peak current estimation error was 13% (Nag et al., 2011). Sample size for evaluation of errors in peak current estimates was 96. In this paper, we carry out a similar evaluation using 89 strokes in 23 flashes triggered at Camp Blanding in 2010 and 2011. Sample size for evaluation of errors in peak current estimates was 56. In 2010–2011, the flash and stroke detection efficiencies were 100% and 72%, respectively. The median location error was 436 m and median absolute peak current estimation error was 15%.

1. INTRODUCTION

Since 1989, the U.S. Lightning Detection Network (NLDN) has been providing lightning data for the contiguous United States. Jerauld et al. (2005) and Nag et al. (2011) used rocket-triggered lightning data, acquired at Camp Blanding, Florida, to study the performance of the NLDN for the periods of 2001–2003 and 2004–2009, respectively.

In 2001–2003 (Jerauld et al., 2005), 37 flashes containing 159 return strokes were triggered at Camp Blanding. The resultant 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 resultant 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) reported an improvement in performance characteristics of the NLDN after its upgrade which was completed in 2004 (Cummins and Murphy, 2009).

The present study is similar to the previous studies of Jerauld et al. and Nag et al., but is based on rocket-triggered lightning data obtained at Camp Blanding in 2010–2011. It is thought that triggered-lightning strokes are similar to subsequent strokes in natural lightning (Rakov and Uman, 2003). Hence the results of this study are expected to be applicable to subsequent strokes in natural lightning.

2. DATA AND METHODOLOGY

In 2010–2011, a total of 61 rockets were launched at Camp Blanding. This resulted in 23 flashes with 89 leader/return stroke sequences. Table 1 gives the summary of flashes and strokes recorded at Camp Blanding. One stroke in 2010 was misidentified by the NLDN as a cloud discharge.

Two rocket launchers (a tower launcher and a ground launcher) were used in 2010–2011 and the positions of the launchers are known within a few meters. The channel-base current was measured by resistive shunts with a bandwidth of 0 to at least 3 MHz. Fiber optic links were used to transmit the signals from the measurement stations to 8-bit and 12-bit digitizing oscilloscopes. The 12-bit oscilloscope sampled at 10 MHz (signals were –3 dB low-pass filtered at 3 MHz) and the 8-bit oscilloscope sampled at 250 MHz (signals were –3 dB low-pass filtered at 20 MHz). Wherever possible, peak currents were measured in the 8-bit oscilloscope records, which have a higher

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Table 1. Summary of flashes triggered at the Camp Blanding in 2001–2011.

Year	Number of Flashes Triggered	Number of NLDN Detected Flashes	NLDN Flash Detection Efficiency (%)	Number of Strokes	Number of NLDN Detected Strokes	NLDN Stroke Detection Efficiency (%)
2010	12	12	100	51	41	80
2011	11	11	100	38	23	61
2010–2011	23	23	100	89	64	72
2004–2009 (Nag et al., 2011)	37	34	92	139	105	76
2001–2003 (Jerauld et al., 2005)	37	31	84	159	95	60

sampling rate. Otherwise, peak currents were measured in 12-bit oscilloscope records. 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 detection efficiency, (b) stroke detection efficiency, (c) stroke location errors, and (d) errors in peak current estimates. For a given stroke, the distance between the location of launcher (used as ground-truth) and the location reported by the NLDN is defined as location error. The errors in NLDN-reported peak currents were computed using the equation $\Delta I = I_{NLDN} - I_{CB}$. Here I_{NLDN} is the NLDN-reported peak current and I_{CB} is the peak value of return-stroke current waveform directly measured at Camp Blanding.

Of the 89 strokes in 23 flashes for 2010–2011, directly measured currents were available for 79 strokes in 21 flashes. Figure 1a shows the peak current histogram for all strokes recorded during 2010–2011 (includes strokes both detected and not detected by the NLDN). The geometric mean (GM) and median peak currents are 10.6 kA and 10.8 kA, respectively. The minimum and maximum peak currents are 2.0 kA and 43.1 kA, respectively. Similar histograms for 2004–2009 and 2001–2003 are shown in Figures 1b and c, respectively.

3. RESULTS AND DISCUSSIONS

3.1. Flash and Stroke Detection Efficiencies

Flash and stroke detection efficiencies of the NLDN are given in Table 1. For 2010–2011, the flash detection efficiency is 100% versus 92% and 84% for 2004–2009 and 2001–2003, respectively. The stroke

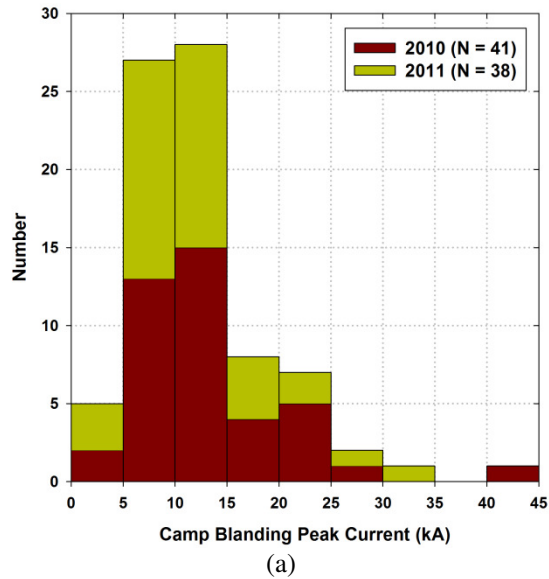
detection efficiency is 72% for 2010–2011 versus 76% and 60% for 2004–2009 and 2001–2003, respectively. It is worth noting that one stroke from 2010 was misclassified by the NLDN as a cloud discharge. All other strokes in 2010–2011 were correctly classified as cloud-to-ground discharge by the NLDN.

From Table 1, one can see that the stroke detection efficiency is 80% for 2010 but 61% for 2011. From Figure 1, one can see that the distributions of return-stroke peak current are similar for all three time periods (except for a more abrupt decrease in the number of events at 15 kA or so for 2010–2011).

Figure 2 shows the NLDN stroke detection efficiency as a function of peak current measured at Camp Blanding for (a) 2010, (b) 2011, (c) 2010–2011, (d) 2004–2009 (Nag et al., 2011), and (e) 2001–2003 (Jerauld et al., 2005). The total number of NLDN-reported strokes for the period of 2010–2011, for which peak currents were measured at Camp Blanding, is 56. For 2010–2011, the stroke detection efficiency is 100% for peak currents above 15 kA and decreases to 48% for strokes in the 5 to 10 kA range. None of the five strokes with peak currents less than or equal to 5 kA was detected by the NLDN. For 2004–2009, the stroke detection efficiency was 100% for peak currents above 20 kA and for 2001–2003, the stroke detection efficiency was 100% for peak currents above 30 kA. Similar to 2010–2011, none of the strokes with peak current less than 5 kA was detected by the NLDN in 2001–2009.

3.2. Location Accuracy

Figures 3a and b show spatial distribution of locations for the 64 NLDN-detected strokes in 23 flashes triggered at Camp Blanding in 2010–2011. The origin (marked X at the center of the plots in Figure 3)



	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
AM (kA)	13.2	11.7	12.5	14	15
SD (kA)	7.7	6.6	7.2	7.9	7.4
GM (kA)	11.4	10.2	10.8	12	13
Median (kA)	11.7	10.3	10.6	12	~ 13
SD(log ₁₀ I)	0.24	0.24	0.24	0.23	0.2
Min (kA)	3.7	2.0	2.0	2.9	2.9
Max (kA)	43.1	32.8	43.1	45	43
N	41	38	79	122	122

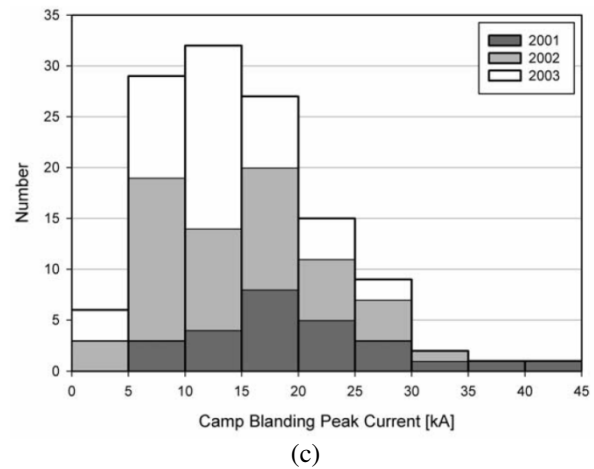
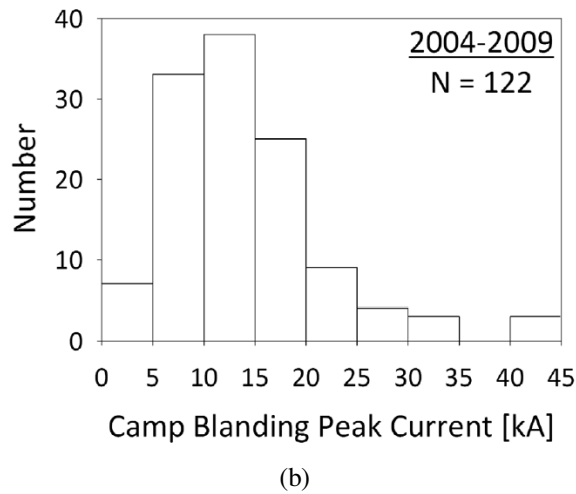
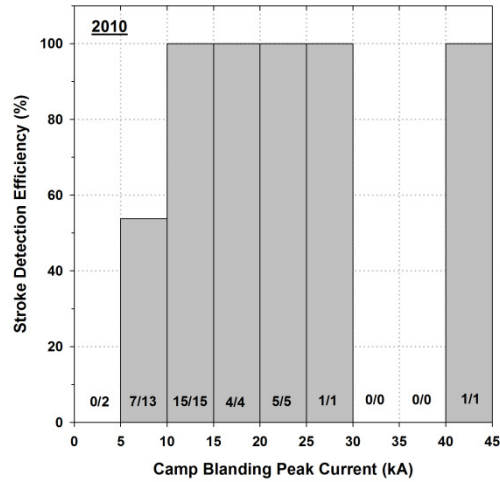
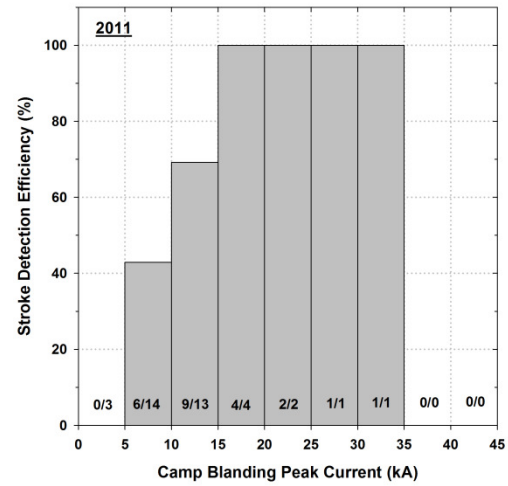


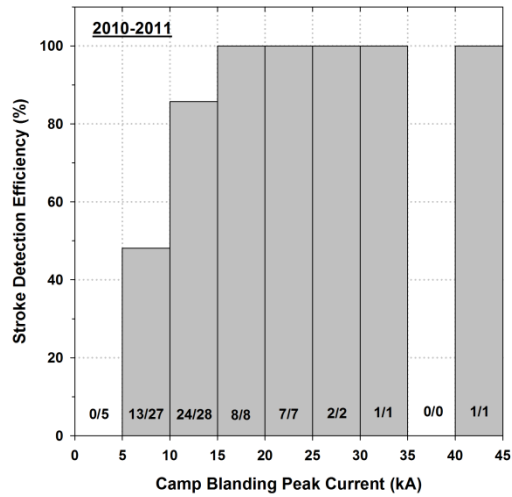
Figure 1. Histograms of Camp Blanding return-stroke peak currents, I , for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005). Statistics given are the arithmetic mean (AM), standard deviation (SD), geometric mean (GM), median, standard deviation of the \log_{10} of the parameter ($SD(\log_{10}I)$), minimum value (Min), and maximum value (Max).



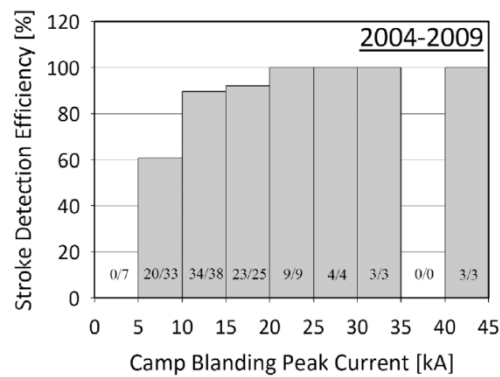
(a)



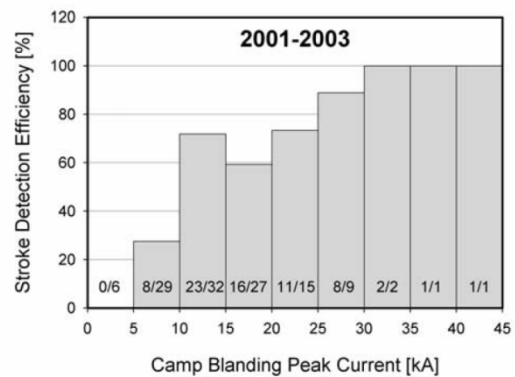
(b)



(c)



(d)



(e)

Figure 2. NLDN stroke detection efficiency as a function of peak current measured at Camp Blanding for (a) 2010, (b) 2011, (c) 2010–2011, (d) 2004–2009 (Nag et al., 2011), and (e) 2001–2003 (Jerauld et al., 2005). 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.

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 are -47 m and -100 m, respectively, while the AM and median east-west location errors are -209 m and -305 m, respectively. Similar plots for 2004–2009 and 2001–2003 are shown in Figures 3c and d, respectively.

To study the effect of launching facility (two launchers were used in 2010–2011; ground launcher for 18 flashes with 42 strokes and tower launcher for 5 flashes with 22 strokes), the spatial distribution of locations for NLDN-detected strokes from 2010–2011 is plotted in Figure 4 using different plot symbols for different launchers. It does not appear that the launching facility influences stroke location errors.

Figure 5a shows the histogram of NLDN absolute stroke location errors for the 64 strokes from 2010–2011. The median absolute location error is 436 m, with the largest error being 3.5 km. Similar histograms for 2004–2009 and 2001–2003 are shown in Figures 5b and 5c, respectively. Nag et al. (2011) had reported a median absolute location error of 308 m and a maximum of 4.2 km for 2004–2009. Jerauld et al. (2005) had reported a median absolute location error of 600 m and a maximum of 11 km for 2001–2003. The median absolute location error for 2010–2011 is higher than that reported for 2004–2009, but lower than that reported for 2001–2003.

Figure 6 shows the NLDN absolute location error plotted versus the peak current measured at Camp Blanding. Eight out of nine cases with location errors greater than 1 km correspond to strokes with peak currents less than 15 kA, and one corresponds to a peak current of 28.3 kA. The largest location error occurred for a stroke having peak current of 12.1 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 location error tends to decrease as the number of reporting sensors increases, which is expected.

3.3. Peak Current Estimates

Figure 8 shows scatter plots of the NLDN-estimated peak current versus peak current measured directly at Camp Blanding. For all 56 NLDN-reported strokes with directly measured currents from 2010–2011, the GM of Camp Blanding peak current is 13.4 kA versus 12.5 kA for NLDN-estimated peak currents. In Figure 8, 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. The AM value of the ratio I_{CB}/I_{NLDN} is 1.1. The AM of I_{CB}/I_{NLDN} ratio was 1.1 for 2004–2009 (Nag et al., 2011) and that for 2001–2003 was 1.2 (Jerauld et al., 2005). A greater than 1 ratio indicates that the NLDN tends to underestimate the peak current (by about 10% on average in 2010–2011).

Figure 9 shows histograms for the signed value 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 2010–2011 are -5.6% and -3.9% , respectively. Figure 10 shows histograms for the unsigned value of NLDN peak current estimation errors as a percentage of Camp Blanding peak current. For absolute value of $\Delta I\%$, the AM and median values for 2010–2011 are 14.5% and 15.1% , respectively. The maximum current estimation error is 41% versus 129% for 2004–2009 and 50% for 2001–2003.

The number of NLDN reporting sensors is plotted against Camp Blanding peak current for 96 strokes in Figure 11. As expected, strokes with higher peak currents tend to be detected by a larger number of NLDN sensors.

4. SUMMARY

The NLDN performance characteristics based on triggered-lightning data acquired at Camp Blanding in 2010–2011 are as follows.

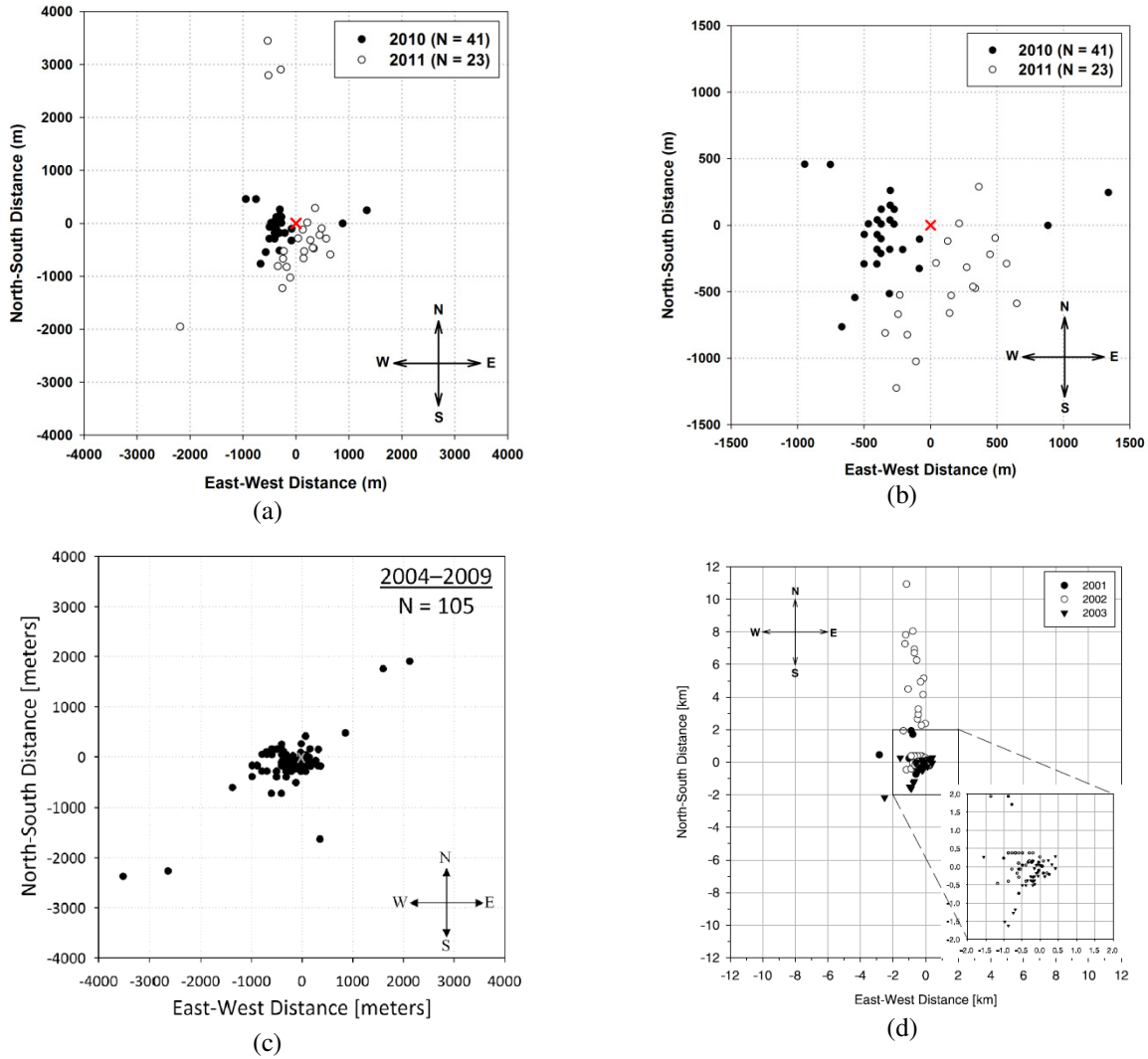
1. Flash detection efficiency is 100%.
2. Stroke detection efficiency is 72%.
3. Median location error is 436 m.
4. Median value of absolute peak current estimation error is 15%.

Acknowledgments:

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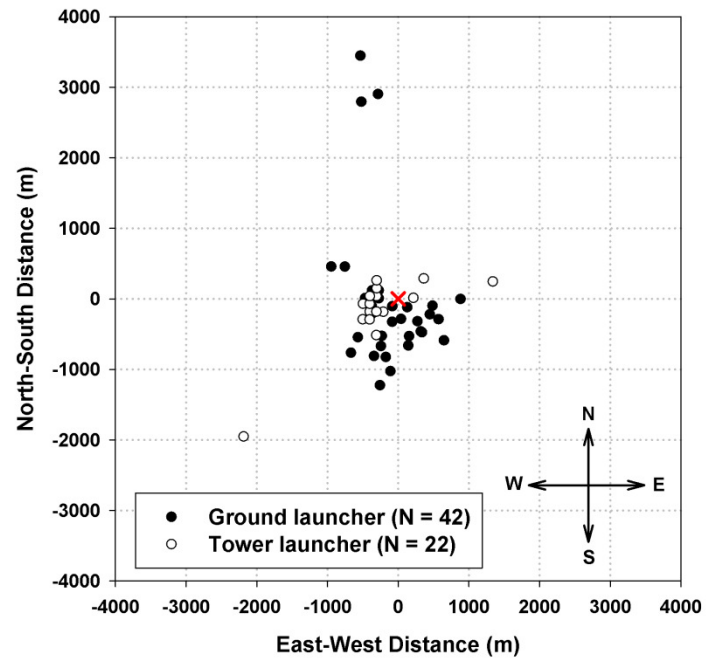
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- Cummins, K. L., and Murphy, M. J., 2009: An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the U.S. NLDN. *IEEE Trans. Electromagn. Compat.*, 51(3), 499–518.
- Jerauld, J., Rakov, V. A., Uman, M. A., Rambo, K. J., Jordan, D. M., Cummins, K. L., and Cramer, J. A., 2005: An Evaluation of the Performance of the U.S. National Lightning Detection Network in Florida using Rocket-Triggered Lightning. *J. Geophys. Res.*, 110(D19106).

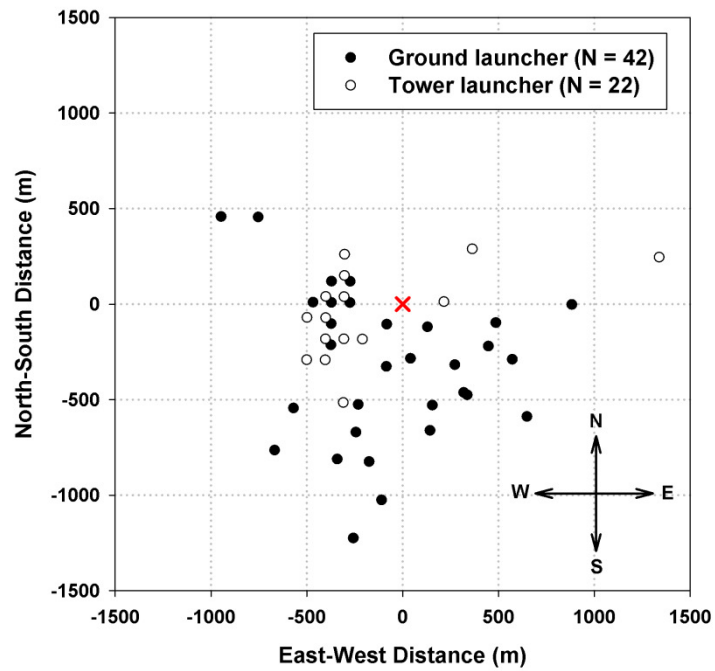


	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
N-S AM (m)	-34	-71	-47	-133	860
N-S SD (m)	246	1320	805	472	2340
N-S Median (m)	9	-462	-100	-84	60
E-W AM (m)	-308	-33	-209	-237	-460
E-W SD (m)	362	582	468	586	520
E-W Median (m)	-371	129	-305	-211	-400
N	41	23	64	105	95

Figure 3. (a) 4 km \times 4 km plot of NLDN-reported stroke locations for 64 strokes in 23 flashes triggered during 2010–2011 at Camp Blanding; (b) same as (a), but for 1.5 km \times 1.5 km; (c) same as (a) but for 2008–2009 (Nag et al., 2011); (d) 12 km \times 12 km plot of NLDN-reported stroke locations for 2001–2003 (Jerauld et al., 2005). 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), standard deviation (SD), and median, for each location error component.

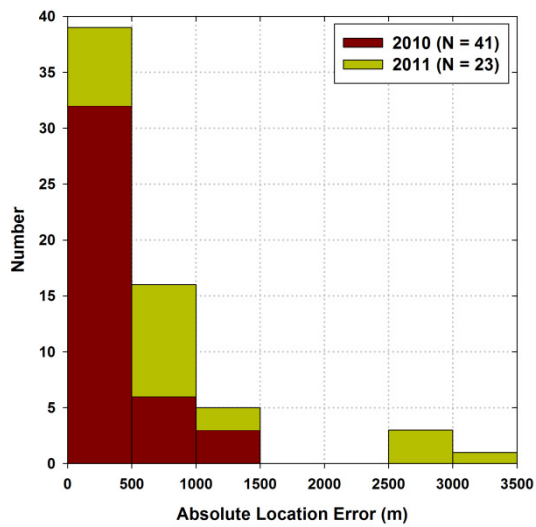


(a)



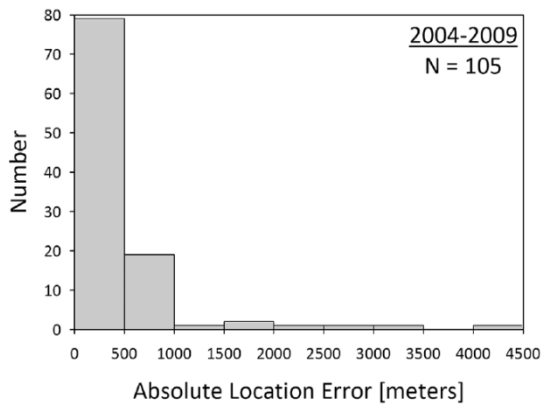
(b)

Figure 4. (a) 4 km \times 4 km plot of NLDN-reported stroke locations for 64 strokes in 23 flashes triggered during 2010–2011 at Camp Blanding with different plot symbols used for different launchers. (b) same as (a), but for 1.5 km \times 1.5 km.

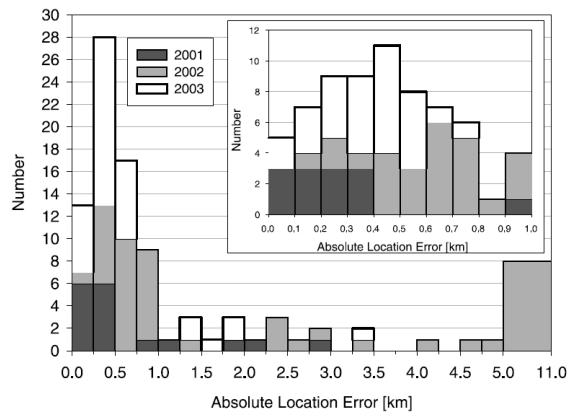


(a)

	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
AM (m)	474	1040	677	489	1470
SD (m)	245	979	669	632	2130
GM (m)	430	746	524	321	680
Median (m)	390	641	436	308	600
Min (m)	134	176	134	23	40
Max (m)	1360	3488	3488	4239	11000
N	41	23	64	105	95

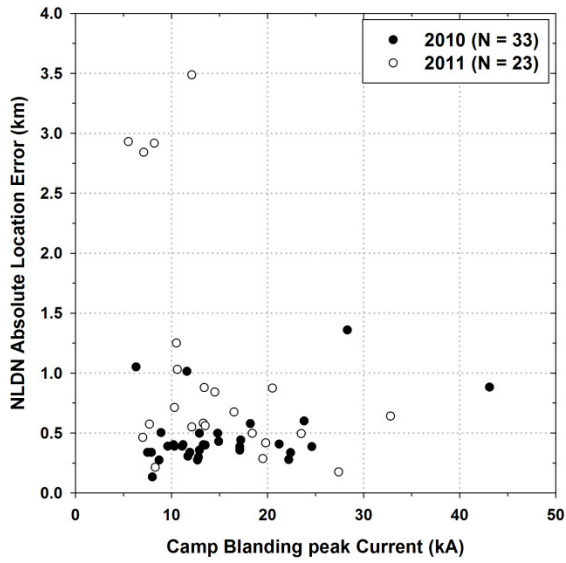


(b)

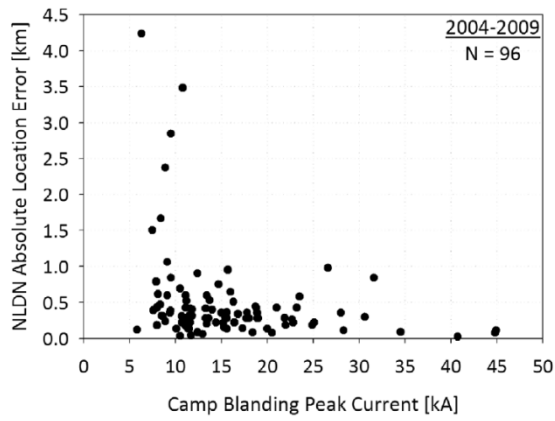


(c)

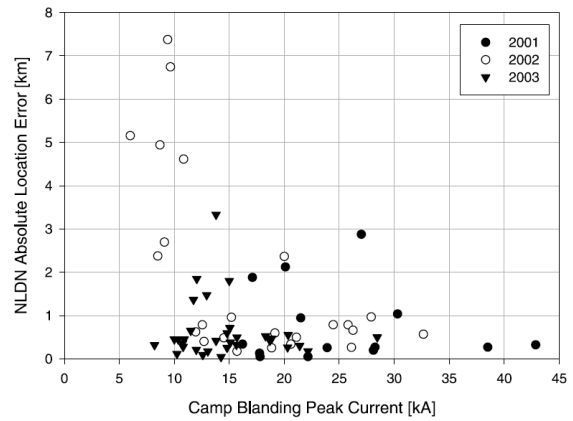
Figure 5. Histograms of the NLDN absolute location errors for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005). Statistics given are the arithmetic mean (AM), standard deviation (SD), geometric mean (GM), median, minimum value (Min), and maximum value (Max) for 2010–2011.



(a)

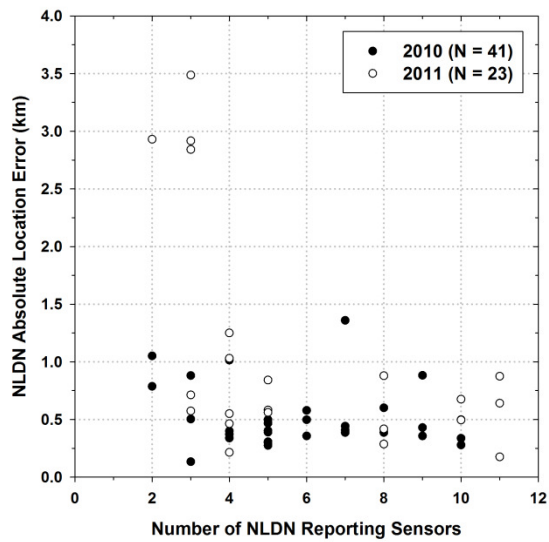


(b)

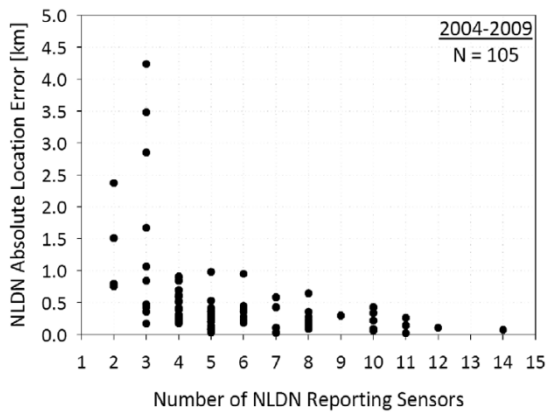


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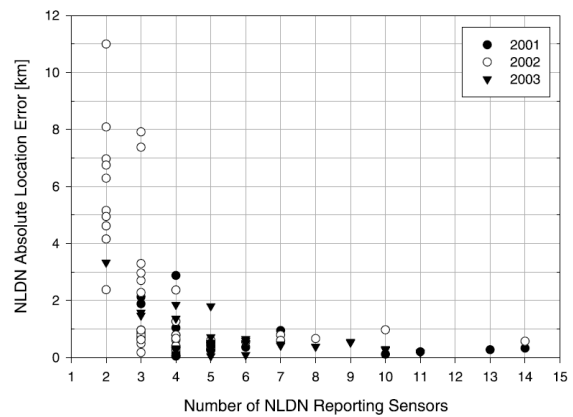
Figure 6. NLDN absolute location error versus Camp Blanding peak current for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005).



(a)

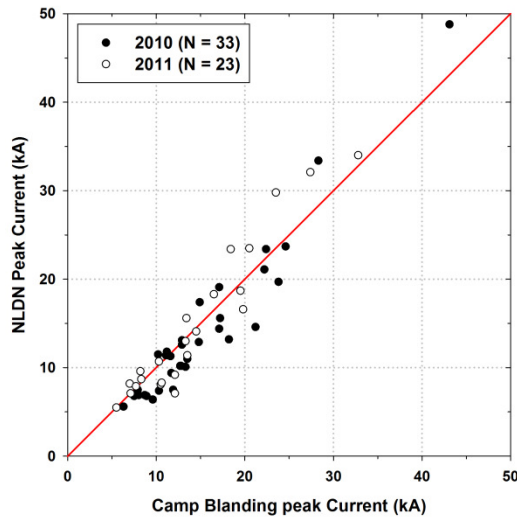


(b)



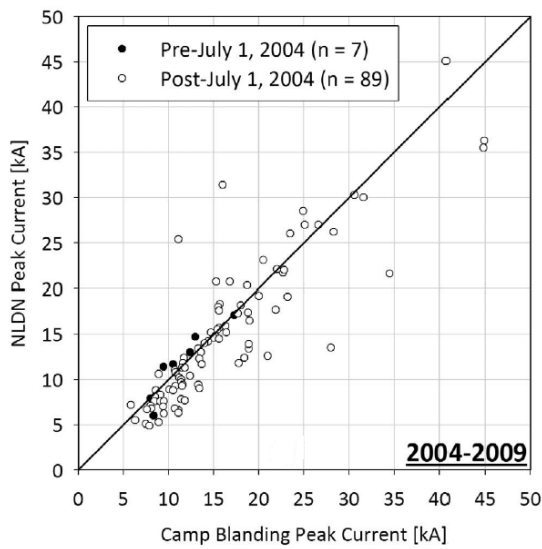
(c)

Figure 7. NLDN absolute location error versus the number of reporting NLDN sensors for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005).

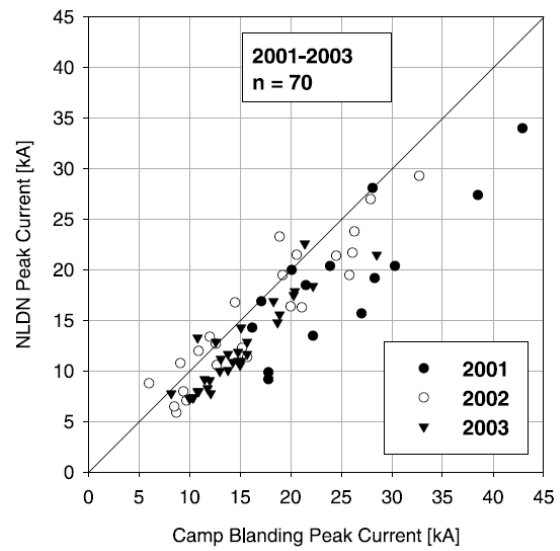


(a)

	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
GM of Camp Blanding peak current (kA)	13.7	13.0	13.4	14	16.2
GM of NLDN peak current (kA)	12.2	12.9	12.5	13	13.5
AM of I_{CB}/I_{NLDN}	1.1	1.0	1.1	1.1	1.2
N	33	23	56	96	70

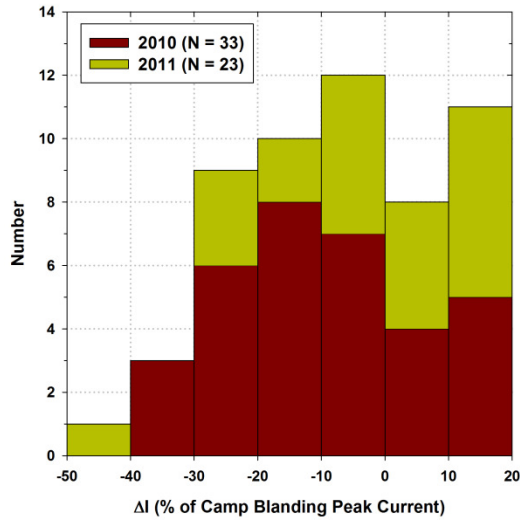


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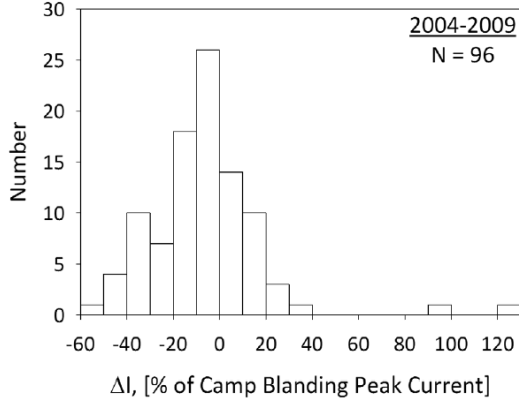
(c)

Figure 8. NLDN-reported peak current versus peak current directly measured at Camp Blanding for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005).

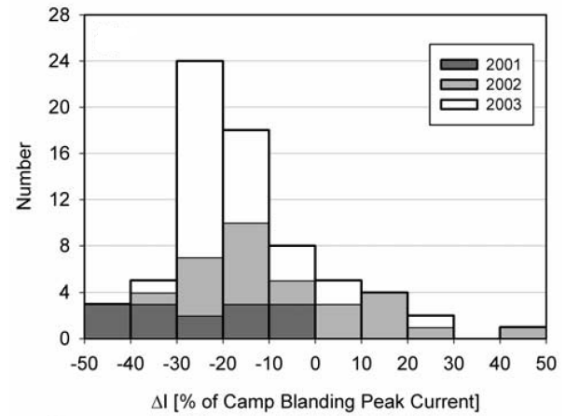


(a)

	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
AM (%)	-9.8	0.5	-5.6	-6.4	-15
SD (%)	15.1	17.6	16.8	25	17
Median (%)	-11.1	2.6	-3.9	-6.1	-18
Min (%)	-37.0	-41.3	-41.3	-52	~ -50
Max (%)	18.0	27.2	27.2	129	~ 50
N	33	23	56	96	70

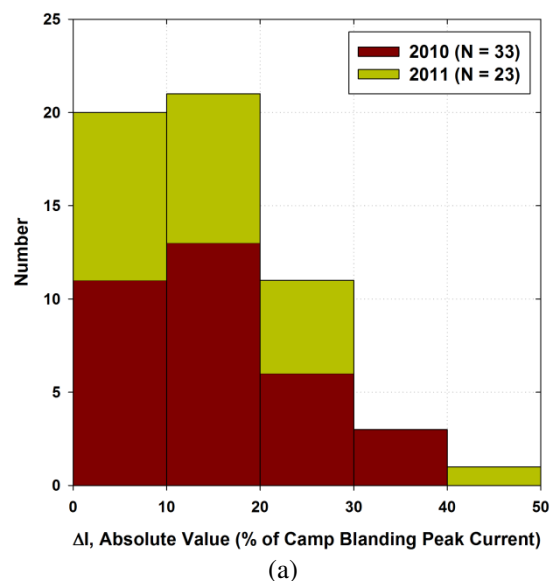


(b)



(c)

Figure 9. Histograms of signed 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 (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005). Statistics given are the arithmetic mean (AM), standard deviation (SD), median, minimum value (Min), and maximum value (Max).



	2010	2011	2010–2011	2004–2009 (Nag et al., 2011)	2001–2003 (Jerauld et al., 2005)
AM (%)	15.1	13.6	14.5	17	20
SD (%)	9.7	10.8	10.1	19	11
Median (%)	13.8	15.6	15.1	13	20
Min (%)	1.6	0	0	0	0
Max (%)	37.0	41.3	41.3	129	~ 50
N	33	23	56	96	70

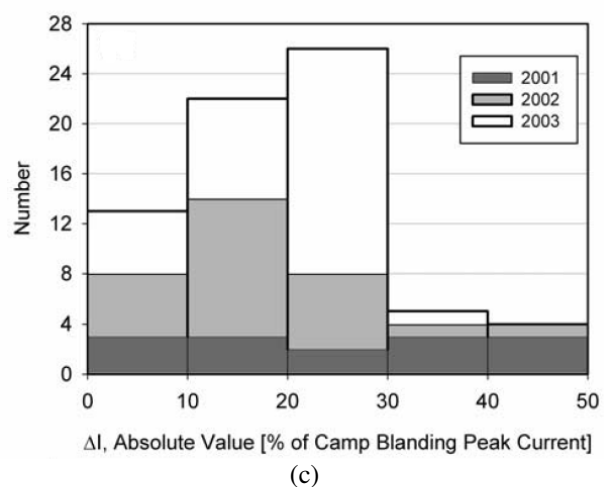
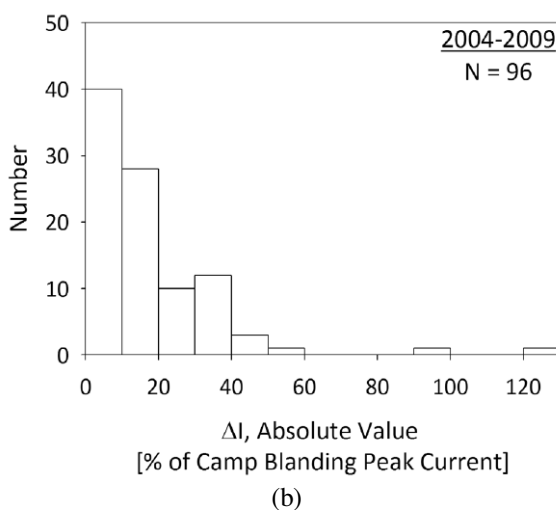


Figure 10. Histograms of unsigned NLDN peak current estimation errors, given as a percentage of the directly measured Camp Blanding current ($\Delta I\% = 100\Delta I/I_{CB}$, where $\Delta I = I_{NLDN} - I_{CB}$) for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005). Statistics given are the arithmetic mean (AM), standard deviation (SD), median, minimum value (Min), and maximum value (Max).

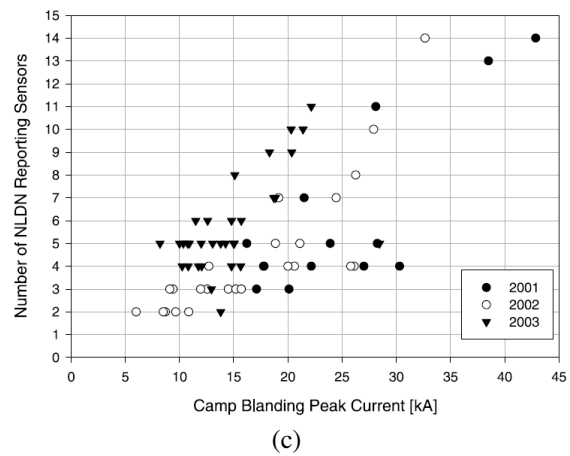
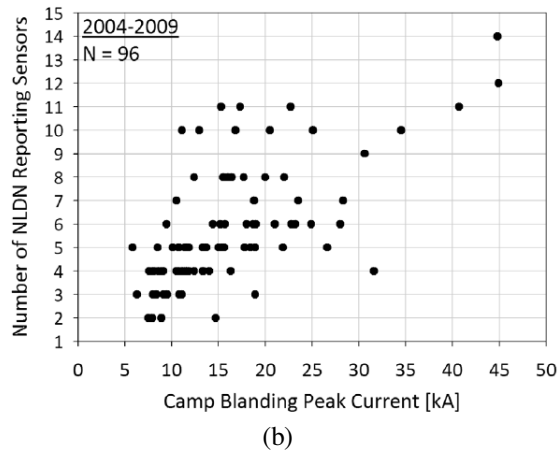
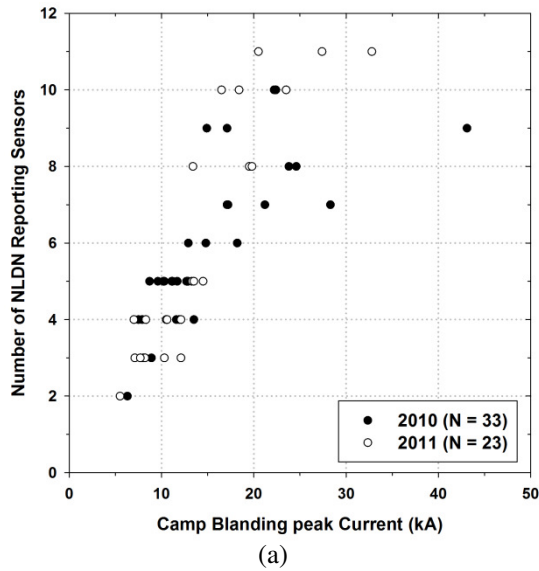


Figure 11. Number of reporting NLDN sensors versus Camp Blanding peak current for (a) 2010–2011, (b) 2004–2009 (Nag et al., 2011), and (c) 2001–2003 (Jerauld et al., 2005).

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