2014
23rd International Lightning Detection Conference
18 - 19 March • Tucson, Arizona, USA
5th International Lightning Meteorology Conference
20 - 21 March • Tucson, Arizona, USA

EVALUATION OF THE PERFORMANCE CHARACTERISTICS OF THE CGLSS AND NLDN SYSTEMS BASED ON TWO YEARS OF GROUND-TRUTH DATA FROM LAUNCH COMPLEX 39B, KENNEDY SPACE CENTER, FLORIDA

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***Abstract*— From May 2011 through July 2013, the lightning instrumentation at Launch Complex 39B (LC39B) at the Kennedy Space Center, Florida, has obtained high-speed video records and field change waveforms (dE/dt and three-axis dH/dt) for 54 negative polarity return strokes whose strike termination locations and times are known with accuracy of the order of 10 m or less and 1 µs, respectively. A total of 18 strokes terminated directly to the LC39B lighting protection system (LPS), which contains three 181 m towers in a triangular configuration, an overhead catenary wire system on insulating masts, and nine down conductors. An additional 9 strokes terminated on the 106 m lightning protection mast of Launch Complex 39A (LC39A), which is located about 2.7 km southeast of LC39B. The remaining 27 return strokes struck either on the ground or attached to low-elevation grounded objects within about 500 m of the LC39B LPS. Leader/return stroke sequences were imaged at 3200 frames/sec by a network of six Phantom V310 high-speed video cameras. Each of the three towers on LC39B had two high-speed cameras installed at the 147 m level with overlapping fields of view of the center of the pad. The locations of the strike points of 54 return strokes have been compared to time-correlated reports of the Cloud-to-Ground Lightning Surveillance System (CGLSS) and the National Lightning Detection Network (NLDN), and the results of this comparison will be presented and discussed.**

I. INTRODUCTION

The lightning electromagnetic environment at the Kennedy Space Center in Florida is continuously monitored by the Cloud-to-Ground Lightning Surveillance System (CGLSS), the National Lightning Detection Network (NLDN) and the Launch Complex 39B (LC39B) lightning instrumentation system. The CGLSS and NLDN systems both utilize long-baseline sensor networks to detect transient lightning events (primarily cloud-to-ground return strokes) at multiple geographic locations. For each qualified event, the systems determine the best estimate for the ground strike location, the time of the flash with microsecond accuracy, and the overall peak current of the flash. Thorough reviews of the history and operation of the CGLSS system are given by *Ward et al*. [2008] and *Merceret et al*. [2010]. Similar reviews of the NLDN system are provided by *Cummins et al*. [1998] and *Cummins and Murphy* [2009].

The location accuracy of the NLDN system has been previously characterized using rocket-and-wire triggered lightning data obtained at the International Center for Lightning Research and Testing (ICLRT) located on the Camp Blanding National Guard base in north-central Florida. In classical triggered lightning, the strike point is controlled and the current is directly measured at the channel base. *Nag et al.* [2012] performed a comparative analysis on a dataset of 37 flashes triggered at the ICLRT between 2004-2009 containing a total of 139 return strokes. They found that the NLDN reported 34 of the 37 flashes and 105 of the 139 return strokes, flash and stroke detection efficiencies of 92% and 76%, respectively. The median NLDN strike location error was 308 m. *Mallick et al.* [2014] recently conducted a similar study on a total of 78 flashes triggered at the ICLRT from 2004-2012 containing 326 return strokes, a subset of which was analyzed by *Nag et al.* [2012]. The authors reported NLDN flash and stroke detection efficiencies of 94% and 75% respectively, with median strike location error of 334 m. Note that both studies pertain strictly to triggered lightning return strokes, which are similar to natural lightning subsequent strokes [e.g., *Rakov and Uman,* 2003].

The LC39B lightning instrumentation system became fully operational in 2011. The system was designed to monitor the lightning activity within and immediately outside the LC39B pad perimeter with 100% flash and stroke detection efficiency. The LC39B lightning protection system (LPS) consists of three 181 m tall towers in a triangular orientation. The fiberglass masts atop each of the three towers support a catenary wire system that includes a total of nine down conductors. Direct and induced lightning currents are measured at each down conductor location. The peripheral sensor network includes 10 electric field derivative (dE/dt) sensors and 12 magnetic field derivative (dH/dt) sensors. In addition, two Phantom V310 high-speed cameras are located at the 147 m level of each of three towers. The cameras monitor lightning activity directly incident on the LPS as well as nearby discharges striking within and outside the pad perimeter. The data acquisition systems and high-speed cameras are triggered to record when pre-defined thresholds are exceeded on any current or field measurement sensor. The measurement triggered thresholds can be adjusted to extend the geographical range of the instrumentation system. All measurement systems are synchronized to IRIG-B timing. A detailed description of the LC39B lightning instrumentation system is given by *Mata et al.* [2010].

The LC39B high-speed camera network provides a unique capability for visually determining the strike point locations of natural cloud-to-ground lightning discharges with meter-level accuracy. Factors that contribute to the system's ability to image lightning strike points include, 1) location in immediate proximity to the highly elevated, well-grounded LC39B LPS, which is struck directly multiple times per calendar year, 2) elevated vantage points that provides unobstructed, multi-angle views of lightning strike points directly to ground or low-altitude grounded structures, and 3) location in an area with high ground strike density of typically 12-18 flashes/km^2/year. These combined attributes have allowed the system to image the strike point locations of 54 negative polarity cloud-to-ground return strokes between May 2011 and July 2013 with accuracy of 10 m or better. In this paper, such are events are considered to be ground truth.

In this paper, the ground truth strike point locations of 54 return strokes are compared directly with those reported for the same cloud-to-ground events by the CGLSS and NLDN systems. The location accuracies of the CGLSS and NLDN systems are evaluated by performing independent statistical analyses for all recorded strokes, first return strokes, subsequent return strokes, strokes attaching directly to the LC39B LPS, and strokes attaching directly to ground or low-altitude ground based structures. Similar analyses were conducted by *Mata et al.* [2012] on an 18 stroke subset of the dataset presented herein. The earlier analyses focused strictly on strokes that attached to the LPS.

II. DATA AND DETECTION EFFICIENCY ANALYSES

Summary statistics for the recorded data are given in Table 1. The 54 ground truth return stroke strike locations recorded by the LC39B system were contained in 18 separate flashes. The dataset includes 21 first strokes (those preceded by stepped leaders) and 33 subsequent strokes (those preceded by dart or dart-stepped leaders). In this paper, observations of a given flash are restricted by the operating sensitivity of the data acquisition system and the fields of view of the high-speed cameras. In some cases, reported flashes contained additional strokes and ground termination points occurring multiple kilometers from LC39B that were undetected as a result of the operating sensitivity of the system during those strokes. In other instances, video evidence shows clearly that a stroke terminated inside the LC39B perimeter, but the exact strike point termination (within the 10 m ground truth accuracy metric establish in this paper) is out of the field of view the cameras. In four cases, flashes with two separate ground termination points were recorded. Both new termination points were considered independent first strokes. Return strokes were classified as first or subsequent based primarily on dE/dt data with supporting evidence from high-speed video recordings. The dE/dt waveforms unambiguously show the characteristics of the preceding leader field changes and allow for accurate leader classification.

Of the 54 total strokes, 18 attached directly to the LC39B LPS. A total of 10 strokes attached to air terminal atop Tower 1, another four struck Tower 2, and two struck Tower 3. An additional two strokes attached directly to the down conductors. During the summer of 2012, the LC39B lightning instrumentation was re-configured to trigger on direct lightning attachments to the LC39A LPS, which consists of a 106 m single mast and two down conductors. A total of nine strokes attached directly to the top of the LC39A LPS during one flash in July 2012. The 27 strokes that attached to the LC39B and LC39A LPS's contained 11 first strokes and 16 subsequent strokes.

A total of 27 return strokes attached to the ground or low-altitude ground based structures within (11 strokes) or immediately outside (16 strokes) the LC39B pad perimeter. The 11 strokes that terminated within the pad perimeter all struck outside the LPS. Five of the 11 strokes terminated directly on facility light poles that ring the pad perimeter. The remaining six strokes terminated directly on the ground. The 16 strokes that terminated outside the LC39B perimeter all struck the ground directly.

An aerial image of the LC39B area is shown in Figure 1. The LC39B, NLDN, and CGLSS strike locations for the 54 return stroke dataset are plotted according to the key. For the

TABLE 1. SUMMARY STATISTICS FOR GROUND TRUTH LC39B FLASHES RECORDED BY NLDN AND CGLSS.

	Flashes	Strokes	First Strokes	Subsequent Strokes	Strokes Attaching to LPS	Strokes Attaching to Ground
LC39B	18	54	21	33	27	27
NLDN	18 (100%)	51 (94.4%)	21 (100%)	30 (90.9%)	24 (88.9%)	27 (100%)
CGLSS	15 (83.3%)	45 (83.3%)	16 (76.2%)	29 (87.9%)	21 (77.8%)	24 (88.9%)

18 flashes recorded by the LC39B lightning instrumentation system, the NLDN and CGLSS systems reported 18 (100%) and 15 (83.3%) flashes, respectively. The three flashes not reported by CGLSS were unique in that they each contained two ground termination points in short time succession (about 1 μs, 1.7 ms, and 7 μs, respectively for the three cases). The first case occurred at 18:25:47.633965 (UTC) on May 27, 2011. The first attachment was to Tower 2 with a second ground attachment occurring about 1 μs later east of LC39B. NLDN reported the flash, though it is unclear what ground termination point the data reference as a result of the very short time duration between the two attachments. The error of the NLDN location relative to the ground truth strike to Tower 2 was 1493 m, nearly all of which was in the easterly direction. The location error of the NLDN relative to the second ground termination, which occurred east of Tower 2 by about 500 m, is of the order of 1000 m. The second case occurred on July 26, 2011 at 19:27:48.520112 (UTC). The LC39B system detected a strike that terminated to the ocean about 1.3 km northeast of the pad center (not ground truth located), followed by a second ground termination that occurred about 802 m northwest of the pad center (about 300 m outside the pad perimeter). NLDN produced location estimates for both ground terminations. The location error for the second termination relative to LC39B ground truth data was 898 m. The third and final case occurred on July 19, 2012 at 23:08:21.757081 (UTC). The LC39B system detected a stroke that terminated inside the pad perimeter (the exact strike location was outside the video field of view) followed 7 μs later by a direct attachment to Down Conductor 4 on the northeast side of the pad. NLDN reported a single strike location estimate, which was located about 429 m NNW of the LC39B ground truth location for the strike to Down Conductor 4.

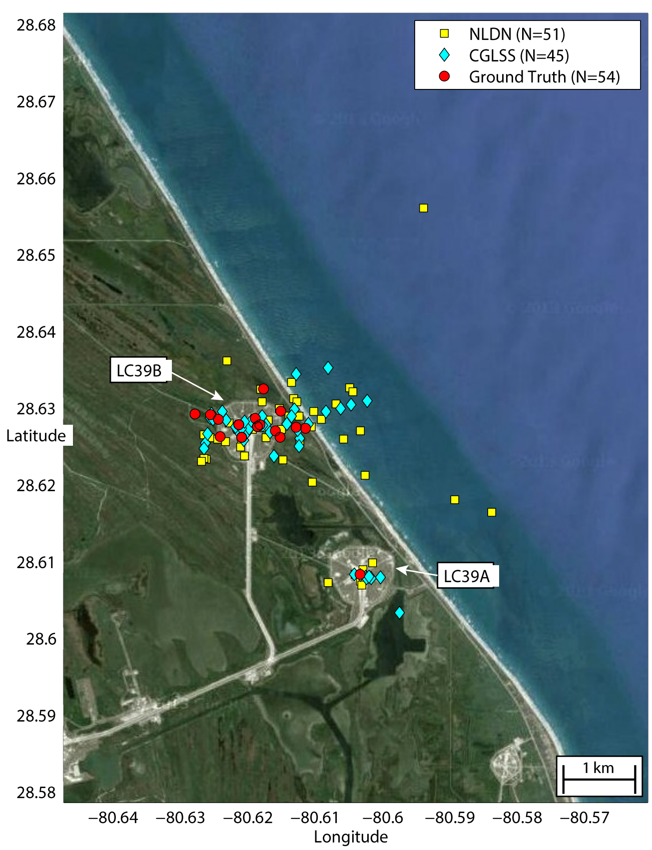

Fig 1. Ground truth, NLDN, and CGLSS strike point locations.

The NLDN reported a total of 51 out of 54 return strokes (94.4%) detected by the LC39B lightning instrumentation system, while CGLSS detected 45 of the 54 strokes (83.3%). The overall stroke detection efficiency of the NLDN significantly exceeds the value reported by *Mallick et al.* [2013] of 75% for triggered lightning return strokes at the ICLRT. Further decomposing the LC39B ground truth dataset based on stroke order shows that the NLDN reported 21 (100%) of the first strokes and 30 (90.9%) of the subsequent strokes. Similarly, CGLSS reported 16 (75.2%) of first strokes and 29 (87.9%) of subsequent strokes. The LC39B dataset was also analyzed based on strokes attaching to the LPS versus those attaching to ground or low-altitude ground-based structures. The NLDN and CGLSS systems reported 24 (88.9%) and 21 (77.8%), respectively, of strokes attaching to the LPS and 27 (100%) and 24 (88.9%), respectively, of strokes attaching to the ground or low-altitude ground based structures. The fact that both the NLDN and CGLSS systems provide higher detection efficiencies for strokes terminating on the ground versus on highly-elevated structures suggests that the radiation field waveforms for those events terminating on elevated structures are perhaps significantly altered.

III. NLDN AND CGLSS ERROR ANALYSES

The strike point location errors of the NLDN and CGLSS systems were analyzed independently for all detected return strokes, first strokes, subsequent strokes, strokes attaching to the LPS, and strokes attaching to ground or low-altitude

TABLE 2. STRIKE POINT LOCATION DIFFERENCE STATISTICS FOR NLDN AND CGLSS RELATIVE TO GROUND TRUTH

	All Strokes			First Strokes			Subsequent Strokes			LPS Attachment			Ground Attachment		
	ΔR	ΔX	ΔY	ΔR	ΔX	ΔY	ΔR	ΔX	ΔY	ΔR	ΔX	ΔY	ΔR	ΔX	ΔY
NLDN															
N	51	51	51	21	21	21	30	30	30	24	24	24	27	27	27
AM	611	467	327	690	506	379	556	439	290	596	481	281	624	454	368
GM	399	220	171	401	201	146	398	234	191	362	184	152	436	257	190
Med	415	101	-42	375	80	-60	431	189	13	334	42	-82	447	339	22
Min	42	-772	-783	42	-772	-783	75	-544	-534	71	-772	-704	42	-493	-783
Max	3500	2321	2620	3500	2321	2620	2110	1907	1082	2110	1907	1082	3500	2321	2620
CGLSS															
N	45	45	45	16	16	16	29	29	29	21	21	21	24	24	24
AM	290	228	143	265	189	154	303	249	137	199	164	90	370	284	190
GM	202	136	82	184	135	75	213	137	86	138	103	51	283	174	126
Med	195	120	-11	180	147	45	234	91	-41	141	91	-33	276	174	45
Min	9	-397	-553	48	-129	-553	9	-397	-367	9	-397	-553	46	-235	-367
Max	1097	1029	874	932	569	874	1097	1029	381	794	569	230	1097	1029	874

ground based structures. The results of these analyses are given in Table 2. For each subset of strike locations, the measured quantities given (in meters) are, 1) total radial distance (ΔR) from the LC39B ground truth location to the NLDN/CGLSS reported location, 2) longitudinal distance (ΔX) from the LC39B ground truth location to the NLND/CGLSS reported location, 3) latitudinal distance (ΔY) from the LC39B ground truth location to the NLND/CGLSS reported location. For each quantity, statistical parameters provided include the arithmetic mean (AM), the geometric mean (GM), median, minimum, and maximum. Note that for the longitudinal and latitudinal differences, which can represent either positive or negative values, the arithmetic and geometric means provided are for the absolute value of the distance difference. Histograms for each measured quantity (ΔR, ΔX, ΔY) are shown in Figures 2, 3, and 4, respectively. The histograms bins are 100 m in width.

For the full dataset, the NLDN (51 strokes) reports had GM and median location errors relative to LC39B ground truth of 399 m and 415 m, respectively. CGLSS (45 strokes) reports had GM and median location errors of 202 m and 195 m, respectively. The CGLSS location errors were approximately half that of the NLDN system. This observation is not unexpected given the higher sensor density of the CGLSS system in the area surrounding LC39B. The results were similar for the subsets of first strokes (NLDN GM/median of 401 m/375 m and CGLSS GM/median of 184 m/180 m) and subsequent strokes (NLDN GM/median of 398 m/431 m and CGLSS GM/median of 213 m/234 m). The similar distributions of absolute radial distance differences for all strokes, first strokes, and subsequent strokes are shown graphically in Figure 2A,B, and C. For the subset of return strokes that attached to the LPS, the NLDN (GM/median of 362 m/334 m) and CGLSS (GM/median of 138 m/141 m) both decreased relative to the full dataset, though the CGLSS GM errors fell by nearly 32% while the NLDN GM errors fell by only about 9%. The decrease in NLDN and CGLSS location errors for strokes attaching to the LPS is clear in Figure 2D relative to Figure 2A, B, and C. Of the 21 direct LPS strokes recorded by CGLSS, 11 (~52%) had location errors less than 150 m. In contrast, for the subset of return strokes that attached to the ground or low-altitude structures, the location errors of the NLDN (GM/median of 436 m/447 m) and CGLSS (GM/median of 283 m/276 m) both increased relative to the full dataset. In this case, the CGLSS GM errors increased by 40% and the NLDN GM errors increased by about 9%. The trend is clear in Figure 2E where 14 of the 21 (67%) reported CGLSS strike locations had errors larger than 250 m.

In Figure 2A, the NLDN reported six strokes with location errors larger than 1 km relative to ground truth. The location errors of these six strokes ranged from 1259 m to 3500 m. Three strokes (errors of 3500 m, 1745 m, and 1259 m) had estimated return stroke peak currents of -8.5 kA, -8.9 kA, and -6.2 kA, respectively. For each of the three strokes, only three NLDN sensors reported data. CGLSS reported the first two strokes with errors of 524 m and 133 m, and corresponding peak current estimates of -7.2 kA and -5.8 kA. Case 1 was a first stroke that terminated on ground about 200 m north of the LC39B pad perimeter. Case 2 was a subsequent stroke that terminated on the top of the LC39A LPS mast. Case 3 was a

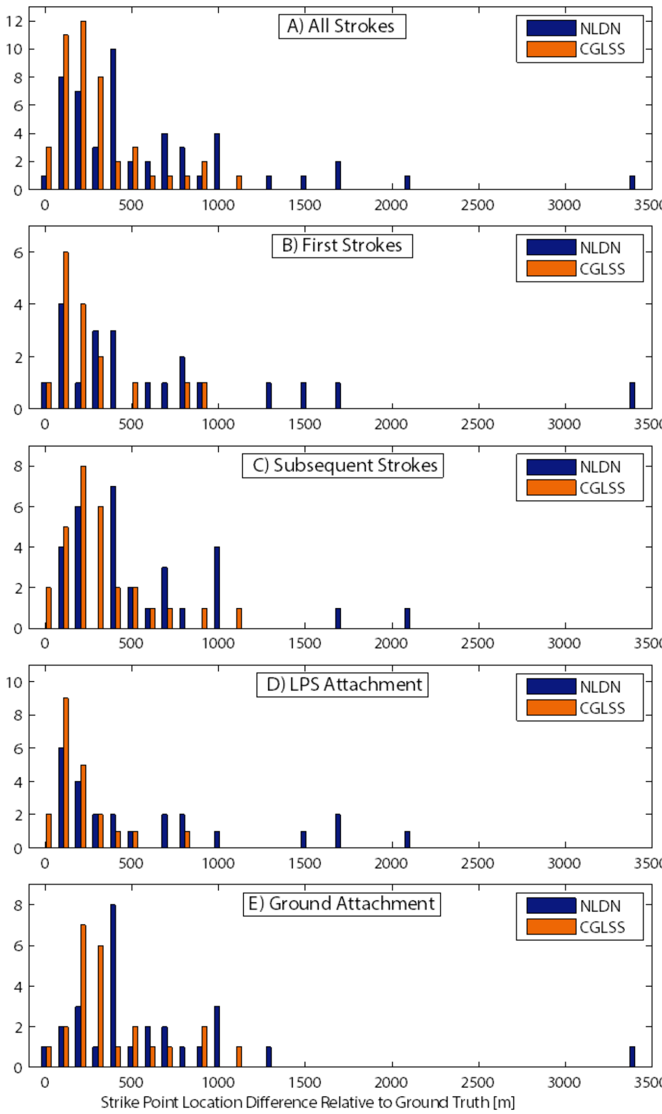

Fig 2. Distributions of strike point location differences of NLDN and CGLSS systems relative to ground truth.

first stroke that terminated within the LC39B pad perimeter and due east of the pad center. Two additional strokes reported by NLDN with errors of 1493 m and 1712 m were both associated with multiple ground attachment points occurring within a period of less than 2 μs (these two events were discussed above in Section 2). CGLSS reported neither of the events. The final stroke reported by NLDN with large error (2110 m) was a subsequent stroke to the LC39A LPS mast. The estimated peak current was -18.6 kA, but only four sensors reported. CGLSS located the event with 87 m of error and estimated the peak current at -15.4 kA. All six CGLSS sensors recorded the event.

The total radial location differences reported by NLDN and CGLSS relative to LC39B ground truth were also analyzed individually as functions of their longitudinal (ΔX) and latitudinal (ΔY) components to determine if there is system error bias towards a certain azimuthal direction. Figure 3 shows the longitudinal component errors for the full dataset and the four subsets of data outlined above. The corresponding statistical parameters are given in Table 2. For the full dataset, NLDN and CGLSS reports have median longitudinal errors of 101 m and 120 m, respectively (i.e., the estimated strike locations were east of the LC39B ground truth location). Figure 3A demonstrates this observation graphically, showing a clear positive skew. CGLSS (median of 180 m) shows a larger bias towards overestimating the longitudinal coordinate of the strike location for first strokes than does NLDN (median of 80 m). The opposite is true for subsequent strokes, where NLDN (median of 189 m) shows a larger bias for overestimating the longitudinal coordinate of the strike location than CGLSS (median of 91 m). The most uniform distribution of longitudinal coordinate errors for both NLDN (median of 42 m) and CGLSS (median of 91 m) is for strokes attaching directly to the LPS. The trend is shown graphically in Figure 3E. The distributions of longitudinal

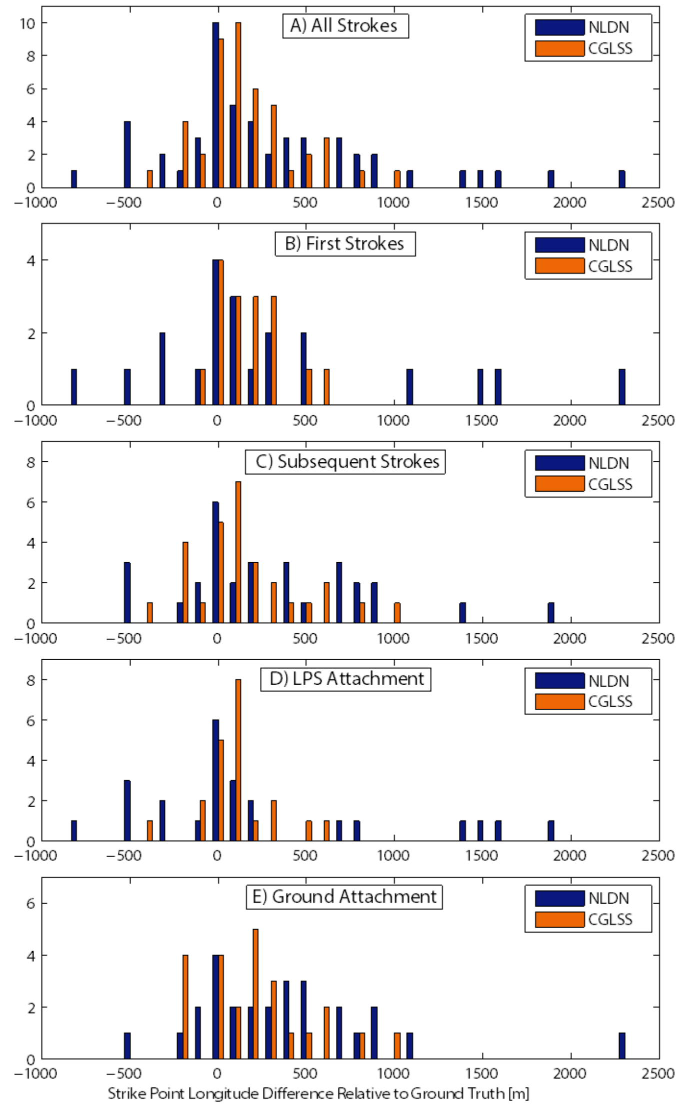

Fig 3. Distributions of longitudinal strike point location differences of NLDN and CGLSS systems relative to ground truth.

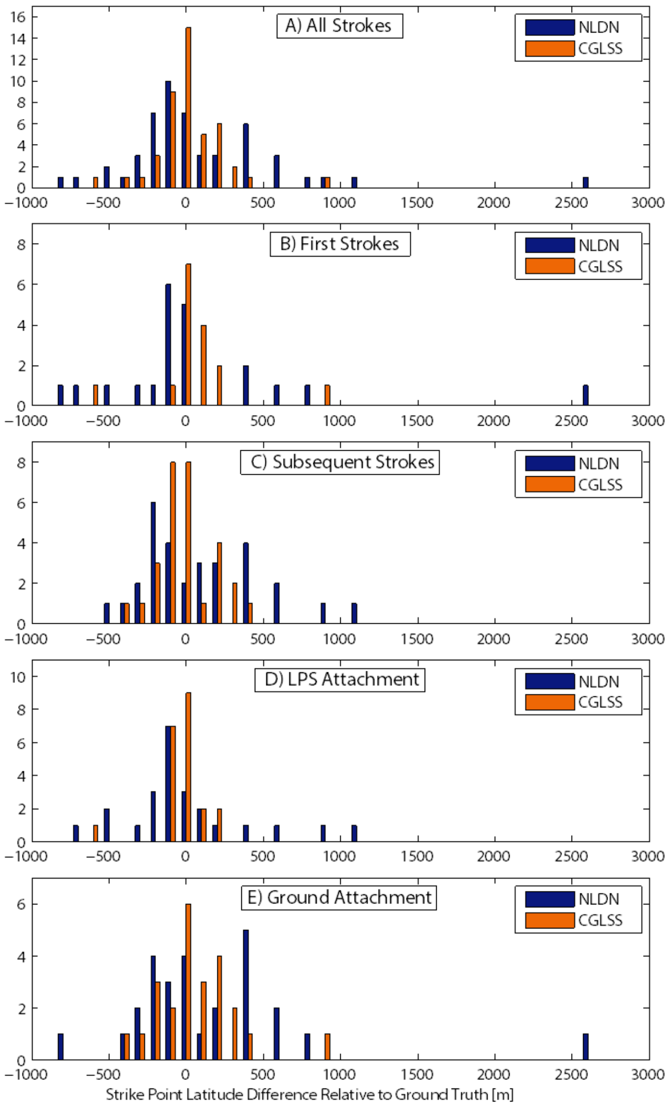

Fig 4. Distributions of latitudinal strike point location differences of NLDN and CGLSS systems relative to ground truth.

coordinate errors for NLDN (median of 339 m) and CGLSS (median of 174 m) were most significantly skewed right for events attaching to ground (Figure 3E). The longitudinal coordinate of the strike location was overestimated by NLDN for 24 of 27 (~89%) strokes and by CGLSS for 18 of 21 (~86%) strokes. Figure 4 shows the latitudinal component errors for the full dataset and the four subsets of data outlined above. Both NLDN and CGLSS performed significantly better in estimating the latitudinal coordinates of the strike locations compared to the distributions of longitudinal coordinate errors shown in Figure 3. For all strokes, NLDN and CGLSS had median latitude errors of -42 m and -11 m, respectively. For first strokes, subsequent strokes, LPS attachments, and ground attachments, NLDN median latitudinal coordinate errors were -60 m, 13 m, -82 m, and 22 m. For the same subsets of data, CGLSS report had median errors of 45 m, -41 m, -33 m, and 45 m.

IV. CGLSS Time series Analysis

The CGLSS system underwent several changes during the data collection period that may have negatively affected system performance. In order to eliminate CGLSS data points from the full dataset that may not be representative of nominal system performance, time series (Figure 5) and histograms (Figure 6) of calculated chi-square values and number of stations reporting (NSR) for each solution were plotted from May 2011-October 2013. The system performance for the period of early July 2012 through all of 2013 can be considered nominal with average NSR values indicating that 6 sensors were operational for most of the time period. The average chi-square is somewhat elevated above the optimal mean of 1.0, suggesting that the expected location errors might be slightly larger (perhaps 20%) than indicated by the semi-major axis (SMA) values. The NSR is uniformly low in 2011 and early 2012, but the chi-square values are similar to 2013. This means that some location errors will be a bit larger than indicated by the SMA's, and that the SMA's will be a bit larger than 2013 (at least in some regions with fewer sensors). CGLSS data reported during May and June 2012 is significantly degraded, likely due to the addition of a new sensor and associated site-error corrections. Fortunately, none of the 45 strokes in the CGLSS dataset occurred during this time period.

V. Summary

The LC39B lightning instrumentation system recorded 54 return strokes with ground truth strike point location accuracy from May 2011-July 2013. The NLDN and CGLSS detection efficiencies for the full dataset were 94.4% (51 strokes) and 83.3% (45 strokes), respectively. For strokes attaching directly to the LPS of LC39B and LC39A, the NLDN and CGLSS detection efficiencies were 88.9% and 77.8%, respectively. *Mata et al.* [2012] reported NLDN and CGLSS detection efficiencies for strokes attaching to the LC39B LPS of 74% and 63%, respectively, for data collected from March 31-December 31, 2011, suggesting that the performance of both systems has perhaps improved. In the present study, both the NLDN and CGLSS systems exhibited better detection efficiency (100% and 88.9%, respectively) for strokes terminating on ground or low-altitude structures versus those attaching to the LPS.

Relative to the ground truth strike locations, CGLSS strike location estimates were in error by about half those reported by NLDN for the full dataset. NLDN reports had GM/median location errors of 399 m/415 m while CGLSS reports had GM/median location errors of 202 m/195 m. The ratios of the GM/median statistics for both systems were very similar for first strokes and subsequent strokes when compared to the full dataset. For strokes attaching to the LPS, the error ratio between CGLSS and NLDN reported locations increased, with CGLSS providing better strike location estimates with GM/median location errors of 138 m/141 m relative to the GM/median errors of 362 m/334 m for NLDN. The opposite

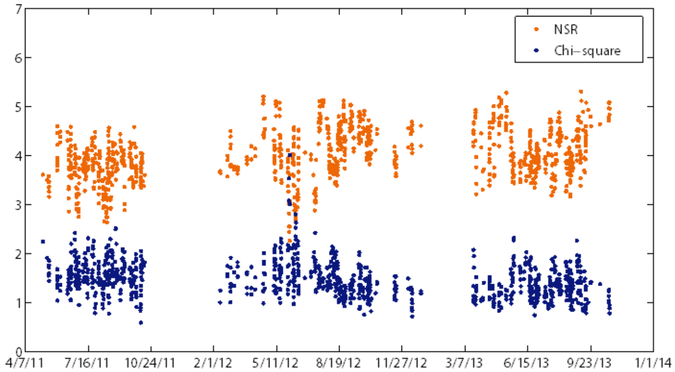

Fig 5. Time series of chi-square and NSR for the CGLSS system from May 2011-October 2013.

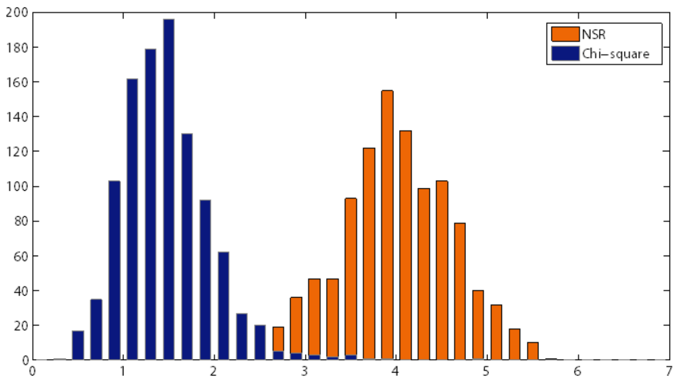

Fig 6. Histograms of chi-square and NSR for the CGLSS system from May 2011-October 2013

was found to be true for strokes attaching to ground or low-altitude structures, where the error ratio decreased in favor of NLDN (GM/median errors of 436 m/447 m) compared to CGLSS (GM/median errors of 283 m/276 m).

Both NLDN and CGLSS were found to overestimate the longitudinal coordinate of the strike point location by median errors of 101 m and 120 m, respectively. The overestimation occurred in ~89% (NLDN) and ~86% (CGLSS) of reported strokes. The trend was present for all subsets of strokes, but was less significant for strokes attaching to the LPS and most significant for strokes attaching to ground or low-altitude structures. In contrast, both NLDN and CGLSS demonstrated uniform location error distributions in the latitudinal directions, with median errors of -42 m and -11 m, respectively.

In summary, NLDN exhibited better detection efficiency than CGLSS, but with larger (typically about a factor of two) location errors. Both systems were biased towards overestimating the longitudinal coordinates of the strike point location. NLDN was able to better locate those events with multiple ground termination points in close time succession. NLDN reported six strokes in the dataset with location error greater than 1 km while CGLSS reported one such stroke, though three of the large-error strokes located by NLDN were not located by CGLSS. NLDN events exhibiting large location errors were associated with strokes with low estimated peak currents or with flashes exhibiting multiple ground attachment points.

REFERENCES

C. T. Mata, V. A Rakov, T. Bonilla, A. G. Mata, E. Navedo and G. P. Snyder, "A new comprehensive lightning instrumentation system for PAD 39B at the Kennedy Space Center, Florida" International Conference on Lightning Protection 2010, Cagliari, Italy, September 2010.

C. T. Mata, V. A Rakov, A. G. Mata, A. Nag and J. Saul, "Evaluation of the performance characteristics of CGLSS II and U.S. NLDN using ground-truth data from Launch Complex 39B, Kennedy Space Center, FL", International Lightning Detection Conference, Broomfield, Colorado, April 2012.

F. J. Merceret and J. C. Willett, Editors, H. J Christian, J. E. Dye, E. P. Krider, J. T. Madura, T. P. O'Brien, W. D. Rust, and R.L. Walterscheid, 2010: A History of the Lightning Launch Commit Criteria and the Lightning Advisory Panel for America's Space Program, NASA/SP-2010-216283, 234 pp.

J. G. Ward, K. L. Cummins and E. P. Krider, "Comparison of the KSC-ER Cloud-To-Ground Lightning Surveillance System (CGLSS) and the U.S. National Lightning Detection Netwrok (NLDN)" 20th International Lightning Detection Conference,Tucson, USA, April 2008.

Mallick, S., *et al.* (2014), Performance Characteristics of the NLDN for Return Strokes and Pulses Superimposed on Steady Currents, Based on Rocket-Triggered Lightning Data Acquired in Florida in 2004–2012, J. Geophys. Res., In press.

K. L. Cummins and M. J. Murphy, An Overview of Lightning Location Systems: History, Techniques, and Data Uses, With an In-Depth Look at the US. NLDN, IEEE Transactions on Electromagnetic Compatibility, Vol. 51, No. 3, August 2009.

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.