

# An Overview of Lightning Locating Systems: History, Techniques, and Uses, With an In-depth Look at the U.S. NLDN

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## Abstract

The technological achievements leading to modern multi-sensor lightning locating systems (LLSs) came about because of the efforts of innovative scientists and engineers who have exploited the development of key enabling technologies over the last 80+ years. Today, lightning in all corners of the world is monitored by one or more land- or space-based LLS. The applications that have driven these developments are numerous and varied. This paper describes the history leading to modern LLSs that sense lightning radiation-fields at multiple remote sensors, focusing on the interactions between enabling technology, scientific discovery, technical development, and uses of the data. An overview of all widely-used detection and location methods is provided, including a general discussion of their relative strengths and weaknesses for various applications. The U.S. National Lightning Detection Network™ (NLDN) is presented as a case study, since this LLS has been providing real-time lightning information since the early 1980's, and has provided continental-scale (U.S.) information to research and operational users since 1989. This network has also undergone a series of improvements during its 20+ year life, in response to evolving detection technologies and expanding requirements for applications. Recent analyses of modeled and actual performance of the current NLDN are also summarized. The paper concludes with a view of the short- and long-term requirements for improved lightning measurements that are needed to address some open scientific questions and fill the needs of emerging applications.

## 1. Background and Early History

Lightning is both beautiful and dangerous. The bright imagery in the sky that entertains us is a direct threat to air and ground-based operations, and is a reflection of other destructive forces associated with thunderstorms and severe weather. Cloud-to-Ground (CG) lightning is the single largest cause of transients, faults, and outages in electric power transmission and distribution systems in lightning-prone areas. Additionally, lightning is a major cause of electromagnetic interference that can affect all electronic systems. These problems have been alleviated somewhat by the development of automatic multi-sensor lightning locating systems (LLSs) dating as far back as the 1920's. Modern LLSs are able to determine the location, intensity, and movement of thunderstorms in real-time and the location of lightning-caused damage to resources and infrastructure. Typical users of lightning information include aviation/air traffic authorities, weather services, land management entities, forest services, and public utilities. Archived and real-time lightning data are also being used in many areas of geophysical research and in forensic and insurance applications.

### 1.1 Background

Lightning flashes can be broadly grouped into two categories – those that strike the ground and those that do not. These two groups are further subdivided based on the specific pathway and direction of the current that travels in the bright channels associated with each flash. The most prevalent flashes do not strike ground, and are commonly referred to as “cloud flashes.” These flashes serve to reduce spatial differences in charge within a cloud or between clouds. A typical cloud flash begins within or close to the main negative charge region in the cloud (typically at a height of 4-8 km) and propagates toward an upper positive charge region (typically at a height of 8-12 km). Other forms of cloud flashes and CG flashes are discussed in detail in Schonland [1] and Rakov and Uman [2]. A concise overview is provided by Uman and Krider [3].

Cloud lightning is important for a number of reasons. Cloud flashes typically outnumber CG flashes by a factor of two to ten in most ordinary thunderstorms (e.g. Boccippio et al. [4]). Severe storms, however, produce much higher rates of cloud lightning than CG flashes, with some storms producing no CG flashes at all [5]-[7]. Cloud flashes, therefore, can provide an important indication of both the growth rate and intensity of thunderstorms, leading to important applications in nowcasting [8]-[9]. In most thunderstorms, cloud flashes precede the first CG flash as the storm begins to develop and become electrified. Typical times between the first cloud flash and first CG flash range from a few minutes to a few tens of minutes [10]-[11]. This lead time makes it advantageous to use observations of cloud lightning to provide lightning warnings when storms develop overhead. Finally, the cloud lightning in larger storm systems such as mesoscale convective systems (MCS) often has a large, horizontal extent [12], and embedded within this activity are intermittent CG flashes. Detecting the cloud lightning associated with large systems provides better warnings of the CG lightning threat.

We briefly introduce the terminology associated with CG flashes for the first-time reader. Details are provided in [1]-[3]. The most common type of flash associated with ground attachment transfers negative charge from an electrified cloud to ground in one or more locations. Much of this charge is transferred in a sequence of individual *return strokes* that have peak currents in the range of a few kA to more than 200 kA. The return strokes have a nominal duration of 10's of microseconds, and are typically separated in time by 20 to 100 milliseconds. A lightning *flash* typically contains 2 to 4 return strokes, but may contain as few as one and as many as 20 strokes. The number of strokes in a flash is frequently referred to as the *multiplicity*. Additional charge may be transferred in a *continuing current* that persists during the inter-stroke intervals. For many flashes, the *subsequent strokes* (i.e. the strokes which occur after the first stroke in a flash)

contact the earth at the same strike point as the first stroke because they travel through the channel established by the first stroke. However, 30% to 50% of all flashes contain strokes that produce different ground strike points, separated by up to several kilometers. For practical purposes, some researchers have defined a *flash* as the ensemble of all CG strokes that strike within 10 km of each other within a one second interval.

Both cloud and CG flashes radiate electromagnetic energy over a wide range of frequencies. Most of this energy is contained in pulses or high-frequency “bursts” that come with a wide range of risetimes and durations in the time domain. These emissions can be broadly categorized and processed in traditional radio-frequency ranges that relate to common signal processing bands. Breakdown processes that create new lightning channels and fast processes that re-illuminate existing channels will produce strong emissions in the VHF band. One type is quasi-continuous over a couple of milliseconds and does not exhibit distinct peaks during that time. The other type consists of well-defined bursts of narrow, microsecond-scale pulses. Fast-moving negative streamers (recoil streamers) and dart leaders tend to emit the more continuous radiation bursts, while preliminary breakdown tends to correspond to impulsive radiation bursts. Stepped leaders in negative CG flashes also produce impulsive emissions associated with step lengths on the order of tens to hundreds of meters, but as the leader approaches ground and the branched structure becomes more complex, the emissions begin to look more continuous in time.

When there are large transient currents in long, previously-established channels (such as those that occur in CG return strokes and some cloud pulses), the most powerful emissions are in the LF and VLF ranges. In the VLF band, the radiation is dominated by return strokes, as first shown by Malan [13, section 13.9]. Cloud discharges produce tens to hundreds of small pulses with most of their energy in the upper LF range and higher. Usually, relatively little VHF activity is produced by the high-current components of lightning such as return strokes. Some typical waveforms of return strokes and cloud pulses are shown in Figure 1, taken from Krider et al. [14]. More information regarding field waveforms for produced by cloud and CG processes are provided in [15]-[16].

Given the differences in the rates and amplitudes of the electromagnetic radiation at the different frequencies, different techniques are better suited for detecting various processes in cloud and CG flashes, as shown in Figure 2. Vertically-polarized transient pulses in the LF and VLF frequency range propagate along the surface of the earth and have been used to detect and locate return strokes in CG flashes for many years. Sensors that operate in the LF and VLF range can also be used to detect and locate the larger pulses produced by cloud flashes. Such sensors can also detect and locate very distant lightning because VLF signals can propagate thousands of kilometers as they reflect between the ionosphere and the ground. This long-range propagation allows some “large” flashes to be detected in very remote areas or over the oceans where sensors cannot be installed.

Sensors that operate in the VHF frequency range are equally sensitive to the breakdown and leader processes that occur in both cloud and CG flashes. Because VHF signals tend to be limited by line-of-sight propagation, VHF sensing systems tend to have a limited range. However, the line-of-sight propagation, coupled with the fact that VHF lightning impulses have a short duration, allows the VHF sources to be modeled as point sources and accurately located in either two or three dimensions.

## 1.2 Early History of Lightning Detection

The development of modern lightning detection instrumentation has been driven by both basic scientific interest and by a variety of applications and practical needs, but of these, applications provided the sustaining force. The requirements for applications come in many forms, including new value-producing capabilities, improvements in quality/reliability of the information, and cost reduction. The detection and location of lightning using ground-based LLSs and satellite-based sensors is no exception.

According to Norinder [17] the earliest measurements directed at understanding the electromagnetic fields produced by distant lightning were carried out by the Russian physicist Popoff in 1895. Popoff employed a “coherer” invented by E. Branley in 1890, which soon became the essential element in wireless telegraphy. The later development of deForest’s vacuum tube triode and the cathode-ray oscilloscope allowed Appleton, Watson-Watt and Herd, and others to visualize the radiation field waveforms associated with these field changes, giving birth to the quantitative analysis of atmospheric radio signals in 1920. At that time, these “radio atmospherics” (sferics) were viewed as a source of interference for the then-emerging field of long-range radio communications. At that time, measurements of electromagnetic fields produced by lightning were typically obtained using narrowband radio receivers in the VLF and LF frequency range, operationally used for ship-to-shore radio communications. These instruments helped to characterize the ionosphere and its effect on radio propagation [18]-[19]. Before the development of weather radars, narrowband VLF “sferics” detection systems employing two or more spatially-separated magnetic-direction-finding (MDF) receivers were the primary means of identifying and tracking thunderstorms at medium and long ranges with location accuracy of several 10’s of km – a broadly utilized tool during World War II. Norinder’s 1953 publication [17] provides an excellent overview of the history of long-distance location of thunderstorms.

Time-of-arrival (TOA) geolocation techniques were developed for marine navigation purposes in the 1930’s and 40’s [20] were first employed in the geo-location of lightning in the late 1950’s, as described by Lewis et al. [21]. A constant difference in the arrival time at two stations defines a hyperbola, and multiple stations provide multiple hyperbolas whose intersections identify a source location. This technique is illustrated in Figure 3 for various geometries. Under some conditions, curves produced from only three sensors will result in two intersections, leading to an ambiguous location (Figure 3b). Lewis et al. geolocated lightning at great distances from the sensor array, resulting in a geometry such that each pair of sensors has one line-segment of their associated hyperbola pointing in roughly the same direction (Figure 3c). This fact caused the technique of Lewis et al. to be referred to as “hyperbolic direction finding.” A major challenge for the early TOA systems was the need for precise time-synchronization of multiple remote sensors. Modern techniques that address the limitations in early direction-finding and TOA methods are discussed in the following sections. More-detailed information about the early history of lightning measurements and detection systems is provided in [2], [22]-[23], including general descriptions of basic lightning geo-location methods.

The following sections provide more detail about modern lightning locating systems. Lightning Mapping systems are covered first, since they provide the most complete representation of lightning flashes and thunderstorms. Modern VLF /LF systems tailored to provide both CG and cloud lightning information are discussed in Section 3. Section 4 covers Long-range and global lightning locating systems. A detailed case study of the U.S. National Lightning Detection Network (NLDN) is provided in Section 5. Single-station lightning locating systems are not addressed in this work.

## *2. TOTAL Lightning Mapping*

Total Lightning Mapping involves visualization of the detailed spatial and temporal behavior of both cloud and CG flashes in two or three dimensions, typically achieved using TOA or direction-finding location methods. Various mapping systems have been developed over the last 50 years, operating in various frequency ranges and bandwidths. These systems focus on detailed discharge structure, but do not provide direct measurements of polarity, charge, or current magnitudes. The most successful systems to date operate with moderate to narrow bandwidth in the VHF range. Efforts to map lightning flashes and thunderstorms using multi-sensor VHF measurements seem to have begun with the approach outlined by Oetzel and Pierce [24] which illustrated the fundamental equivalence of modern-day interferometric and TOA-based location methods.

This section provides an overview of interferometric direction finding and time-of-arrival system for lightning mapping, and discusses their relative strengths and weaknesses.

### **2.1 Direction Finding Based on Interferometry**

As noted in Section 1.2 (related to VLF detection) and as suggested by Oetzel and Pierce (related to VHF detection), one can derive arrival-angle information based on arrival-time-difference information using an “interferometric array” of two or more “closely-spaced” sensors (antennas). “Closely spaced” means that the separation distance between the sensors in the array is small compared to the distance from the array to the signal source. In the VHF case, the antenna separation is on the order of meters, and the distances are 10s to 100s of km. This geometry is illustrated in Figure 3d, where it is clear that pairs of sensors provide hyperbolas that point in the same direction. Hayenga and Warwick [25] showed that a narrowband radio interferometer could be used to measure the azimuth and elevation angles of lightning sources at VHF frequencies. Rhodes et al. [26] and Shao et al. [27] have developed this technique further and have used single-station interferometers to improve our understanding of the development of both IC and CG lightning. These were single-station systems that provided a “projection” of lightning onto a plane. It is possible to obtain 3D locations using interferometry by deriving an elevation angle using special antenna arrangements [28]-[29]. The source location is then obtained by computing the triangulation of the azimuth and/or elevation from at least 2 sensors [30]. For such networks, the typical distance between sensors is in the range of 50-150 km, and they are composed of at least 3 sensors. By assuming that the source does not move significantly in azimuth for a given duration, these systems can take advantage of the numerous periods of the signal to determine an average time difference over the whole integration period (in the form of a phase difference). Richard et al. developed a commercial version of this system operating in 2 dimensions that is able to locate both IC and CG flashes [31]-[32]. Their sensor integrates over a 100  $\mu$ Sec period, resulting in azimuth errors in the range of 0.3 – 1.0 degrees. As with LF/VLF direction finding systems, the location accuracy of these systems is dependent on sensor (array) spacing. Based on simple geometry, the location uncertainty of a sensor with 0.5 degree azimuth error for a discharge at a distance of 150 km is 1.3 km. The location error for a practical network of such sensors (with sensor baseline distance of ~100 km) will range from half to double this value, depending on the number and geometry of the sensors that detect the discharge. The principles of interferometric lightning location are described in detail by Lojou et al. [33].

Most interferometric systems operate over very narrow frequency bands (a few hundred kHz to a few MHz in the VHF/UHF bands), since this allows the system to have high sensitivity in a specific “quiet” band of operation. However, it also makes the system performance subject to local broadband interference, may not provide the highest possible signal-to-noise ratio, and places a specific limitation in the spacing of the antenna array elements to avoid arrival-time

(phase) ambiguity. However, work by Shao et al. [34] and more-recent independent work in Japan [35]-[36] demonstrate a trend towards using broadband interferometry. This trend is made possible by the advent of affordable broadband RF and digital signal processing electronics.

## **2.2 TOA Methods Operating at VHF**

Proctor [37] provided the first accurate system to perform 3-D “total lightning mapping” by measuring the difference in the time of arrival of temporally-isolated VHF pulses measured at five “widely spaced” sensors that were time-synchronized to within  $\sim 100$  nS. “Widely spaced” means that the separation distance between the sensors in an array is on the order of the distance from the array to the signal source, with the assumption that the signal is essentially produced by a point source. Four or more independent arrival-time measurements allow calculation of the time, latitude, longitude, and altitude of a “source”. Typical distances between sensors, to allow accurate data reconstruction, are in the range of 10-40 km. In most cases, such networks are composed of 7 to 12 sensors. This location method is a direct extension of the two-dimensional hyperbolic method discussed in Section 2.2 and illustrated in Figure 3. The first real-time system to employ this technique was developed at NASA Kennedy Space Center. This Lightning Detection and Ranging (LDAR) System was capable of providing three-dimensional locations of more than a thousand lightning sources within each lightning flash [38]-[39]. This system was similar to that of Proctor, but the data acquisition was automatic, and the data displays were generated in real-time. In 1997 NASA entered into a technology transfer agreement with Global Atmospherics (now Vaisala) to build a commercial version of the LDAR system. Only a few of these LDAR-II systems were produced, given that most of the current interest in such systems is related to applied research. These include a continuously-operated system at Kennedy Space Center (owned and operated by the U.S. Air Force of behalf of NASA), and one in the Dallas, Texas area (owned and operated by Vaisala, for research purposes).

In 1998, researchers at the New Mexico Institute of Mining and Technology (NMT) began work on a portable “Lightning Mapping Array” (LMA) employing this 3D TOA technique that was designed for research purposes. Their first system was initially deployed in Oklahoma in 1998 [40] and then in central New Mexico [41]. The LMA system and its performance are detailed by Thomas et al. [42]. This paper shows that sources over the network can be located with an uncertainty of 6–12 m rms in the horizontal and 20–30 m rms in the vertical, resulting less than a 100m 3-dimensional error for most located sources. This exceptional location accuracy is a direct result of arrival-time measurement errors of 40-50 nS rms.

Today, 3-dimensional VHF TOA lightning mapping systems provide the most complete record of the spatial and temporal development of lightning channels, making it possible to infer complex charge structures in clouds [43], [7]. A sample record from one of these systems, first shown by Rison et al. [44], is shown in Figure 4 and illustrates the time evolution of a negative CG flash as detected using an LMA system. During this “bolt from the blue” flash, the system was operating with an extremely short time window (10  $\mu$ s), and more than 600 hundred VHF “sources” were located for this flash. The top panel of the display shows an altitude (km) vs. time (seconds) plot of about 500 ms of data (10 ms per small division). Each point in this plot represents a radiation source that was located in three dimensions and is associated with localized air breakdown caused by very high local electric field at the tip of a self-propagating leader. The color changes denote the time sequencing of the located events. Note that the mapping system first detected a sequence of upward-going sources starting at a height just below 9 km and going up to about 10 km. These sources are associated with a developing negative leader. Current flowing in the channel established by this leader would have produced one or more vertically-polarized small cloud pulses in the LF frequency range which could be detected at distances of over 100 km. Approximately 10 ms after flash initiation, 2-3 channels are clearly visible travelling horizontally for the

next 200 ms. Given the horizontal nature of current flow in these channels, any LF cloud pulses generated in the LF frequency range will have a horizontal polarization, resulting in very small peak fields at distances greater than a few 10's of km. This early portion of the flash is similar in behavior to a typical cloud flash. Starting at approximately 01:28:26 GMT, the remaining propagating leader begins a step-wise decent toward ground with an average downward speed of about  $1.3 \times 10^5$  m/s, striking the ground at 01:28:26.060 GMT. The small triangle represents the detection of a typical magnitude (-19.5 kA) negative first return stroke by the U.S. NLDN, removing charge from the ionized channel established by the stepped leader. The small number of sources located in time between 26.060 and 26.210 seconds reflect reorganization of charge in the cloud as a result of charge removal by the return stroke current. Starting just prior to 26.220, a fast-propagating "dart leader" begins its decent toward ground with a vertical speed in excess of  $10^6$  m/s, reaching the ground in less than 10 ms. The subsequent return stroke that removed the charge from this leader channel was not detected by the NLDN, and likely had a peak current below 10 kA. Even though all the leader processes that produced VHF emissions also produced visible light, none of the activity above about 4-6 km altitude could be seen by an observer on the ground due to obscuration by clouds.

The lower right panel in Figure 4 contains a histogram of the number of sources as a function of height. The largest fraction of the sources was located in what is presumed to be a positive charge region between 8 and 10 km altitude. The primary negative charge region is likely between 6 and 8 km, suggested by the small number of VHF sources (other than the stepped leader itself) in this altitude range, thought to be produced by "quieter" positive breakdown [7], [45]. The sources below 6 km are associated with branching in the downward negative leader. The lower left panel shows an altitude vs. horizontal distance plot of this flash, looking from the South to the North. The located sources in this panel use the same color:time coding as the upper panel. It is clear that during the early portion of the flash there is one major upward channel and one horizontal channel at an altitude of about 9 km. The downward leader appears to originate at the same location as the two earlier leaders before it begins its decent towards ground. Given the high time-resolution of these data, one can also see much of the radial branching of the downward stepped leader (green and yellow sources) that is typical of negative CG flashes. Finally, it is clear that the dart leader (red sources) travel in the main "trunk" of the earlier channel associated with the first return stroke. The clear depiction of the low-altitude stepped leader and the dart leader are generally not possible using TOA-based VHF lightning mapping techniques when using the more typical time resolutions of 80-500  $\mu$ s.

Clearly, this technique provides unprecedented detail about the time evolution of lightning discharges. However, it should be noted that as the number of simultaneous branches increases, the random time interval between VHF emissions becomes sufficiently short to prevent detection of all branches. Current algorithms for sorting and matching sensor responses to these discharges suggest that the highest yield of located sources ((6-8 thousand located sources per flash) seems to be achieved by limiting the analysis to the largest pulses in 30-40 microsecond periods (personal communication, Hareld Edens and Ron Thomas, New Mexico Tech). Modern high-end PC's and Sun Workstations are capable of processing these data in real-time for networks with up to about 12 sensors, covering a domain radius of a few hundred km.

### **2.3 Inter-comparison of VHF Interferometry and TOA techniques**

The fundamental practical difference between interferometry and time-of-arrival techniques resides in the interdependence of measurements among the various sensors. Each time-of-arrival sensor identifies a unique feature of the signal in order to provide precise arrival times ( $\sim 100$  ns accuracy), and that feature must be seen in common among several widely-spaced sensors. Potential features must be sufficiently separated in time to avoid miscorrelation among sensors. Since an interferometric sensor (a closely-spaced array of antennas) provides a single angle

measurement from one location, the simultaneous signals detected by these antennas can be assumed identical, other than differences in their arrival time (or phase, for a narrowband signal). Therefore an interferometer does not require any specific signal shape, and can integrate the signal arrival-time differences over long time intervals (e.g, 10's of  $\mu\text{s}$ ). This allows interferometry to operate quite well on noise-like signals.

Given this background, some broad generalizations can be made. Intermittent or isolated pulses are best suited to Time-of-Arrival techniques where each sensor reports the precise arrival time of the largest VHF emission "feature" in short ( $\sim 100 \mu\text{s}$ ) time intervals. Longer-duration VHF emissions with little amplitude modulation are well suited for interferometry. This categorization is somewhat of a simplification. In fact, Time-of-Arrival networks are also able to locate multi-pulse events or even continuous emission as long as there is sufficient modulation of the amplitude to allow a precise time stamping of the events, as demonstrated in Figure 4 above. Similarly, Interferometric networks are able to operate on short pulses as long as the integrated signal level over the acquisition period is large enough to ensure a sufficient signal-to-noise ratio [28]. Figure 5 shows a recorded waveform that can be used to illustrate the conditions under which each of these techniques operates best. The waveform is the r.m.s. amplitude of a narrowband waveform (centered at 114 MHz) integrated over  $4 \mu\text{s}$  time windows. The narrow pulses are well suited for time-of-arrival mapping techniques while the more-continuous one near the end of the record (lasting about 300  $\mu\text{s}$ ) does not produce a unique time-feature with sufficient time-resolution. However, this later more-continuous process provides an excellent signal for interferometry to obtain one or more azimuth values.

There have been a few direct comparisons of VHF interferometry and time-of-arrival systems. Mazur et al. [46] found that the NASA LDAR time-of-arrival system preferentially detected sources associated with virgin breakdown processes, with propagation speeds on the order of  $10^4 - 10^5 \text{ m/s}$ . This is consistent with studies suggesting that the LMA and LDAR systems are well-suited to detect the pulse-like emissions produced by negative leader propagation in a step-like fashion. Mazur et al. also found that the ONERA 3D interferometer responded best to fast-propagating ( $10^6 - 10^7 \text{ m/s}$ ) processes that produced fairly continuous VHF emissions for 10's of microseconds, such as those produced by dart leaders. More recently Lojou and Cummins [47] carried out a detailed study based on observations obtained during summer 2005. They have shown that although the two techniques preferentially detect different processes in a flash, both provide similar representation of the two-dimensional spatial and temporal characteristics of cells and storms, including counts of flashes. They have also shown that 2D VHF interferometric networks can cover larger areas with fewer sensors than 3D VHF Time-of-Arrival systems, because the sensors can be spaced farther apart. They note that this wider sensor spacing has the side effect of poorer source location accuracy – approximately 1-2 km, as compared to 100m for VHF Time-of-Arrival. This study also confirmed the greater flash and storm detail provided by both VHF networks, when compared to systems operating in the LF frequency range. Of course, this comes at a cost of additional sensors and system complexity. The complementary nature of the two VHF technologies for basic research was clearly reflected in the detailed spatial and temporal evolution of individual flashes shown in this paper and in the work of Mazur et al. [46]. It is clear that VHF Time-of-arrival provides a more complete representation of the three-dimensional time evolution of a flash, but interferometry provides information about important faster leader and streamer processes that are generally not well-represented by time-of-arrival data. This fact supports the concept for a new combined research system currently being developed at ONERA [48]. It should be noted that limitations in sensitivity prevent both of these systems from regularly detecting and mapping positive leaders which are known to occur in all



lightning flashes. Additionally, a VHF mapping system must include height information (or supplementary information about return strokes) to reliably distinguish between cloud and cloud-to-ground flashes, because the VHF activity directly associated with return strokes is limited and difficult to detect and locate.

### *3. Wide-Area Lightning Detection in the VLF/LF Frequency Range*

In this section we review the history and technical evolution of “precise” lightning detection systems that operate on ground-waves in the VLF/LF frequency range. Essentially all methods that provide accurate information about the location, polarity, and peak current of return strokes in CG lightning operate in this frequency range. We briefly describe the enabling technologies, the applications of the data, and the detection methods.

#### **3.1 Enabling Technology and Uses of the Data**

The technical “roots” of precise CG lightning detection started with the commercial development of gated, wide-band magnetic direction finder (DF) by Lightning Location and Protection (LLP) in the late 1970’s [49]. These sensors operated in the time-domain over the full VLF/LF frequency range and used a set of waveform discrimination criteria to limit the response to just return strokes in CG flashes. This technique provided many advantages over previous systems because by sampling the proper waveform at the proper time within that waveform (the initial peak), non-lightning sources and cloud discharges could be eliminated and the azimuth measurement was optimized for determining the ground strike location. These systems were magnetic direction-finders that used two orthogonal loop antennas in conjunction with an electric field antenna to eliminate a phase ambiguity [49]-[50]. It is worth mentioning here that this sensor and the associated signal processing elements only became practical after the development of large-scale, analog and digital integrated circuits in the 1960’s and 1970’s.

Initially, the LLP sensors were developed for the U.S. Bureau of Land Management to address a critical need - early detection of lightning-caused fires. For this application, individual directional sensors were placed at BLM operational facilities and were coupled to signal processing electronics and an x-y plotter. Each detected CG stroke would produce a “vector” on a compass grid, and the length of the vector was proportional to the signal strength. A particularly valuable benefit of employing magnetic-field sensing is that the field strength measurement is minimally sensitive to antenna height and nearby conducting “boundary conditions.” The information from these sensors could be used independently, or combined with data from weather radars and/or additional DF stations to locate thunderstorms more precisely. Eventually, large networks of LLP sensors were established throughout the western US, Canada, and Alaska [14]. The early systems only responded to negative return strokes, but because positive strokes are important for the ignition of wildland fires, and with encouragement from researchers at the U.S. National Severe Storms Laboratory (NSSL), an “option” to process positive strokes was incorporated around 1980.

By the early 1980’s, the LLP DF sensor was being used in a variety of operational and research applications throughout the U.S. and Canada. One of the networks was the “East Coast” network operated out of the State University of New York at Albany (SUNY/A), under the direction of Richard Orville. This network eventually evolved to become the “first instance” of the U.S. National Lightning Detection Network (NLDN), described in detail in Section 5.

Properly calibrated DF systems that were corrected for site errors [51] and that employed an optimization-based location algorithm were able to locate CG strokes with an accuracy better

than 500m for sensor baseline distances of less than 50 km [52]. However, location errors for DF systems are directly proportional to baseline distances, so a network composed of DF sensors with 200-300 km baselines can only provide location accuracy in the range of 2-4 km at best [53]. This location accuracy was generally sufficient for storm characterization and tracking in nowcasting applications, but could not satisfy applications that involved analysis of individual strokes and their interactions with specific points-of-interest. Key examples include insurance claims processing related to lightning damage, and power line fault analysis [54].

The need for improved location accuracy for some applications of lightning information led to the development of systems based on broadband time-of-arrival (TOA) techniques. To first order, the location accuracy in the interior for these systems is independent of sensor baseline distances, and is directly proportional to the error in the arrival-time measurements. The mechanism for the small relative error in the interior of a TOA-based network is illustrated in Figure 6. The stroke occurring inside the network is located by three sensors (A,B,C) , represented by the intersection of two hyperbolas (solid lines). The dotted lines placed symmetrically along the solid lines represent hyperbolas of fixed timing deviation (error) from the ‘true’ value. For this stroke, these lines are essentially parallel to each other, suggesting a relatively small location uncertainty (solid diamond that is nearly square). The stroke occurring outside the network has a very elongated region of location uncertainty, resulting from both the more parallel intersection of the hyperbolas and the diverging nature of the dotted lines that represent the effect of timing error.

The first commercial lightning detection network employing time-of-arrival sensors (manufactured by Atmospheric Research Systems (ARSI)) was installed throughout the continental U.S. in the late 1980’s [55]-[56]. Unlike the system of Lewis et al., this system located lightning in the interior of the network of TOA-measuring. This technique is capable of sub-kilometer location accuracy for CG lightning strokes using information from 3-4 ground-based remote sensors operating in the VLF/LF frequency range.

The lightning location methods commercialized by ARSI and LLP were eventually merged into a common technique, referred to as the “IMproved Accuracy through Combined Technology” (IMPACT) algorithm that allowed simultaneous use of azimuth information from DFs, arrival-time information from LPATS sensors, and combined DF:TOA information from IMPACT sensors [2], [23], [57]. The algorithm produces three estimated parameters -- latitude, longitude, and discharge time. Thus as few as two combined IMPACT sensors provide redundant information which allows for an optimized estimate of location. The IMPACT algorithm can utilize information from any combination of direction finding, TOA, or combined (DF/TOA) sensors. Figure 7 shows a typical lightning stroke in Florida that was detected by five sensors in the NLDN – three IMPACT and two LPATS sensors. The direction (azimuth) measurements are shown as straight-line vectors, and “range circles” centered on each sensor represent the time-of-arrival measurements in the form of the propagation time from the discharge to each sensor. The IMPACT systems are now the most common configuration, given the small number of sensors required to produce a location, and the use of calibrated magnetic field measurements for peak-current estimation [58].

One of the benefits unique to LLS’s operating in the VLF/LF band is that the electromagnetic fields produced by CG return strokes contains useful information about the return stroke current. Uman and others have developed models that describe the shape of the electric and magnetic fields that are produced by return strokes at different distances [59] – [64]. The goal of much of this work has been to understand better how lightning transients couple to electric power systems. Most of these models are consistent with the thought that during the initial rising edge of a return

stroke, i.e., up to the time of the initial peak current, the waveform of the distant (radiation) field can be well-approximated by the simple “transmission line model” [62],

$$E_{\text{RAD}}(t) = -\frac{\mu_0 v I(t - D/c)}{2\pi D} \quad (1)$$

where  $E$  is the vertical electric field on the ground (assumed perfectly conducting) at time  $t$ ,  $\mu_0$  is the permeability of free space,  $v$  is the upward velocity of the stroke (assumed constant) near the ground,  $I$  the current at the base of the channel,  $c$  is the speed of light, and  $D$  is the horizontal distance to the flash [59]. (Note: An upward propagating, positive current produces a downward directed electric field.) The expression for the horizontal magnetic radiation field is the same, scaled down by the speed of light. This finding suggests that the rise-to-peak parameters and peak current in a return stroke can be estimated from a remote measurement of the electric and/or magnetic field if the source location and the return stroke velocity are known, if the propagation losses due to finite conductivity are accounted for, and if the sensors have sufficient bandwidth to measure the peak field without significant distortion. Work over the past 15 years, summarized by Rakov [65] has shown that a calibrated LLS can provide reasonable peak current estimates for subsequent strokes in negative CG flashes that remain in an existing channel, with errors in the range of 10-15% between 15 and 60 kA. Lower-current strokes have larger percentage errors. To date, there is little experimental data that can be used to evaluate errors in LLS-based peak current estimates for negative strokes creating a new ground attachment (first strokes and new-channel strokes) and for positive first strokes, although work by Jerauld et al. [66] suggests that the transmission line model may also accurately represent the current:field relationship in the case of the above-ground attachment that occurs in new-channel negative strokes.

### 3.2 Modern VLF/LF systems

This section briefly reviews modern lightning locating systems and capabilities. The specific systems were selected for discussion because they demonstrate the global “installed base” of operational LLS, or because they represent some innovation beyond what has been discussed thus far. The U.S. NLDN is discussed separately in Section 5, including its history, technical evolution, and current status.

The largest single-owner LLS other than the NLDN is the U.S. Precision Lightning Network (USPLN). This network employs the VLF/LF time-of-arrival technique pioneered by ARSI in the late 1980’s, recently re-engineered by TOA systems, Inc. This system employs over 100 E-field sensors covering the continental U.S. and other portions of North America. No formal performance validation studies regarding this system have been reported, but the operators of the system report greater than 90% stroke detection efficiency (DE) and 250 m typical location error.

There are more than 60 LLS networks worldwide that employ commercial instrumentation operating in the VLF/LF frequency range. Most of these networks employ IMPACT sensors developed by LLP/Global Atmospheric (now Vaisala), and focus primarily on CG lightning. Examples of large networks include the multi-national European network called EUCLID [67], [68], the Japan Lightning Detection Network called JLDN [69], the Brazilian National Network called BrasilDAT [70]-[72], the Canadian Lightning Detection network called CLDN [73], and the South African national network [74]. The highest resolution CG LLS networks are the Austrian Lightning Detection Network called ALDIS [67] which also contributes to the EUCLID network, and NASA’s CGLSS covering Kennedy Space Center in Florida, USA [52]. A small number locally manufactured LLS are located in China, and some limited studies using data from these systems are in the literature [75]-[76].

A number of recent system approaches have focused on locating pulses produced by cloud flashes and in-cloud components of CG flashes. The relative amplitude of radiation fields for cloud pulses and return strokes is a complicated function of the bandwidth of the sensor and the distance to the source of the discharge. Spectral analysis of broadband waveforms produced by in-cloud and CG flashes indicate that the largest positive and negative intracloud pulses exhibit about 10 dB lower amplitude than return strokes in the frequency range of 100 kHz to 1 MHz [77], with even greater differences below 100 kHz. Sensors that employ an upper-frequency limit less than about 400 kHz will therefore inherently show a preference to detect CG strokes. This is illustrated by an experiment carried out by Murphy and Cummins in 1998 [78]. During this experiment, an electric field sensor with a bandwidth from 1 kHz to 400 kHz was used to detect all pulses with peak amplitude greater than about 0.2 V/m. These pulses were time-correlated with observations of cloud flashes produced by NASA's LDAR VHF lightning mapping system [46]. The cloud flashes were within a 100 km range of the VLF/LF sensor. Figure 8 shows cumulative distributions of "equivalent peak current estimates" (normalized in the same way as for CG strokes) for all cloud discharge pulses, for the two largest cloud discharge pulses in any given second, and for a sample of first return strokes in CG flashes. The axis on the left is for cloud pulses, and the one on the right is for CG first strokes. The majority (about 70%) of all LF pulses from cloud discharges had equivalent peak current less than 1% of the typical first return stroke in a CG flash (equivalent to about 0.5 kA). Only the largest 1-2 pulses in each flash were consistent with a median equivalent peak current of about 1.2 kA. On the basis of the data in Figure 8, we infer that large cloud pulse amplitudes in this frequency range have a median value that is 10 to 20 times smaller than those found with first return strokes as reported in [79]. It is likely that for longer propagation distances between the sensor and the source of the discharge, the amplitude difference between first-strokes and cloud pulses is likely to increase, due to the preferential loss of higher-frequency signals [80] that contribute more to the peak amplitude in cloud pulses. We note that there are no cloud pulses larger than about 12 kA in this experimental dataset, although there is a known class of narrow bipolar events (NBEs) with equivalent peak current values in the same range as return strokes [81]. Since NBEs are thought to occur in about 15-20% of lightning-producing cells and constitute about 0.5% of all flashes [81], they must not be strongly represented in this dataset.

This finding does not mean that pulses produced by cloud flashes cannot be detected in the VLF/LF frequency range. Given the large number of pulses produced during the active stage of cloud flashes, it is not uncommon for them to produce some pulses that are comparable in amplitude to small return strokes. The challenge of detecting these pulses is addressed by various combinations of improved sensitivity produced by lower front-end noise, reducing the sensitivity at lower frequencies to better equalize the signal amplitudes for cloud pulses and CG strokes, specialized signal processing, and the use of shorter sensor baselines distances to increase the number of sensors that can detect the small signals. This has been shown by Betz et al. [82]-[83] and Shao et al. [84].

Coupled with the ability to detect a large numbers of cloud pulses is the need to differentiate between these events and CG return strokes. This can be accomplished by analyzing waveform parameters, as was initially done by Krider et al. [49], or by estimating the height of lightning "sources" in the VLF/LF band. The first system designed to determine the height of lightning pulses in this frequency range was developed by Thomson et al. [85]. This system operated on the time-derivative of electric field ( $dE/dt$ ) measured using 5 ground stations in a 15x15 km domain. The authors describe a "weighted hyperbolic" (time-of-arrival) location technique which is an optimization technique that extends the 3D location method described by Proctor [37] for VHF sources. A similar approach was taken by Ishii et al. in Japan [86]-[87], who determined the

altitude of bipolar pulses associated with cloud and CG flashes in the frequency range of 0.32 kHz to 1.2 MHz using five electric field antennas separated by 5-10 km. The wide-area LINET LLS developed by Betz et al. [82]-[83] routinely employs height information derived from the arrival time at the nearest reporting sensor to assist in classification and to determine the initiation height of cloud and CG flashes. The basic location method used in this system is time-of-arrival, although the magnetic-field sensors (bandwidth of 1-200 kHz) provide arrival angle information that is employed as a “plausibility check” on computed locations. These authors indicate that reliable separation of return strokes and cloud pulses can be achieved as long as the closest sensor is within ~100 km of the lightning discharge. This separation distance is determined by the accuracy of the timing measurements and the consistency among the reporting sensors. This suggests that practical operational LLS’s employing this technique to classify discharges should probably employ baseline distances of less than 200 km, in order to assure that classification can be achieved even when a sensor becomes inoperative or when there are significant differences in ground-wave propagation characteristics between sensors.

Shao et al. [84] provide a detailed description of a “New and Improved” Los Alamos Sferic Array (LASA) used to support Los Alamos National Lab’s (LANL’s) satellite lightning observations. Their array of broadband VLF/LF E-field sensors located in Florida consists of a six-station short-baseline region having a ~100 km diameter, and two remote stations forming longer baselines of ~200 km from the central region. This system employs waveform parameters to differentiate between cloud pulses and CG strokes, although the authors demonstrate the ability of the short-baseline region to provide a reliable height estimate using a full 3D optimization calculation. It is shown that within the range of 100 km from the center of the short-baseline region, LASA detected 2–5 times more cloud flashes than CG flashes (the authors employ an algorithm to group cloud discharges and CG strokes into flashes), suggesting that the cloud flash DE is quite high. As the range increases to 200 km and beyond, LASA system in Florida starts to see fewer cloud flashes than CG flashes, because of the general disparity between the peak fields produced by return and weaker cloud pulses. LANL also operates a longer-baseline LASA system in the U.S. Great Plains.

All the papers discussed in this section are quick to acknowledge that these systems are not able to map detailed lightning channel structures like the VHF mapping systems, because of the LF/VLF signals they observe. The VHF systems detect the radiation signals produced by smaller-scale processes, whereas the systems discussed in this section detect “cloud pulses” associated with the field changes produced by larger-scale high-current processes. Based on a study comparing these cloud pulses with KSC’s LDAR system [78], they are generally clustered near the initial breakdown location in the flash, or areas associated with abrupt vertical breakdown between charge regions. A representative example obtained from Vaisala’s research networks in the Dallas-Fort Worth (DFW) region in north Texas is shown in Figure 9. The pulses detected by the short-baseline LF cloud detection system (red dots) are shown to cluster near the initial breakdown region shown in the 2D flash depiction produced by Vaisala’s LDAR II lightning mapping system (blue dots). Although LF cloud lightning systems do not provide a full description of the spatial extent of a cloud flash (or the charged regions of a mature thunderstorm), the practical benefit of these systems is their ability to provide storm onset information. They also have the benefit that VLF/LF signals propagate well through mountainous terrain (no line-of-sight constraint).

#### *4. Long-range and Global Lightning Detection*

In remote regions where conventional radar and surface observations are not available, tracking of thunderstorms and assessing cyclone intensification are important challenges in weather prediction for civilian and military purposes. Thunderstorms over the ocean represent a threat to airborne carriers and ocean shipping and are mostly beyond the range of weather radars. Although today's operational geostationary satellites provide continuous visible and infrared imagery, cirrus anvils often obscure convective activity. Convective clouds that produce lightning have significant updrafts, increasing the threat of turbulence and icing. This section provides a brief overview of both ground- and space-based approaches capable of providing real-time global information about lightning and thunderstorms.

#### **4.1 Lightning Mapping from Space**

Continuous high-quality observations of lightning on a global scale remain an unmet challenge. Global observations (latitudes below  $\sim 75$  degrees) of cloud and CG (Total) lightning produced by NASA's Optical Transient Detector (OTD, onboard OV-1) and augmented by the Lightning Imaging Sensor (LIS, as part of the Tropical Rainfall Measuring Mission, TRMM) have provided over a decade of high-quality lightning observations. Although these devices only view a specific region for a few minutes at a time [88], NASA scientists have been able to produce the first "world-wide" estimates of (Total) lightning flash density with a spatial resolution of 0.5 degrees. A limitation of these data is that they currently do not accurately separate out CG and cloud lightning incidence. The next generation series of GOES-R (Geostationary Operational Environmental Satellite) is planned to carry a Geostationary Lightning Mapper (GLM) based on the pioneering work by NASA, as discussed by Christian [89], which will monitor lightning continuously over a wide field of view. Until these instruments are in orbit, tested and calibrated, ground-based long-range lightning detection remains the only method to provide a continuous lightning observation over the oceans. The launch of the first GOES-R series satellite is scheduled for 2014.

VHF emissions from lightning have also been observed from space. Much of the literature on such observations has derived from the FORTE satellite built by Los Alamos National Laboratory [90]. FORTE was designed as a more specialized follow-on platform to study lightning-associated signals that had previously been observed by an instrument called Blackbeard. The FORTE satellite combined optical and VHF observations. Among its many research objectives, FORTE was used as part of a demonstration of the possibility of performing multiple-satellite geolocation of VHF lightning emissions from space [91].

#### **4.2 Ground-based Systems**

When propagation distances between a lightning discharge and a remote electromagnetic sensor are less than about 1000 km, significant energy in both the VLF and LF band can propagate as a ground wave. At greater distances, energy in the VLF frequency range can propagate effectively in the waveguide defined by the earth's surface below and by the ionosphere above, specifically its lowest layer, the D region. Out to distances of 3000-4000 km, most of the energy is carried in signals that can be accounted for using the first two "ionospheric hops" ([92], and Shao and Jacobson, this issue). At even greater distances, propagation is more efficiently characterized using modal analysis, as described by Wait [93]. Given these characteristics, long-range LLSs have the potential to provide cost-effective and accurate monitoring of convective storms over large synoptic-scale regions.

All modern long-range ground-based LLS employ location algorithms based on time-of-arrival, magnetic direction finding, or a combination of the two. The earliest history of lightning detection

dealt with the geolocation of long-range “sferics” in the 1920’s, as described in Section 1. These early systems employed narrowband magnetic direction finding sensors. Today, The Zeus long-range network described by Chronis and Anagnostou [94]-[95] uses an arrival-time-difference method, and is located in the Mediterranean region and Africa. This network is reported to typically locate 20% of the CG flashes at a distance of about 5000 km, with higher DE closer to the sensor array. The location error is a few 10’s of km in the interior of the network, increasing to typically 100-200 km at long range. The U.K. Met Office also employs an arrival-time-difference method (ATDNET - [96]-[97]). This network currently employs 11 operational sensors that were chosen to provide maximum coverage over Europe. A recent paper by Gaffard et al. [98] comparing this system with local LLS’s in France and Austria found a relative stroke DE in the range of 50% (resulting in a higher flash DE), with typical location errors in the range of 5-6 km. Pessi et al. [92] describe a network covering the north-central Pacific (PacNet) that employs both magnetic direction finding and time-of-arrival methods, and can therefore locate a lightning discharge with as few as two sensors. Based on performance models and comparison with NASA’s Lightning Imaging Sensor in the TRMM orbital satellite, the daytime and nighttime flash DE in the north-central Pacific is in the range of 17-23 and 40-61 percent, respectively. The median LA is in the range of 13-40 km. This network has the unusual attribute that it seamlessly ties in with the broadband (VLF/LF) sensors in the U.S. NLDN and the Canadian Lightning Detection Network. Although these broadband sensors have poorer sensitivity than the PacNet sensors for ionospherically-propagated sferics, they contribute significantly to the overall performance of the integrated network between the North American Pacific coast and the Hawaiian Islands.

The World Wide Lightning Location Network (WWLLN – [99]-[102]) utilizes a time-of-group-arrival (TOGA) method to locate lightning strikes. This is currently the only ground-based LLS that strives to provide lightning information on a global basis. As of 2006, this system employed 25 sensors located on all continents, as reported by Rodger et al. [100]. The highest CG stroke detection efficiency is estimated to be ~18% in Australia and Indonesia, as this is the area with the highest density of sensors. This roughly equates to a minimum detectable peak current of 30-40 kA. The performance falls off elsewhere in the world, dropping to under 5% between Africa and the Americas, with minimum detectable currents at or above 100 kA. The estimated global median location accuracy for this network ranges between 2.9 km [99] and 15 km [101].

### *5. The U.S. National Lightning Detection Network (NLDN)*

The U.S. NLDN has its roots in gated wide-band direction-finding technology, and currently employs the IMPACT technology described in Section 3. Primary applications areas include forestry (fire detection), the electric utility industry, the insurance industry, and areas of meteorological and aviation nowcasting. The NLDN has been providing real-time lightning information since the early 1980’s, and has provided continental-scale (U.S.) information to research and operational users since 1989. This network has undergone several improvements during its 20+ year life. This section briefly discusses the history and “evolution” of the technical aspects and applications of this network, and summarizes some of the many studies that have been carried out to validate its performance.

#### **5.1 Early History of the NLDN**

As noted in Section 3, one of the earliest “LLP networks” was the “East Coast” network operated out of the State University of New York at Albany (SUNY/A). It was the early success of this network that led to the interest and support from the Electric Power Research Institute (EPRI) to develop a U.S. national network to serve the needs of the electric power industry. EPRI support

began in June 1983, and the network entered an expansion period that would not stop until the entire continental U.S. (lower 48 states) was covered in 1989 [103]-[104]. During this 6-year period, EPRI funded the development of the NLDN based on the electric utility needs for real-time lightning information for repair crew management, and for the long-term objective of producing an 11-year (solar cycle) lightning ground flash density (GFD) dataset for the continental U.S.

Although primary funding for this “early” NLDN was provided by EPRI, many researchers and meteorologists also used lightning data during this expansion of the NLDN. This fact is evidenced by over 100 publications about lightning detection systems between 1983 and 1988, more than a dozen of which used data from the emerging NLDN. By 1987 the value of lightning data in operational meteorology was sufficiently established that the U.S. Office of the Federal Coordinator for Meteorology facilitated national coverage throughout the U.S. The final network configuration was a “composite” produced by combining the EPRI-funded network with smaller networks operated by the Bureau of Land Management and The National Severe Storms Lab. Figure 10 shows the evolution of coverage during this 6-year period, taken from the recent paper by Orville [105]. A detailed early history of the NLDN is also provided in this paper.

### **5.2 – NLDN Commercialization and Performance Improvements**

The expansion of the NLDN in the late 1980’s brought about two pivotal realizations on the part of EPRI and the SUNY/A scientists. First, it was clear that real-time and historical lightning information had value in a number of applications beyond meteorology and the electric utility industry. Second, it was very expensive to operate and maintain a national-scale network with over 100 sensors. As a result of these realizations, the decision was made to find a means to commercialize the NLDN. In late 1990, a commercialization agreement was made between EPRI, SUNY/A and LLP, resulting in the formation of GeoMet Data Services (GDS) as the operator of the NLDN. By 1993, it became clear that the primary “growth” applications areas for lightning data use in the U.S. were as follows:

- Point-specific lightning warning in government and commercial applications;
- Point-specific determination of the past occurrence of lightning for use by the insurance industry and its clients;
- Assessment of power line faults and failures, as part of a broad national initiative to improve power quality and reliability.

The most demanding of these applications is power line reliability. The essential elements of this application are discussed in [54], which includes an overview of electric utility applications of lightning information. The three applications noted above imposed new requirements on the performance of the NLDN, specifically:

- Detection of both first and subsequent strokes of CG flashes;
- Location accuracy in the range of 0.5-1 km;
- Better flash detection efficiency (FDE) (as good as possible)

The location accuracy requirement could not be met using direction-finding by itself, without reducing the sensor baseline separation to less than 100 km. Therefore it was essential to include time-of-arrival location methods in the location algorithm, which had become quite viable with the advent of GPS timing subsystems. On the other hand, the detection efficiency requirement, coupled with the continued need for the best-possible estimates of peak current, made it impractical for the existing time-of-arrival network (then owned and operated by ARSI) to



address these emerging requirements. Given these facts and the difficulty in establishing a profitable lightning data business with two competing national networks, the solution was found in the merger of LLP, GDS and ARSI. This resulted in the re-deployment of ARSI's LPATS III sensors in conjunction with new combined MDF:TOA (IMPACT) sensors during late 1994 and early 1995 [53].

The upgraded network employed the IMPACT location algorithm that allowed simultaneous use of arrival-time information from LPATS sensors and combined DF:TOA information from IMPACT sensors. Performance of the NLDN after the upgrade was modeled in [53], and validated in independent studies [106]-[107], [52]. The upgrade resulted in 80-90% FDE and 0.5 km median location accuracy in most regions, falling off rapidly near the edges of the network. Partial funding for the re-deployment of the NLDN, validation of the upgraded network, and development of tools for the electric utility industry was provided by EPRI [57]. As a result of the 1995 upgrade and the associated increase in the user community, EPRI was no longer required to provide financial support for the network.

Performance of the NLDN was further improved in 1998 along its border with Canada, as a result of the installation of the Canadian Lightning Detection Network and its combined operation with the NLDN. The resulting "North American Lightning Detection Network" [108]-[109] provides contiguous lightning information throughout a nearly 20 million km<sup>2</sup> region with latitudes ranging from 25 to over 60 degrees north latitude.

Performance of the NLDN for CG lightning also improved as a result of an upgrade in 2002-3, principally due to replacement of the TOA-only LPATS III sensors with IMPACT sensors. This upgrade allowed the NLDN to locate CG strokes with as few as two sensors, reducing the effective baseline of the network. Model estimates of the post-upgrade CG FDE are in the range of 90-95% throughout the continental U.S., and stroke DE increased from the (estimated) value of 50% after the 1995 upgrade to the range of 60-80%. The modeled post-upgrade NLDN DE is indirectly represented in Figure 11. This figure shows the estimated minimum detectable peak current (50% probability) in the U.S. portion of the complete NALDN. Representing the detection capability in this manner reflects our growing understanding that there are regional and temporal variations in the CG flash characteristics (peak current and multiplicity). In order to model the overall DE of an LLS, one must assume that there is a specific peak current distribution common to all regions. However, the video-based validation studies by Biagi et al. [110] show that there may 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 distributions of negative first stroke peak current and multiplicity between Texas-Oklahoma and Southern Arizona.

During the 2002-3 upgrade period, Global Atmospheric and the NLDN were purchased by Vaisala, who had strong interest in expanding the capability of the NLDN to include cloud lightning detection [111]. This focus was in response to the growing research and operational interest in both cloud and CG lightning. As part of this upgrade, the sensors were modified to allow the detection of large-amplitude VLF/LF pulses in cloud flashes. Only a small fraction of cloud flashes contain pulses of sufficient amplitude to be detected and located by NLDN, given the 300-350 km baselines between the NLDN sensors. As of April 2006, cloud lightning data has been a part of the real-time and archived NLDN dataset.

### **5.3 Validation**

In conjunction with the 2002-3 upgrade, field campaigns were carried out in Southern Arizona and in Oklahoma/Texas in 2003 and 2004 by University of Arizona researchers, and at the

International Center for Lightning Research and Testing (ICLRT) in Florida in 2001-2003 by University of Florida researchers (see test regions in Figure 11). A key objective of these studies was to validate the NLDN performance characteristics for CG lightning. Data from the Arizona/Oklahoma/Texas studies were also used to evaluate the classification of lightning type. The main findings from these studies are summarized below. Complete results can be found in Biagi et al. [110] and Jerauld et al. [112].

### 5.3.1 Detection Efficiency and Location Accuracy

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. These studies in 2003-2004 evaluated both detection efficiency (DE) and location accuracy (LA) in southern Arizona (S AZ) and in Texas/Oklahoma (TX-OK) after the upgrade. Both stroke and flash DE were studied. A CG 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 [113] and Kehoe et al. [114]. 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.

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 (bias) errors are implicitly excluded. The reported location error is the measured position difference scaled down by  $\sqrt{2}$  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). 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).

The Florida ICLRT validation 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. The principal findings of this study are also summarized in Table 1.

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)
<b>Tucson 2001</b>	--	--	--	<b>73<sup>a</sup></b>
<b>S. AZ 2003-4</b>	<b>424<sup>b,c</sup> (667)</b>	<b>76 (3620)</b>	--	<b>93 (1097)</b>
<b>TX-OK 2003-4</b>	<b>282<sup>b,d</sup> (193)</b>	<b>85 (885)</b>	--	<b>92 (367)</b>
<b>Florida RTL 2001</b>	<b>270<sup>e</sup> (17)</b>	<b>52 (33)</b>	<b>82 (11)</b>	<b>91<sup>f</sup> (11)</b>
<b>Florida RTL 2003</b>	<b>450<sup>e</sup> (34)</b>	<b>69 (49)</b>	<b>84 (12)</b>	<b>95<sup>f</sup> (12)</b>

<sup>a</sup> Obtained from Kehoe and Krider (2004)

<sup>b</sup> Median position difference, divided by  $\sqrt{2}$  due to the involvement of two random variables

<sup>c</sup> Data only from 2003

<sup>d</sup> Data only from 2004

<sup>e</sup> Median location error for subsequent strokes

<sup>f</sup> Estimated flash DE, using Stroke and RTL DE values in equation (2)

Due to the nature of rocket-triggered lightning (RTL), only return strokes thought to be similar to natural subsequent strokes are evaluated with this technique. 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 an under-estimate of the flash DE in Florida, since these flashes do not include a natural first stroke. The flash DE can be estimated 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

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

where

$DE_{fl}$  = Natural Flash Detection Efficiency

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

$DE_{rtl}$  = Rocket triggered FDE (“any-subsequent stroke” DE)

The rationale of this equation is that a flash is detected if either “the first stroke is detected (so we do not care about subsequent strokes)” (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 (though it is thought to be higher), the estimated flash DE values in Table 1 are obtained. Although there are only a small number of flashes in these studies, the CG 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 270 m and 450 m, respectively (Table 1). The difference between the two years is probably a result of the small sample sizes.

### 5.3.2 Cloud Flash Detection in the NLDN

To estimate the fraction of cloud discharges detected by the NLDN, Vaisala operated a regional network of IMPACT-ESP sensors near Dallas, Texas that was co-located with an LDAR II VHF total lightning mapping network [115]. The LDAR II network served as the reference system for the cloud lightning detection capability of the regional IMPACT-ESP network. Because of the relatively short sensor baseline distances of the regional LF test network in this area, the modeled detection efficiency exceeds 25% in a region of about 100-km radius surrounding Dallas-Fort Worth and in the corridor between Dallas and Houston. The performance of the regional IMPACT-ESP system (Texas Test Network) was evaluated against the LDAR II for several storms in the Dallas area during 2004. This analysis took advantage of prior NLDN validation field work by classifying all positive-polarity events with peak currents less than 10 kA as cloud discharges, even if they were originally classified as CG strokes. In this analysis, when multiple LF cloud discharge events were associated with a single LDAR flash, they were grouped together and counted as a single flash. In this way, the analysis provides a value for the cloud flash detection efficiency (FDE). Table 2 shows that the LDAR-relative cloud FDE varied between 16-

38% for a sample of 4 storms. The significant result from this study is that the observed cloud FDE values are consistent with the modeled detection efficiency.

Table 2 - Summary of analysis of LF cloud detection efficiency relative to LDAR II for four isolated storms near Dallas, Texas, in spring 2004.

date	All VHF flashes	LF cloud	relative DE (%)	modeled DE (%)
5/1 A	537	72	16.7	15-25
5/1 B	122	35	38.5	25-30
5/1 C	381	101	36.7	25-30
5/13	58	9	23.1	25-30

As of April 2006, cloud lightning data has been a part of the real-time and archived NLDN dataset. Given the longer baseline distances in today's operational NLDN relative to the Texas Test Network, the modeled cloud FDE for the NLDN itself is in the range from 10-20%, depending on local differences in sensor baseline distances. Under typical conditions, the number of reported cloud discharges is similar to the number of CG flashes. During widespread severe weather conditions, we have seen this ratio increase by more than a factor of two.

### 5.3.3 Misclassified Events

The NLDN upgrade clearly increased the detection of lower amplitude sources, and thereby increased the potential for reporting cloud discharges. However, some of these low-current discharges are difficult to accurately classify. The UA campaigns in S. AZ and TX-OK suggested that most (~90%) of the positive small events (<10 kA) are actually cloud pulses and that most (~90%) larger positive events (>20 kA) are likely to be CG strokes. The population of positive discharges between 10-20 kA are a mix of CG and cloud pulses. These studies also indicated 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 2005, the UA carried out a 2-week field campaign in the region of Colorado-Kansas-Nebraska (KS-NE) shown in Figure 11 that focused on evaluating lightning classification in this "positive dominated lightning" region, an area unique in the continental U.S. for the frequency of positive CG lightning [116]-[117]. A detailed analysis of findings from this campaign is provided in Fleenor et al. [118]. As part of this study, simultaneous video, electric field waveforms, and NLDN measurements were examined in order to evaluate the classification of NLDN reports during 3 single-cell storms, one dominated by negative discharges and two by positives. Based on the waveform data, 204 out of a total of 376 video-correlated NLDN reports (54%) of CG were determined to be for cloud pulses as observed through combined video and waveform data. Many of the misclassified events were positive discharges with estimated peak current ( $I_p$ ) below 15 kA. Since April 2006, the NLDN has classified all such low-current positive discharges as cloud pulses, and had this same rule applied in 2005, the overall percentage of misclassified discharges would only have been 30%. Based on an analysis of electric field waveforms, the classification problem appears to be worse when the cloud pulses are bipolar with nearly equal positive and negative peak amplitudes. This is reflected in the fact that 59% of the misclassified cloud pulses were also assigned an incorrect initial polarity by the NLDN, and the majority of these events were bipolar pulses. The degree of misclassification seems to vary by region, because the prior studies noted above in Texas, Oklahoma, and southern Arizona, which all lie outside the uniquely positive-dominated region studied in 2005, show a much smaller

degree of misclassification [110]. As a result of the 2005 findings, Vaisala has been working with the University of Arizona to develop a new classification scheme for the NLDN that is in the final stages of validation.

### *6. Possible Future Needs and Directions*

Modern LLS's are both a blessing and a source of frustration. Depending on the nature of a given application's needs, information from several different LLS systems may be required. Current long-range LLS's may be able to cover the globe with as few as 25 sensors, providing information in regions where no other lightning data are available, but the CG stroke detection efficiency varies from a few percent up to 18% depending on local network geometry. Additionally, peak current estimates are inaccurate or not available, and the polarity and discharge type are difficult to estimate. Shorter-baseline wide-area VLF/LF systems provide continuous, uniform detection of most (80-95%) of CG flashes and a lower percentage of cloud flashes over very large areas, with median location accuracy of 200-500 m. These systems can cover 25,000 to 150,000 km<sup>2</sup> per sensor, depending on the desired detection efficiency for CG strokes and cloud pulses. They also provide polarity information and useful estimates of peak current, and have the potential to provide accurate classification of type (CG or cloud). However, they do not provide information about the space-time behavior of individual flashes, or the spatial extent of the charged region of a large thunderstorm. VHF mapping systems provide much more information about the spatial and temporal behavior of flashes and thunderstorms and can locate specific discharge features with an accuracy of 10's to 100's of meters, depending in the technique and type of feature. These VHF systems require much higher sensor density than VLF/LF systems, and they cannot directly locate CG strokes or provide estimates of their peak current. All modern LLSs can determine the time of lightning discharge features with an accuracy of a few microseconds, providing the ability to time-correlate this information to virtually any other measurable event. These strengths and limitations explain why these three types of systems exist today, and will probably be needed in the foreseeable future.

Given the growing need for more precise information about convective storms over the oceans and in parts of the world where detailed meteorological information does not exist, coupled with the renewed efforts in long-range lightning detection over the last decade, it is safe to say that long-range LLS's are likely to improve over the next decade. This is likely to result in global systems with fewer than 50 sensors that can uniformly detect a larger portion of CG flashes, as well as some cloud flashes. It is unlikely that such systems will have location accuracy better than 10 km, given the complex spatial and temporal variations in ionospheric propagation. Such systems would nicely complement satellite-based Total Lightning observations.

VHF lightning mapping systems already provide information that exceeds the needs of most operational users. The practical problem for operational use is the sensor density required, particularly for VHF TOA systems. From the perspective of scientific research, these systems still have limitations that inhibit our understanding of the physics of lightning and the organization of charge in clouds. Limitation in sensitivity prevents both of these systems from regularly detecting and mapping positive leaders which are known to occur in all lightning flashes. The inability of TOA and interferometry to regularly map both fast- and slow-propagating leaders is also a practical problem. This latter problem may soon be addressed through LLS's that combine these detection methods into a single system.

Wide-area LLS's that detect broadband lightning emissions in the VLF/LF band have a number of areas where they can improve to meet the increasing needs of various applications. The value of cloud lightning information provided by these systems, in combination with the trade-offs between sensor sensitivity, signal processing capability, and sensor baseline distances, will need to be determined. More specifically, it is currently not known if cloud lightning information provided by these systems will adequately address the demand for improvements in early warning and cession of CG threat or identification thunderstorms with the potential of producing severe weather (high winds, hail, or tornadoes). There are also a number of performance limitations caused by propagation of lightning electromagnetic fields over mountainous and finite-conducting terrain. Recent research has clearly demonstrated that it is possible to remove some of the errors in arrival time (used for TOA locations) and in signal strength measurement by correcting for terrain and conductivity [119]-[121]. It is not difficult to achieve 200-meter median accuracy with such corrections.

Peak current estimates for CG strokes provided by these systems suffer from measurement noise, calibration errors, and imperfect correction of propagation and terrain effects. This fact also opens up the possibility that improvements in ground-wave propagation modeling noted above will further improve the peak current estimates provided by these systems. It will also be important to validate and/or refine the peak current estimates for negative flashes creating new ground contacts and for positive flashes. Various research groups are currently obtaining relevant data in controlled experimental conditions, and there should be clear answers within the next few years.

### *6. Closing Comments*

There is a growing number of ground-based lightning locating systems and techniques. This shows the expanding importance of lightning, and more specifically its impact on modern human life and infrastructure. As in the past, new capabilities in lightning detection will be driven by the demands of new and existing applications, constrained by technology and cost. There is room for improvements in all areas of lightning detection, and technology and scientific knowledge are available to provide them. No one technique or frequency range can meet all the needs, but it is likely that we will see a growing overlap between the capabilities of long-range VLF systems, wide-area VLF/LF systems, and VHF mapping systems.

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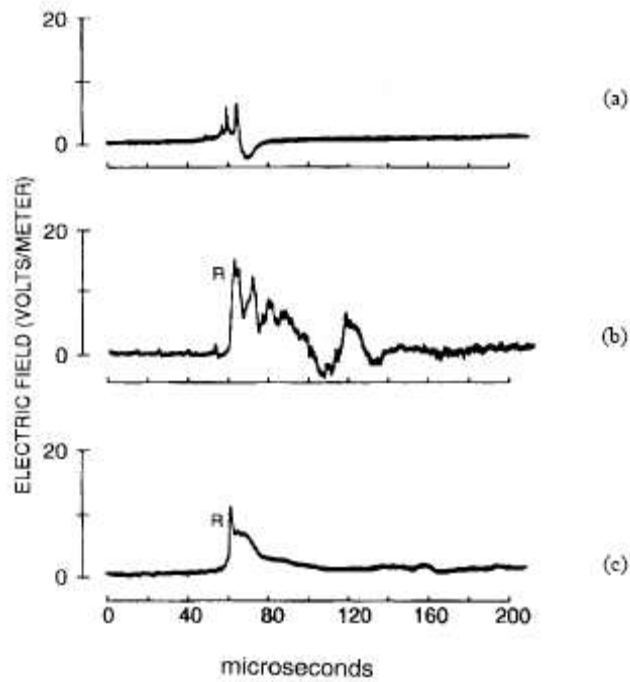
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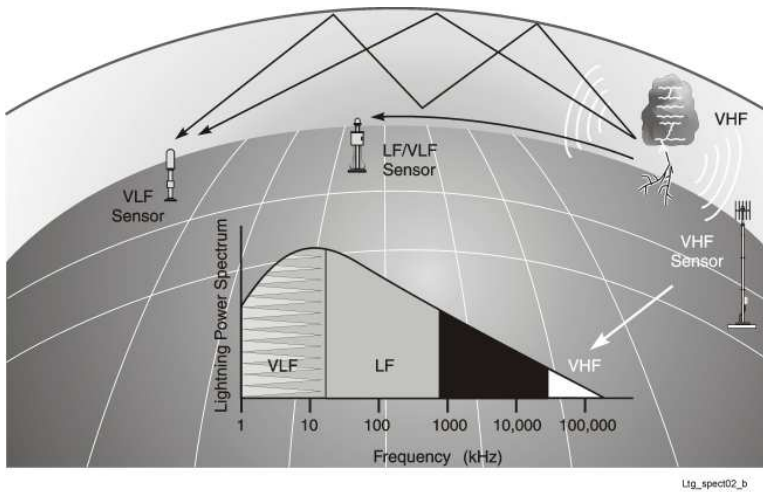
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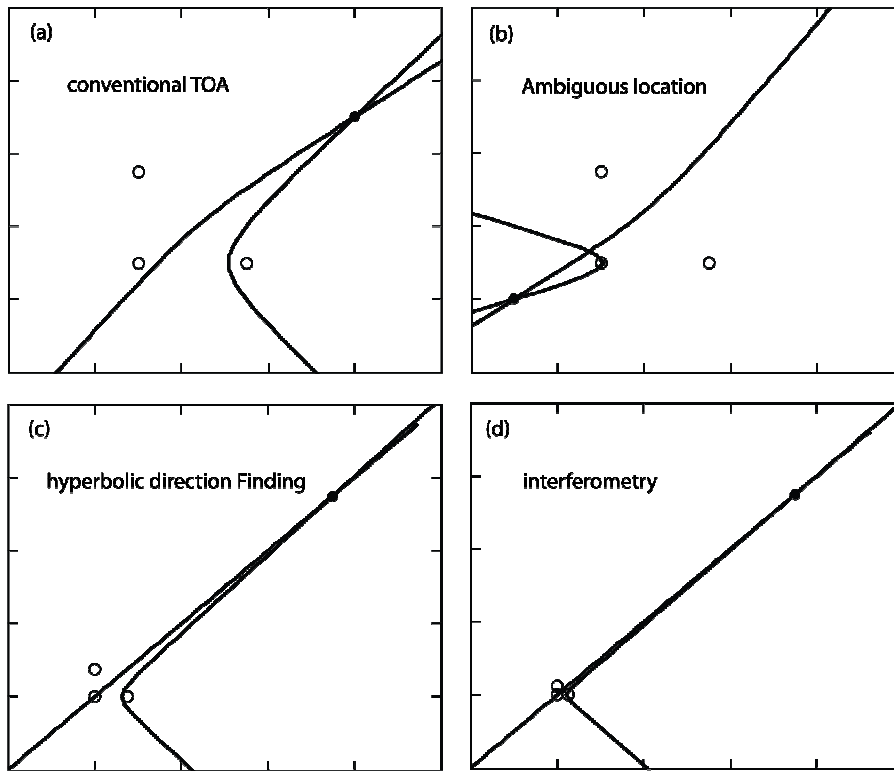
## Figures



**Figure 1** Three representative electric field impulses that were radiated by a CG flash at a distance of about 60 km. (a) Trace from the preliminary breakdown within the cloud; (b) Trace from the first return stroke; (c) Trace from a subsequent return stroke in a preexisting channel. (Adapted from [14], with permission)



**Figure 2.** Illustration of lightning locating techniques and operating frequencies. See text for details.



**Figure 3.** Illustration of time-of-arrival (TOA) location using three sensors (open circles) for various geometries. (a) Conventional use of TOA showing intersection of hyperbolas (black dot) determined by time-differences between pairs of sensors; (b) Ambiguous location created by hyperbolas crossing at two nearby points; (c) early “hyperbolic intersections” method where the distance to the signal source is far greater than the distance between sensors; (d) approximation to interferometry, where the distance between sensing elements is very small (usually a fraction of a wavelength), leading to a clear “direction vector” pointing to a distant signal source.



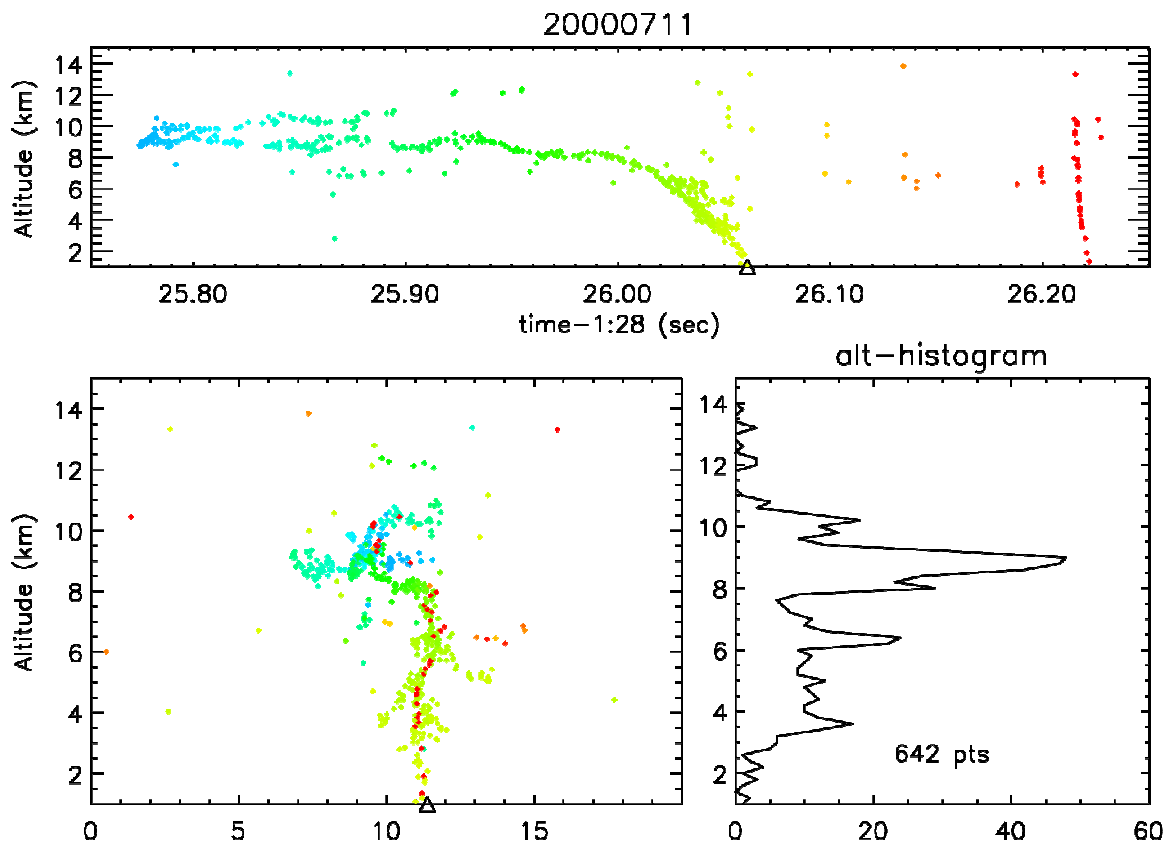
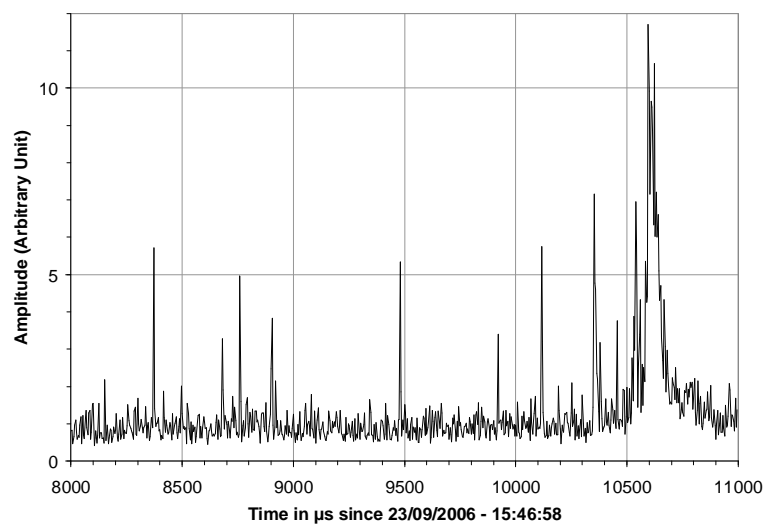
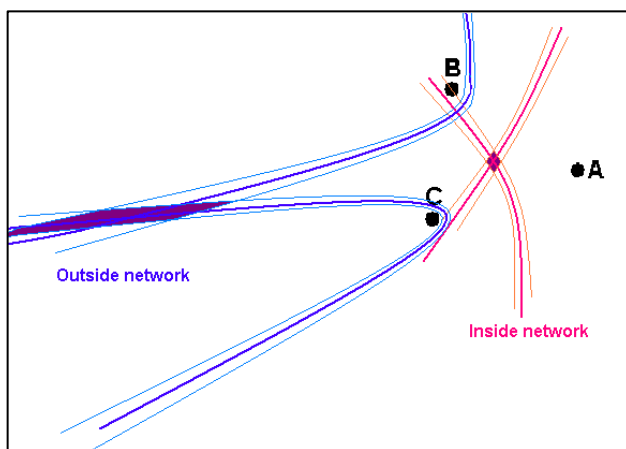


Figure 4. “Bolt from the blue” cloud-to-ground flash detected using VHF time-of-arrival lightning mapping. See text for details.



**Figure 5.** Smoothed amplitude waveform for a typical lightning-generated VHF signal showing several impulsive events and one burst of radiation lasting about 300  $\mu\text{s}$ .



**Figure 6** Illustration of differences in TOA-based location accuracy for sources located inside and outside a 3-sensor network (locations A-C).

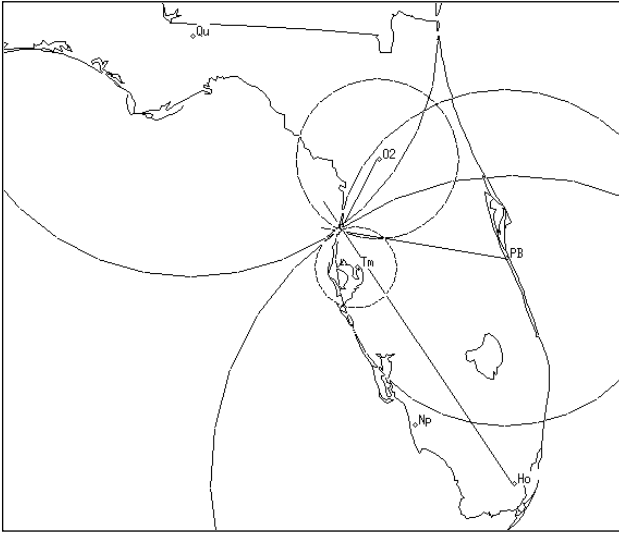


Figure 7- Example of the IMPACT location algorithm using three time-of-arrival sensors and two IMPACT sensors.

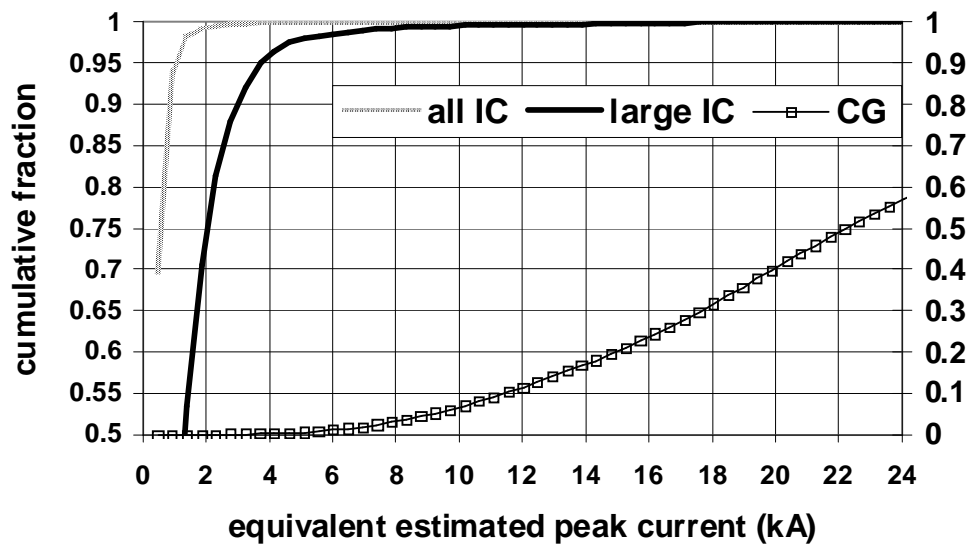


Figure 8 – Cumulative “equivalent peak current” distributions for all IC pulses, the largest IC pulses, and first strokes in CG flashes.

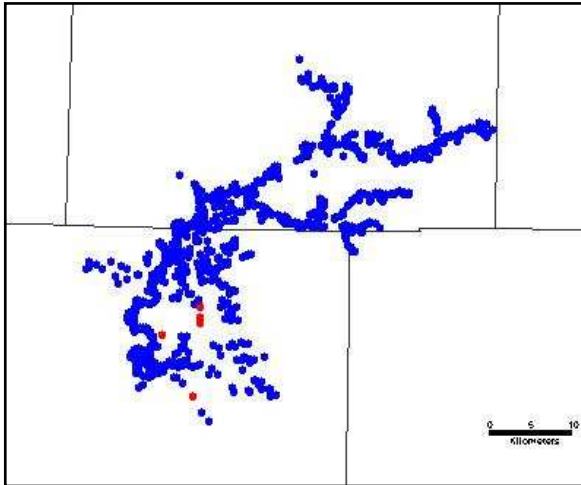


Figure 9 – Cloud pulse detection using LF methods (red dots), compared to total lightning mapping at VHF (blue dots).

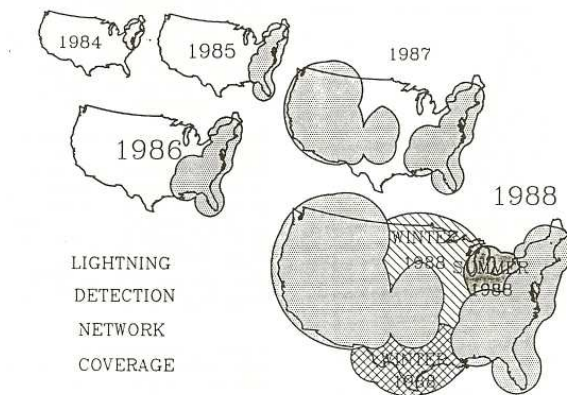


Figure 10 – Coverage areas for the expanding SUNY/A NLDN from 1984 through 1988. Adapted from [105], with permission.

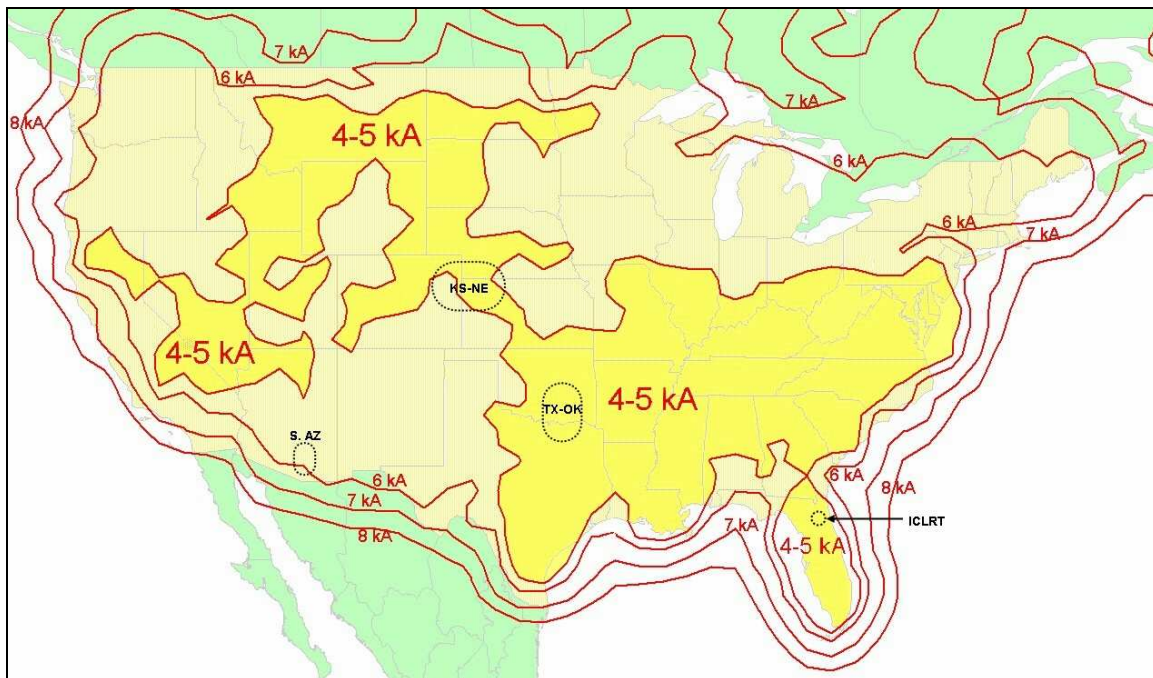


Figure 11. Estimated minimum detectable peak current (50% probability) for the upgraded NLDN in 2002-3. Validation studies in 2003-4 were carried out in the four small regions identified by black circles.