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EVALUATION OF THE PERFORMANCE CHARACTERISTICS OF CGLSS II AND U.S. NLDN USING GROUND-TRUTH DATA FROM LAUNCH COMPLEX 39B, KENNEDY SPACE CENTER, FLORIDA

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ABSTRACT

A new comprehensive lightning instrumentation system has been designed for Launch Complex 39B (LC39B) at the Kennedy Space Center, Florida. This new instrumentation system includes seven synchronized high-speed video cameras, current sensors installed on the nine downconductors of the new lightning protection system (LPS) for LC39B; four dH/dt, 3-axis measurement stations; and five dE/dt stations composed of two antennas each. The LPS received 8 direct lightning strikes (a total of 19 strokes) from March 31 through December 31 2011. The measured peak currents and locations are compared to those reported by the Cloud-to-Ground Lightning Surveillance System (CGLSS II) and the National Lightning Detection Network (NLDN). Results of comparison are presented and analyzed in this paper.

1 INTRODUCTION

After over 40 years of deploying and using Lightning Instrumentation (Lightning Detection and Location Systems) at or around the vicinities of the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) much has been improved and gained; from monitoring the electric field during the Apollo days (mid-late 1960's) *Merceret et al.* [2010] to the precise location of a lightning strike at LC39B with the deployment of the LC39B LPS lightning instrumentation (2011).

Both, the Cloud-to-Ground Lightning Surveillance System (CGLSS II) and the National Lightning Detection Network (NLDN), have been providing lightning detection and location data for KSC and CCAFS with some expected margin of error (both detection and location) since these systems monitor big areas. Even though over the years the location error has decreased and the detection efficiency has improved, these systems cannot provide accurate lightning location with a 100% detection efficiency, which is required when protecting expensive and delicate flight hardware.

The most recent NLDN performance characteristics have been evaluated using rocket triggered lightning data from 2004 to 2009 *Nag et al.* [2011] with the resulting flash and stroke detection efficiencies being 92% and 76%, respectively; the median absolute location error was 308 m, and the largest error was 4.2 km.

The most recent comparison between CGLSS II and NLDN was performed using historical data from 2005 and 2006 *Ward et al.* [2008] where it is found that the CGLSS II fails to report about 28% of high-current strokes reported by the NLDN and the NLDN fails to report about 17.5% of the low current strokes reported by CGLSS II and their calculated median position difference is 656 m (for data analyzed over four days).

The LC39B LPS provides precise location and total detection for only a relatively small area at KSC (LC39B and its vicinity) but there is a possibility of implementing this system at multiple launch pads (like LC39A and CCAFS) which could all be interconnected, providing 100% detection efficiency for all the launch pads within KSC and CCAFS.

2 KSC LIGHTNING LOCATION SYSTEMS DESCRIPTION

2.1 LC39B LPS, KSC

The LC39B LPS and its lightning instrumentation are described in detail in *Mata et al.* [2008] and [2010], respectively. This lightning instrumentation is a 100 MS/s event-driven DAQ system running 24/7 with sub-microsecond time accuracy, whose trigger signal can be generated from any of the thirty one (31) ground level sensors (9 downconductor currents, 12 dH/dt, and 10 dE/dt). Additionally a TTL signal from the LC39A lightning instrumentation system has been provided, because the LC39B lightning instrumentation was used to monitor the last two Space Shuttle launches from LC39A. After a qualified trigger is received, the signals of all the ground level sensors are recorded in a 30 ms time window

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with 50% pre-trigger sampling at 100 MS/s, additionally, seven[1] high speed video cameras record up to 455 frames at 3,200 fps with 50% pre-trigger and a resolution of 1280x800.

Figure 1. Lightning protection system of LC39B, Kennedy Space Center, Florida. Seen at the launch pad is the standby rescue Shuttle during the Hubble repair mission in 2009.

The LC39B LPS data provide the capability of locating lightning strikes by means of:

- Time of Arrival (using dE/dt waveforms)
- Magnetic Direction Finding (using dH/dt waveforms)
- High speed video frames
- Downconductor currents

2.2 CGLSS II, CCAFS

The first Cloud-to-Ground Lightning Surveillance System (CGLSS) was installed at the KSC-Eastern Range (ER) during the summer of 1979 (before the first shuttle launch, 1981) as a prototype system consisting of three magnetic direction finders. During 1995-1998, the system was converted to a 6-station, short-baseline network of medium-gain IMPACT (IMproved Accuracy from Combined Technology) sensors and it currently has an effective range of about 100 km, covering the KSC-ER launch and operation areas, operating 24 hours a day, 7 days a week *Merceret et al.* [2010]. Its daily lightning reporting has also seen improvements in recent years *Flinn et al.* [2010] and it mainly includes the following parameters: latitude, longitude, microsecond time, number of sensors used, peak current, and polarity of lightning strike.

The CGLSS II has been working with a reduced network (5 out of 6 sensors) since August of 2009.

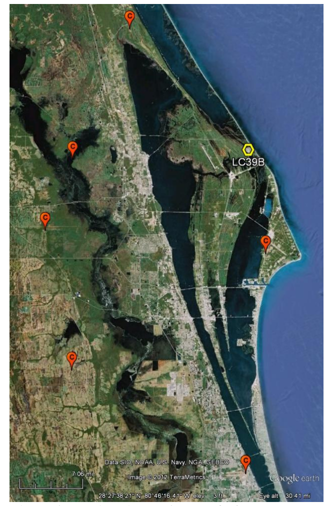


Figure 2. Map showing the location of 6 CGLSS II sensors.

2.3 U.S. NLDN

The U.S. National Lightning Detection Network (NLDN) has been providing real-time, continental-scale lightning information since 1989 and it has undergone several improvements and updates *Cummins et al.* [2009].

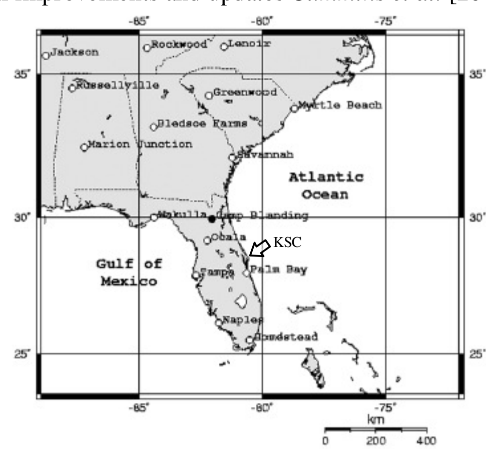


Figure 3. Map showing the locations of 15 U.S. National Lightning Detection Network (NLDN) sensors in and around the Florida region as of late 2003. The approximate locations of Camp Blanding (ICLRT) and the Kennedy Space Center (KSC) are also shown. The current network configuration is essentially the same as shown here, except for the additional sensor in the Bahamas installed in mid - 2006 *Nag et al.* [2011].

It currently consists of a nationwide network of 114 Vaisala Thunderstorm CG Enhanced Lightning Sensors LS7001, *Nag et al.* [2012], specifying a median location accuracy of 250-500 meters, which basically use a low frequency combined Magnetic Direction Finding and Time of Arrival techniques and is capable of producing the following parameters: latitude, longitude, microsecond time, peak current, polarity, number of sensors used, Cloud/Cloud-to-Ground indication, and multiplicity for lightning strikes.

Based on the last published performance characteristic evaluation results *Nag et al.* [2011] it has a flash and stroke detection efficiencies of 92% and 76%,

[1] Originally the system was designed with 6 video cameras and one additional high-speed video camera was temporarily installed (June 2011) about five kilometers southwest of LC39B. This camera is located in the firing room 1 of the Launch Control Center (LCC) and is currently pending final installation atop the Vehicle Assembly Building (VAB).

respectively, with a median absolute location error of 308 m, the largest error was 4.2 km, and the peak current estimation errors never exceeded 129%. It is worth noting the validation test was done at the International Center for Lightning Research and Testing (ICLRT), at Camp Blanding, Florida, using rocket-triggered lightning data that are only representative of regular subsequent strokes in natural lightning. Consequently, the given performance characteristics a) are representative of the portion of the NLDN covering the Florida region shown in Figure 3 (whose performance characteristics are not expected to be superior to those of the other parts of the network) and b) the flash detection efficiency 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).

3 DATA

During the year of 2011, from late March until December, the LPS was subjected to a total of 48 lightning flashes (8 direct and 40 nearby) with a total of 89 return strokes (19 direct and 70 nearby) recorded on 14 different days.

Each of the three towers of the LC39B LPS was struck directly by lightning at least once. About 17% of all the lightning flashes detected by the LC39B LPS attached directly to it (8 of 48) all of which were negative flashes. About 63% of these direct strikes were multiple-stroke flashes (5 of 8) and only 20% of them (1 of 5) had all its return strokes (3) terminating in the same location.

CGLSS II and NLDN data were provided for each day the LC39B LPS was directly struck by lightning. Data consist of a text file providing: date, time stamp (Coordinated Universal Time, UTC) with millisecond accuracy, decimal coordinates (latitude and longitude) with six significant figures, peak current (positive or negative) number of reporting sensors, cloud or ground discharge (only for NLDN), and error ellipse parameters.

The following CGLSS II and NLDN performance characteristics were analyzed: 1) flash and stroke detection efficiency, 2) location errors, and 3) differences in peak currents estimates. Both systems, CGLSS II and NLDN, were compared against LC39B LPS data.

Each direct return stroke was correlated using GPS (Global Positioning System) time stamps to determine stroke detection efficiencies.

Geographical coordinates were used to calculate location errors. Only 4 strokes (out of the 19 directly attached strokes) did not attach to the towers' air strike terminal. For those four events, downconductor current waveforms and video records were used to estimate their strike location.

LC39B LPS peak current values are calculated by algebraically adding currents of all (9) downconductors. The sum of the downconductor currents for strokes with larger 10-90% rise times match better the incident current than for strokes with shorter rise times. The latter suffer from transmission line propagation effects which result in larger current magnitudes being measured at the ground level.

Only one flash out of a total of 5 multiple-stroke direct flashes, ranging from a minimum of 2 to a maximum of 8 return strokes, had all return strokes (3) attaching to the same termination point with both CGLSS II and NLDN detecting 2 return strokes (the first and the third). For the remaining 4 multiple-stroke direct flashes the subsequent return strokes did not attach to the strike location of the first return stroke. Overall there were a total of 11 subsequent return strokes directly attaching to the LC39B LPS with 8 of them following the same channel as the previous return stroke.

There were two strokes attaching at two different locations simultaneously, both of these strokes were reported by the NLDN (one as cloud and one as ground discharge) but CGLSS II failed to report either of them. In both cases the attachment points were: 1) the air strike terminal atop the insulator of Tower 2 (about 181 meters above ground level) and 2) ground level east and outside the LC39B perimeter about 560 and 615 meters (east and south-east, respectively) from Tower 2. Tower 2 is the east-most tower of the LC39B LPS and its closest distance to the coast line is about 650 meters (north-east direction). For the purpose of this work, location calculations of these return strokes were made using the direct strike location on the LPS.

There was a 2-stroke flash where the first stroke attached to the LC39B LPS and the subsequent stroke struck the ground, both CGLSS II and NLDN detected both strokes but only the first stroke is included in this work. Additionally, there was a 3-stroke flash where the first stroke attached to the LC39B LPS (tower 3), the second stroke had two simultaneous attachment points (tower 2 and nearby ground, 615 meters south-east of tower 2) and the third stroke struck the ground (at the same nearby location as the second stroke). CGLSS II reported only the first stroke and NLDN reported all three strokes, the third stroke of this flash is not included in this work.

4 RESULTS

These results are based only on direct strikes to the LC39B LPS. Pertaining to the NLDN data, the only data used for comparison purposes are those from reported ground strokes.

4.1 Flash and Stroke Detection Efficiencies

Table 1 shows the CGLSS II and NLDN flash detection efficiencies. Multiple return strokes are considered to be part of the same flash if the inter-stroke interval is less or equal than 500 ms. Calculated inter-stroke interval from 11 subsequent strokes are: arithmetic mean 84 ms, standard deviation 45 ms, median 82 ms, minimum 23 ms and maximum 180 ms. The criteria used to determine if either CGLSS II or NLDN detected a flash was if at least one of their detected strokes matched (UTC times) a LC39B LPS detected stroke belonging to a flash.

The flash detection efficiency of the NLDN was 75% (6 of 8), appreciably lower than 92% (34 of 37) reported from the most recent NLDN performance evaluation *Nag et al.* [2011], the latter being considered an underestimate, since rocket triggered lightning data (2004-2009) were used. It is worth pointing out that if the ground/cloud categorization were ignored, then the NLDN flash detection efficiency would be 100% (8 of 8). The two missed ground strokes (both single-stroke flashes) were categorized as cloud events and one of them had multiple simultaneous attachment points. Consequently, this ground/cloud categorization strongly affected the single-stroke flash detection efficiency going from 33% (1 of 3) to 100% (3 of 3) if the ground/cloud categorization is ignored. CGLSS II has the same 33% (1 of 3) detection efficiency for single-stroke flashes.

Table 1 Summary of LC39B LPS Direct Lightning Strikes (March-December, 2011) with CGLSS II and NLDN Flash Detection Efficiencies (DE).

Direct Lightning Flashes (March-December, 2011)	No. of Flashes	No. of NLDN Ground Flashes	NLDN Ground Flash DE	No. of CGLSS II Flashes	CGLSS II Flash DE
Total	8	6	75%	5	63%
Single-Stroke Flashes	3	1	33%	1	33%

Table 2 shows the CGLSS II and NLDN stroke detection efficiencies for all strokes, first, subsequent and also those having multiple simultaneous attachment points. For the NLDN, the total stroke detection efficiency is 74% (14 of 19) which is very close to the results based on the most recent NLDN performance evaluation *Nag et al.* [2011] and coincidentally very similar to the flash detection efficiency (see Table 1). Additionally, the LC39B LPS allows us to segregate first and subsequent strokes, obtaining stroke detection efficiencies of 75% (6 of 8) and 73% (11 of 8), respectively. Again, it is worth noting that if the ground/cloud categorization were ignored, the obtained stroke detection efficiency would improve to 84% (16 of 19) and 100% (8 of 8) for all and first strokes, respectively.

Table 2. Summary of LC39B LPS Direct Strikes (March-December, 2011) with CGLSS II and NLDN Stroke Detection Efficiencies (DE).

Direct Return Strokes (March-December, 2011)	No. of Strokes	No. of NLDN Ground Strokes	NLDN Ground Stroke DE	No. of CGLSS II Strokes	CGLSS II Stroke DE
Total	19	14	74%	12	63%
First	8	6	75%	5	63%
Subsequent	11	8	73%	7	64%
Multiple simultaneous attachment points	2	1	50%	0	0%

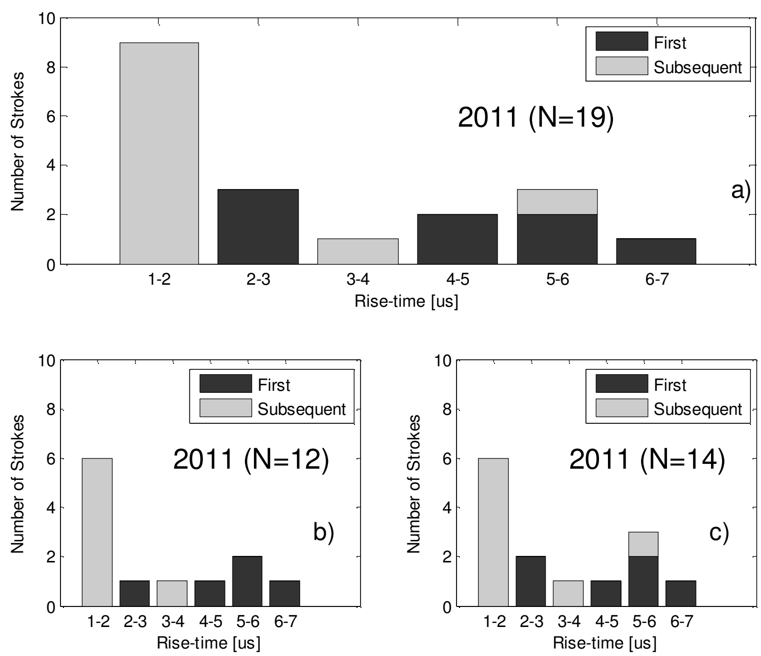


Figure 4 Histograms of the total number of strokes directly attaching to the LC30B LPS (a) detected by CGLSS II (b) and NLDN (c) versus rise-time (10%-90%). The rise-time was obtained from the LC39B LPS total calculated incident current.

For CGLSS II, the stroke detection efficiency is 63% (12 of 19), coincidentally the same as the flash detection efficiency (see Table 1), maintaining this number for the detection efficiency of first strokes and improving to 64% (7 of 11) for subsequent strokes.

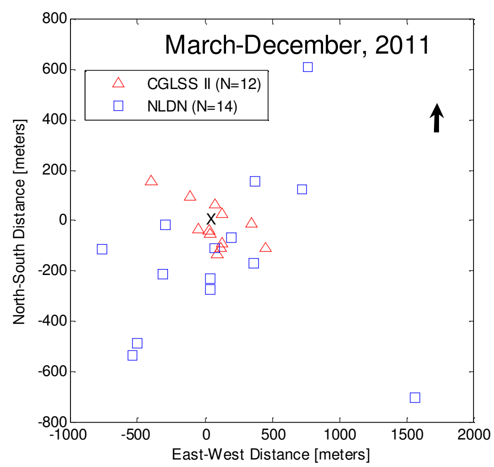
The NLDN outperformed CGLSS II with 50% (1 of 2) detection efficiency for strokes with multiple simultaneous attachment points (direct and nearby) compared to 0% (0 of 3) for CGLSS II. Again, if the ground/cloud categorization were ignored, then NLDN's figure would go to 100% (2 of 2).

Figure 4 shows the distribution of the LC39B LPS, CGLSS II, and NLDN detected strokes (a, b and c, respectively) versus the LC39B LPS total measured incident current rise-time. Rise-times were between 1.07 and 6.04 with arithmetic mean of 2.87, standard deviation of 1.9 and median of 2 microseconds.

4.2 Location Accuracy

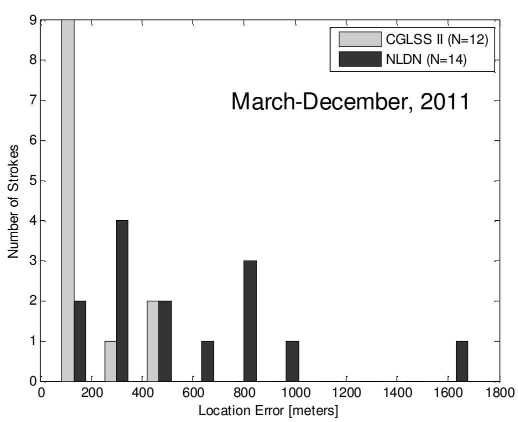
Figure 5 shows a spatial distribution of locations for all the direct strokes detected by the CGLSS II (12) and all the ground strokes detected by the NLDN (14). The origin (X at the center of Figure 5) corresponds to the known strike location at LC39B. For one case (CGLSS II) and two cases (NLDN) the attachment point was on the downconductors, then video records (for one case) and downconductors current waveforms (for both cases) were used to approximate the geographical coordinates of these locations which were estimated to be at about half the distance from the tower to the downconductor grounding point for both cases. Lack of video records was due to a previous direct strike to one of the towers which upset of the communication system used by the camera covering the area of the strike to the downconductor. After this event, efforts have been made to improve the protection against lightning strikes of the fiber optic communication system, service provided to the LC39B LPS by KSC.

Figure 6 shows the histogram of GCLSS II and NLDN absolute stroke location errors for the 12 and 14 strokes shown in Figure 5. CGLSS II outperforms NLDN regarding location errors with minimum, median and



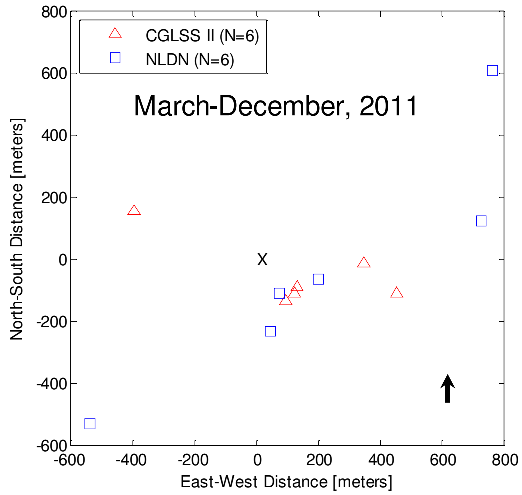
March-December, 2011		NLDN	CGLSS
N-S	AM, m	-145	-20
	SD, m	325	90
	Median, m	-143	-36
E-W	AM, m	124	73
	SD, m	619	213
	Median, m	58	85
N		14	12

Figure 5 Stroke location errors of detected CGLSS II (12) and NLDN (14) direct strikes to LC39B LPS. The origin is indicated by a cross and indicates the actual strike location. The horizontal axis corresponds to the east-west component of the location error (positive values correspond to the east). The vertical axis corresponds to the north-south component of the location error (positive values correspond to the north). The arrow indicates the north. Statistics given are arithmetic mean (AM), standard deviation (SD), and median.



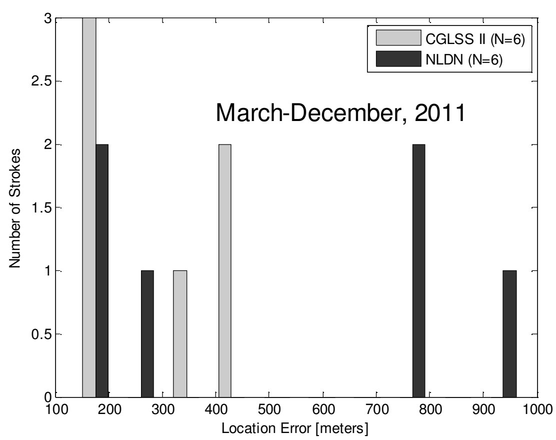
March-December, 2011	NLDN	CGLSS
AM, m	572	190
SD, m	420	143
Median, m	405	155
Min, m	133	51
Max, m	1714	467
N	14	12

Figure 6 Histograms of absolute location errors for direct return strokes to LC39B LPS detected by CGLSS II (12) and NLDN (14). Statistics given are arithmetic mean (AM), standard deviation (SD) median, minimum, and maximum.



March-December, 2011		NLDN	CGLSS
N-S	AM, m	-35	-50
	SD, m	384	109
	Median, m	-89	-100
E-W	AM, m	211	125
	SD, m	488	293
	Median, m	136	127
N		6	6

Figure 7 Stroke location errors of subsequent strokes following the same channel as its previous stroke and detected by CGLSS II (6) and NLDN (6). All these strokes attached directly to the LC39B LPS. The origin is indicated by a cross and indicates the actual strike location. The horizontal axis corresponds to the east-west component of the location error (positive values correspond to the east). The vertical axis corresponds to the north-south component of the location error (positive values correspond to the north). The arrow indicates the north. Statistics given are arithmetic mean (AM), standard deviation (SD), and median.



March-December, 2011	NLDN	CGLSS
AM, m	510	287
SD, m	358	143
Median, m	487	256
Min, m	133	159
Max, m	980	467
N	6	6

Figure 8 Histograms of absolute location errors for direct subsequent strokes to LC39B LPS following the same channel as its previous stroke and detected by CGLSS II (6) and NLDN (6). Statistics given are arithmetic mean (AM), standard deviation (SD) median, minimum, and maximum.

maximum location errors of 51, 155 and 467 meters (for CGLSS II) compared to 133, 405 and 1,714 meters (for the NLDN), the latter to be compared to 23, 308 and 4,239 meters given by *Nag et al.* [2011].

Figure **7** and Figure 8 are the analogous of Figure 5 and Figure 6 but only for subsequent strokes following the same channel as a previous stroke. Ideally the CGLSS II and the NLDN should locate all these strokes in the same position since all these strokes are following the same channel, instead the minimum, median and maximum location errors of 159, 256 and 467 meters (for CGLSS II) and 133, 487 and 980 meters (for the NLDN) are corroborated, indicating that a detected subsequent stroke was erroneously located about 0.5 and 1 kilometer away (CGLSS II and NLDN, respectively), which would erroneously constitute a flash with multiple earth striking locations.

Figure 9 shows the absolute location error with respect to the number of reporting sensors. The range of reporting sensors was 2-5 for the CGLSS II and 2-15 for the NLDN, with the largest absolute location error corresponding to as many as 15 sensors contributing to the solution for the NLDN. From these results, it is not obvious that the location error tends to decrease as the number of reporting sensors increases, for both CGLSS II and NLDN.

Figure 10 shows the absolute location error with respect to the measured rise-time of the LC39B LPS calculated total incident current where CGLSS II shows a tendency of decreasing the absolute location error for slower rise times (first return strokes) and shows bigger location errors for faster rise times (subsequent return strokes) which in turn account for more that half (58%) of the CGLSS II sample size (7 of 12), on the other hand, NLDN shows bigger location errors for both extremes, the slowest and fastest return strokes.

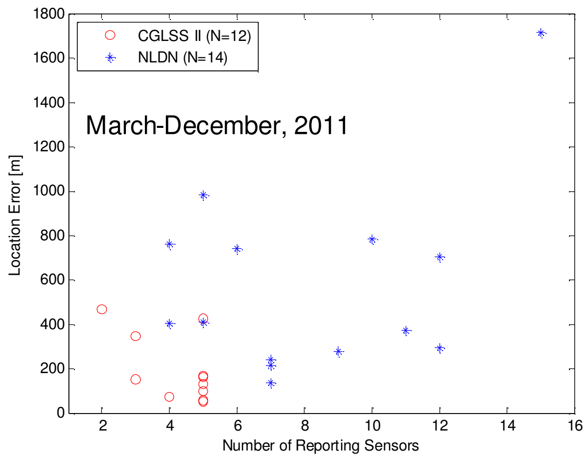


Figure 9 Absolute location error versus the number of reporting sensors for CGLSS II and NLDN.

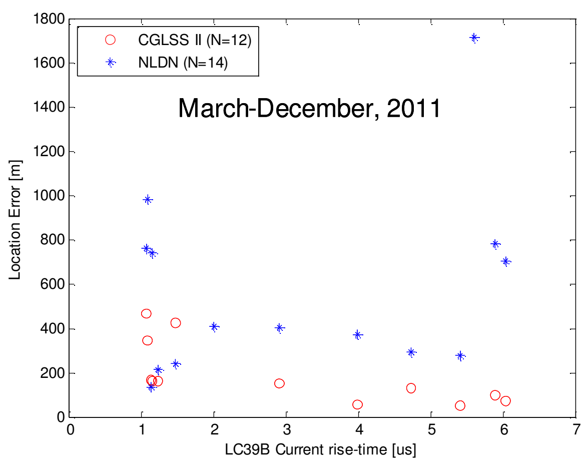


Figure 10 Absolute location error versus the calculated rise-time (10%-90%) of the LC39B LPS calculated total incident current.

4.3 Peak Current Estimates

Figure 11 shows the peak current difference for each of the two systems, CGLSS II and NLDN, and the LC39B LPS, both systems underestimate the peak current by 20-40%, although it is important to point out that the LC39B LPS measured peak current is the sum of multiple (9) partial currents. There is one event for which the NLDN measured a higher current than the LC39B LPS and this corresponds to one stroke with two simultaneous attachment points; there was another similar event but the NLDN categorized it as a cloud flash, hence it is not included in this plot. CGLSS II did not detect any of these strokes with multiple simultaneous attachment points.

Figure 12 shows a histogram for all the LC39B LPS recorded strokes and their corresponding range of peak currents and it identifies the range of peak currents for which CGLSS II and NLDN detected strokes. The largest recorded current saturated the LC39B LPS at 174.3 kA and, excluding this event, the median LC39B LPS peak current was about 30 kA.

Figure 13 shows a relation between LC39B LPS peak currents and the number of reporting sensors for each system, CGLSS II and NLDN.

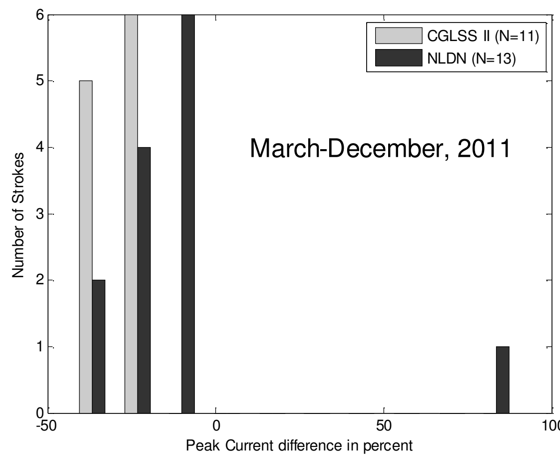


Figure 11 Peak current difference in percent for both CGLSS II and NDLN reported peack currents using the LC39B LPS peak current (calculated total incident current) as reference. For one event NLDN shows a positive difference, this is due to that event having simultaneous multiple attaching points (tower 2 and nearby ground). Only 11 and 13 return strokes instead of 12 and 14 (CGLSS II and NLDN respectively) are included here due to LC39B LPS current saturation for one event.

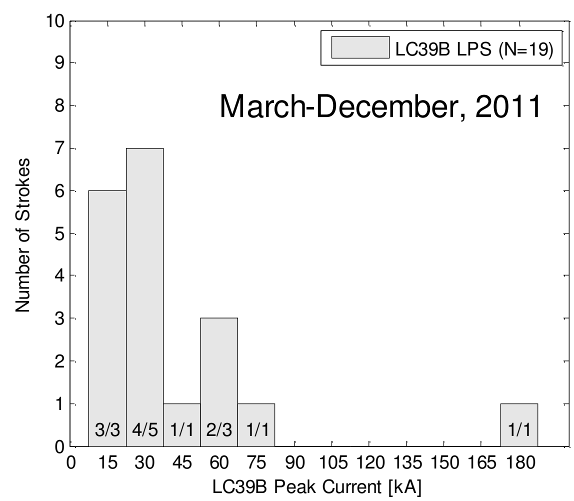


Figure 12 Detected strokes as a function of LC39B LPS measured peak current. For each peak current range (bin size of 15 kA) the ratio given inside the column indicates the number of strokes detected by CGLSS II (numerator) and NLDN (denominator) for that peak current range.

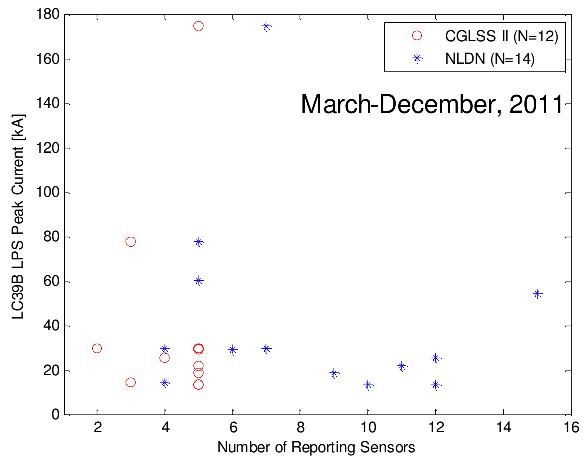


Figure 13 LC39B LPS measured peak current (calculated total incident current) versus the number of sensors detecting that event for CGLS II and NLDN.

5 CONCLUSIONS

The lightning instrumentation recently installed at LC39B, Kennedy Space Center, FL, provides ground-truth data, which were used to evaluate the detection efficiency and location errors of the CGLSS II and the NLDN from March to December of 2011. Realizing the small sample size, LC39B acquired data seem to indicate that the stroke detection efficiency of either the CGLSS II or the NLDN (63% and 74%, respectively, with both systems experiencing a 33% detection efficiency of single-stroke flashes) is lower than expected, especially since these two systems are used to monitor lightning activity and to locate cloud-to-ground strokes near launch pads at KSC and CCAFS. Also, it seems like both systems, CGLSS II and NLDN tend to underestimate the channel base peak current by about -40 to -10%. Out of the 19 strokes recorded, 8 were first strokes and 11 were subsequent strokes. One direct stroke saturated two of the nine LC39B downconductor transient measurements. The peak of the sum of the currents to ground for this particular event was 174.3 kA, but a reasonable extrapolation on the two downconductor current measurements could make this a 200-220 kA negative stroke. The median of all 18 direct strokes (excluding the event that saturated the downconductor currents) is about 30 kA, with rise-times between 1 and 6 microseconds, with an arithmetic mean of about 2.9 microseconds (the rise-time is measured as the 10-90% of the sum of currents to ground). Inter stroke time intervals were between 23 and 180 ms, with an arithmetic mean of 84 ms. The CGLSS II and NLDN minimum, median, and maximum absolute location errors (in meters) for all detected return strokes were 51, 155, 467 and 133, 405, 1,714, respectively. Also, the CGLSS II and NLDN minimum, median, and maximum absolute location errors (in meters) for subsequent strokes following the same channel as the previous stroke were 159, 256, 467 and 133, 487, 980, respectively. During 2011 (from late March until December) the LC39B LPS was struck by 19 strokes, but the lightning instrumentation system detected additional 70 strokes, which did not attach to the LC39B LPS directly. The 70 nearby strokes are being analyzed to increase the sample size and obtain a better estimate of detection efficiency for both, CGLSS II and NLDN. Future publications will include the analysis of some of these nearby strokes as well as future direct strikes to the LC39B LPS. Although the fidelity of the stroke detection efficiency presented in this paper is very high, the flash detection efficiency calculation is still being investigated due to the complexity of the assessment. The latest flash detection efficiency results will be presented at the conference.

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