P. 2.6 COMPARISON OF THE KSC-ER CLOUD-TO-GROUND LIGHTNING SURVEILLANCE SYSTEM (CGLSS) AND THE U.S. NATIONAL LIGHTNING DETECTION NETWORK™ (NLDN)

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Introduction

The NASA Kennedy Space Center (KSC) and Air Force Eastern Range (ER) are located in a region of Florida known as “Lightning Alley”. This corridor experiences the highest number of lightning ground strikes per square kilometer per year in the United States, with area densities approaching 16 fl/km^2/yr when accumulated in 10x10 km (100 km^2) grids (see Figure 1). The KSC-ER employ data from two cloud-to-ground (CG) lightning detection networks, the “Cloud-to-Ground Lightning Surveillance System” (CGLSS) that is owned and operated by the Air Force, and the U.S. National Lightning Detection Network (NLDN™) that is owned and operated by Vaisala, Inc. These data are used to provide warnings for ground operations and to insure mission safety during space launches at the KSC-ER. In order to protect the rocket and shuttle fleets, NASA employs a set of lightning safety rules referred to as the Lightning Launch Commit Criteria (LLCC). These rules are designed to insure that vehicles are not launched in weather conditions that would in any way jeopardize a mission or cause harm to shuttle astronauts. Also, any lightning strike that occurs too close to a vehicle on a launch pad can cause time-consuming mission delays due to the extensive retests that are often required for the vehicle and/or it’s payload when this occurs. If a CG lightning strike is missed or mis-located by even a small amount, the result could have significant safety implications, require expensive retests, or create unnecessary delays or scrubs in launches. Therefore, it is important to understand the performance of each lightning detection system in considerable detail.

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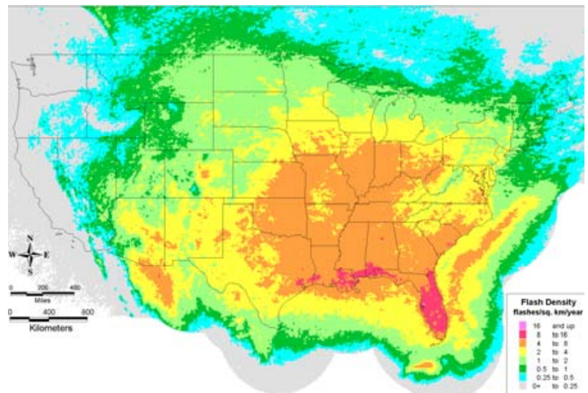


Figure 1. Map of the annual area density of CG lightning in the U.S. for years 1996 – 2005 (Courtesy Vaisala, Inc.).

Given the mission-critical nature of the NLDN and the CGLSS, a comparison of the detection efficiency and location accuracy of these lightning detection systems was carried out in 1996 (Maier and Wilson, 1996) after an upgrade to the NLDN in 1995 (Cummins et al., 1998). At that time, the NLDN was found to have a flash detection efficiency of 90% and a median location accuracy of 0.6 km, based on comparisons with CGLSS. Since 1996, both networks have undergone additional upgrades to improve performance, and this warrants a re-examination of the relative performance of both networks. The 1998 CGLSS upgrade added a sixth sensor and implemented a location algorithm that included time-of-arrival information. These upgrades increased the flash detection efficiency of CGLSS inside the network to ~98% and the location accuracy to ~250m from the previous 92% and 500m, respectively (Boyd, et al, 2000). The 2002-2003 upgrades to the NLDN included replacing all of the old sensors, a combination of out-dated time-of-arrival LPATS and early IMPACT sensors, with a uniform network of IMPACT ESP sensors. This increased the overall sensitivity of the NLDN, particularly near the boundaries of the network (Cummins at al, 2006).

Here, we will examine specific subsets of CG strokes and flashes that were reported individually and in-common by the NLDN and CGLSS networks. We will evaluate the fraction of CGLSS “strike points” that are reported by the NLDN (relative NLDN strike-point DE), the spatial separation between the strike points reported by both networks (relative location accuracy), and the values of the estimated peak current, I_p, reported in common by both networks. Where applicable, these results will also be compared to the findings of Maier and Wilson (1996), which were obtained prior to the most-recent upgrades of both networks.

NLDN and CGLSS Instrumentation

The NLDN is a national network of 113 IMPACT ESP sensors[4] placed 200-350 km apart. Figure 2 shows the evaluation region at the KSC-ER (100 km radius) and its location relative to the 10 closest NLDN sensors (black triangles). The three closest sensors to the KSC-ER are located in Palm Bay, Tampa, and Ocala, FL. The NLDN system operates using the following process: sensors detect a lightning event; the data are then transferred via satellite communications to a network control center in Tucson, Arizona; information from multiple sensors are used to geo-locate the event using an IMPACT location algorithm (Cummins et. al, 1998); processed data are forwarded to users in real-time via either terrestrial or satellite data links. This entire process takes approximately 30-40 seconds (Cummins et al., 2006).

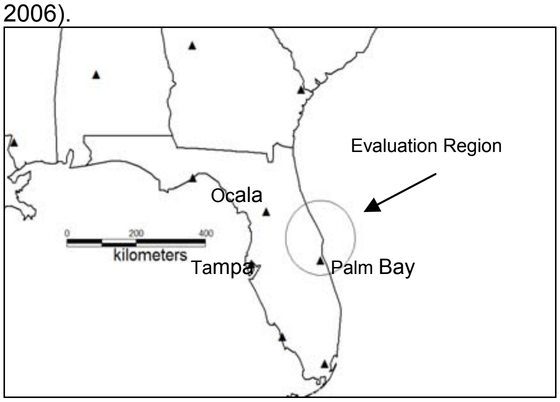


Figure 2. Evaluation region centered at the KSC-ER and the locations of the nearest NLDN sensors.

The CGLSS is a local network covering the KSC-ER operations area with six Vaisala IMPACT ESP sensors located ~30km apart. Its data processing steps are similar to the NLDN, except that land-line communications are used instead of satellite links. The sensor locations are shown in Figure 3 (black triangles).

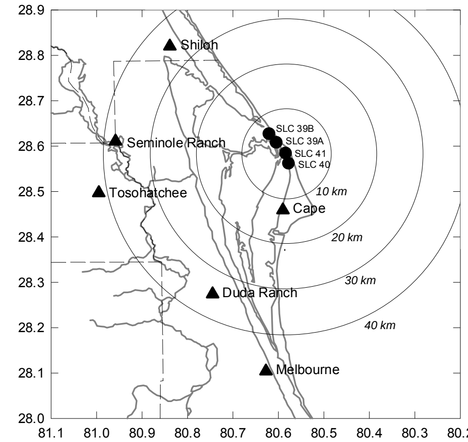


Figure 3. Location of the CGLSS sensors at the KSC-ER.

The NLDN and CGLSS systems differ somewhat in their processing of the lightning information. Currently, the NLDN locates all detected strokes, optionally groups them into flashes, and estimates the I_p for each stroke by scaling the range-normalized signal strength by a factor of 0.185 (Cummins et al., 2006). The reported time is the estimated time-of-occurrence of the stroke. The CGLSS on the other hand, locates the first stroke in each flash and a fraction of the subsequent strokes that have strike locations more than 0.5 km from the first-stroke location (Maier and Wilson, 1996). In the following text, we refer to both of these types of events as CGLSS strokes. It then estimates I_p by scaling the range-normalized signal strength by a factor of 0.23. The CGLSS event time is the time that the radiated lightning waveform exceeds a fixed detection threshold at the nearest reporting sensor. This time can be up to ~0.2 ms after the time-of-occurrence of the NLDN strokes in the evaluation region. When more than one stroke is detected at the same strike point, the CGLSS reports the highest I_p in any stroke.

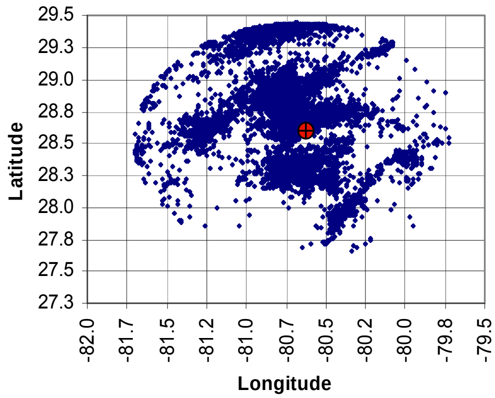
Methods

Case Selection Process

Lightning counts during the summers of 2005 and 2006 (June through August) were computed using CGLSS data. The four days that had the most lightning counts and had events distributed in all directions around the KSC-ER were chosen for further analysis (2005: June 15, 17, and August 1; 2006: July 23). Next, all CGLSS “flashes” (new strike points) within a 100 km radius from an origin near the Space Shuttle launch complex were compared with the NLDN strokes. Figure 4 shows the locations of all lightning events on July 23, 2006. The locations of NLDN strokes (14,457) are shown as blue diamonds,

[4] Manufactured by Vaisala Inc., Tucson, AZ

the CGLSS locations (3,565) as magenta squares, and the central origin is a red dot. (Here, the number of NLDN strokes is much larger than the number of CGLSS locations, due to the exclusion of subsequent strokes in the same channel.)



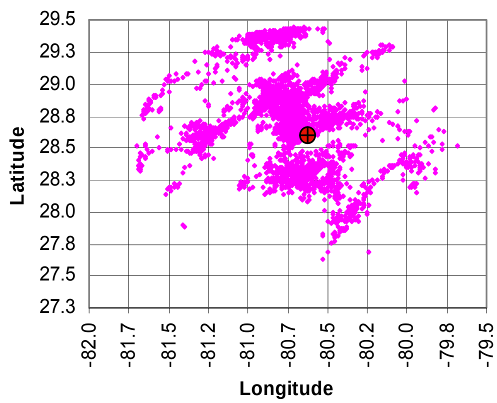


Figure 4. CG lightning locations reported by NLDN (top) and CGLSS (bottom) on July 23, 2006.

Data and Data Processing

The NLDN data were provided by Vaisala and contain for each stroke the date, time (to ms), latitude and longitude (in degrees), I_p (kA), the length of the error-ellipse semi-major axis (km), the chi-square value, and the number of sensors reporting the stroke (NSR). A short segment of data is provided in Table 1.

Table 1. NLDN raw data provided by Vaisala Inc.

Date	HH:MM:SS.ms	Latitude	Longitude	-Ip (kA)	semi-major	chi-squ.	NSR
6/15/2005	16:49:30.042	29	-81.166	-23.3	0.4	0.4	10
6/15/2005	16:59:50.218	28.982	-81.16	3.4	4.5	0.7	2
6/15/2005	17:02:33.828	28.953	-81.197	-7.6	1	0.6	3
6/15/2005	17:02:33.931	28.957	-81.194	-8.5	0.9	0.8	4
6/15/2005	17:05:17.896	28.956	-81.18	21.9	0.5	0.9	8
6/15/2005	17:05:17.925	28.943	-81.178	-20.1	0.4	0.7	9
6/15/2005	17:05:17.974	28.963	-81.182	-17.5	0.4	0.4	8
6/15/2005	17:05:18.035	28.963	-81.173	-10.2	1.1	0.2	3
6/15/2005	17:06:42.339	28.944	-81.171	-27.7	0.4	0.4	11
6/15/2005	17:06:42.435	28.944	-81.172	-13.5	0.5	0.4	6
6/15/2005	17:06:42.491	28.948	-81.17	-4.2	1.1	1.1	3
6/15/2005	17:06:42.595	29.002	-81.162	-5.7	6.2	0.2	2
6/15/2005	17:06:42.668	28.945	-81.175	-6.2	1.1	1.1	3
6/15/2005	17:13:42.547	28.944	-81.154	11.8	0.5	0.5	6
6/15/2005	17:19:00.549	29.042	-80.929	-19.2	0.5	0.5	6
6/15/2005	17:21:57.551	29.058	-80.935	-27.1	0.4	0.6	11
6/15/2005	17:21:57.553	29.025	-81.004	-6.1	9.7	0.8	2
6/15/2005	17:21:57.586	29.041	-80.938	-9.4	1.2	0.5	4

The CGLSS data were provided by Computer Sciences Raytheon, Patrick Air Force Base, FL, and delivered in a standard APA output format. They were then reformatted to match, as closely as possible, the same fields as the NLDN data. The differences are the addition of flash multiplicity and semi-major axis, and the removal of NSR. The semi-major and semi-minor axes are in units of nm rather than km. A short segment of reformatted CGLSS data is provided below in Table 2.

Table 2. Reformatted CGLSS data

HH:MM:SS.ms	Date	Latitude	Longitude	Mult.	-Ip(kA)	chi squ.	semi-major	semi-minor
16:49:30.042	6/15/05	29	-81.166	1	-25.1	0.7	0.4	0.1
17:02:33.828	6/15/05	28.945	-81.176	2	-8.7	1.1	0.4	0.1
17:05:17.925	6/15/05	28.941	-81.177	3	-22	0.5	0.3	0.1
17:06:42.339	6/15/05	28.941	-81.169	5	-29.3	0.5	0.3	0.1
17:19:00.550	6/15/05	29.045	-80.928	1	-25.5	1.2	0.6	0.1
17:21:57.552	6/15/05	29.071	-80.935	2	-30.3	0.8	0.6	0.1
17:23:53.021	6/15/05	29.077	-80.813	1	-17.4	1.2	0.8	0.1
17:26:32.804	6/15/05	29.045	-80.904	1	-43.7	0.9	0.5	0.1
17:33:13.324	6/15/05	28.917	-80.859	1	-21.7	1	0.4	0.1
17:33:54.160	6/15/05	28.919	-80.82	1	-18.5	4.2	0.6	0.1
17:34:09.571	6/15/05	28.873	-80.844	1	-13.3	6.6	0.3	0
17:34:37.743	6/15/05	28.898	-80.847	1	-16.8	0.9	0.4	0.1
17:35:36.866	6/15/05	28.904	-80.841	2	-25.4	1.6	0.3	0
17:36:20.597	6/15/05	28.885	-80.827	1	-10.8	5.7	0.7	0
17:39:16.852	6/15/05	28.921	-80.854	1	-25.6	0.5	0.4	0.1

The NLDN and CGLSS strokes were considered to be time-correlated if the CGLSS event occurred within the 2 ms following the corresponding NLDN event. Only time-correlated events were used for the I_p comparisons (linear regression analysis), detection efficiency analysis, and the location accuracy analysis. The detection efficiency analysis was carried out for negative first strokes and negative subsequent strokes that produced new ground contacts (as reported by the CGLSS) and was reported as the percentage of lightning events seen in common with the NLDN. In addition, we determined the relative number of large strokes ($|I_p| \geq 50$ kA) reported by the two networks. The location accuracy analysis involved calculating the horizontal distances between time-correlated stroke locations (positive and negative polarity) in kilometers.

Results and Discussion

Peak Current Analysis

Figure 5 is a scattergram showing the relationship between NLDN I_p values (x-axis) and CGLSS I_p values (y-axis) for all time-correlated strokes on July, 23 2006. This day is representative of the entire dataset. This figure also shows that the regression coefficient is 1.1066, and the R^2 value is 0.8986 which means that 90% of the variance can be explained by a linear relationship between these variables. Note that the I_p values are highly correlated over the range of ±150 kA, with the largest scatter for high-current positive and low-current negative values. The RMS error (average standard deviation in y) was 2.8 kA. On average, the CGLSS estimates are slightly higher than NLDN. This difference was expected because of the different scaling values (0.23 for CGLSS and 0.185 for NLDN) that are used for the field-to-current relationship discussed above. This scaling difference predicts a slope of 1.23 (0.23/0.185), which is within 10% of the empirically-derived slope. The remaining difference is likely associated with differences in the propagation models that are used to compute range-normalized signal strengths, since the propagation paths to NLDN sensors are roughly 3-6 times larger than for the CGLSS sensors in this area.

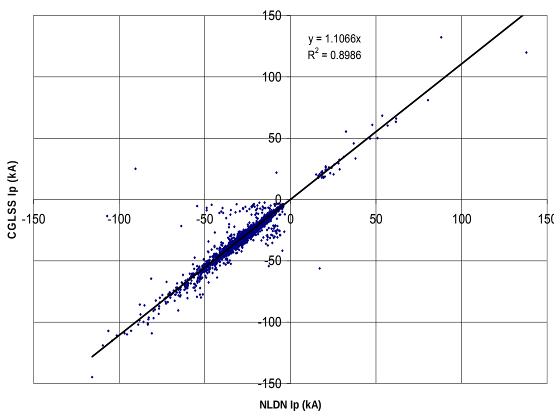


Figure 5. CGLSS I_p values vs. the corresponding NLDN I_p values.

Detection Efficiency

The NLDN detection efficiency (DE) relative to the CGLSS on July, 23 2006, is shown in Figure 6. The blue diamonds in Figure 6a show the fraction of NLDN strokes reports relative to the CGLSS reports, with the value "1.00" corresponding to 100% detected. Each diamond represents the average value over a 2 kA bin. The error bars were calculated assuming a normalized binomial distribution using the relation

$$\sigma = \sqrt{p(1-p)/n}$$

Where σ is the standard deviation of the distribution, p is the fraction of strokes detected by the NLDN, and n is the total number of strokes in each bin. The bar graph below in Figure 6b shows the total number of CGLSS events (red) that are in each I_p bin as well as the total number of time-correlated (TC) NLDN events (blue) in that bin. The NLDN reported less than half of the strokes that had an estimated $|I_p|$ between 2-4 kA, but it steadily increased to 90% or more above 10 kA. The NLDN failed to detect 17.5 % of the CGLSS-reported negative strokes with $|I_p|$ < 12 kA. Since 12% of the CGLSS strokes on this day were less than 12 kA, the total percentage of strike points missed by the NLDN was approximately 2%. These percentages also hold true for the entire dataset. Failure of the NLDN to report low-current strokes was expected, given the much larger sensor spacing in the NLDN.

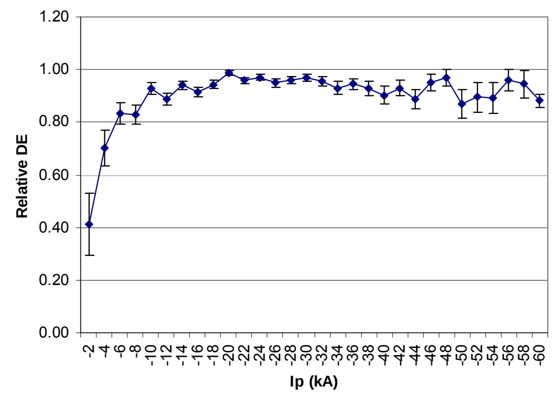


Figure 6a. Percentage of NLDN strokes relative to CGLSS strokes as a function of I_p.

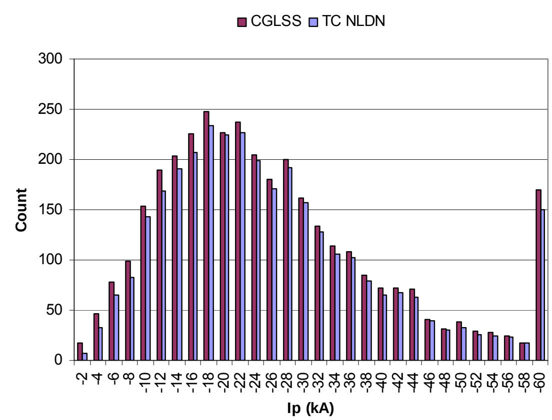


Figure 6b Number of CGLSS strokes (red) and time-correlated NLDN strokes (blue) as a function of I_p (2 kA < $|I_p|$ <150 kA).

Given the short sensor baselines and the small number of sensors in the CGLSS network, one can readily imagine cases where high-current strokes could saturate most (or all) of the CGLSS sensors, or produce inconsistent measurements among the sensors. The NLDN is less likely to miss high-current strokes because of its longer baselines and the larger number of sensors in that network. In order to explore this possibility further, we have compared the populations of high-current negative strokes with $|I_p| \geq$ 50 kA within the evaluation region. The CGLSS I_p values were first corrected to match the NLDN I_p values using the regression slope shown in Figure 5. Then strokes reported by two or more CGLSS sensors (including those not reported as first strokes or new ground strike points) were time-correlated with the high-current NLDN reports. The frequency histograms of the NLDN and correlated CGLSS counts vs. the NLDN Ip values for July, 23 2006 are shown in Figure 7. The blue bars show the total number of strokes reported by the NLDN and the red bars show the time-correlated CGLSS strokes. The 0.1 bin shows counts of the time-correlated negative events that NLDN reported with $|I_p| \geq 50$ kA but the CGLSS reported with $|I_p| < 50$ kA. Based on the measurements for all days, it appears that the CGLSS fails to report about 28% of the high-current strokes that were reported by the NLDN. Since only about 10% of the negative strokes have an $|I_p| \geq 50$ kA, the total percentage of events missed by the CGLSS network (due to a high I_p) is approximately 2.8%.

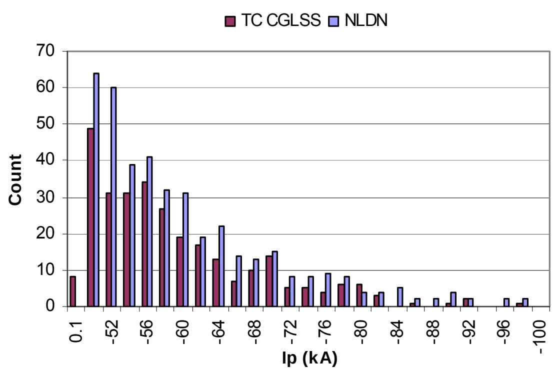


Figure 7. Number of NLDN strokes (blue) and time-correlated CGLSS strokes (red) as a function of I_p ($|I_p| \geq 50$ kA).

Location Accuracy

Analysis of the relative location accuracy of the two networks on July 23, 2006 is illustrated in Figure 8. Here, distance (location difference) bins of 200 m are shown on the x-axis, and the primary y-axis shows the number of time-correlated events in each bin in the form of a frequency histogram. The secondary y-axis is a cumulative distribution showing the fraction of time-correlated events that have a location difference ≤ the value of the associated bin (blue diamonds). The median position difference (50th percentile) is 683 m km on this day and 656 m overall for the four case studies.

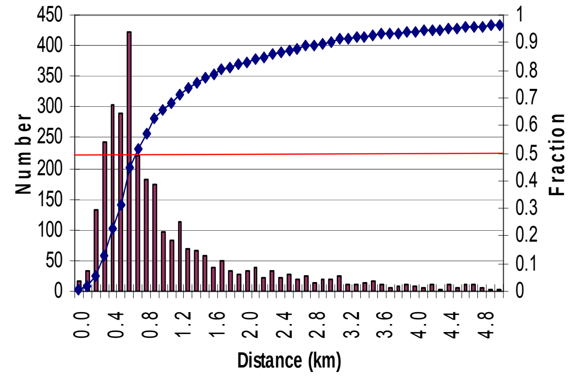


Figure 8. Distribution of the horizontal distances between the time-correlated CGLSS and NLDN locations.

Discussion and Conclusions

It seems clear that the upgrades to the NLDN have improved its overall performance, even when compared to the upgraded CGLSS. The I_p values from each network are highly correlated over the range of ±150 kA, with the largest scatter for high-current positive and low-current negative values. Once the different scaling factors (0.23 for CGLSS; 0.185 for NLDN) were accounted for, a regression slope near unity was achieved.

Both systems appeared to detect most of the strokes associated with new ground strike points, with specific exceptions. The NLDN failed to detect 313 out of 1789 (17.5%) of the CGLSS negative first strokes (and subsequent strokes that produce new ground contacts) with $|I_p| <12$ kA. However, the NLDN detection threshold was improved (lowered) by the upgrade in 2002-2003. This is reflected in the fact that CGLSS-reported strokes with $|I_p|$ above 12 kA were detected more than 95% of the time by the upgraded NLDN, whereas this level of detection was never reached in 1996. Formerly, the best DE (90%) only occurred for strokes with $|I_p|$ above 15 to 20 kA (Maier and Wilson, 1996 – Figure 4). The CGLSS failed to detect 444 out of 1591 (28%) of the NLDN-reported high-current strokes. In summary, the NLDN failed to report about 2% of all events (primarily low-I_p strokes) and the CGLSS failed to report about 2.8% of all events (primarily high-I_p strokes).

The relative location accuracy between the two networks is consistent with Vaisala model estimates of a 300m median for CGLSS and 600-700m median for NLDN in this geographic region (Cummins et al, 1998). Assuming that the NLDN and CGLSS location errors are uncorrelated, the expected median difference in locations would be at least $(300^2 + 600^2)^{1/2}$, or ~670m, which is consistent with our measured median distance of 656m. We note that the median position difference found in 1996 was 800m. Given that a much larger fraction of low-current events are now located by both networks, and given the fact that low-current strokes do have inherently larger location errors, this result is seen as a modest but clear improvement.

Failure of the CGLSS to report about 28% of the high-current NLDN strokes and the NLDN to report about 17.5% of the low current CGLSS strokes clearly highlights the need to use both networks to meet all the operational requirements at the KSC-ER.

Acknowledgement

This work has been supported in part by the NASA Kennedy Space Center, Grant NNK06EB55G, the Vaisala Inc. Thunderstorm Business Unit, Tucson, AZ, and Computer Sciences Raytheon, Patrick Air Force Base, FL.

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