RECENT UPGRADES TO THE U.S. NATIONAL LIGHTNING DETECTION NETWORK

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1. INTRODUCTION

The National Lightning Detection Network (NLDN) has been in operation since 1987. The network has been upgraded several times since the original equipment installation, each resulting in improved reliability and performance. The latest of these upgrades was initiated in late 2001. This paper describes this upgrade and subsequent network validation activities.

The history of the network has been described by Cummins et al. (1998). Although the 1995 upgrade produced a significant improvement in location accuracy (LA), both LA and detection efficiency (DE) fall off near the edges of the network. The addition of the Canadian Lightning Detection Network in 1997 eliminated these limitation 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 were getting difficult to obtain, creating a support problem. The LPATS III sensor was the predominant sensor employed in the NLDN at the time, comprising roughly 60 percent of the total sensors. Since the 1995 upgrade, there have been significant improvements in sensor technologies. These and other factors contributed to the decision to upgrade the NLDN to a single sensor type, the IMPACT-ESP.

The upgrade goals were to increase sensor reliability and reduce maintenance costs, to provide enhanced DE and LA on the boundary of the network, and to provide some level of LF cloud detection capability. Use of a single sensor that provided both accurate time-of-arrival (TOA) and azimuth information (from magnetic direction finding) allowed these goals to be met.

In subsequent sections we review the operation of the NLDN, describe the IMPACT-ESP sensor, report on location algorithm changes completed before and during the current upgrade, and discuss validation studies carried out by Vaisala, the University of Arizona and the University of Florida. The problem of misclassified cloud events is examined as well.

2. NLDN OPERATIONAL - OVERVIEW

The operation of the National Lightning Detection Network has been described before [Cummins et al, 1998]. This section provides a brief review, as an update to information previously presented.

Individual sensor data is transmitted from remote sensors (1) via a satellite link (2). The downlink site (3) forwards data via an internet link to the Network Control Center (NCC) in Tucson (4). Here the data is processed and archived. Lightning data are forwarded using both terrestrial and satellite links to customers (5-6) within 30-40 seconds.

Congestion of the sensor communications links has occasionally been a problem in the past. The result of this congestion was for some data to arrive too late at the NCC to be used in real-time processing. The links between the downlink site and the NCC have been upgraded in an effort to minimize this issue. While weather related communications issues can still lead to late data and possibly missed events in the real-time datastream, rate-based congestion has largely been eliminated from the network. Reprocessed data still tends to have a slightly larger number of events in the summer months - now normally on the order of 1 to 2 percent.

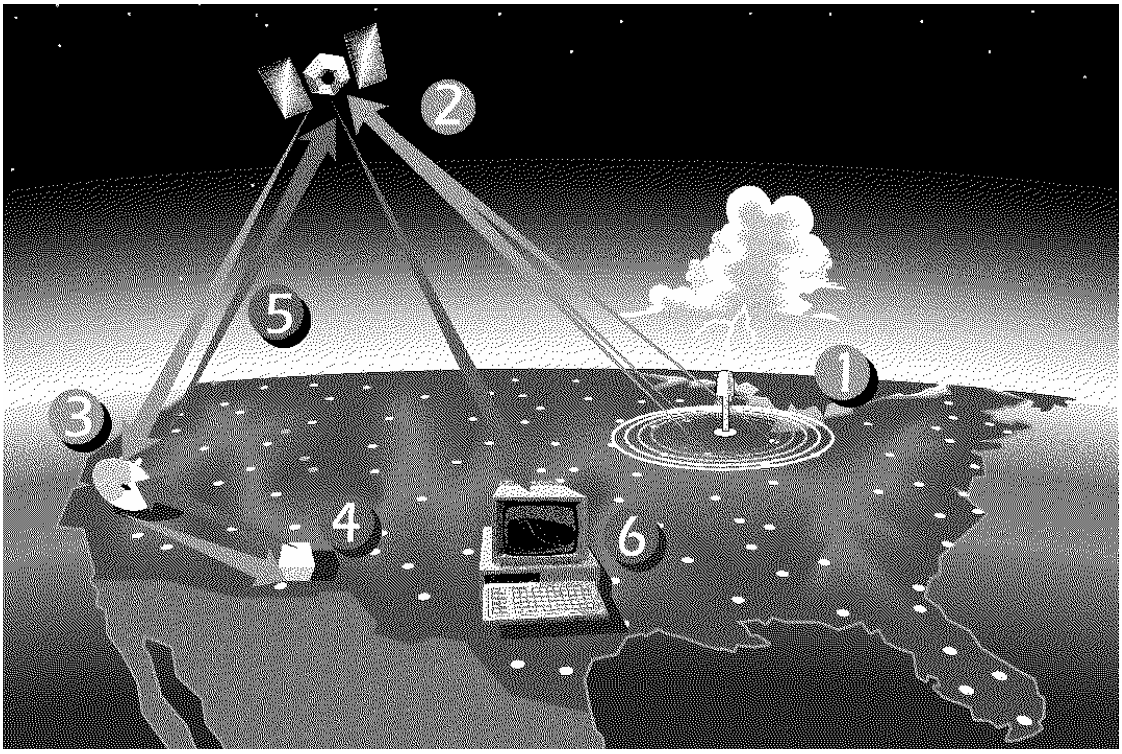

Figure 1. NLDN data and processing path

The procedure for initial calibration and maintenance of the Magnetic Direction Finding (MDF) site errors has also been improved. Site errors are continuously monitored, and they can now be quickly corrected. In the past, corrections for relocated or modified sites might not be implemented for up to a month after the change. With the implementation of new software, site error corrections can be quickly verified and applied within a few hours of data collection.

3.NLDN UPGRADES

3.1 Sensor Technologies

Prior to the 2002 upgrade, the NLDN consisted of a mixture of 63 LPATS III sensors, which provided only TOA information, and 43 IMPACT sensors, which combined TOA and information. The recent upgrade consisted of replacing all sensors in the network with modern IMPACT-ESP sensors. This 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 the effect this upgrade has on the network we examine each of these refinements separately.

The improved analog front end reduces noise, and allows for better detection of small amplitude signals. This has the direct affect of improving detection efficiency, especially for small peak current events.

Older sensor technologies had significant deadtime after an event was detected. This was due to the time required to process and report the event. Impact ESP sensors have a deadtime on the order of one millisecond. This performance increase is especially significant when a network is detecting both cloud (CLD) and cloud-to-ground (CG) events.

Configurable waveform and noise-rejection criteria allow the ESP sensor to reject or accept different waveform shapes (as a function of angle and signal strength), and to categorize the event as CLD or CG based on a set of rules that can be modified as needed.

The most significant change to the network is the fact that all sensors provide both TOA and directional information. This means that only two sensors are required to locate an event, and that the resulting location is computed with “excess” information (one degree of freedom). Prior to this upgrade, 3-4 sensors were required in order to compute a location, since 60 percent of the sensors in the network only provided TOA information. This change allows the network to detect much small events, such as small subsequent strokes and large cloud discharges. In addition, since all sensors now include magnetic field measurements, the peak field measurements do not require calibration, and are more accurate than in the past. This improves the peak current estimates provided by the NLDN.

3.2 Location Processing Algorithms

The locations of lightning strikes are calculated in the same manner as described in earlier documents [Cummins et al., 1998]. Refinements have been added to reduce CLD events being miscategorized as CG events, and to minimize false solutions associated with miscorrelation of sensor reports. In addition, models accounting for propagation have been modified to increase the accuracy of peak current estimates.

The pre-upgrade configuration of the NLDN's location algorithm required unanimous agreement among sensors classifying an event as a CLD discharge. Two modifications have made to this rule. First, we now employ a “best” subset of reporting sensors to identify the event as CLD. In addition, we have refined the waveform classification method that separates CLD and CG events. These changes reduce the number of miscategorized events, but do not eliminate the problem. Unfortunately, due to the enhanced sensitivity of the IMPACT-ESP sensors, the actual percentage of miscategorized CLD events is larger than before the upgrade. We have reduced the percentage of “large” (>10 kA) misclassified positive discharges, but there are a large number of small (<10 kA) positive discharges that appear to be misclassified. As will be illustrated in the network validation section, it is very likely that any positive event with a positive peak current less than 10 kA is a cloud discharge.

In addition to modifications to the cloud processing parameters, a number of checks were incorporated into the location algorithm to reduce the likelihood of reporting a “false” or “misplaced” (outlier) solution as a valid event. These checks verify consistency among the various pieces of information that contribute to a solution, and have minimal impact on solutions which have consistent data.

The final algorithm change associated with this upgrade involves peak current estimates. The estimation of peak current relies on the accurate modeling of propagation related attenuation for each sensor. In the past, with sensors having less sensitivity, the NLDN used a simple power-law model to compensate for signal attenuation due to propagation (Orville et al., 1991; Idone et al., 1993). The increased sensitivity of IMPACT-ESP sensors prompted the reinvestigation of this model. As noted in past work [Cummins, et al. 1998], range normalized signal strength is obtained using the formula

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

where RNSS is the range normalized signal strength, 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 (10^5 km), and the attenuation exponent was 1.13. This set of model parameters was sufficient for lightning events that were located within 400 km of a sensor, but they underestimated 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 estimates of propagation losses.

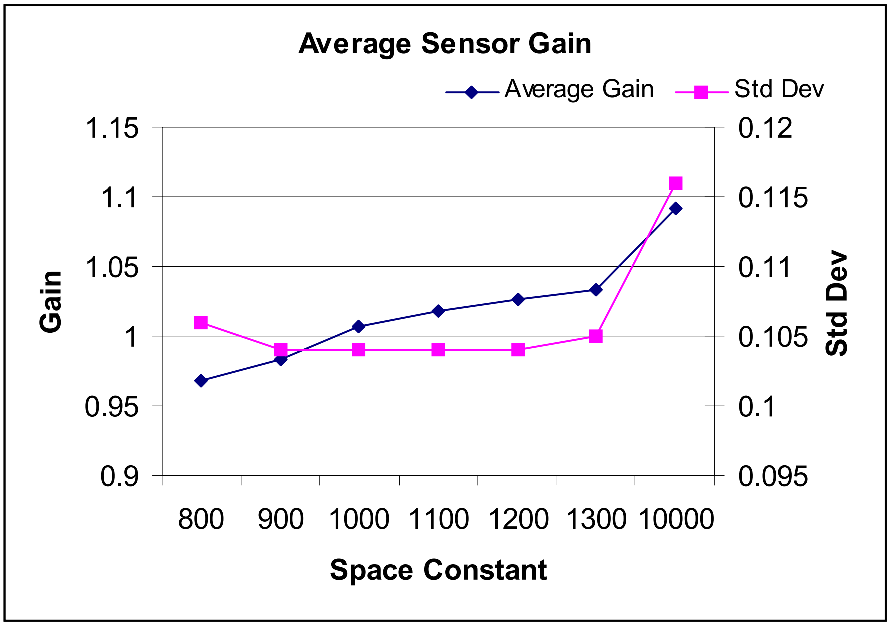

Figure 2: Sensor Gain and Standard Deviation for various model parameter values. For the one condition having a space constant of 10000, p=1.13; elsewhere, p=1.

By varying space constant (A) while monitoring the average of all sensor gains, the best value can be found. The (relative) gain that can be computed for each sensor is the ratio of the RNSS reported by that sensor, to the overall average of all sensors that report the same lightning event. The mean value of these individual relative 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 yields a mean gain of very close to unity, and minimizes the standard deviation of that statistic. Figure 1 shows the results obtained for several values of A. The best results are obtained with A set to 1000 km. Note that the mean value for the prior model parameters (p=1.13; A=10^5) 9.2% larger than 1. Changing to the new model parameters (p=1; A=1000) reduces the random error by 11% (the ratio of the two standard deviations).

This change also has some effect on the overall peak current distribution. Sample distributions taken from the central U.S. before and after the change are presented in Figures 3. The mean value for negative flashes has increased from –16.7 kA to –18.8 kA (12.6%), and the median value has increased from –13.6 kA to –15.2 kA (11.8%).

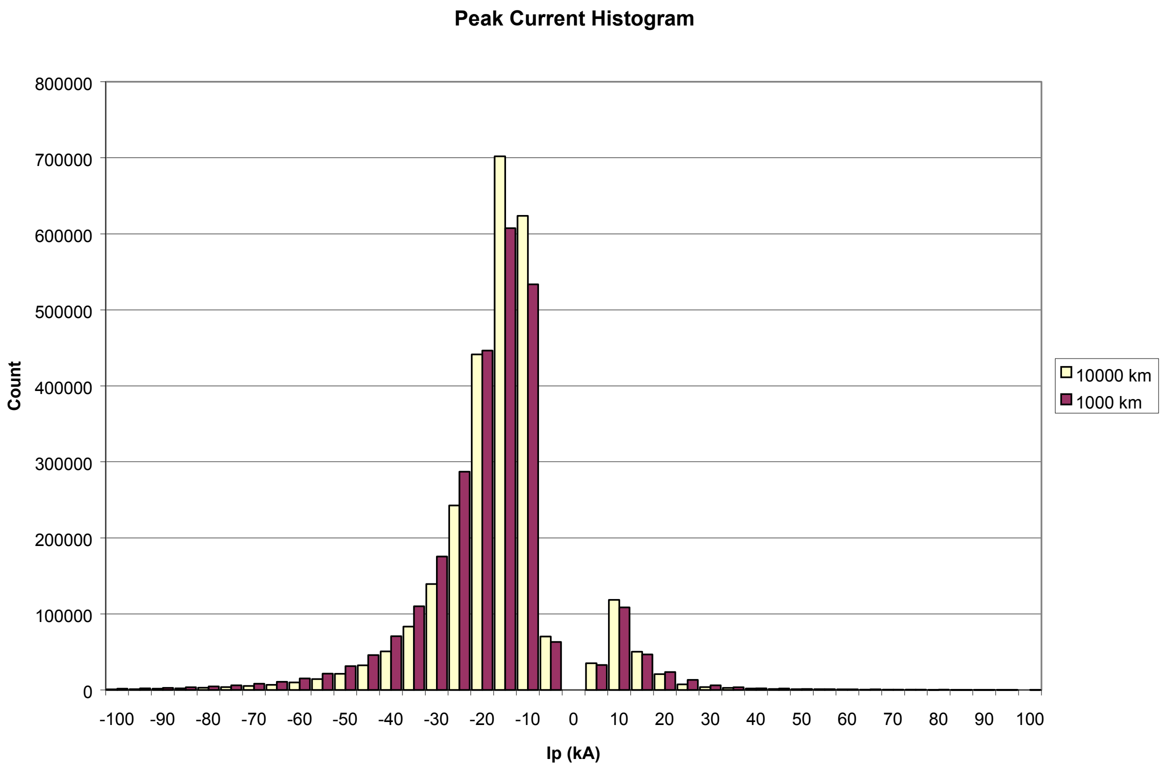

Figure 3: Comparison of Peak Current Histograms using Exponential Vs. Power Law method of computing propagation attenuation. The 10000 km space constant used p=1.13, while the 1000 km space constant used p=1.

4. UPGRADE DESIGN AND LOGISTICS

The network upgrade was planned to take advantage of existing NLDN sensor locations whenever possible. Emphasis was placed on increasing sensor densities in urban regions where the improved network performance would be most beneficial. It was expected that these concentrations of sensors would provide the opportunity to detect a small fraction of cloud events. To accomplish this, several new sensor sites where selected.

To select new sensor sites, and validate the existing locations, procedures and equipment were developed to evaluate the electromagnetic environment. Spectrum analysis was performed using data from each site to determine the existence of potential interference sources. For existing sites, maintenance histories were examined to ensure that retained sites had no long-term issues. LPATS sensor locations received special scrutiny, since the siting requirements for these sensors are not as strict as those of an MDF sensor. Sites that had a history of interference, and those that were unsuitable for MDF sensors were relocated.

Ten (10) existing sites were designated for relocation; 8 LPATS and 2 ALDF. 8 additional new sensor locations were identified. All former LPATS sensor sites, the relocated sites, and the additional new sites typically required extensive site preparation prior to the actual installation of the Impact ESP upgrade. Site preparation consisted primarily of civil works, such as: trenching for the laying of cable and conduit; pouring of cylindrical concrete mounting pads for the sensor and satellite dish; pouring of concrete pads for positioning of a trailer or fiberglass enclosure; electrical hookups; installation of roof mount hardware, as needed; and clearing of trees, if necessary. Simple site upgrades of former ALDF sensor sites usually required minimal site preparation.

The actual on-site upgrade process consisted of three or four phases:

1. New Sensor Site Selection – Surveying for ideal site conditions, negotiation of Site Lease Agreements, identification of site contact(s), and establishment of electrical power accounts.
2. Site preparation – Performed by a Vaisala field technician dedicated to performing civil works, as needed. This individual spent a significant portion of his time on the road and towed a large trailer filled with tools, equipment, and materials from site to site.
3. Installation of Impact ESP upgrade – Performed by Vaisala Customer Service Technicians or certified private contractors.
4. Decommissioning and de-installation of LPATS or ALDF sensors – Performed by Vaisala Customer Service Techs or certified private contractors.

To date, 108 Impact ESP sensors have been shipped, 107 have been installed and 5 of the 8 identified new sites are operational. 3 existing LPATS sites remain to be moved and upgraded, and 3 new sites are still to be completed. We estimate that over 350,000 miles were traveled, with more than 965 person days of effort.

Once initial installation was completed, the sensors were closely monitored to ensure correct operations. Site Error corrections were obtained as soon as possible, and network relative detection efficiency, gain and other parameters were examined daily. Once sufficient data was accumulated, each sensor was certified for normal operations. Automated monitoring after certification is ongoing, and provides early notification of sensor failure or site changes.

5. PERFORMANCE VALIDATION

The expected performance of the network is presented in Figures 4-5. Figure 4 shows the projected flash DE for the NLDN, as part of the North American Lightning Detection Network (NALDN). There is no longer a 5 kA lower limit on the estimated DE – it includes all flashes. Virtually all of the continental U.S. has >90% flash DE. Figure 5 shows the projected location accuracy. All areas except Southern Florida should have a median LA of 500m or better. If we are able to find an acceptable site in the Florida Keys, then Southern Florida will have 1 km or better LA.

Measurement and validation of the NLDN DE and LA is complicated by the difficulty in obtaining definitive ground truth data. Past investigations [Idone, et. al., 1998] have used networks of video cameras combined with electromagnetic waveform recordings. Both before and after this NLDN upgrade, video camera, electric field and optical recordings were used by the University of Arizona to validate performance at specific locations. Ongoing examination of rocket triggered lightning at the University of Florida's International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida are also providing ground truth data. In addition, media and eyewitness reports of lightning strikes have also been used to verify network performance.

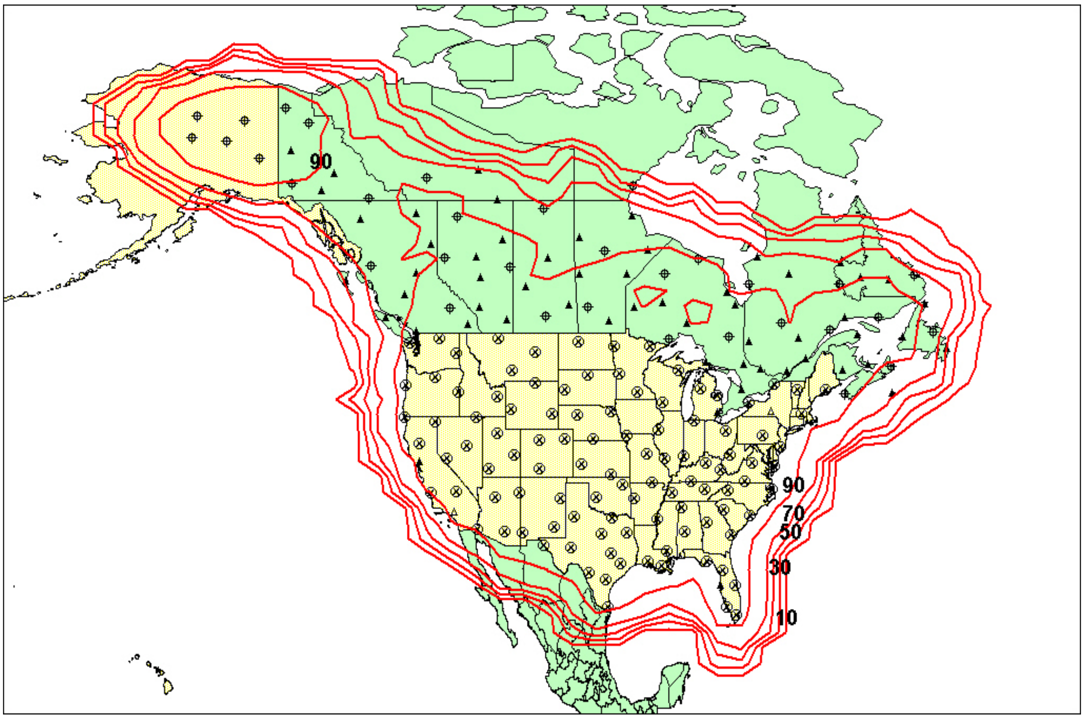

Figure 4: Post-upgrade (2003) NALDN Projected Flash Detection Efficiency

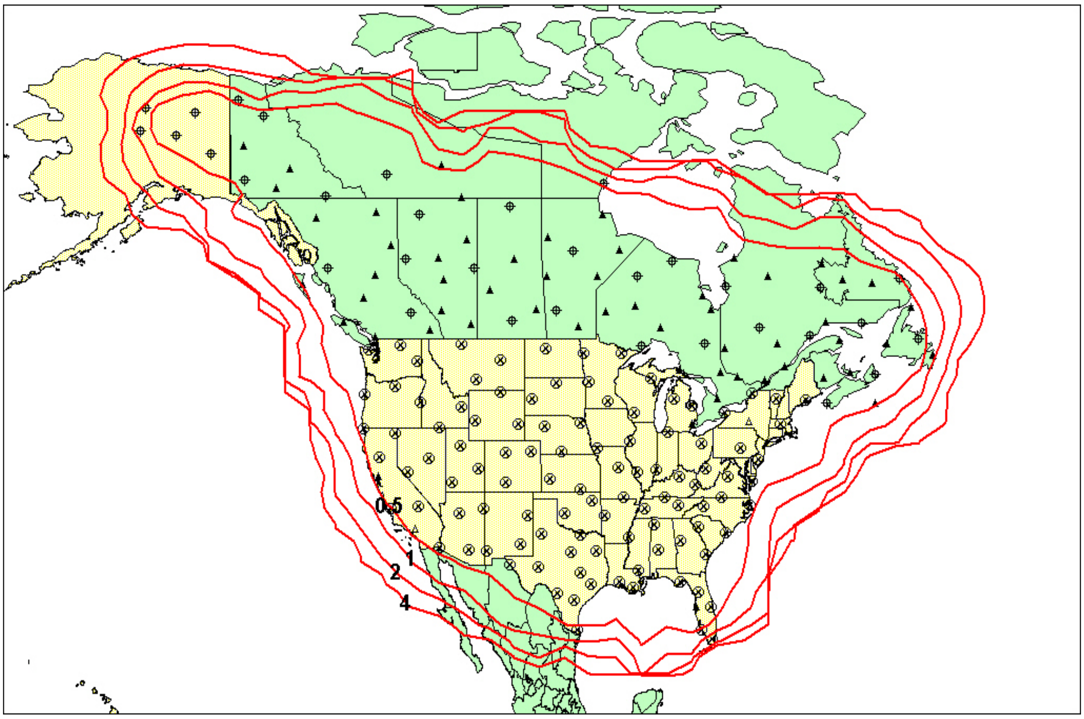

Figure 5: Post-upgrade (2003) NALDN Projected Location Accuracy

The University of Arizona's post-upgrade camera study was undertaken in both Arizona and Texas. The objectives for Vaisala and the NLDN were to investigate small positive events that were thought to be cloud contamination of the CG data, and to evaluate DE. Results from the Tucson region clearly show a large improvement in DE in this area, as reported by Krider and Kehoe at this conference. This region is on the boundary of the network -- an area that both models and measurements indicated poor DE before the upgrade. The UA study validates current network performance in the Tucson area (>90% Flash DE). Additional measurements are being made this summer in the Texas area in order to produce a sufficient data set for analysis in that area.

Rocket triggered data has been used in the NLDN to evaluate DE and LA, and for the calibration of peak current estimates. Results of LA analysis using Camp Blanding triggered data has been presented before [Cramer, et. al., 2001]. Although this method only validates LA in a single location (North-East Florida), this is a particularly challenging region of the NLDN. Geographic characteristics limit the number of sensors that are close enough to participate in solutions in this region. If the network models correctly reflect actual performance in this region, it is likely projections for the rest of the network are accurate. Camp Blanding results are presented in detail by Jerauld et al. at this conference, showing that the observed flash DE is consistent with the expected subsequent stroke DE. Note that triggered lightning events essentially match the characteristics of subsequent strokes, having a channel predefined by the triggering wire. They study by Jerauld et al. also found the errors in peak current estimates were about 20% or less. This will only improve with the inclusion of the new propagation parameters.

Location accuracy can also be measured using rocket-triggered ground truth data. NLDN model projections indicate an expected median location accuracy of 500 meters for most of the US, including the Camp Blanding area, as shown in Figure 5. The observed median value of location accuracy for the 2003 Blanding data supports this expected value. Examination of the error ellipse values also serves to confirm that NLDN models accurately reflect LA for individual events. The ellipse values provided with each located event are at the 50% (median) confidence level, where half of the actual event locations are expected to fall outside the boundaries of the ellipse. The Camp Blanding measurements indicate that 67% of the strokes were actually located inside the error ellipse boundaries. This suggests that the network is somewhat more accurate in Northeast Florida than projections indicate.

Evaluations of individual events indicate that ellipse orientation also predicts the direction that the actual event lies with respect to the computed position, even when the actual location lies outside the error ellipse. This is illustrated in Figure 6, where the semi-major axis of the ellipse for the event at 15:06:34.829 points in the direction of the actual location (the tower). Were this 50% confidence level ellipse to be scaled to the 90% level, this larger ellipse would enclose the actual strike location.

The peak current estimates provided by the NLDN were originally calibrated using rocket triggered measured peak current values. Recent investigations [Jerauld, et al., this conference] confirm that Camp Blanding's measured peak current values match very well with estimated peak current values produced by the NLDN. More details can be found in the referenced material.

In summary, the NLDN upgrade is essentially complete, and independent evaluations have shown the actual performance matches well with predicted values.

6. MISCLASSIFIED EVENTS

The upgrade has allowed the network to detect lower peak current events. The University of Arizona study has confirmed that most (~90 percent) of the positive small events (< 10 kA) are actually cloud discharges and that most larger positive events (>20 kA) are CG strokes. Although further study is required, their studies indicate that almost all of the negative polarity small peak current events (in Texas) are cloud-to-ground. It is clear that IC:CG classification methods need to be improved. More sophisticated classification methods are being examined. Plans are underway to develop an "ambiguous" category to assign those events that cannot be clearly identified as “cloud” or “cloud-to-ground”. While this is not intended to be a long-term solution, it can provide the user with some additional information, and the “ambiguous” class events can be removed for users that require a cloud-free dataset.

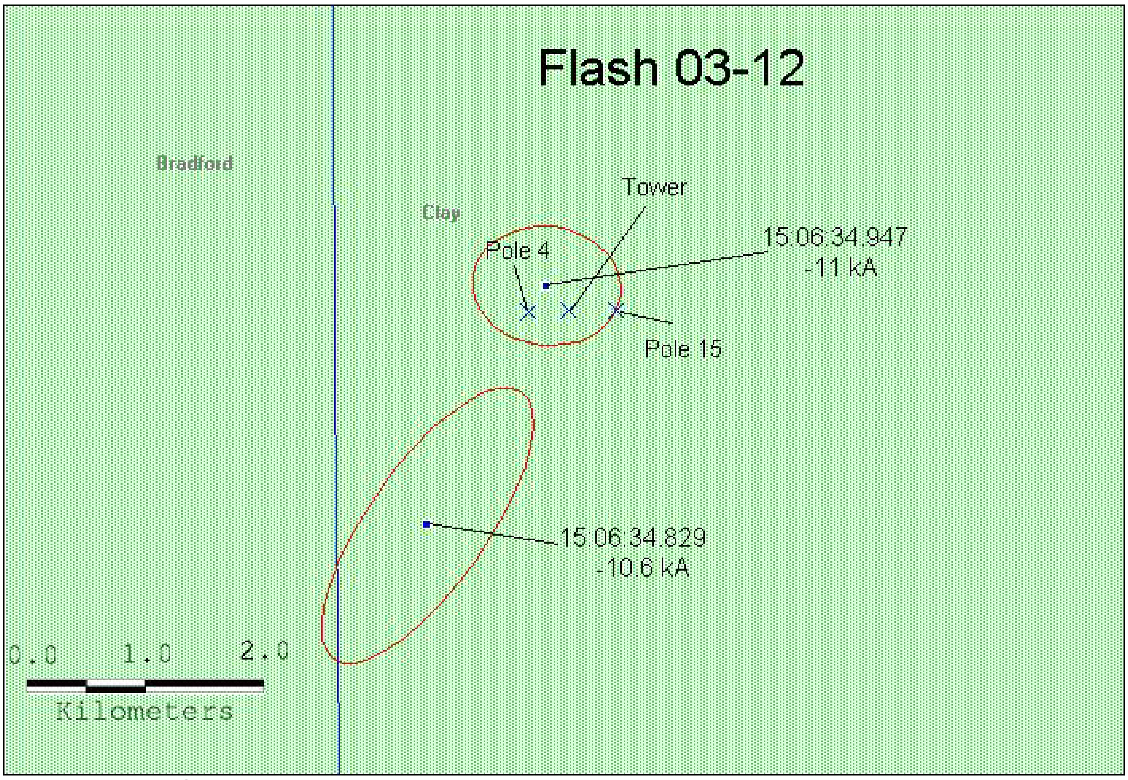

Figure 6. Ellipse Orientation example.

7. SUMMARY AND FUTURE WORK

The details of the latest upgrade the National Lightning Detection Network have been provided. The network now consists of a homogenous network of IMPACT-ESP sensors having both TOA and MDF capabilities, and processing improvements have also been implemented. Network projections indicate >90% Flash DE and 500 meter median location accuracy for virtually the entire United States. The most substantial improvements were in regions near the edge of the network, including the state of Florida, the Gulf Coast, and U.S./ Mexico border region. Validation studies to confirm network performance are ongoing, and initial results have met or exceeded expectations.

The cloud classification issue is a key area where work is ongoing. Investigations related to classification both at the sensor and during location processing are ongoing. Future sensor technologies will offer improved classification, both for elimination of the unwanted cloud event information in CG-only systems, and to assist in classification for total lightning systems. Location processing algorithm improvements are being developed which will better handle cloud events.

Performance verification work will also continue. The Camp Blanding rocket triggered lightning has been a key source of ground truth for several years, and should continue to be important. The University of Arizona study will continue in Texas. These and other investigations will continue to ensure network performance is maintained at the quality level that exists now.

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