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A Combined TOA/MDF Technology Upgrade of the U.S. National Lightning Detection Network

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Abstract. The U.S. National Lightning Detection Network™ (NLDN) has provided lightning data covering the continental United States since 1989. Using information gathered from more than 100 sensors, the NLDN provides both real-time and historical lightning data to the electric utility industry, the National Weather Service, and other government and commercial users. It is also the primary source of lightning data for use in research and climatological studies in the United States. In this paper we discuss the design, implementation, and data from the time-of-arrival/magnetic direction finder (TOA/MDF) network following a recent system-wide upgrade. The location accuracy (the maximum dimension of a confidence region around the stroke location) has been improved by a factor of 4 to 8 since 1991, resulting in a median accuracy of 500 m. The expected flash detection efficiency ranges from 80% to 90% for those events with peak currents above 5 kA, varying slightly by region. Subsequent strokes and strokes with peak currents less than 5 kA can now be detected and located; however, the detection efficiency for these events is not quantified in this study because their peak current distribution is not well known.

Introduction

The U.S. National Lightning Detection Network (NLDN) began in 1987, when data from regional networks covering the western United States [*Krider et al.*, 1980] and the Midwest [*Mach et al.*, 1986] were merged with the University at Albany (UA) network (so-called SUNYA/EPRI network) [*Orville et al.*, 1983; *Orville and Songster*, 1987] to provide lightning information on a national scale. This network began real-time operation in 1989 [*Orville et al.*, 1990; *Orville*, 1991b]. The sensors in this network were gated, wideband magnetic direction finders (MDFs) that were manufactured by Lightning Location and Protection, Inc. (LLP) and were designed to sample return stroke waveforms in cloud-to-ground (CG) lightning [*Krider et al.*, 1976, 1980]. At about the same time, a network of time-of-arrival (TOA) sensors manufactured by Atmospheric Research Systems, Inc. (ARSI) was installed nationwide [*Lyons et al.*, 1989; *Casper and Bent* 1992]. A brief history of lightning locating systems is given in *Krider* [1996].

The principal catalyst for developing the NLDN began in 1983, when the electric utility industry recognized the operational benefit of locating CG lightning and therefore funded the expansion and operation of the east coast UA network through the Electric Power Research Institute (EPRI). Combining the three separate networks into a national network was carried out with the assistance and encouragement of the U.S. Federal Coordinator for Meteorological Services. By 1991, there was sufficient commercial interest in national-scale lightning information to justify the establishment of a commercial data service company. To meet this need, GeoMet Data Services, Inc. (GDS) was formed by EPRI and LLP. Today, GDS, LLP, and ARSI have been combined to form Global Atmospherics, Inc. (GAI), a wholly owned subsidiary of the Sankosha Corporation.

The growing uses of NLDN data over the last 6 years have led to a demand for improving the location accuracy, the percentage of lightning discharges that are detected (detection efficiency), and estimates of the peak current for all strokes in CG flashes. These demands have led to an upgrade of the network that was jointly funded by EPRI and GDS. There were four principal objectives of the NLDN upgrade. The primary objective was to improve the location accuracy of the network in order to meet the growing needs of the electric utilities. The second was to provide an infrastructure that could process and deliver both stroke and flash information in real-time. The third was to improve the detection efficiency for strokes with peak currents of 5 kA and greater, and the final objective was to improve the long-term reliability of the NLDN. The upgrade involved combining MDF and TOA detection methods using sensors manufactured by both ARSI and LLP.

The purpose of this paper is to describe the improved NLDN. We first discuss the combination of MDF and TOA sensors, the resulting hybrid network, and the improved signal processing algorithms. We then compare the expected performance of the current NLDN with that of the original NLDN. We also review the independent evaluations of the network's performance that are based on multiple-camera video studies of storms in New York and on rocket-triggered lightning and MDF measurements in Florida. A summary of the network coverage and performance improvements over the last 5 years is also presented, and the effects of the locating system performance on reported lightning parameters are discussed.

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NLDN Operations and Communications

A graphical representation of the real-time NLDN operation and data flow is shown in Figure 1. Ground-based sensors trans-

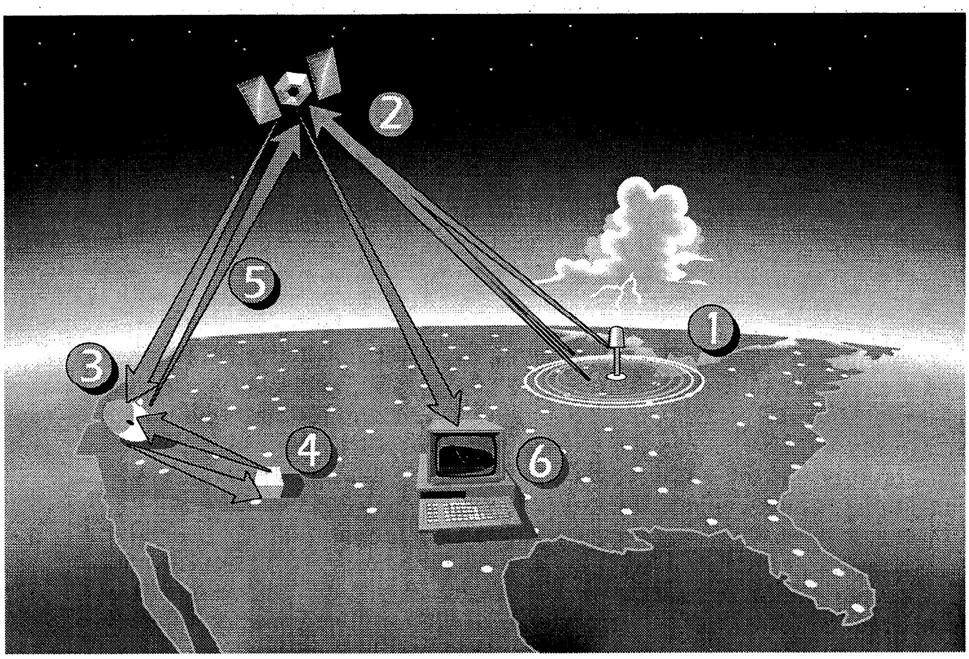

Figure 1. Data flow in the NLDN (see text for a description).

mit salient information (1) to the Network Control Center (NCC) in Tucson, Arizona, via a two-way satellite system (2-3). Data from the remote sensors are processed in the NCC (4) to provide the time, location, and peak current of each detected discharge. This processed information is then sent back out the communications network for satellite broadcast dissemination (5) to real-time users (6). All this takes place within 30-40 s of the lightning discharge. This delay consists of a fixed, 30-s hold time and a variable processing and communications delay. Cloud-to-ground flash information with 0.1-s time resolution is distributed via the satellite broadcast link. Higher resolution flash and stroke data are available through other communications links. Data are also reprocessed within a few days of real-time acquisition and archived in a permanent database that can be accessed by users who do not require real-time data. The NCC and real-time data delivery system have an uptime that typically exceeds 99.5%.

The real-time data are subject to two sources of error that do not affect the reprocessed data. These sources are sensor calibration errors and communications delays. Calibration errors consist of systematic MDF site errors [*Mach et al.*, 1986; *Passi and Lopez*, 1989] and peak field amplitude calibration errors. Corrections for these errors can only be obtained after sufficient lightning data have been accumulated (typically after 1 to 3 months of operation). Prior to applying the corrections, the information from uncalibrated sensors is either ignored or deemphasized by the lightning locating algorithms. Sensor calibration errors in the real-time data are limited to periods when the network is undergoing major changes that involve installation or relocation of sensors. Corrective calibrations are always implemented prior to data reprocessing. The last such period occurred during the upgrades described in this paper. Sensor communications delays result from rain fade or data congestion during periods of high data rates. These delays typically occur if the lightning rate over the entire United States exceeds 35000-50000 flashes per hour. In these situations, the reprocessed data typically contain 2 to 5% more strokes than the real-time data. Once or twice a year, the reprocessed data contain up to 20% more strokes for periods of an hour or less.

NLDN Sensors

Most of the methods for locating CG lightning are based on either MDF or TOA methods, as summarized by *Krider* [1996]. In 1992, LLP developed a lightning location method for combining MDF and TOA information that is referred to as the improved accuracy from combined technology (IMPACT) method. This method can employ information from TOA sensors, MDF sensors, and IMPACT sensors, which measure the arrival times and directions of all strokes.

The upgraded NLDN contains 59 of the TOA sensors from the original ARSI national network (Lightning Positioning And Tracking System, LPATS-III, sensors) and 47 IMPACT sensors. The locations of these sensors are shown in Figure 2. Both types of sensors were modified before their installation in the NLDN.

Figure 2. NLDN sensor locations. Triangles represent IMPACT sensors, and circles show LPATS sensors.

For example, the gain of the IMPACT sensor was increased, the trigger threshold was reduced, and the waveform acceptance criteria were changed to allow the detection of more distant lightning. The LPATS sensors were sometimes triggered by nearby cloud discharges and leader pulses, and to reduce this problem, the sensor gains were reduced and various waveform selection criteria, similar to those used in the IMPACT sensors, were added. As a result of these modifications, both sensor types detect CG flashes with similar sensitivity and discrimination.

In the early 1990s, several IMPACT sensors were placed in the existing NLDN for calibration and testing purposes. Prior to the upgrade, the gain of the IMPACT sensors relative to the original NLDN sensors was determined. After the upgrade, gain corrections were derived for the LPATS sensors to normalize their signal strengths to the values reported by the calibrated IMPACT sensors. In this way, the peak current estimates of the original NLDN were not changed by the upgrade.

As part of the upgrade, in 1995, the total number of NLDN sensors was reduced from over 130 to 106 because of an increase in the effective range of the sensors. The effective range of a sensor has been quantified by its network-relative detection efficiency (NRDE), a measure of the sensor's performance in the network. The NRDE is defined as the ratio of the number of strokes detected by the sensor to the number of strokes detected by the network and is typically computed as a function of range. Figure 3 shows how the changes to the IMPACT sensor have affected its NRDE. In Figure 3 the solid curve is for a standard IMPACT sensor, and the dashed curve is for a sensor that has been modified for use in the NLDN. Both sensors were in the center of the network, and both characterizations were made in the early 1990s, when the network was in its original configuration. Owing to this improvement in sensor range, it was possible to increase the typical sensor baselines to values between 275 and 325 km.

Location and Stroke Processing Algorithms

Data from the 106 NLDN sensors are used to compute an optimum lightning location using the least squares method described by *Hiscox et al.* [1984]. In its original form, this optimization procedure minimized an unconstrained error function that was the sum of the squares of the angle deviations. The angle deviation is the difference between the angle measured by the reporting sensor and the angle from the sensor location to the optimum stroke location. This error function, when normalized by the expected angle error and degrees of freedom, is referred to as the normalized chi-square. The best estimate of the stroke location (latitude and longitude) is determined by iteratively moving the stroke position along the surface of an oblate spheroidal earth (WGS-84) in the direction of the gradient of the error until a minimum is found.

The IMPACT generalization of the location algorithm operates in much the same manner except that, in addition to stroke location, the time at which the return stroke begins at the ground is also estimated, and there is an additional term in the error function for each sensor that contributes precise timing information. The accuracy of the estimated stroke time is determined by the overall timing errors of the reporting sensors and has a standard deviation of approximately 1.0 μs. The relative contribution of timing and angle errors to the total chi-square value is determined by taking into account their individual measurement errors, expressed in the form of standard deviations. The various algorithms are described in greater detail by *Cummins et al.* [1993]. The improved location algorithm overcomes many of the problems that are inherent in either an MDF or a TOA method taken alone. For example, a discharge that occurs along the baseline between two IMPACT sensors will be more precisely located by the intersection of two azimuth vectors and two range circles than by the azimuth intersection alone [*Cummins et al.*,

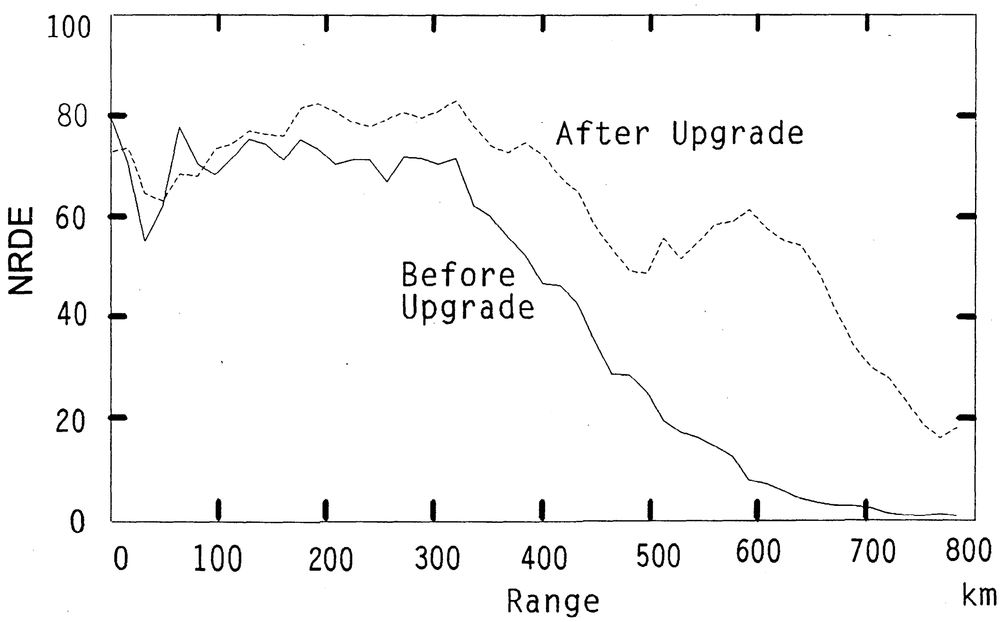

Figure 3. Network-relative detection efficiency of standard IMPACT sensor (solid line) and IMPACT sensor with increased gain, reduced trigger threshold, and improved waveform acceptance criteria (dotted line) as functions of range. Network relative detection efficiency is defined as the ratio of the number of strokes detected by the sensor to the total number of strokes detected by the network.

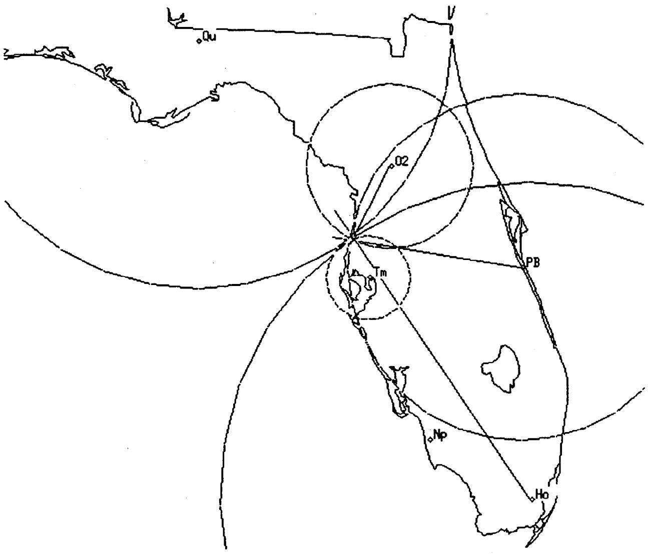

Figure 4. Example of a stroke located by two LPATS sensors and three IMPACT sensors.

1993]. The IMPACT location algorithm is sufficiently general to allow arbitrary combinations of LPATS (TOA) and IMPACT (MDF and TOA) data.

Figure 4 shows a lightning stroke in Florida that was detected and located by five sensors: three IMPACT sensors and two LPATS sensors. The angle information is represented by the straight-line vectors emanating from the sensors, and the TOA information is represented by range circles that are centered on each sensor. This event is typical of strokes detected by the NLDN. Strokes with a peak current of 25 kA are detected by an average of six to eight sensors, and 5-kA strokes are usually detected by two to four sensors. Typically, 20 or more sensors detect a 100-kA stroke.

The NLDN upgrade also includes a new method for grouping individual strokes into a flash and computing the flash multiplicity. In the past the MDF sensors accumulated a count of all strokes that occurred within 2.5° of the first stroke for a period of 1 s after the first stroke. The flash multiplicity was then taken to be the largest number of strokes detected by any of the sensors that were used to derive the flash location. This method tended to overestimate the true multiplicity because concurrent flashes could be detected at similar azimuths relative to one or more sensors. Figure 5 illustrates this problem. In the current NLDN, strokes are grouped into flashes using a spatial and temporal clustering algorithm that is illustrated in Figure 6. Strokes are added to any active flash for a period of 1 s (the traditional NLDN flash duration limit) after the first stroke, as long as the additional strokes are within 10 km of the first stroke and the time interval from the previous stroke is less than 500 ms. In the unlikely event that a stroke qualifies as part of more than one flash, it is placed into the flash with the closest first stroke. Additionally, if a stroke is more than 10 km from a first stroke (and less than a 50-km clustering radius) but is not clearly separated from the flash because their location confidence regions overlap (see the *Measures of NLDN Performance: Location Accuracy and Detection Efficiency* section), then the stroke is included in the flash. The multiplicity limit is 15 strokes; any strokes after the 15th are considered part of a new flash. As in the former NLDN algorithm, the reported flash location is the location of the first stroke, and the peak current estimate is still for the first

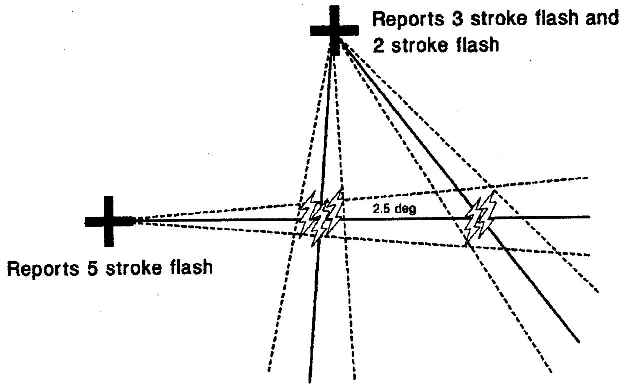

Figure 5. Angle-based flash grouping algorithm, illustrating how multiplicity can be overestimated.

stroke. Subsequent strokes are counted even if they have the opposite polarity from the first stroke, but the reported polarity of the flash is that of the first stroke.

Measures of NLDN Performance: Location Accuracy and Detection Efficiency

The primary measure of location accuracy in the NLDN and other direction-finding networks designed by GAI has been the semimajor axis of the location error ellipse (50th percentile) that results from the assumption that angle and time errors are Gaussian [*Stansfield*, 1947]. The region bounded by the ellipse is a confidence region in which there is a 50% probability of finding the true stroke location. The error ellipse is discussed in more detail in the appendix. This and related measures of location accuracy have been described by *Cummins et al.* [1995] for the NLDN and by *Maier* [1991], *Murphy et al.* [1996], and *Idone et al.* [this issue (b)] for other networks.

Detection efficiency for the network as a whole is determined by a number of factors, including the sensors' individual detection efficiencies, the average number of sensors contributing to stroke locations, and the sensor baselines. Additionally, the distribution of peak currents strongly influences network detection efficiency.

In order to quantify these measures of performance, Global Atmospherics uses models to compute the location accuracy and detection efficiency for given sensor types and locations. *Cum-*

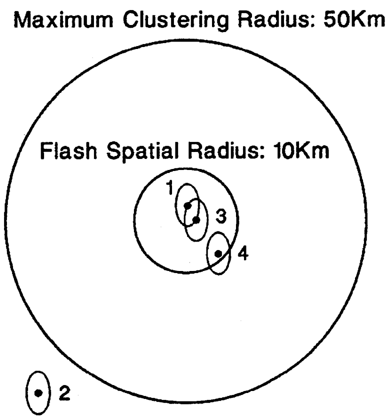

Figure 6. Location-based flash grouping algorithm. Strokes 1, 3, and 4 comprise one flash; stroke 2 is part of a separate flash.

Table 1. Estimated Location Accuracy and Flash Detection Efficiency (DE) for the NLDN Between 1989 and 1995.

Year	50% Semimajor Axis, km	95% Semimajor Axis, km	Flash DE*, %
1995	0.5-1.0	1-2	80-90
1994	2-4	4-8	65-80
1993	2-4	4-8	65-80
1992	2-4	4-8	65-80
1991	4-8	8-16	70
1990	4-8	8-16	70
1989	4-8	8-16	70

Between 1989 and 1991, detection efficiency was not well characterized [*Orville*, 1994].

* For first stroke peak currents greater than 5 kA.

mins et al. [1992, 1995] have described these models and the assumptions that are used to estimate the network detection efficiency and location accuracy. For completeness, these models are discussed in the appendix.

Comparison of Past and Present NLDN Performance

Location Accuracy

Table 1 summarizes the historical changes in the location accuracy of the NLDN, including the most recent upgrade. Prior to 1992, GDS estimated that the average location accuracy varied from 8 to 16 km in the NLDN. This estimate was based largely on observations and the assumption that there were residual angle errors of 1° to 3° in the MDF sensors. A comparative study in 1990 validated these accuracy estimates prior to the correction of site errors [*Cummins et al.*, 1992]. In early 1992, GDS calibrated the sensors and determined that the average location accuracy was 2 to 4 km in the vicinity of NASA Kennedy Space Center, Florida [*Cummins et al.*, 1992]. At that time, these values were in agreement with the estimated accuracy for that region of the network. Figure 7 shows estimated contours of constant median accuracy (in kilometers) in the NLDN after the 1995 upgrade. These contours were computed using the location accuracy model that is described in the appendix. The model predicts that most of the continental United States should have a median accuracy of 500 m. The standard deviation in the measured TOA was assumed to be 1.5 μs, and the standard deviation in angle was assumed to be 0.9°. For this network, increasing the angle standard deviation to 1.5° and the time standard deviation to 2.0 μs has little effect on the estimated location accuracy. We believe that such increases in errors more than account for variable terrain effects, such as propagation differences between the central Great Plains and the Rocky Mountains.

Occasionally, outlier events are detected with location errors greater than or equal to 50 km; experience with the new location algorithm indicates that somewhere between 0.1% and 0.01% of events are in this category. Most outliers are identified and removed by the requirement that the error ellipse semimajor axis is less than 50 km and the chi-square value is less than 15. Currently, efforts are under way to reduce the frequency of these events.

The actual location accuracy of the upgraded NLDN has been tested in a variety of ways. The first was an analysis of locations of rocket-triggered strokes at Camp Blanding, Florida. Figure 8 shows a scatterplot of the data that were obtained in 1993 during an evaluation of the IMPACT algorithm. Seven triggered strokes are shown in this figure; three of the NLDN locations were within 0.6 km of the triggering site. Comparisons have also been made between NLDN locations and those made by a short baseline network of MDF sensors that is operated by the NASA Kennedy Space Center and the U.S. Air Force Eastern Range at Cape Canaveral, Florida. This network has an average location accuracy of 0.6 km [*Maier and Wilson*, 1996], and therefore it is a reliable ground-truth reference for the NLDN. Since the NLDN upgrade and its subsequent calibration during the summer of 1995, the median location difference has been only 0.8 km between the two networks, with a standard deviation of approximately 2.3 km. Finally, Idone and his associates at the University

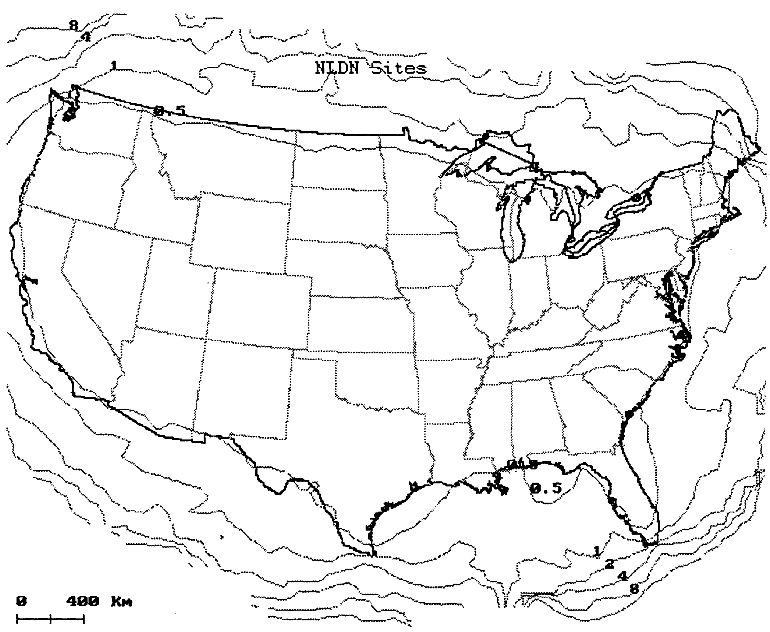

Figure 7. Projected semimajor axis of the error ellipse for the NLDN after the upgrade. Contour labels give the value in kilometers and represent median location accuracy.

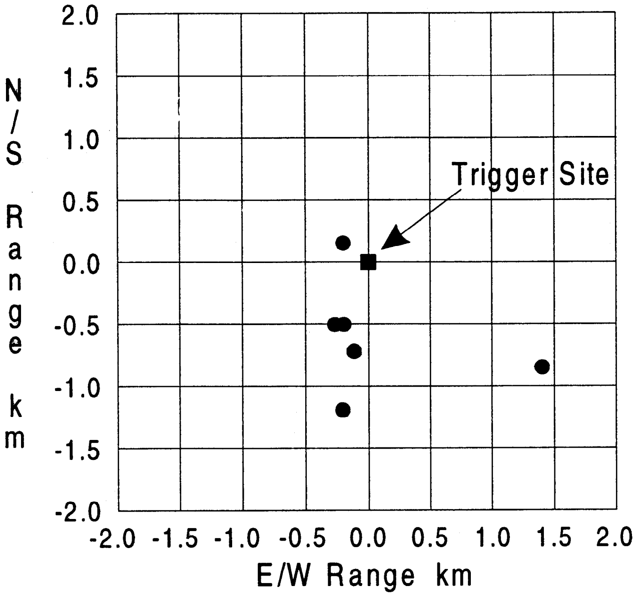

Figure 8. Locations of seven triggered strokes detected by the NLDN relative to the triggering site.

at Albany evaluated the location accuracy of the NLDN near Albany, New York, in 1994, before the NLDN upgrade was completed, and again in 1995. They used multiple video cameras and located 219 strokes independent of the NLDN. The results of this comparison support the accuracy estimates produced by our model and are described in detail by *Idone et al.* [this issue (b)].

Flash Detection Efficiency

Cummins et al. [1995] estimated that the flash detection efficiency (DE) of the NLDN was between 65% and 80% during the period from 1992 through 1994. These values were lowered from earlier estimates to reflect improvements in the DE model. The NLDN upgrade was designed to provide typical flash DEs in the range of 80% to 90% for first strokes with peak currents of 5 kA and larger. Figure 9 shows the flash DE model projection for negative flashes in the upgraded network. Although the network is capable of detecting flashes with small peak currents, the model estimates do not include flashes with peak currents below 5 kA because of large uncertainties in the peak current distribution at these low values. Note that the DE falls off rapidly as the sea coasts and borders are approached, owing to the lack of sensors outside the United States.

To verify the projections in Figure 9, *Idone et al.* [this issue (a)] obtained an experimental estimate of the NLDN flash DE. They considered a flash to have been detected by the NLDN if any of the NLDN strokes were identified on video. This study showed that the overall NLDN flash DE was 84% in 1994, when the test region was undergoing the upgrade and had an excess of sensors. This study was repeated during 1995 and supports the model projections of an 85% DE for flashes with peak currents above 5 kA [*Idone et al.*, this issue (a)].

Stroke Multiplicity and Detection Efficiency

It is generally thought that the average multiplicity in CG lightning is 3-4 [*Thomson et al.*, 1984]. The angle-based method for determining multiplicity originally used in the NLDN produced an average multiplicity of about 2.7 in the United States when averaged over individual years. The accuracy of this estimate is affected by the sensor spacing, sensor detection efficiency, spatial separation of subsequent strokes, and overall flash rate. The new location-based multiplicity estimate described in the *Location and Stroke Processing Algorithms* section will tend to be inherently lower because it is directly related to the overall stroke detection efficiency of the network. Over the past 2 years, the average multiplicity determined by the NLDN has ranged from 1.9 to 2.1. The differences in observed multiplicity between the two algorithms are illustrated in Figure 10. If we assume that the true average multiplicity is 3.5, then our result is consistent with a subsequent stroke detection efficiency of about 50%. Subsequent strokes are thought to have peak cur-

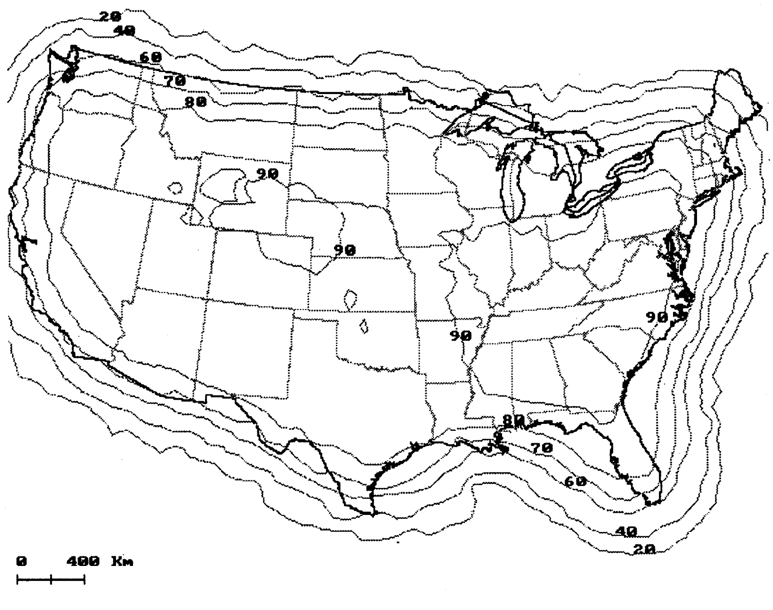

Figure 9. Projected flash detection efficiency for the NLDN after the upgrade for peak currents greater than 5 kA. Contour labels give the value in percent.

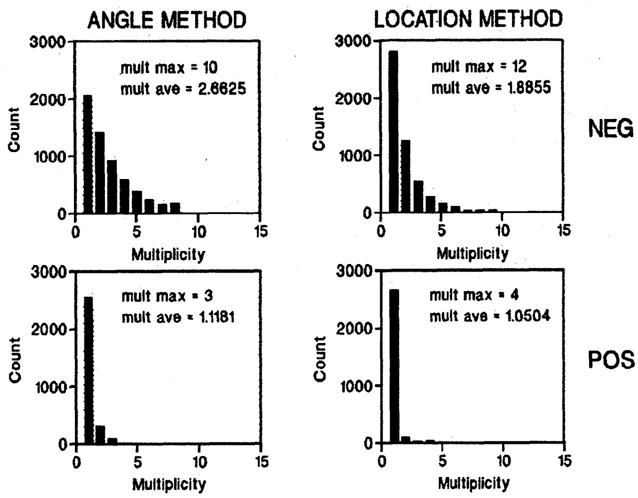

Figure 10. Comparison of measured flash multiplicities determined using angle-based and location-based algorithms for both positive (POS) and negative (NEG) flashes.

rents that are about half as large as those in first strokes [*Berger et al.*, 1975], and therefore our result is consistent with an overall flash detection efficiency of 80-90%. A more quantitative analysis of the stroke/flash relationship is currently in progress.

Peak Current

An estimate of the stroke peak current is another parameter that is provided by the NLDN using measurements of peak field (signal strength). The relationship between peak field and peak current assumes that the simple transmission line model (TLM) [*Uman et al.*, 1975] is valid for the peak field, which is supported by *Thottapillil and Uman* [1993]. This relationship has been investigated by many, such as *Willett et al.* [1988, 1989], *Mach and Rust*, [1989], *Orville* [1991a], *Rakov et al.* [1992], and *Idone et al.* [1993]. As a first step in the estimation procedure, propagation effects are taken into account to produce a range-normalized value of the signal strength (RNSS) for each reporting sensor using the following signal propagation model [*Schutte et al.*, 1988; *Herodotou*, 1990; *Idone et al.*, 1993]:

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

where SS is the raw signal strength, r is range in kilometers, I is the normalization range which is set to 100 km, p is an attenuation exponent, A is the e-folding length for attenuation, and C is a constant. The attenuation exponent currently used in the NLDN, $p = 1.13$, was determined empirically in Florida by *Orville* [1991a] assuming that A was infinite. The current value of A in the NLDN is 10^5 km. *Herodotou* [1990], using a form of the model with $p = 1$, found values of A between 600 and 1000 km in Ontario. We are currently working to derive site-specific values of these two parameters.

The values of RNSS for all reporting sensors within 625 km (to avoid polarity reversals due to ionospheric skip) are averaged, and then the stroke-average RNSS is converted to an estimate of peak current. This conversion has been investigated for rocket-triggered lightning by *Orville* [1991a] and *Idone et al.* [1993]. Prior to the NLDN upgrade, the conversion used by GAI was done with a linear regression equation that was derived by *Idone et al.* [1993]. For the case of $p = 1.13$, this relationship has the form

$$I_{\mathrm{peak}} = 5.2 + 0.148\,\mathrm{RNSS} \quad (2)$$

where I_{peak} is in kiloamperes. The unphysical nonzero intercept in the above relation may reflect the fact that the former NLDN did not detect many strokes with peak currents below 5 kA, thereby allowing the intercept to deviate from zero.

The improved sensors, however, do detect smaller signal strengths, and therefore (2) is no longer appropriate [*Cummins et al.*, 1996]. We have therefore constrained the intercept to be zero and recomputed the linear regression using the data of *Idone et al.* [1993]. The result is

$$I_{\mathrm{peak}} = 0.185\,\mathrm{RNSS} \quad (3)$$

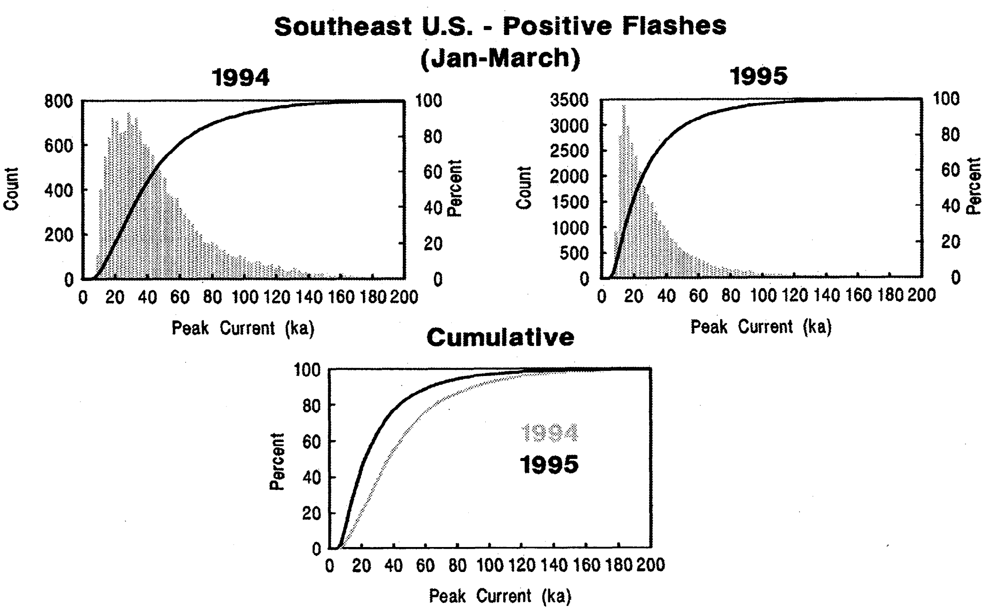

Figure 11. Peak current histograms and cumulative distributions for positive flashes in the southeastern United States during January-March 1994 (before the upgrade was complete) and 1995 (after).

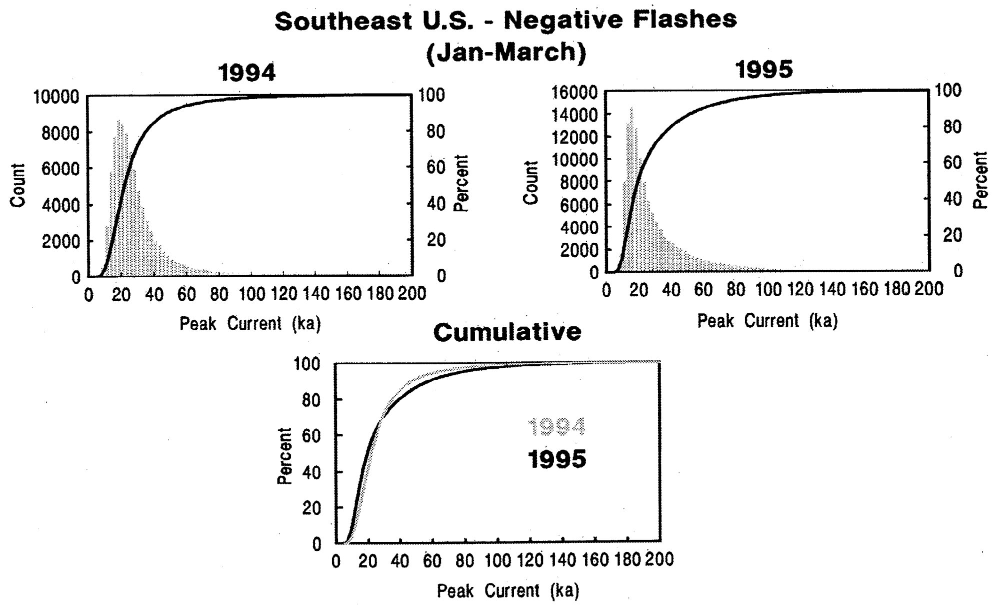

Figure 12. Same as Figure 11, but for negative flashes.

The new regression decreases the Pearson product moment correlation coefficient from 0.88 to 0.85, but this is not significant. It should be noted that the slope of this line is close to the best fit value of 0.2 cited by *Orville* [1991a]. The available data on rocket-triggered lightning show that the variability in peak current estimates is typically about 5 kA; this produces a median variability of 20-30%, with the larger uncertainties on events with small currents. The absolute accuracy of the peak current estimates on natural lightning has yet to be determined. To the best of our knowledge, no ground truth data exist for peak currents exceeding 60 kA, and therefore it is not yet possible to determine whether the relationship between RNSS and I_{peak} is linear for the large peak current strokes.

Small Positive Discharges

The increase in NLDN sensitivity and changes to waveform acceptance criteria have generated a previously undetected population of small positive waveforms. Specifically, it appears that a reduction in the minimum waveform width criterion, which was intended to allow detection of near-threshold signals, may allow the detection of a class of relatively large, long-duration cloud pulses. For example, some of these events may be due to isolated bipolar positive pulses identified by *Weidman and Krider* [1979]. The effect of these events is illustrated in Figure 11, which shows the distribution of peak currents in positive flashes obtained in both 1994 and 1995. In 1995 the total number of positive discharges detected was approximately a factor of 2 greater than in 1994. Many of the positive discharges now being detected by the NLDN have peak currents between 5 and 15 kA, and it is likely that not all of these events are CG discharges. This issue is currently being investigated. The fraction of small positive discharges varies from approximately 0 to 15% and varies with storm and region. We recommend that the subset of small positive discharges with peak currents less than 10 kA be regarded as cloud discharges unless they are verified to be cloud-to-ground.

For comparison, Figure 12 shows the same distributions as in Figure 11 but for negative flashes. In 1995 there was a slight increase in the number of small negative flashes, and this is indicative of an improvement in detection efficiency. However, this increase is rather small compared to the increase in small positive discharges.

Summary

In this paper, we have discussed the evolution of the NLDN that delivers real-time cloud-to-ground flash data within 40 s and continuously archives flash and stroke data sets. We have also described a number of modifications and upgrades that have improved both the detection efficiency and location accuracy of this network. The NLDN now has an expected location accuracy of 0.5 km over most of the United States and an estimated flash detection efficiency of 80-90% over the same region. As discussed above, these advances have improved performance, but with them should come changes in the way the data are interpreted. Specifically, we discussed changes in stroke grouping and multiplicity determination, peak current estimation, and the increased detection of small positive discharges.

Appendix: Location Accuracy and Detection Efficiency Models

In order to evaluate the effects of different sensor configurations and to provide potential users with a prediction of the performance of proposed networks, GAI has developed location accuracy and detection efficiency models. These models have proven to be useful for the design and evaluation of the NLDN. The purpose of this appendix is to provide a brief description of these models.

Location Accuracy Model

The location accuracy model is used to calculate the error ellipse that characterizes the stroke location accuracy using error ellipses and that is used as a measure of location accuracy in the real-time NLDN data. Figure A1 illustrates a two-dimensional Gaussian distribution of location errors from which an error ellipse is derived. The optimum stroke location is, of course, at the most probable point or the peak of the error distribution. The error ellipse circumscribes the cross section of the distribution at

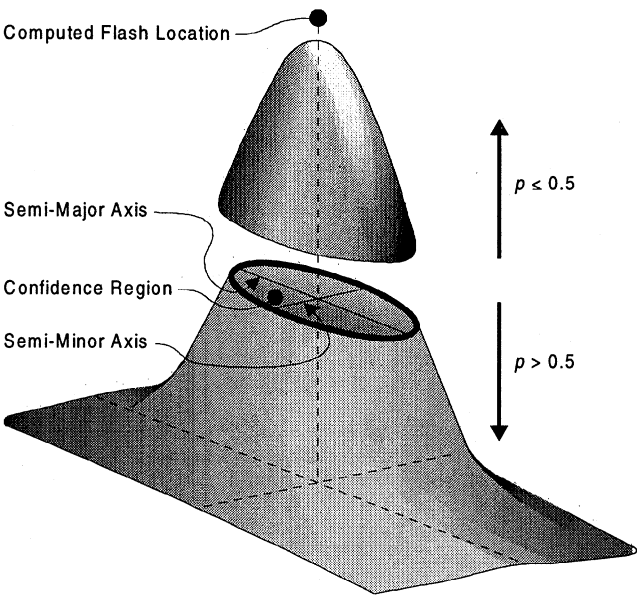

Figure A1. Two-dimensional Gaussian distribution of location errors showing the estimated stroke location at the most probable point (peak). The 50th percentile error ellipse is derived by cutting the distribution at a probability level of 0.5.

any desired probability level. Specifically, at any probability level *p* this elliptical region is a confidence region in which there is a probability *p* of finding the true stroke location. In the NLDN the reference probability level is always 0.5, so that the error ellipse describes the median location accuracy. The two-dimensional Gaussian distribution of errors in latitude and longitude is a consequence of the assumption that the random errors in the sensor time and angle measurements are uncorrelated and approximately Gaussian in nature. This should be a valid assumption after sensor site errors have been corrected and when propagation-based timing errors are small. Even if this assumption is not completely valid, the approach is still appropriate because the overall errors tend to be Gaussian when a large number of sensors are used in the calculations. Significant deviations from the assumptions would appear as large chi-square values in the IMPACT optimization algorithm, as discussed in the *Location and Stroke Processing Algorithms* section of this paper. Given the above, the standard deviations in latitude and longitude that the error ellipses represent are a direct mathematical result of the procedure that determines the least squares location from the sensor information and knowledge of the time and angle standard deviations. A specific mathematical discussion of error ellipses in lightning locations can be found in the work by *Stansfield* [1947].

The shapes of the error ellipses depend on the location of the stroke relative to the sensors. For example, when a stroke is outside the network and the distance from the nearest sensor is several times the sensor baseline length, the ellipse is very elongated and points in the direction of the sensors. On the other hand, the error ellipse is small and nearly circular when a stroke is in the middle of a group of several sensors.

In practice, the location accuracy model computes the semimajor axis of the error ellipse at each point on a 50-by-50 grid over the region of network coverage. The locations and types of sensors and the average angle and/or timing errors must be specified. The model output is a contour map of the semimajor axis, as shown in Figure 7 of this paper.

Detection Efficiency Model

The detection efficiency (DE) model computes estimates of the DE on a 50-by-50 grid over the region of network coverage. At each grid point, the model generates specific values of peak current and computes the signal strength that should arrive at each sensor in the network using the signal propagation model discussed in the *Peak Current* section. The DE model then uses a look-up table to relate the computed signal strength at each sensor to that sensor's detection efficiency, and this produces a probability that the stroke will be detected by that sensor. This look-up table contains the response of each type of lightning sensor as a function of the incident signal strength. In its most simple form there would be a probability of 1 for all events above threshold and a probability of zero for all events below. Realistic tables have been derived for all GAI sensors using the measured response to tens of thousands of lightning events, and the look-up table values increase from zero probability at threshold to a maximum probability (less than one) at 2-3 times threshold.

Finally, the "total probabilities" are computed for all combinations of sensors that report a discharge, assuming that the sensor probabilities are all independent. This assumption yields a "total probability" for any combination of sensors, which is simply the product of the probabilities of detection (and nondetection) for each sensor. This process is repeated over the entire range of peak currents at each grid point, and an overall estimate of the network detection efficiency is produced. The model output is a contoured map of "percent detected," as shown in Figure 9 of this paper.

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