6.1 THE U.S. NATIONAL LIGHTNING DETECTION NETWORK: POST-UPGRADE STATUS

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1. INTRODUCTION

The U.S. National Lightning Detection Network (NLDN™) has been providing real-time, continental-scale information on cloud-to-ground (CG) lightning to research and operational users since 1989, and has been the lightning data source for the NOAA National Weather Service for more than a decade. This network has undergone regular improvements during its 15-year lifetime. The intent of this paper is to provide research and operational users of NLDN data with a contemporary view of the strengths and limitations of this data resource.

Beginning in the spring of 2002, the NLDN underwent its most-recent system-wide upgrade. The objectives of the upgrade were to increase sensor reliability and reduce maintenance costs, to improve the detection efficiency (DE) and location accuracy (LA) on the boundaries of the network, and to provide a capability of detecting some cloud discharges. The original (1995) time-of-arrival LPATS sensors and early IMPACT sensors (Cummins et al., 1998a) were replaced by new IMPACT ESP sensors, and several additional sensor sites were installed. The new IMPACT ESP sensors provide accurate time-of-arrival and direction information, as well as increased sensitivity. Model estimates of the CG stroke DE are now in the range of 60-80%, and the CG flash DE is in the range of 90-95% throughout the continental U.S.

In conjunction with this upgrade, field campaigns were carried out in Southern Arizona and in Oklahoma/Texas in 2003 and 2004, and at the International Center for Lightning Research and Testing (ICLRT) in Florida in 2001-2003, to validate the NLDN performance characteristics. Data from the Arizona/Oklahoma/Texas studies were also used to evaluate the classification of lightning type.

This paper provides an overview of the current NLDN configuration and data processing, a description of recent changes that have been made to the NLDN, and it will compare modeled and measured performance parameters before, during, and after the upgrade. The effect of the upgrade on the NLDN estimates of the peak current will also be presented.

2. BACKGROUND AND HISTORY

Improvements in the NLDN have been motivated primarily by the applications that require lightning data. The first application, early detection of lightning-caused forest fires, could tolerate moderately large errors in location (4 to 8 km) when directing spotter aircraft to areas where there was CG lightning. Expanding use of NLDN data by the electric utilities and insurance industries in the early 1990's motivated the initial upgrade in 1995 (Cummins et al., 1998a). Power line fault location and analysis required higher accuracy (Cummins et al., 1998b), which was made possible by the advent of GPS technology. Forensic investigations typically required a network with a high DE and extremely accurate locations. Use of NLDN data for these applications was made possible by the 1995 upgrade. Insurance investigators now routinely use lightning data in claim verification. Use of lightning data by meteorological agencies both for research and forecasting has created demand for continued improvement in the lightning detection technology, primarily related to detection of cloud discharges. These applications, combined with increasing use of lightning data in support of aviation operations and safety applications, has motivated the latest upgrade.

The history of the NLDN has been briefly reviewed by Cummins et al. (1998a), and is covered in more detail in a paper by Orville (this conference). Although the 1995 upgrade produced a significant improvement in LA, both

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LA and DE decrease near the edges of the network. The addition of the Canadian Lightning Detection Network in 1997 eliminated these limitations on the northern border of the NLDN, but the coastal and southern borders continued to have LA and DE limitations. Additionally, by 2001 replacement parts for the aging LPATS III and early-generation IMPACT sensors had become difficult to obtain, and this created a support problem. The LPATS III sensors made up about 60 percent of the total NLDN sensors at that time. Additionally, since the 1995 upgrade, a number of important improvements were made in the design of the IMPACT sensors. These and other factors all led to the decision to upgrade the NLDN to a single sensor type, the IMPACT-ESP, in 2002.

3. NLDN OPERATIONAL OVERVIEW

The operation of the NLDN has been described in Cummins et al., (1998a). Individual stroke reports are transmitted from the remote sensors (1) to a central station (4) via a satellite link (2) (see Figure 1). Three downlink sites (3) forward data via dedicated communications links to the Network Control Center (NCC) (4) in Tucson, Arizona. Here the data are processed and archived, and the results are forwarded to customers (5-6) via both terrestrial and satellite data links within 30-40 seconds. CG stroke and flash data are also available via the Internet, and limited (survey level) information of the occurrence and frequency of cloud discharges is expected to be available via the Internet in the Spring of 2006.

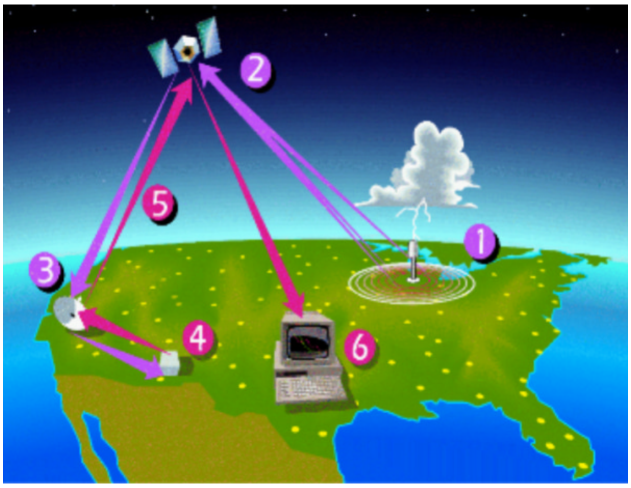

Figure 1 Communications data flow in the NLDN. Actual system employs three satellite down-link locations represented by item (3).

Although the satellite-based sensor communications links employed in the NLDN have proven to be more reliable that any other communications method, occasional congestion in the data links was a problem in the past. This caused the data from some sensors to arrive at the NCC too late to be used in real-time processing. As part of the upgrade, the downlink sites and the links between these sites and the NCC were upgraded in an effort to minimize this problem. Although weather-related communication failures can still lead to data delays and possibly missed events in real-time, this data congestion has largely been eliminated from the NLDN. Differences between the real-time and reprocessed data archives are now in the range of 1 to 2 percent.

4. NLDN EQUIPMENT AND ALGORITHM CHANGES

4.1 Sensors

Prior to the 2002 upgrade, the NLDN consisted of a mixture of 63 LPATS III sensors, which provided only arrival-time information, and 43 IMPACT sensors, which combined arrival-time with gated wideband magnetic direction finding (MDF) information. During the recent upgrade, all sensors in the NLDN were replaced with improved IMPACT-ESP sensors. The ESP sensor is a refinement of the earlier IMPACT sensor, having improved analog front end circuitry, a higher speed processor, and configurable waveform criteria. To understand how the ESP sensors have affected NLDN performance, we will examine each of the sensor refinements separately. These are:

- Improved analog circuitry has reduced noise, and allowed better detection of small amplitude signals. This in turn has improved the network DE, especially for small amplitude strokes.

- Older sensors had significant dead time (several ms) after a stroke was detected due to the time required to process and report the event. The Impact ESP sensors have significantly faster processing, and this is significant when detecting both CG strokes and cloud pulses.

- Configurable waveform and noise-rejection criteria allow the ESP sensor to reject or accept different waveform shapes (as a function of azimuth and signal strength), and to categorize the event as a pulse of cloud discharge or CG stroke based on a set of rules that can be modified as needed. This allows the NLDN to adapt to changing noise conditions at individual sites and to incorporate (to some degree) new understanding of how the waveform characteristics of cloud discharges differ from CG return strokes.

The most significant improvement in the NLDN has been the fact that all sensors now provide both time-of-arrival and direction-of-arrival information. Therefore, just two sensors are needed to accurately locate an event, and that location is provided using an "excess" of information (one degree of freedom). Prior to the upgrade, 3-4 sensors were needed to compute a location, because 60 percent of the sensors in the network provided just arrival-time information. This improvement enables the NLDN to detect small lightning impulses, such as the subsequent strokes in CG flashes that have low amplitudes and many cloud pulses. In addition, since all sensors now include magnetic field measurements, the peak field measurements are more accurate, and this improves the estimates of peak current that are provided by the NLDN.

4.2 Location Processing Algorithms

The locations of lightning discharges are computed in the same manner as described in the past (Cummins et al., 1998a), but refinements have been added to minimize the number of cloud pulses that are misclassified as CG strokes and to remove "false" solutions that are associated with miscorrelations of the sensor reports. In addition, the propagation model has been modified to account for attenuation if the lightning signal and increase the accuracy of peak current estimates.

Vaisala's work on discharge classification algorithm has reduced the number of misclassified events that have an estimated peak current greater than 10 kA, but does not completely eliminate the problem. Unfortunately, with the increased sensitivity of the IMPACT-ESP sensors, the percentage of detected events that are misclassified cloud discharges is probably larger than before the upgrade (see Section 6 for further details).

A number of "quality checks" have been incorporated into the location algorithm to reduce the likelihood of reporting a "false" or "misplaced" (outlier) event. These checks verify consistency among the various measurements that contribute to a solution, and are designed to have minimal impact on solutions that have consistent data. We note that a recent observation of a reduction in the number of very large (>200 kA, frequency of roughly 1 in 10,000 events) flashes since implementing these quality checks in 2002 (Lyons and Huffines, personal communication) is due to one of these changes. This problem will be corrected in the near future.

The final algorithm change associated with this upgrade involves the NLDN estimates of the peak current in CG strokes. The estimation of the peak current relies on accurate modeling of the attenuation of the radiation field amplitude due to propagation over imperfectly conducting ground from the source to the measuring sites. In the past, when the sensors had lower sensitivity, the NLDN used a simple power-law model to compensate for propagation (Orville et al., 1991; Idone et al., 1993). A more general formulation for the "range-normalized signal strength" (RNSS) is obtained using the expression

$$RNSS = C \cdot SS \cdot \left(\frac{r}{I}\right)^{p} \exp\left(\frac{r-I}{A}\right) \qquad (1)$$

where C is a constant currently set to 1 in the NLDN, SS is the signal strength reported by the sensor, r is the range in kilometers, I is the normalization range (set to 100 km in the NLDN), p is an attenuation exponent, and A is the space constant. The space constant has historically been set to a very large number (105 km), and the attenuation exponent was 1.13 (Cummins, 1998a). This set of model parameters was adequate for lightning events that were located within 400 km of a sensor, but they have been shown to lead to underestimation of the propagation losses for more-distant events. We have subsequently found that the exponential form of the model (p=1, and A set to a smaller value) produced better accounting for propagation losses.

A "best" value for the space constant (A) can be found, as follows. The (relative) sensor gain is first computed for each sensor, as the ratio of the RNSS reported by that sensor to the average value for all consistent sensors that reported the same lightning event. The mean value of these individual gain values can be larger or smaller than unity, if the space constant is not set correctly. The "best" value for A is defined as the value that provides an average gain very close to unity, and minimizes the standard deviation of that statistic. Figure 2 shows the results for several values of A. The best results are obtained when A is set to 1000 km. Note that the mean value for the prior model parameters (p=1.13; A=105) is 9.2% larger than 1. Changing to the new model parameters (p=1; A=1000 km) reduces the random error by 11% (the ratio of the two standard deviations).

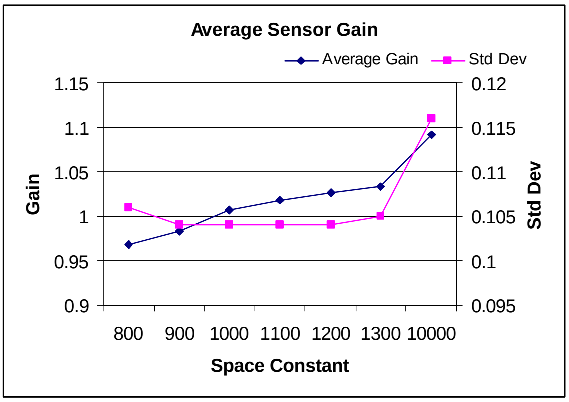

Figure 2 Average sensor gain and standard deviation for various propagation model parameter values

The new propagation model also improves the agreement between the NLDN estimated peak current and the currents measured directly during rocket-triggered lightning (RTL) at the Camp Blanding ICLRT. The study by Jerauld et al. (2005) found that the NLDN underestimated the measured peak currents of subsequent return strokes by about 18 percent, and this is consistent with the NLDN underestimates of the RNSS in equation (1). The impact of the improved NLDN propagation model has been evaluated by re-calculating the estimated peak currents of 55 time-matched rocket-triggered strokes from 2002-2003, after the NLDN sensors in or near Florida had been mostly upgraded to IMPACT ESP sensors. Results using the new model parameters are found in Figure 3 which shows a scattergram of the NLDN estimated peak current vs the measured peak current at the ICLRT. The three regression lines are for an un-constrained linear regression (green), zero-intercept constrained (magenta), and slope=1 (blue). Note that the slope=1 line has the same overall RMS error as the unconstrained linear regression. This result indicates that the conversion constant for RNSS to peak current obtained using KSC rocket-triggered data obtained in the late 1980's (0.185) also applies to the recent RTL data obtained from Camp Blanding, once propagation effects are properly accounted for.

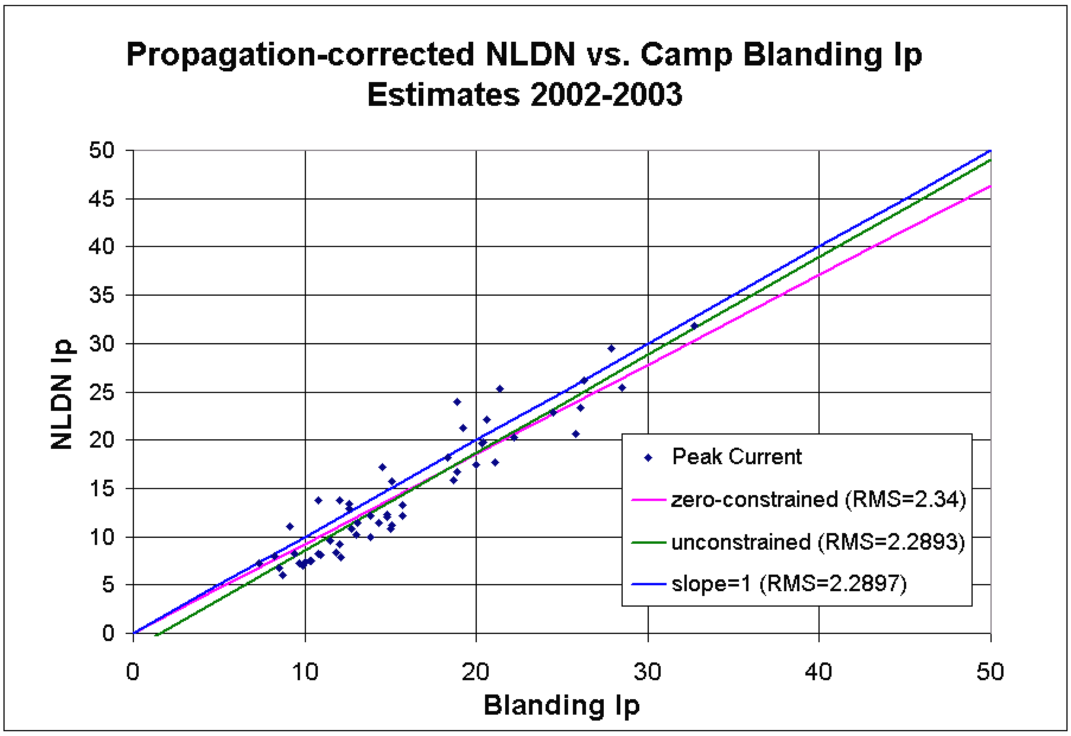

Figure 3 Scattergram of NLDN estimated peak current (kA) vs measured rocket-triggered lightning prak current for 55 subsequent strokes from 2002-2003. Various regresión lines and related RMS deviations are shown (see inset for details)

The propagation model parameter change was implemented in the NLDN on July 1, 2004. Since it does have an effect on the overall peak current distribution, it should be considered when closely comparing recent NLDN peak current distributions with earlier time periods. A detailed treatment of the changes in the NLDN peak current calibration is contained in a recent paper by Rakov (2005). As an illustration of the effect, sample distributions taken from the central U.S. using the old and new propagation model are shown in Figure 4. The mean value for negative flashes (first strokes) increased from -16.7 kA to -18.8 kA (12.6%), and the median value increased from -13.6 kA to -15.2 kA (11.8%).

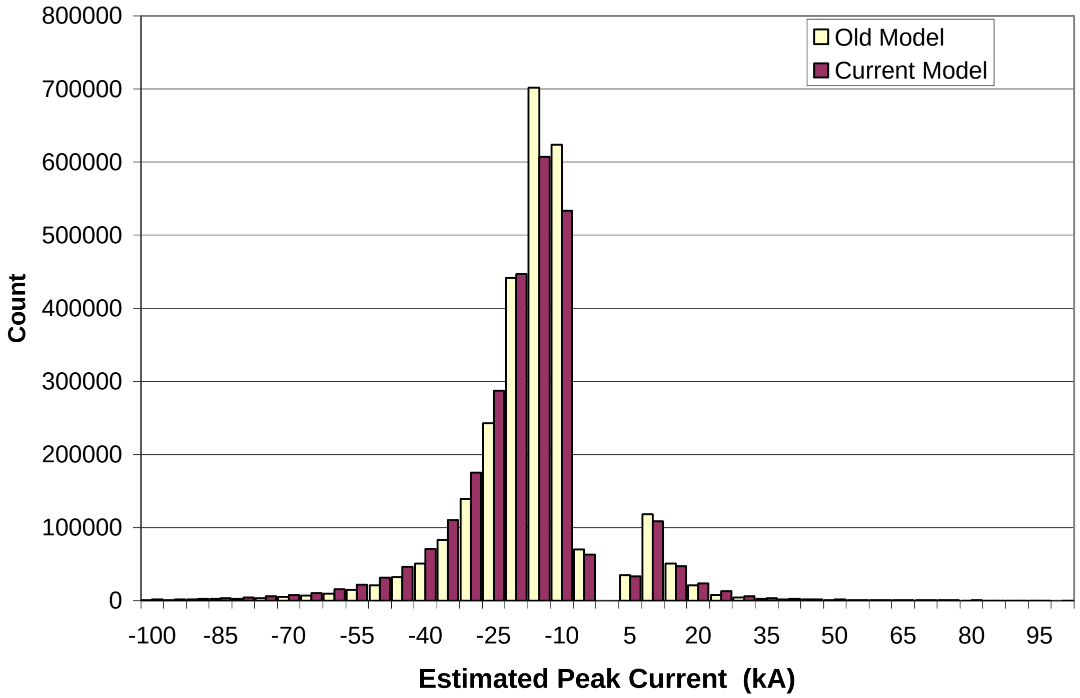

Figure 4 Sample estimated peak current distribution from the central US illustrating the effect of changing the propagation model parameters.

5. VALIDATION OF PERFORMANCE CHARACTERISTICS

5.1 Location Accuracy and Detection Efficiency

Measurement and validation of the DE and LA of the NLDN is complicated by the difficulty in obtaining definitive ground truth data with precise timing. Both before and after the current NLDN upgrade, the University of Arizona (UA) used GPS-synchronized video cameras in conjunction with broadband electric field and optical (light pulse) recordings to evaluate the NLDN performance at specific geographic locations (Kehoe et al., 2004; Biagi et al., in preparation). Ongoing examination of rocket-triggered lightning at the ICLRT at Camp Blanding, Florida has also provided essential ground truth data (Jerauld et al., 2005). The principal results of these validation studies are summarized below.

The modeled post-upgrade NLDN DE is presented in Figure 5. This figure shows the estimated minimum detectable peak current in the U.S. portion of the complete North American Lightning Detection Network (NALDN). Representing the detection capability in this manner reflects our growing understanding that there are significant regional and temporal variations in the CG flash characteristics (peak current and multiplicity). In order to model the NLDN DE, one must assume that there is a specific peak current distribution common to all regions. Unfortunately, the video-based validation studies by Kehoe et al. (2004) and Biagi et al. (in preparation) show that there can be factor-of-two variations in the average negative peak current from storm-to-storm, and large differences in the average stroke multiplicity. Biagi et al. have also found significant differences in the shapes of the negative first stroke peak current and multiplicity distributions between Texas-Oklahoma and Southern Arizona.

The three regions where video validation studies took place over the last three years are also shown in Figure 5. The region in Texas-Oklahoma (TX-OK) was selected because of its central location and proximity to Vaisala's Dallas test networks (Demetriades et al., 2002). The southern Arizona region (S. AZ) was selected because it was near the edge of the network (where performance can fall off) and has near ideal visibility, high cloud bases, and most storms are isolated. The Kansas-Nebraska-Colorado region (KS-NE) was selected because of its (unusual) large fraction of positive lightning (Carey and Rutledge, 2003), and because recent observations by Lyons and Cummer (2005) raised concerns about misclassification of small negative strokes in this region.

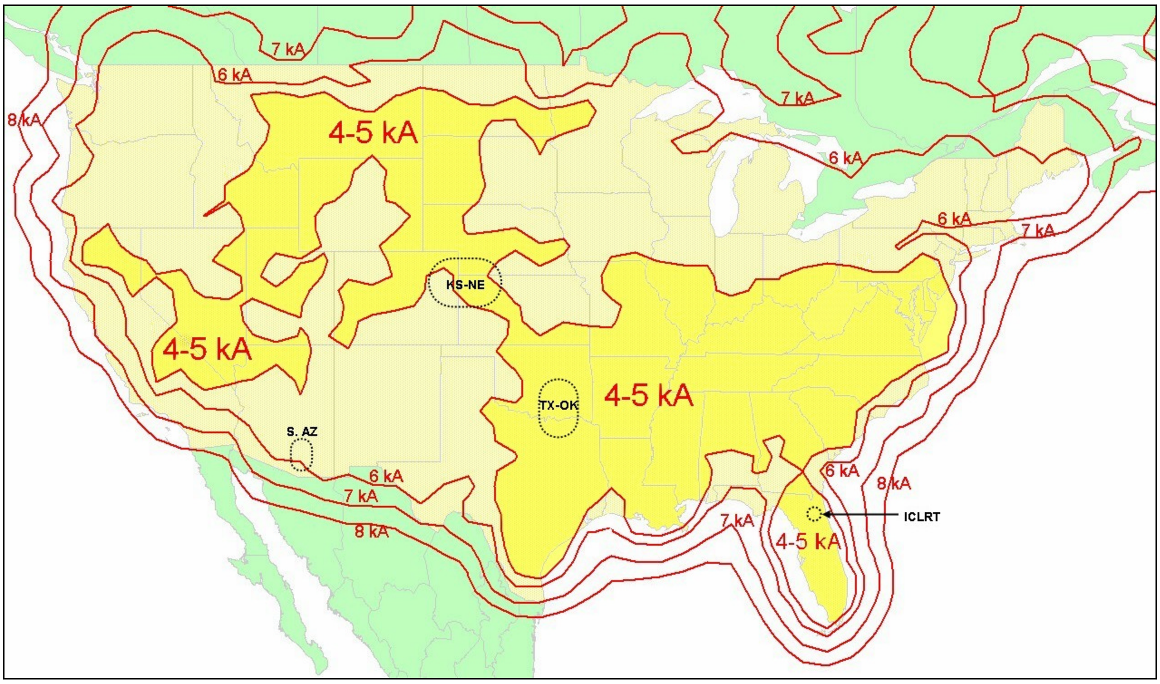

Figure 5 Estimated minimum detectable peak current for the upgraded NLDN. Validation studies in 2003-4 were carried out in the four small regions identified by black circles.

The UA camera studies in 2003-2004 evaluated both DE and LA in southern Arizona (S AZ) and in Texas-Oklahoma (TX-OK) after the upgrade. Both stroke and flash DE were studied. A flash was considered to be detected if at least one stroke in the flash was detected, and the results are summarized in Table 1. Measured flash DE near Tucson in 2001 (pre-upgrade) is included for reference; these data have been taken from video studies reported by Parker and Krider (2003) and Kehoe et al. (2004). Note the large number of flashes and strokes evaluated in 2003-2004 study. The stroke DE values from the video evaluation are thought to be ~11 percent high due to an inability to time-resolve strokes with interstroke intervals below the 16.7 ms video field time. This problem does not impact the flash DE values. It is interesting to note that the flash DEs in the two regions are nearly identical, even though the estimated minimum detectable peak current is 1-2 kA higher in southern Arizona (see Figure 5). This observation is thought to reflect the difference in first-stroke peak current distributions in these two regions; namely, southern Arizona does not seem to have as many negative first strokes with very small (4-6 kA) estimated peak currents. This observation should not be biased by the NLDN's inability to detect small strokes events in these regions, because the flashes in question are selected on the basis of their visibility on video. If anything, the poorer visibility in Texas and Oklahoma would produce a loss of small first strokes in that region.

LA in this study was assessed by computing the position differences reported by the NLDN between first strokes (of negative flashes) and any subsequent strokes that followed the same channel to ground (based on video observation). This measure of LA principally reflects the random error in location, since any location-specific propagation related (bias) errors are implicitly excluded. The reported location error is the measured position difference scaled down by v2 to compensate for the involvement of two measurements with (assumed) independent random errors. These results are also summarized in Table 1. The mean error in southern Arizona (424 m) is not as good as in Texas and Oklahoma (282 m), and this is expected because southern Arizona is on the edge of the network, and the geometry of the NLDN is not as good for locating lightning (sensors on one side of the location, rather than "encircling" the location).

A detailed report on the Florida ICLRT validation study is provided in Jerauld et al. (2005). This study included data for the summers of 2001-2003. Although this study only validates performance at a single location, it represents a particularly challenging region for the NLDN. Geographic constraints to the east and west limit the number of sensors that are close enough to participate in lightning locations in this region.

Due to the nature of rocket-triggered lightning (RTL), only return strokes thought to be similar to natural subsequent strokes are evaluated. The observed subsequent stroke DE increased steadily from 2001 to 2003, with a value of 69% (34/49) in 2003 (see Table 1). The RTL-based flash DE is probably an under-estimate of the natural flash DE in Florida, since these flashes do not include a natural first stroke. We estimate the natural flash DE by viewing the RTL flash DE as the probability of detecting any subsequent stroke, and then relating overall flash DE to the RTL DE using the equation

$$DE_{fl} = DE_{1st} + (1 - DE_{1st}) * DE_{rtl} \qquad (2)$$

where

$DE_{fl} =$ Natural Flash Detection Efficiency

$DE_{1st} =$ Natural First Stroke Detection Efficiency

$DE_{rtl} =$ Rocket triggered Flash Detection Efficiency ("any-subsequent stroke" DE)

The rationale of this equation is that a flash is detected if either NO subsequent strokes are detected and only the first stroke is detected (e.g., DE_{1st}), or NO first stroke is detected and one or more subsequent strokes are detected (e.g. the second term in Equation (2)). If we make the conservative assumption that the first return stroke DE is the same as the average individual stroke DE for rocket triggered lightning (it is thought to be even higher), the estimated flash DE values in Table 1 are obtained. Although there are only a small number of flashes in these studies, the flash DE results are consistent with other regions and with Vaisala's estimate of 90-95% within the interior of the US.

Location accuracy can also be measured using rocket-triggered ground truth data. NLDN model projections provide an expected median location accuracy of 500 meters for most of the US, including the Camp Blanding area. The observed median value of location accuracy for the 2001 (pre-upgrade) and 2003 (post-upgrade) ICLRT data supports this expected value, with measured values of 270m and 450m, respectively (Table 1). The difference between the two years is probably a result of the small sample sizes. As in the earlier study by Idone et al. (1998), the Camp Blanding study also shows that the confidence ellipse values available with each NLDN stroke location are a conservative measure of LA. The ellipse values are at the 50% (median) confidence level, where half of the actual event locations are expected to fall inside the boundaries of the ellipse. The Camp Blanding measurements indicate that 66% of the strokes were actually located inside the 50% confidence ellipse boundaries, and that 96% of the strokes were located within the 90% confidence level (computed from the NLDN ellipse information). This suggests that the network is somewhat more accurate in northeast Florida than projections indicate.

Several events in 2002 in the Camp Blanding study had location errors of several km (Jerauld, et al., 2005). These events had small estimated peak current values and were only seen by the two closest sensors. During much of the 2002 RTL season, an LPATS sensor in the Florida panhandle was not operational. This contributed to the poor geometry that caused the poor location accuracy for these events. In 2001, these small magnitude events were not detected, since the two closest sensors had not been upgraded. By 2003, all sensors in Florida had been replaced by an IMPACT-ESP. This resulted in better location accuracy for small magnitude events.

Table 1. Summary of Results from NLDN Validation Studies

Test Region and period	***Median Location Accuracy (m) (count)***	***Stroke Detection Efficiency (%) (count)***	***RTL "Flash: DE (%) (count)***	***Flash Detection Efficiency (%) (count)***
Tucson 2001	--	--	--	73[a]
S. AZ 2003-4	424[b,c] *(667)*	76 (*3620*)	--	93 (*1097*)
TX-OK 2003-4	282[b,d] *(193)*	85 (*885*)	--	92 (*367*)
Florida RTL 2001	270[e] *(17)*	52 *(33)*	82 *(11)*	91[f] *(11)*
Florida RTL 2003	450[e] *(34)*	69 *(49)*	84 *(12)*	95[f] *(12)*

[a] Obtained from Kehoe and Krider (2004)
[b] Median position difference, divided by v2 due to the involvement of two random variables
[c] Data only from 2003
[b] Data only from 2004
[e] Median location error for subsequent strokes
[f] Estimated flash DE, using Stroke and RTL DE values in equation (2)

5.2 Misclassified Events

The NLDN upgrade has increased the detection of lower amplitude sources, and thereby increased the potential for misclassified cloud discharges. The UA campaigns in S. AZ and TX-OK suggest that most (~90%) of the positive small events (<10 kA) are actually cloud discharges and that most (~90%) larger positive events (>20 kA) are likely to be CG strokes. The (small) population of positive discharges between 10-20 kA are a mix of CG and cloud discharges. Although further work is required, these studies also indicate that most clearly-identifiable negative polarity reports with estimated peak current < 10 kA are CG flashes in S AZ and TX-OK, although the studies were hampered by low visibility and the limited dynamic range of the camera.

During the summer of 2004, the UA carried out a 2-week field campaign in the region of Colorado-Kansas-Nebraska (KS-NE) shown in Figure 6 that focused on evaluating lightning classification in this "positive dominated lightning" region. Although the analysis in this region is incomplete, it can be said that a majority of the small (<10 kA) negative discharges in the positive-dominant storms are cloud discharges. This finding is consistent with a study by Johnson et al. reported at this conference. Prior to the recent upgrade, most of these cloud discharges were either below the NLDN detection threshold or were excluded by the waveform discrimination criteria in the IMPACT sensors. The improved network sensitivity coupled with modifications for the reporting of cloud lightning has clearly provided a capability of detecting cloud discharges, but unfortunately many of them are misclassified.

6. SUMMARY AND FUTURE PLANS

The NLDN now consists of a homogenous network of IMPACT-ESP sensors that provides both time-of-arrival and direction-of-arrival measurements, and improvements in the data processing algorithms have also been implemented. Performance projections indicate the ability to detect discharges as small as 4-5 kA in most regions of the network. Validation studies have shown Flash DE to be between 90-95% in a number of regions, and location errors less than 500 meters. The largest improvements in the NLDN detection capability are in regions near the edge of the network, including the state of Florida, the gulf coast, the west coast, and U.S./ Mexico border region.

The improved detection of small events has resulted in an ability to detect some cloud discharges but some cloud pulses are misclassified as CG strokes. It is clear that the current IC:CG classification methods in the NLDN need to be improved, and more sophisticated classification methods are being examined by Vaisala. Vaisala also plans to add an "ambiguous" category for events that cannot be clearly identified as "cloud" or "cloud-to-ground" pulses. Although this is not intended to be a long-term solution, it can provide the user with additional information that might be useful in warning applications, and the "ambiguous" events can be removed for users that require a "cloud-free" dataset. Finally, the observed decrease in the number of flashes with estimated peak currents greater than 200 kA (roughly 1 in 10,000) that began early in 2002 is understood and will be corrected in the near future.

Verification of NLDN performance characteristics will continue. The Camp Blanding rocket-triggered lightning experiments have been a key source of ground truth for several years, and should continue to provide useful information. The University of Arizona study will complete its analysis of data acquired in the KS-NE region, and will continue to make video studies. These and other investigations will continue to ensure that NDLN performance characteristics are properly validated.

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