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

Kenneth L. Cummins, *Senior Member, IEEE*, and Martin J. Murphy

(Invited Paper)

***Abstract*—Lightning in all corners of the world is monitored by one or more land- or space-based lightning locating systems (LLSs). 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 1980s, 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.**

***Index Terms*—Electromagnetic measurements, lightning, remote sensing.**

I. 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 multisensor lightning locating systems (LLSs) dating as far back as the 1920s. Modern LLSs are able to determine the location, intensity, and movement of thunderstorms in real time, and can help locate 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.

Manuscript received October 24, 2008; revised March 12, 2009. First published July 24, 2009; current version published August 21, 2009.

K. L. Cummins is with the Department of Atmospheric Sciences, University of Arizona, Tucson, AZ 85721-0081 USA (e-mail: ken.cummins@vaisala.com).

M. J. Murphy is with Vaisala, Inc., Tucson, AZ 85756 USA.

Digital Object Identifier 10.1109/TEMC.2009.2023450

A. 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 by 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 2–10 in most ordinary thunderstorms (e.g., [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 can provide an important indication of both the growth rate and intensity of thunderstorms, thus 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 (MCSs) 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 kiloamperes to more than 200 kA. The return strokes have a nominal duration of tens of microseconds, and are typically separated in time by 20–100 ms. A lightning *flash* typically contains two to four 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 interstroke intervals. For many flashes, the *subsequent strokes* (i.e., the strokes that 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%–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 1-s 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 rise times 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 reilluminate existing channels will produce strong emissions in the very high frequency (VHF) band. One type is quasi-continuous over a couple of milliseconds and does not exhibit distinct peaks during this 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 very low frequency (VLF) ranges. In the VLF band, the radiation is dominated by return strokes, as first shown by Malan [13, Sec. 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 Fig. 1, which are taken from Krider *et al.* [14]. More information regarding field waveforms produced by cloud and CG processes are provided in [15] and [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 Fig. 2. Vertically polarized transient pulses in the LF and VLF range propagate along the surface of the Earth and have been used to detect and locate return strokes

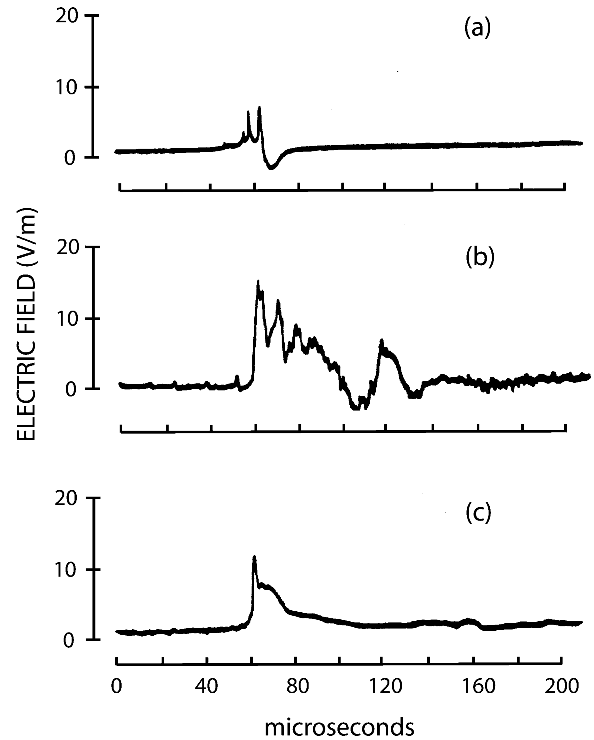

Fig. 1. Three representative electric field impulses that were radiated by a CG flash at a distance of about 60 km. (a) Trace from the preliminary breakdown within the cloud. (b) Trace from the first return stroke. (c) Trace from a subsequent return stroke in a preexisting channel. (Adapted from [14]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

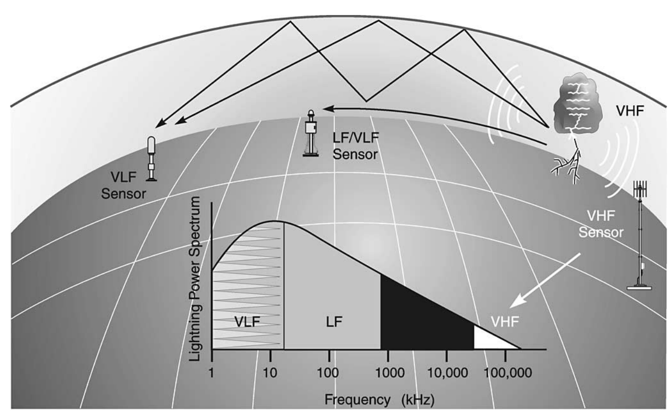

Fig. 2. Illustration of lightning locating techniques and operating frequencies (see text for details).

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 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.

B. 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 are 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. Measurements of electromagnetic fields produced by lightning were typically obtained using narrow-band radio receivers in the VLF and LF 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, narrow-band 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 (LA) of several tens of kilometers—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 developed for marine navigation purposes in the 1930s and 1940s [20] were first employed in the geolocation of lightning in the late 1950s, 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 Fig. 3 for various geometries. Under some conditions, curves produced from only three sensors will result in two intersections, thus leading to an ambiguous location [Fig. 3(b)]. Lewis *et al.* geolocated lightning at great distances from the sensor array, thus resulting in a geometry such that each pair of sensors has one line segment of their associated hyperbola pointing in roughly the same direction [Fig. 3(c)]. 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. More detailed information about the early history of lightning measurements and detection systems is provided in [2], [22], and [23], including general descriptions of basic lightning geolocation methods.

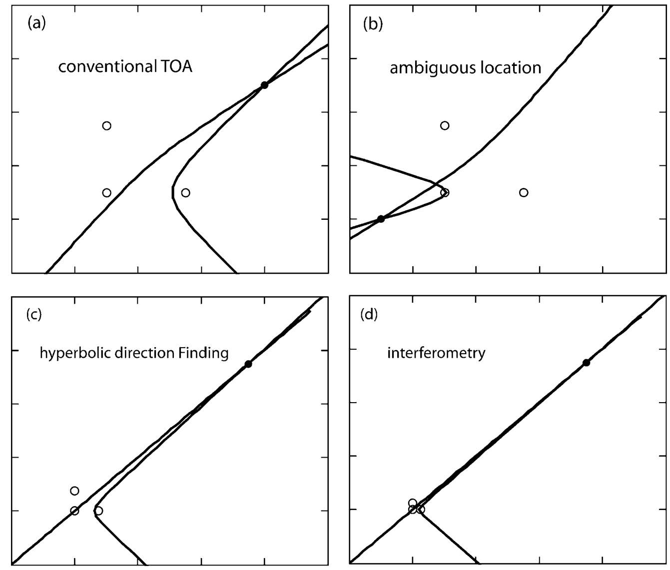

Fig. 3. Illustration of TOA location using three sensors (open circles) for various geometries. (a) Conventional use of TOA showing intersection of hyperbolas (black dot) determined by time differences between pairs of sensors. (b) Ambiguous location created by hyperbolas crossing at two nearby points. (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.

The following sections provide more detail about modern LLSs. 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 III. Section IV covers long-range and global LLSs. A detailed case study of the U.S. National Lightning Detection Network (NLDN) is provided in Section V. Single-station LLSs are not addressed in this paper.

II. 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 multisensor 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 TOA systems for lightning mapping, and discusses their relative strengths and weaknesses.

A. Direction Finding Based on Interferometry

As noted in Section I-B (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 tens to hundereds of kilometers. This geometry is illustrated in Fig. 3(d), 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 VHFs. 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 intracloud (IC) and CG lightning. These were single-station systems that provided a "projection" of lightning onto a plane. It is possible to obtain 3-D locations using interferometry [28], [29]. The source location is then obtained by computing the triangulation of the azimuth and elevation from at least two 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 three sensors. By assuming that the source does not move significantly in azimuth for a given duration, these systems can take advantage of the long 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 two dimensions that is able to locate both IC and CG flashes [31], [32]. Their sensor integrates over a 100-μs period, thus resulting in azimuth errors in the range of $0.3°$–$1.0°$. As with LF/VLF direction-finding systems, the LA of these systems is dependent on sensor (array) spacing. Based on simple geometry, the location uncertainty of a sensor with $0.5°$ 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 $\sim$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 kilohertz to a few megahertz 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 (SNR), 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 toward using broadband interferometry. This trend is made possible by the advent of affordable broadband RF and digital signal processing electronics.

B. 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 TOA 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 2-D hyperbolic method discussed in Section I-B and illustrated in Fig. 3. The first real-time system to employ this technique was developed at the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC). This Lightning Detection and Ranging (LDAR) system was capable of providing 3-D locations of more than 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 KSC (owned and operated by the U.S. Air Force on behalf of NASA), and one in the Dallas, TX, 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 3-D 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, thus resulting in less than a 100-m 3-D error for most located sources. This exceptional LA is a direct result of arrival-time measurement errors of 40–50 ns rms.

Today, 3-D VHF TOA lightning mapping systems provide the most complete record of the spatial and temporal development of lightning channels, thus making it possible to infer complex charge structures in clouds [7], [43]. A sample record from one of these systems, first shown by Rison *et al.* [44], is shown in

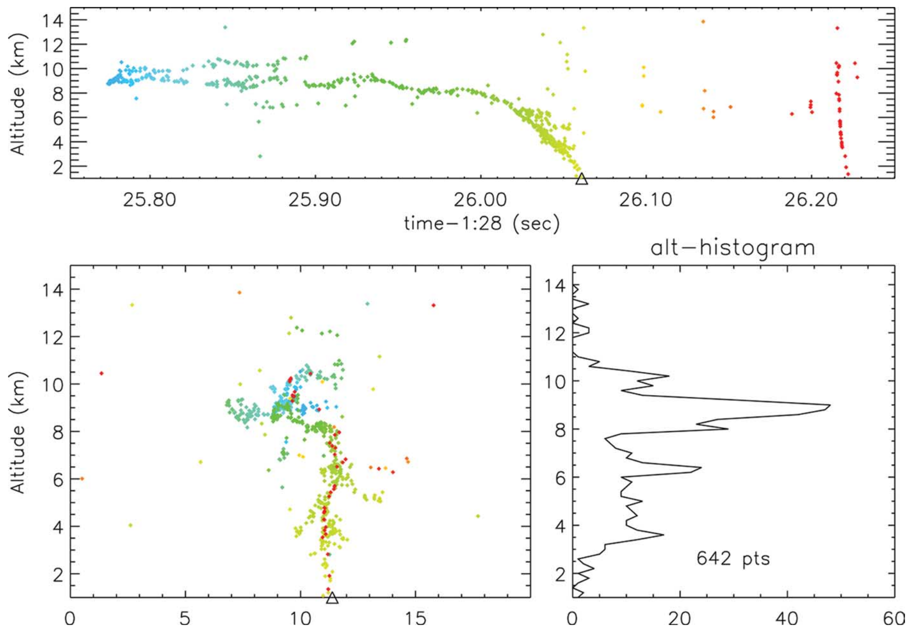

Fig. 4. "Bolt from the blue" CG flash detected using VHF TOA lightning mapping (see text for details).

Fig. 4 and illustrates the time evolution of a negative CG flash as detected using an LMA system. During this "bolt from the blue" flash (attached the ground well outside the precipitation region of the cell), the system was operating with an extremely short time window (10 μs), and more than 600 VHF "sources" were located for this flash. The top panel of the display shows an altitude (in kilometers) versus time (in 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 range, which could be detected at a distance of more than 100 km. Approximately 10 ms after flash initiation, two to three 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 range will have a horizontal polarization, thus resulting in very small peak fields at distances greater than a few tens of kilometers. 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 stepwise decent toward ground with an average downward speed of about 1.3×10^5 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 s reflect reorganization of charge in the cloud as a result of charge removal by the return stroke current. Starting just prior to 26.220 s, a fast-propagating "dart leader" begins its decent toward ground with a vertical speed in excess of 10^6 m/s, thus 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 Fig. 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, as suggested by the small number of VHF sources (other than the stepped leader itself) in this altitude range, which is thought to be associated with "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 versus 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 toward 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 depictions 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 μs.

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 (6000–8000 located sources per flash) seems to be achieved by limiting the analysis to the largest pulses in 30–40 μs periods (personal communication, Hareld Edens and Ron Thomas, New Mexico Tech). Modern high-end personal computers and Sun Workstations are capable of processing these data in real time for networks with up to about 12 sensors, thus covering a domain radius of a few hundred kilometers.

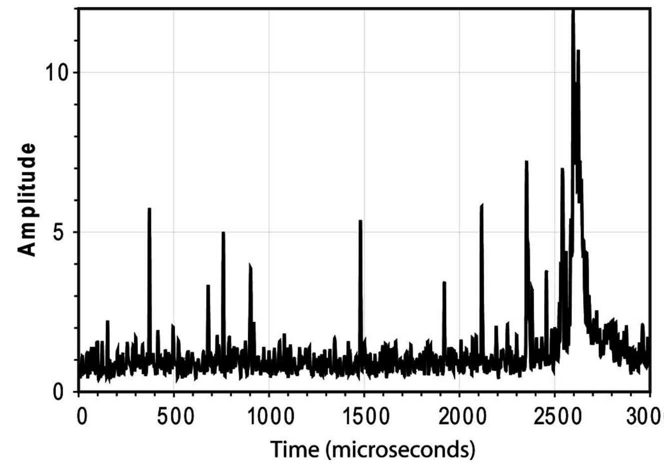

Fig. 5. Smoothed amplitude waveform for a typical lightning-generated VHF signal showing several impulsive events and one burst of radiation lasting about 300 μs.

C. Intercomparison of VHF Interferometry and TOA Techniques

The fundamental practical difference between interferometry and TOA techniques resides in the interdependence of measurements among the various sensors. Each TOA 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. On the other hand, 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 narrow-band 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., tens of microseconds). 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 TOA techniques where each sensor reports the precise arrival time of the largest VHF emission "feature" in short ($\sim$100 μs) time intervals. Longer duration VHF emissions with little amplitude modulation are well suited for interferometry. This categorization is somewhat of a simplification. In fact, TOA networks are also able to locate multipulse 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 Fig. 4. 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 SNR [28]. Fig. 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 rms amplitude of a narrow-band waveform (centered at 114 MHz) integrated over 4-μs time windows. The narrow pulses are well suited for TOA mapping techniques while the more continuous one near the end of the record (lasting about 300 μs) does not produce a unique time feature with sufficient time resolution. However, the latter 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 TOA systems. Mazur *et al.* [46] found that the NASA LDAR TOA system preferentially detected sources associated with virgin breakdown processes, with propagation speeds on the order of 10^4–$10^5\,\mathrm{m/s}$. 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 3-D interferometer responded best to fast-propagating (10^6–$10^7\,\mathrm{m/s}$) processes that produced fairly continuous VHF emissions for tens 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 2-D spatial and temporal characteristics of cells and storms, including counts of flashes. They have also shown that 2-D VHF interferometric networks can cover larger areas with fewer sensors than 3-D VHF TOA systems, because the sensors can be spaced farther apart. They note that this wider sensor spacing has the side effect of poorer source LA—approximately 1–2 km, as compared to 100 m for VHF TOA. This study also confirmed the greater flash and storm detail provided by both VHF networks, when compared to systems operating in the LF 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 by Mazur *et al.* [46]. It is clear that VHF TOA provides a more complete representation of the 3-D time evolution of a flash, but interferometry provides information about important faster leader and streamer processes that are generally not well represented by TOA 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 should include height information (or supplementary information about return strokes) to reliably distinguish between cloud and CG flashes, because the VHF activity directly associated with subsequent return strokes is limited and difficult to detect and locate [28].

III. Wide-Area Lightning Detection in the VLF/LF 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 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.

A. Enabling Technology and Uses of the Data

The technical "roots" of precise CG lightning detection started with the commercial development of gated, wideband magnetic direction finder (DF) by Lightning Location and Protection (LLP) in the late 1970s [49]. These sensors operated in the time domain over the full VLF/LF 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), nonlightning sources and cloud discharges could be eliminated to a large extent and the azimuth measurement was optimized for determining the ground strike location. These systems were magnetic DFs that used two orthogonal loop antennas to determine direction-of-arrival, in conjunction with an electric field antenna to eliminate 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 1960s and early 1970s.

Initially, the LLP sensors were developed for the U.S. Bureau of Land Management (BLM) 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 U.S., 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.

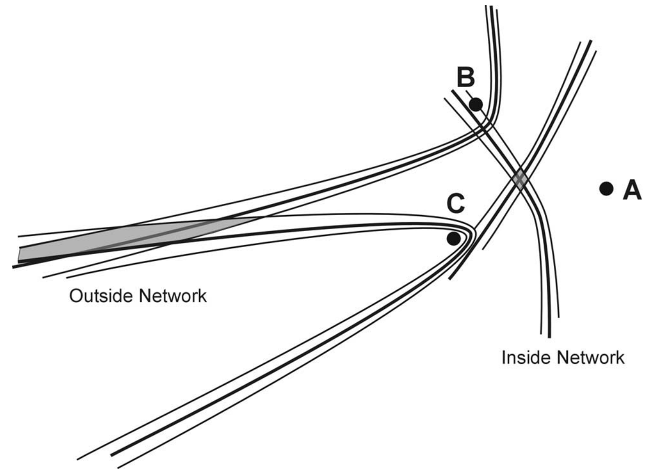

Fig. 6. Illustration of differences in TOA-based LA for sources located inside and outside a three-sensor network (locations A–C).

By the early 1980s, 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. NLDN, which is described in detail in Section V.

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 500 m 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 LA in the range of 2–4 km at best [53]. This LA 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 LA for some applications of lightning information led to the development of systems based on broadband TOA techniques. To first order, the LA in the interior of 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 Fig. 6. The stroke occurring inside the network is located by three sensors (A, B, and 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

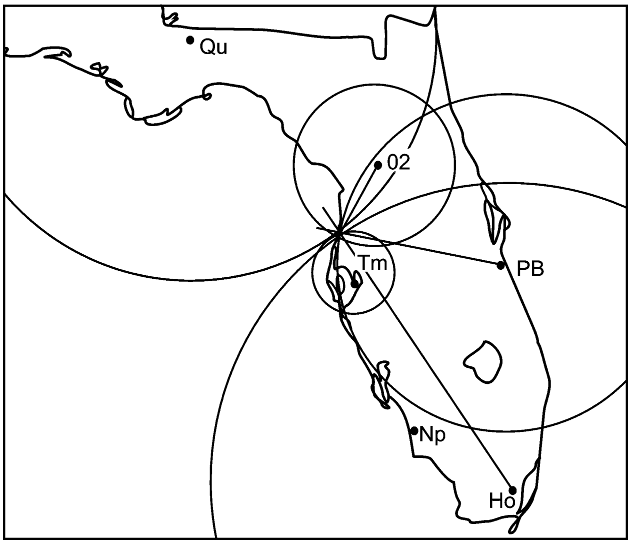

Fig. 7. Example of the IMPACT location algorithm using three TOA sensors and two IMPACT sensors.

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 TOA sensors [manufactured by Atmospheric Research Systems (ARSI)] was installed throughout the continental U.S. in the late 1980s [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 subkilometer LA for CG lightning strokes using information from three to four ground-based remote sensors with sensor baseline distances of 300–400 km.

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 lightning position and tracking system (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 that allows for an optimized estimate of location. Fig. 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 TOA 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 LLSs 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]

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

where E_{RAD} is the vertical electric field on the ground (assumed perfectly conducting) at time t, μ_0 is the permeability of free space, v is the vertical velocity of the stroke (assumed constant) near the ground, I is the current at the base of the channel, c is the speed of light, and D is the horizontal distance to the stroke [59]. (Note: An upward propagating, positive current produces a downward directed electric field.) The expression for the horizontal magnetic radiation (B) 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, which is 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. However, work by Jerauld *et al.* [66] suggests that the transmission-line model may also represent the current–field relationship in the case of the above-ground attachment that occurs in new-channel negative strokes.

B. Modern VLF/LF Systems

This section briefly reviews modern LLSs 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 V, 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 TOA technique pioneered by ARSI in the late 1980s, recently reengineered 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 range. Most of these networks employ IMPACT sensors developed by LLP/Global Atmospherics (now Vaisala), and focus primarily on CG lightning. Examples of large networks include the multinational European networks called EUCLID [67], [68] and LINET [83], 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, portions of the LINET network in Europe [82], [83], and NASA's CGLSS covering KSC in Florida, USA [52]. A number of locally manufactured LLSs are located in China, and some limited studies using data from these systems are in the literature [75], [76].

Several 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 indicates that the largest positive and negative IC pulses exhibit about 10 dB lower amplitude than return strokes in the frequency range of 100 kHz–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, a calibrated electric field sensor with a bandwidth from 1 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 recorded by the NASA's LDAR VHF lightning mapping system [46]. The cloud flashes were within a 100-km range of the VLF/LF sensor. Fig. 8(a) shows cumulative distributions of "equivalent peak current estimates" (normalized in the same way as for CG strokes) for all cloud pulses, for the largest cloud pulses in any given half second ("large cloud"), and for a representative sample of first return strokes in CG flashes. The majority (about 70%) of all LF pulses from cloud discharges had an 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 one or two pulses in each flash were consistent with a median equivalent peak current of about 1.2 kA. The uncertainty in the equivalent peak current estimates for these cloud pulses could be up to a factor of 2, due to the low-signal amplitudes and uncertainly in the distance estimates. On the basis of the data in Fig. 8(a), 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 will 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 a median equivalent peak current of about 20 kA [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.

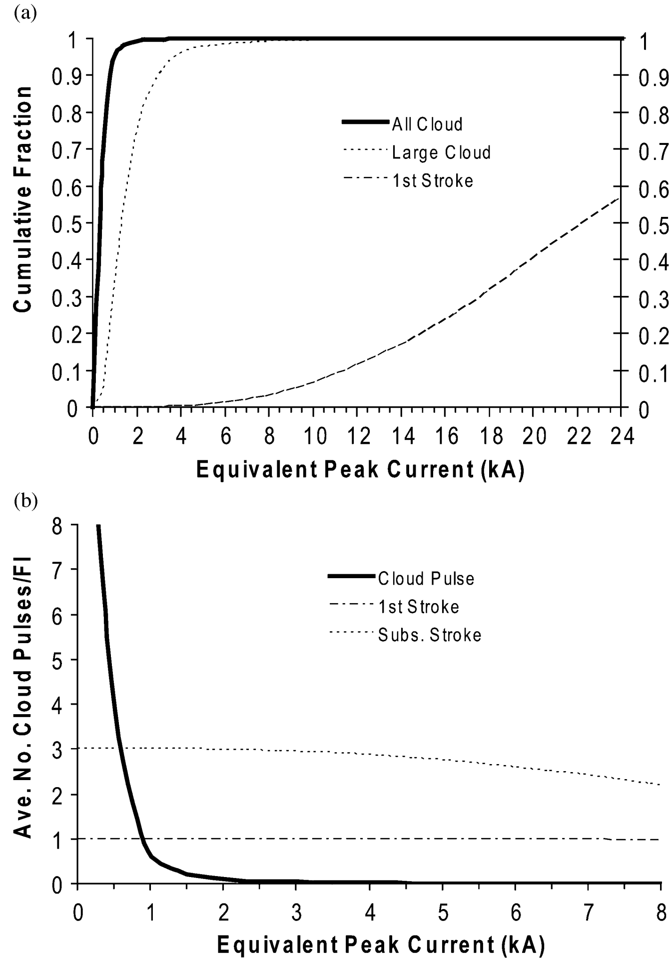

Fig. 8. Cumulative frequency distributions of various discharges as a function of equivalent peak current. (a) Cumulative distributions for all cloud pulses, the largest cloud pulses, and first strokes in CG flashes. (b) Reverse cumulative distributions of pulse occurrence rates (pulses per flash). The subsequent stroke rate was synthesized assuming the peak values are a factor of two smaller than first strokes, and that there are three subsequent strokes per CG flash.

This finding does not mean that pulses produced by cloud flashes cannot be detected in the VLF/LF range. Given the large number of pulses during the active stage of cloud flashes, it is not uncommon for them to produce a number of pulses that can be detected by sensitive VLF/LF networks. This fact is illustrated in Fig. 8(b) using data from the experiment by Murphy and Cummins. The average number of cloud pulses aggregated over all 0.5-s periods (considered to represent a typical flash) containing at least one cloud pulse was computed in 0.46 kA bins. The maximum value of 10.4 pulses per flash occurred for equivalent peak currents less than 0.46 kA. The second largest value of 3.6 pulses/flash occurred in the range of 0.46–0.92 kA. The results over the 0–8 kA range are depicted as a "reverse cumulative" distribution (solid line) in Fig. 8(b). The number of pulses/flash dropped to 1.0 at approximately 1.0 kA. Fig. 8(b) also includes reverse cumulative distributions for first and subsequent strokes in negative CG flashes. The first stroke distribution is the same dataset as shown in Fig. 8(a). The subsequent stroke distribution was synthesized by downscaling the first-stroke peak currents by a factor of 2 and assuming the average number of strokes per flash to be 4. Very few synthesized subsequent strokes had peak currents below 3 kA, exemplified by the horizontal nature of the associated cumulative distribution below 3 kA. By considering the horizontal axis in Fig. 8(b) as the minimum detectable peak current of an LLS, we can crudely estimate the LLS "detection threshold" that would result in the detection of an equal number of cloud pulses and CG strokes. Assuming a climatological IC:CG ratio of 10 : 1, the LLS would need to detect all discharges greater than about 1.5–2 kA for this to occur. The challenge of detecting these low-amplitude pulses is addressed by various combinations of improved sensitivity resulting from lower front-end noise, reduced 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 number 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 five ground stations in a 15 × 15 km domain. The authors describe a "weighted hyperbolic" (TOA) location technique, which is an optimization technique that extends the 3-D 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 TOA, 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 LLSs 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 Laboratory'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 3-D optimization calculation. It is shown that within the range of 100 km from the center of the short-baseline region, LASA detected two to five 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 (FDE) is quite high. As the range increases to 200 km and beyond, the 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 strokes and weaker cloud pulses. LANL also operates a longer baseline LASA system in the U.S. Great Plains. Weins *et al.* [81] provide a detailed analysis of the LASA network in the 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 the 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 Fig. 9. The pulses detected by the short-baseline LF cloud detection system (black dots) are shown to cluster near the initial breakdown region shown in the 2-D flash depiction produced by the Vaisala's LDAR II lightning mapping system (white squares). 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).

IV. 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

Post-publication note:
Symbols are reversed
(black dots are VHF)

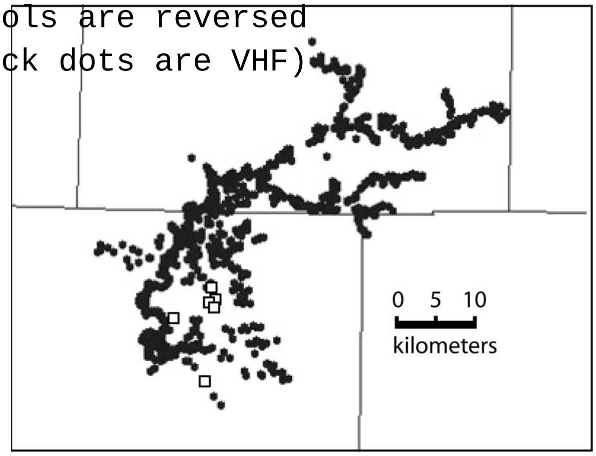

Fig. 9. Cloud pulse detection using LF methods (black dots), compared to total lightning mapping at VHF (white squares).

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, thus increasing the threat of turbulence and icing. Lighting measurements can be very useful in these situations. This section provides a brief overview of both ground- and space-based approaches capable of providing real-time global information about lightning and thunderstorms.

A. *Lightning Mapping From Space*

Continuous high-quality observations of lightning on a global scale remain an unmet challenge. Global observations (latitudes below $\sim 75^{\circ}$) 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 "worldwide" estimates of (total) lightning flash density with a spatial resolution of 0.5°. A limitation of these data is that they currently do not separate out CG and cloud lightning incidence. The next-generation series of Geostationary Operational Environmental Satellite (GOES-R) 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 continuous lightning observations 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 Fast On-Orbit Rapid Recording of Transient Events (FORTE) satellite built by LANL [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].

B. *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 range can propagate effectively in the waveguide defined by the Earth's surface below and by the ionosphere above, specifically its lowest layer, i.e., 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], [93, appears in this issue]. At even greater distances, propagation is more efficiently characterized using modal analysis, as described by Wait [94]. 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 LLSs employ location algorithms based on TOA, MDF, or a combination of the two. The earliest history of lightning detection dealt with the geolocation of long-range "sferics" in the 1920s, as described in Section I. These early systems employed narrow-band MDF sensors. Today, the Zeus long-range network described by Chronis and Anagnostou [95], [96] 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 tens of kilometers 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) [97], [98]. This network currently employs 11 operational sensors that were placed to provide maximum coverage over Europe. A recent paper by Gaffard *et al.* [99] comparing this system with local LLSs in France and Austria found a relative stroke DE in the range of 50% (resulting in a higher FDE), 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 MDF and TOA methods, and can, therefore, locate a lightning discharge with as few as two sensors. Based on performance models and comparison with NASA's LIS aboard the TRMM orbital satellite, the daytime and nighttime FDE in the north-central Pacific is in the range of 17%–23% and 40%–61%, 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 CLDN. 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) [100]–[103] 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.* [101]. The highest CG stroke DE is estimated to be $\sim$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 error for this network ranges between 2.9 [100] and 15 km [102].

V. U.S. National Lightning Detection Network

The U.S. NLDN has its roots in gated wideband direction-finding technology, and currently employs the IMPACT technology described in Section III. 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 1980s, 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.

A. Early History of the NLDN

As noted in Section III, one of the earliest "LLP networks" was the "East Coast" network operated out of the 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 contiguous U.S. (48 states) was covered in 1989 [104], [105]. During this six-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 BLM and the NSSL. Fig. 10 shows the evolution of coverage during this six-year period, taken from the recent paper by Orville [106]. A detailed early history of the NLDN is also provided in the paper by Orville.

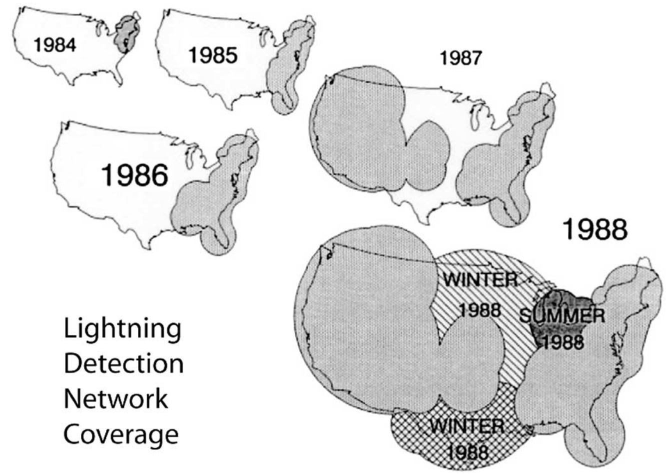

Fig. 10. Coverage areas for the expanding SUNY/A NLDN from 1984 through 1988. Adapted from [106], with permission.

B. NLDN Commercialization and Performance Improvements

The expansion of the NLDN in the late 1980s 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, thus resulting in the formation of GeoMet Data Services (GDS) as the operator of the NLDN. By 1993, it became clear that the primary "growth" application areas for the use of lightning data in the U.S. were as follows:

1) point-specific lightning warning in government and commercial applications;
2) point-specific determination of the past occurrence of lightning for use by the insurance industry and its clients;
3) 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 before imposed new requirements on the performance of the NLDN, specifically:

1) detection of both first and subsequent strokes of CG flashes;
2) LA in the range of 0.5–1 km;
3) better FDE (as good as possible).

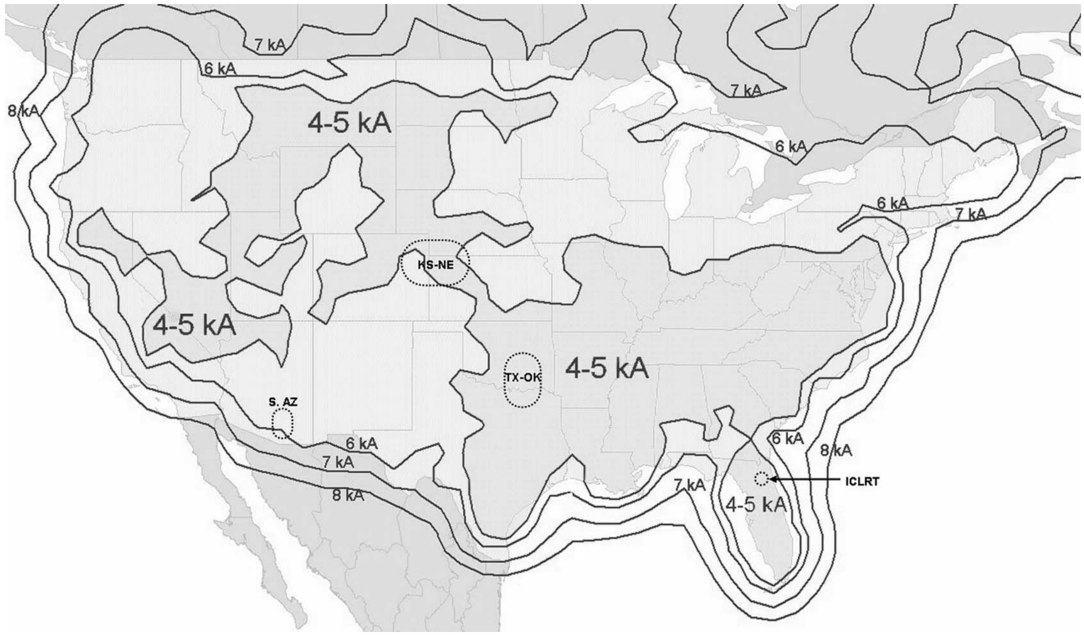

Fig. 11. Estimated minimum detectable peak current (50% probability) for the upgraded NLDN in 2002–2003. Validation studies in 2003–2004 were carried out in the four small regions identified by dotted circles.

The LA 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 TOA location methods in the location algorithm, which had become quite viable with the advent of GPS timing subsystems. On the other hand, the DE requirement, coupled with the continued need for the best possible estimates of peak current, made it impractical for the existing TOA 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 redeployment 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 [52], [107], [108]. The upgrade resulted in 80%–90% FDE and 0.5 km median location error in most regions, falling off rapidly near the edges of the network. Partial funding for the redeployment 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 CLDN and its combined operation with the NLDN. The resulting "North American Lightning Detection Network" [109], [110] provides contiguous lightning information throughout a nearly 20 million $\cdot$ km^2 region with latitudes ranging from 25° to over 60° north latitude.

Performance of the NLDN for CG lightning also improved as a result of an upgrade in 2002–2003, 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, thus resulting in an improved detection threshold. Model estimates of the postupgrade 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 postupgrade NLDN DE is indirectly represented in Fig. 11. This figure shows the estimated minimum detectable peak current (50% probability) in the U.S. portion of the complete North American Lightning Detection Network (NALDN). Representing the detection capability in this manner reflects our growing understanding that there are 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.* [111] show that there may be factor-of-2 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 (TX-OK) and southern Arizona (S AZ).

During the 2002–2003 upgrade period, Global Atmospherics and the NLDN were purchased by Vaisala, which had strong interest in expanding the capability of the NLDN to include cloud lightning detection [112]. 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

TABLE I
SUMMARY OF RESULTS FROM NLDN VALIDATION STUDIES

Test Region and period	*Median Location Accuracy (m) (count)*	*Stroke Detection Efficiency (%) (count)*	*RTL "Flash: DE (%) (count)*	*Flash Detection Efficiency (%) (count)*
Tucson 2001	--	--	--	73[a]
S. AZ 2003-4	424[b,c] *(667)*	76 *(3620)*	--	93 *(1097)*
TX-OK 2003-4	279[b,d] *(193)*	85 *(885)*	--	92 *(367)*
Florida RTL 2001	270[e] *(17)*	52 *(33)*	82 *(11)*	91[f] *(11)*
Florida RTL 2003	450[e] *(34)*	69 *(49)*	84 *(12)*	95[f] *(12)*

[a] Obtained from [115].
[b] Median position difference, divided by $\sqrt{2}$ due to the involvement of two random variables.
[c] Data only from 2003.
[b] Data only from 2004.
[e] Median location error for subsequent strokes.
[f] Estimated flash FDE, using stroke and RTL DE values in (2).

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 became a part of the real-time and archived NLDN dataset.

C. Validation

In conjunction with the 2002–2003 upgrade, field campaigns were carried out in S AZ and in Oklahoma/Texas in 2003 and 2004 by University of Arizona (UA) 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 Fig. 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 [111] and [113].

1) DE and LA: The 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 DE and LA in S AZ and in TX-OK after the upgrade. Both stroke and FDE 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 I. Measured FDE near Tucson in 2001 (preupgrade) is included for reference; these data have been taken from video studies reported by Parker and Krider [114] and Kehoe and Krider [115]. 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 $\sim$11% high due to an inability to time-resolve the strokes with interstroke intervals below the 16.7-ms video field time. This problem does not impact the FDE 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 I. The median error in S AZ (424 m) is not as good as in Texas and Oklahoma (279 m). This is expected because S AZ 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). For both regions, 90% of the location errors were smaller than 1.3 km (from [111, Fig. 7]).

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 I.

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 I). The RTL-based FDE is an underestimate of the FDE in Florida, since these flashes do not include a natural first stroke. The FDE can be estimated by viewing the RTL FDE as the probability of detecting any subsequent stroke, and then, relating overall FDE to the RTL DE using the equation

$$\mathrm{DE}_{\mathrm{fl}} = \mathrm{DE}_{\mathrm{1st}} + (1 - \mathrm{DE}_{\mathrm{1st}}) \times \mathrm{DE}_{\mathrm{RTL}} \qquad (2)$$

where

$\mathrm{DE}_{\mathrm{fl}}$ = natural flash DE;
$\mathrm{DE}_{\mathrm{1st}}$ = natural first stroke DE;
$\mathrm{DE}_{\mathrm{RTL}}$ = rocket triggered FDE ("any subsequent stroke" DE).

The rationale for this equation is that a flash is detected if either "the first stroke is detected (so we do not care about

TABLE II
SUMMARY OF ANALYSIS OF LF CLOUD DE RELATIVE TO LDAR II FOR FOUR ISOLATED STORMS NEAR DALLAS, TX, 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

subsequent strokes)" (e.g.,$\mathrm{DE}_{1\mathrm{st}}$), or "no first stroke is detected and one or more subsequent strokes are detected" [e.g., the second term in (2)]. If we make the conservative assumption that the first return stroke DE is the same as the average individual stroke DE for RTL (though it is thought to be higher), the estimated FDE values in Table I are obtained. Although there are only a small number of flashes in these studies, the CG FDE results are consistent with other regions and with Vaisala's estimate of 90%–95% within the interior of the U.S.

LA can also be measured using rocket-triggered ground truth data. NLDN model projections provide an expected median location error of 500 m for most of the U.S., including the Camp Blanding area. The observed median value of location error for the 2001 (preupgrade) and 2003 (postupgrade) ICLRT data supports this expected value, with measured values of 270 and 450 m, respectively (Table I). The difference between these two years is probably a result of the small sample sizes. The range of location errors was reported in detail by Jerauld *et al.* [113]. For 2001 and 2002, 90% of the location errors were less than 2 km (see [113, Fig. 6]). Larger errors were reported in 2002 (median of 600 m, 80% <5 km) due to a transitioning network configuration during the test period.

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, TX, that was colocated with an LDAR II VHF total lightning mapping network [116]. 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 DE exceeds 25% in a region of about 100 km radius surrounding DFW 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. For this analysis, all positive polarity events with peak currents less than 10 kA were classified as cloud discharges, even if they were originally classified as CG strokes. 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 FDE. Table II shows that the LDAR-relative cloud FDE varied between 16% and 38% for a sample of four storms. The significant result from this study is that the observed cloud FDE values are consistent with the modeled DE.

As of April 2006, cloud lightning data have 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% to 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 that this ratio increases by more than a factor of 2.

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 classify. The UA campaigns in S AZ and TX-OK had 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 is a mixture of CG and cloud pulses. Based on this analysis, the NLDN was updated to classify all positive polarity reports <15 kA as cloud pulses, starting in April 2006. These studies also indicated that most clearly identifiable negative polarity reports with estimated peak current <10 kA are CG strokes 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 two-week field campaign in the region of Colorado–Kansas–Nebraska (KS-NE) shown in Fig. 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 [117], [118]. A detailed analysis of findings from this campaign is provided by Fleenor *et al.* [119]. 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 three 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. Had the 15-kA rule for positive discharges been applied in 2005, the overall percentage of misclassified discharges would 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 by the fact that 59% of the misclassified cloud pulses were also assigned an incorrect initial polarity (polarity of first peak) by the NLDN, with the majority of these events being bipolar pulses with initial positive polarity that were reported to have negative polarity. The degree of misclassification seems to vary by region, because the prior studies noted before in Texas, Oklahoma, and S AZ, which all lie outside the uniquely positive-dominated region studied in 2005, show a much smaller degree of misclassification [111]. As a result of the 2005 findings, Vaisala has been working with the UA to develop a new classification scheme for the NLDN that is in the final stages of validation.

VI. Possible Future Needs and Directions

Modern LLSs are both a blessing and a source of frustration. Depending on the nature of a given application's needs, information from several different LLSs may be required. Current long-range LLSs 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 DE 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%) CG flashes and a lower percentage of cloud flashes over very large areas, with median location error in the range of 200–500 m. These systems can cover 25 000–150 000 km^2 per sensor, depending on the desired DE 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 (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 small location errors (tens to hundreds of meters), depending on 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 with virtually any other measurable event. These strengths and limitations explain why all 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 LLSs 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 fraction of CG flashes, as well as some cloud flashes. It is unlikely that such systems will have location errors smaller 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 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 LLSs that combine these detection methods into a single system.

Wide-area LLSs that detect broadband lightning emissions in the VLF/LF band have a number of areas where they can be improved to meet the increasing needs of various applications. The value of cloud lightning information provided by these systems, in combination with the tradeoffs between sensor sensitivity, signal-processing capability, and sensor baseline distances, will have 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 terrains. 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 [120]–[122]. It should not be difficult to achieve 200-m median accuracy when such corrections are implemented.

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 before 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 strokes 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.

VII. Closing Comments

There is a growing number of ground-based LLSs 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 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.

Acknowledgment

We would like to acknowledge a number of people that have made it possible for us to produce this overview of modern lightning locating systems. We thank E. Philip Krider, Martin Uman, Paul Krehbiel, and Vlad Rakov for many years of teaching, collaboration, and perspective. We thank our primary long-term collaborators at Vaisala (John Cramer, Nick Demetriades, Ron Holle, Jean-Yves Lojou, Carl Noggle, Burt Pifer, and Tommy Turner) for their creativity and insights as they worked with us on problems in lightning detection and application of lightning information. We also thank the many hundreds of scientists, engineers, and entrepreneurs that have developed, sold, or operated lightning locating systems since the early 1900's, for shaping this fascinating field.

REFERENCES

[1] B. F. J. Schonland, *The Flight of Thunderbolts*, 2nd ed. Oxford, U.K.: Clarendon, 1964.

[2] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*. New York: Cambridge Univ. Press, 2003.

[3] M. A. Uman and E. P. Krider, "Natural and artificially initiated lightning," *Science*, vol. 246, pp. 457–464, 1989.

[4] D. J. Boccippio, K. L. Cummins, H. J. Christian, and S. J. Goodman, "Combined satellite and surface-based estimation of the intracloud–cloud-to-ground lightning ratio over the continental United States," *Monthly Weather Rev.*, vol. 129, pp. 108–122, 2001.

[5] D. R. MacGorman, D. W. Burgess, V. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson, "Lightning rates relative to tornadic storm evolution on 22 May 1981," *J. Atmos. Sci.*, vol. 46, pp. 221–250, 1989.

[6] E. Williams, B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan, and D. Buechler, "The behavior of total lightning activity in severe Florida thunderstorms," *Atmos. Res.*, vol. 51, pp. 245–265, 1999.

[7] K. C. Wiens, S. A. Rutledge, and S. A. Tessendorf, "The 29 June 2000 supercell observed during STEPS. Part II: Lightning and charge structure," *J. Atmos. Sci.*, vol. 62, pp. 4151–4177, 2005.

[8] P. Richard, "Data fusion concepts for storm nowcasting," in *Proc. 17th Int. Lightning Detection Conf., Preprints*. Tucson, AZ: Vaisala, Oct. 16–18, 2002.

[9] G. R. Patrick and N. W. S. Demetriades, "Using LDAR II total lightning data in an operational setting: Experiences at WFO Forth Worth TX," in *Proc. 21st Conf. Weather Anal. Forecasting/17th Conf. Numerical Weather Prediction, Preprints*. Washington, DC: Amer. Meteorol. Soc., Jul. 31–Aug. 5, 2005, p. 8.

[10] D. MacGorman, I. Apostolakopoulos, A. Nierow, M. Murphy, N. Demetriades, J. Cramer, and P. Krehbiel, "Improved timeliness of thunderstorm detection from mapping a larger fraction of lightning flashes," presented at the Lightning Imag. Sens. Int. Workshop, Huntsville, AL, Sep. 11–14, 2006.

[11] M. E. Weber, E. R. Williams, M. M. Wolfson, and S. J. Goodman, "An assessment of the operational utility of a GOES lightning mapping sensor," Lincoln Lab., Massachusetts Inst. Technol. (MIT), Lexington, Project Rep. NOAA-18, 1998.

[12] V. Mazur, X. M. Shao, and P. R. Krehbiel, ""Spider" lightning in intracloud and positive cloud-to-ground flashes," *J. Geophys. Res.*, vol. 103, pp. 19811–19822, 1998.

[13] D. J. Malan, *Physics of Lightning*. London, U.K.: The English Univ. Press, 1963, p. 176.

[14] E. P. Krider, C. Noggle, A. E. Pifer, and D. L. Vance, "Lightning direction finding systems for forest fire detection," *Bull. Amer. Meteorol. Soc.*, vol. 61, pp. 980–986, 1980.

[15] C. D. Weidman and E. P. Krider, "The fine structure of lightning return stroke waveforms," *J. Geophys. Res.*, vol. 83, no. C12, pp. 6239–6247, 1978.

[16] C. D. Weidman and E. P. Krider, "The radiation field wave forms produced by intracloud lightning processes," *J. Geophys. Res.*, vol. 84, no. C6, pp. 3159–3164, 1979.

[17] H. Norinder, "Long distance location of thunderstorms," in *Thunderstorm Electricity*, H. Y. Byers, Ed. Chicago, IL: Univ. of Chicago Press, 1953.

[18] R. A. Watson-Watt and J. F. Herd, "An instantaneous direct-reading radio goniometer," *J. Inst. Electr. Eng.*, vol. 64, pp. 611–622, 1926.

[19] R. A. Watson-Watt, J. F. Herd, and L. H. Bainbridge-Bell, *Applications of the Cathode Ray Oscillograph in Radio Research*. London, U.K.: His Majesty's Stationery Office, 1933.

[20] R. I. Colin, "Dr. Meint Harms and hyperbolic navigation: A vignette of radio navigation history," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-6, no. 1, pp. 2–9, Jan. 1970.

[21] E. A. Lewis, R. B. Harvey, and J. E. Rasmussen, "Hyperbolic direction finding with sferics of transatlantic origin," *J. Geophys. Res.*, vol. 65, pp. 1879–1905, 1960.

[22] V. A. Rakov, "Modern passive lightning locating systems," *Meteorol. Gidrol.*, vol. 11, pp. 118–123, 1990.

[23] R. L. Holle and R. E. López, "Overview of real-time lightning detection systems and their meteorological uses," Nat. Severe Storm Lab., Norman, OK, NOAA Tech. Memo. ERL NSSL-102, 1993.

[24] G. N. Oetzel and E. T. Pierce, "VHF techniques for locating lightning," *Radio Sci.*, vol. 4, pp. 199–201, 1969.

[25] C. O. Hayenga and J. W. Warwick, "Two-dimensional interferometric positions of VHF lightning sources," *J. Geophys. Res.*, vol. 86, pp. 7451–7462, 1981.

[26] C. T. Rhodes, X.-M. Shao, P. R. Krehbiel, R. J. Thomas, and C. O. Hayenga, "Observations of lightning phenomena using radio interferometry," *J. Geophys. Res.*, vol. 99, pp. 13059–13082, 1994.

[27] X. M. Shao, P. R. Krehbiel, R. J. Thomas, and W. Rison, "Radio interferometric observations of cloud-to-ground lightning phenomena in Florida," *J. Geophys. Res.*, vol. 100, pp. 2749–2783, 1995.

[28] E. Defer, P. Blanchet, C. Thery, P. Laroche, J. E. Dye, M. Venticinque, and K. L. Cummins, "Lightning activity for the July 10, 1996, storm during the stratosphere-troposphere experiment: Radiation, aerosol, and ozone-a (STERAO-A) experiment," *J. Geophys. Res.*, vol. 106, no. D10, pp. 10151–10172, 2001.

[29] Q. Meng, Y. Zhang, H. Ping, X. Xiaofeng, J. Zhao, P. Rouquier, and J.-Y. Lojou, "Lightning observation and field experiment with 3D SAFIR system during summer 2003 in Beijing-Hebei area," presented at the 27th Int. Conf. Lightning Protection, Avignon, France, Sep. 13–16, 2004.

[30] P. Richard, A. Soulage, P. Laroche, and J. Appel, "The SAFIR lightning monitoring and warning system: Application to aerospace activities," in *Proc. Int. Aerosp. Ground Conf. Lightning Static Electr*. Oklahoma City, OK: Nat. Interagency Coordination Group, 1988, pp. 383–390.

[31] P. Richard, A. Soulage, and F. Broutet, "The SAFIR lightning warning system," in *Proc. 1989 Int. Conf. Lightning Static Electr.* Bath, U.K.: Ministry of Defence Procurement Executive, 1989, pp. 2 B.1.1–2 B.1.5.

[32] P. Richard, "The SAFIR system: Early detection and alarm alert for risk of storms," in *Proc. Lightning Mountains 1994*. Paris, France: Soc. Electr. Electron., 1994, pp. 77–83.

[33] J.-Y. Lojou, M. J. Murphy, R. L. Holle, and N. W. S. Demetriades, "Nowcasting of thunderstorms using VHF measurements," in *Lightning: Principles, Instruments and Applications*, H.-D. Betz, U. Schumann, and P. Laroche, Eds. Dordrecht, NL: Springer-Verlag, 2008.

[34] X. M. Shao, D. N. Holden, and C. T. Rhodes, "Broad band radio interferometry for lightning observations," *Geophys. Res. Lett.*, vol. 23, pp. 1917–1920, Jul. 1996.

[35] A. Akita, T. Motimoto, T. Ushio, and Z. Kawasaki, "Comprehensive study on K-events by means of VHF broadband interferometer observations," presented at the 29th Int. Conf. Lightning Protection, Uppsala, Sweden, Jun. 23–26, 2008.

[36] R. Mardiana and Z. Kawasaka, "Broadband radio interferometers utilizing sequential triggering technique for locating fast electromagnetic sources emitted from lightning," *IEEE Trans. Instrum. Meas.*, vol. 49, no. 2, pp. 376–381, Apr. 2000.

[37] D. E. Proctor, "A hyperbolic system for obtaining VHF radio pictures of lightning," *J. Geophys. Res.*, vol. 76, pp. 1478–1489, 1971.

[38] L. Maier, C. Lennon, T. Britt, and S. Schaefer, "Lightning detection and ranging (LDAR) system performance analysis," in *Proc. 6th Conf. Aviation Weather Syst.*. Dallas, TX: Amer. Meteorol. Soc., 1995, Paper 8.9.

[39] D. J. Boccippio, S. Heckman, and S. J. Goodman, "A diagnostic analysis of the Kennedy Space Center LDAR network 1. Data characteristics," *J. Geophys. Res.*, vol. 106, pp. 4769–4786, 2001.

[40] P. R. Krehbiel, R. J. Thomas, W. Rison, T. Hamlin, J. Harlin, and M. Davis, "Three-dimensional lightning mapping observations during MEaPRS in central Oklahoma," in *Proc. 11th Int. Conf. Atmos. Electr.* Guntersville, AL, 1999, pp. 376–379 (NASA Conf. Publ. 1999-209261).

[41] W. R. Rison, R. Scott, R. J. Thomas, P. R. Krehbiel, T. Hamlin, and J. Harlin, "3-dimensional lightning and dual-polarization observations of thunderstorms in central New Mexico," in *Proc. 11th Int. Conf. Atmos. Electr*. Guntersville, AL, 1999, pp. 432–435 (NASA Conf. Publ. 1999-209261).

[42] R. J. Thomas, P. R. Krehbiel, W. Rison, S. J. Hunyady, W. P. Winn, T. Hamlin, and J. Harlin, "Accuracy of the lightning mapping array," *J. Geophys. Res.*, vol. 109, p. D14207, 2004. DOI: 10.1029/2004JD004549.

[43] W. D. Rust, D. R. MacGorman, E. C. Bruning, S. A. Weiss, P. R. Krehbiel, R. J. Thomas, W. Rison, T. Hamlin, and J. Harlin, "Inverted-polarity electrical structures in thunderstorms in the Severe Thunderstorm Electrification and Precipitation Study (STEPS)," *Atmos. Res.*, vol. 76, no. 1–4, pp. 247–271, 2005.

[44] W. Rison, W. P. Krehbiel, R. Thomas, T. Hamlin, and J. Harlin, "A time-of-arrival lightning mapping system with high time resolution," presented at the Fall Meeting Amer. Geophys. Union, San Francisco, CA, Dec. 2000.

[45] V. Mazur and L. H. Ruhnke, "Common physical process in natural and artificially triggered lightning," *J. Geophys. Res.*, vol. 98, no. D7, pp. 12913–12930, 1993.

[46] V. Mazur, V. E. Williams, R. Boldi, L. Maier, and D. E. Proctor, "Initial comparison of lightning mapping with operational time-of-arrival and interferometric systems," *J. Geophys. Res.*, vol. 102, no. D10, pp. 11071–11085, 1997.

[47] J.-Y. Lojou and K. L. Cummins, "Total lightning mapping using both VHF interferometry and time-of-arrival techniques," in *Proc. Int. Lightning Detection Conf., Preprints*. Tucson, AZ: Vaisala, Apr. 24–25, 2006.

[48] P. Blanchet, P. Lalande, and P. Laroche, "PROFEO: Programme fancilien d'etudes des orages," (in English), presented at the Int. Lightning Detection Conf., Tucson, AZ, Preprints, Apr. 24–25, 2006.

[49] E. P. Krider, R. C. Noggle, and M. A. Uman, "A gated wideband magnetic direction-finder for lightning return strokes," *J. Appl. Meteorol.*, vol. 15, pp. 301–306, 1976.

[50] M. A. Uman, Y. T. Lin, and E. P. Krider, "Errors in magnetic direction finding due to nonvertical lightning channels," *Radio Sci.*, vol. 15, pp. 35–39, 1980.

[51] R. M. Passi and R. E. López, "A parametric estimation of systematic errors in networks of magnetic direction finders," *J. Geophys. Res.*, vol. 94, pp. 13319–13328, 1989.

[52] M. W. Maier and M. B. Wilson, "Accuracy of the NLDN real-time data service at Cape Canaveral, Florida," in *Proc. Int. Lightning Detection Conf., Preprints*. Tucson, AZ: Global Atmospherics, Nov. 6–8, 1996.

[53] K. L. Cummins, M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, "A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network," *J. Geophys. Res.*, vol. 103, pp. 9035–9044, 1998.

[54] K. L. Cummins, E. P. Krider, and M. D. Malone, "The U.S. National Lightning Detection Network and applications of cloud-to-ground lightning by electric power utilities," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 4, pp. 465–480, Nov. 1998.

[55] W. A. Lyons and R. B. Bent, "Evaluation of the time-of-arrival (TOA) technique for real-time ground strike measurements using the lightning position and tracking system (LPATS)," in *Proc. 13th Conf. Severe Local Storms.*. Tulsa, OK: Amer. Meteorol. Soc., Oct. 17–20, 1983, pp. 37–40.

[56] W. A. Lyons, D. A. Moon, J. S. Schuh, N. J. Petit, and J. R. Eastman, "The design and operation of a national lightning detection network using time-of-arrival technology," in *Proc. 1989 Int. Conf. Lightning Static Electr*. Bath, U.K.: Univ. of Bath, 1989.

[57] R. Bernstein, R. R. Samm, K. Cummins, R. B. Pyle, and J. Tuel, "Lightning detection network averts damage and speeds restoration," *IEEE Comput. Appl. Power*, vol. 9, no. 2, pp. 12–17, Apr. 1996.

[58] K. L. Cummins and M. J. Murphy, "Overview of lightning detection in the VLF, LF, and VHF frequency ranges," in *Proc. Int. Lightning Detection Conf., Preprints*. Tucson, AZ: Global Atmospherics, Nov. 7–8, 2000.

[59] M. A. Uman, D. K. McLain, and E. P. Krider, "The electromagnetic radiation from a finite antenna," *Amer. J. Phys.*, vol. 43, pp. 33–38, 1975.

[60] M. A. Uman, "Lightning return stroke electric and magnetic fields," *J. Geophys. Res.*, vol. 90, pp. 6121–6130, 1985.

[61] C. A. Nucci, G. Diendorfer, M. A. Uman, F. Rachidi, M. Ianoz, and C. Mazzetti, "Lightning return stroke current models with specified channel-base current: A review and comparison," *J. Geophys. Res.*, vol. 95, pp. 20395–20408, 1990.

[62] R. Thottappillil and M. A. Uman, "Comparison of lightning return-stroke models," *J. Geophys. Res.*, vol. 98, pp. 22903–22914, 1993.

[63] R. Thottappillil, V. A. Rakov, and M. A. Uman, "Distribution of charge along the lightning channel: Relation to remote electric and magnetic fields and to return-stroke models," *J. Geophys. Res.*, vol. 102, pp. 6987–7006, 1997.

[64] V. Rakov and M. A. Uman, "Review of lightning return stroke models including some aspects of their application," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 4, pp. 403–426, Nov. 1998.

[65] V. A. Rakov, "Evaluation of the performance characteristics of lightning locating systems using rocket-triggered lightning," presented at the VIII Int. Symp. Lightning Protection, Sao Paulo, Brazil, Nov. 21–25, 2005.

[66] J. Jerauld, M. A. Uman, V. A. Rakov, K. J. Rambo, and G. H. Schnetzer, "Insights into the ground attachment process of natural lightning gained from an unusual triggered-lightning stroke," *J. Geophys. Res.*, vol. 112, p. D13113, 2007. DOI: 10.1029/2006/JD007682.

[67] W. Schulz, K. Cummins, G. Diendorfer, and M. Dorninger, "Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system," *J. Geophys. Res.*, vol. 110, p. D09101, 2005. DOI: 10.1029/2004JD005332.

[68] G. Diendorfer, "EUCLID—Technical structure and performance of the European wide lightning location system," in *Proc. Int. Conf. Grounding Earthing 3rd Brazilian Workshop Atmos. Electr.*, Rio de Janeiro, Brazil, Nov. 4–7, 2002, pp. 39–42.

[69] A. Sugita, M. Matsui, and M. Osada, "Lightning characteristics in Japan observed by the JLDN from 2000 to 2004," in *Proc. 28th Int. Conf. Lightning Protection, Preprints*, Kanazawa, Japan, Sep. 18–22, 2006, pp. 426–429.

[70] O. Pinto, Jr., I. R. C. A. Pinto, and K. P. Naccarato, "Maximum cloud-to-ground lightning flash densities observed by lightning location systems in the tropical region: A review," *Atmos. Res.*, vol. 84, pp. 189–200, 2007.

[71] O. Pinto, Jr. and I. R. C. A. Pinto, "On the sensitivity of cloud-to-ground lightning activity to surface air temperature changes at different timescales in Sao Paulo, Brazil," *J. Geophys. Res.*, vol. 113, p. D20123, 2008. DOI: 10.1029/2008JD009841.

[72] K. P. Naccarato and O. Pinto, Jr., "Improvements in the detection efficiency model for the Brazilian lightning detection network (BrasilDAT)," *Atmos. Res.*, vol. 91, pp. 546–563, 2009.

[73] W. R. Burrows, P. King, P. J. Lewis, B. Kochtubajda, B. Snyder, and V. Turcotte, "Lightning occurrence patterns over Canada and adjacent United States from lightning detection network observations," *Atmos. Ocean*, vol. 40, pp. 59–81, 2002.

[74] T. Gill, "A lightning climatology of South Africa for the first two years of operation of the South African Weather Service Lightning Detection Network: 2006–2007," presented at the 2nd Int. Lightning Meteorol. Conf., Tucson, AZ, Preprints, Apr. 2008 (CD-ROM).

[75] F. Guili, X. Q. Xiushu, T. Yuan, and S. N. Shuzhen, "Analysis on lightning activity and precipitation structure of hailstorms," *Sci. China Series D-Earth Sci.*, vol. 50, no. 4, pp. 629–639, 2007.

[76] G. Feng, X. Qie, J. Wang, and D. Gong, "Lightning and Doppler radar observations of a squall line system," *Atmos. Res.*, vol. 91, pp. 466–478, 2009.

[77] C. D. Weidman, E. P. Krider, and M. A. Uman, "Lightning amplitude spectra in the interval from 100 kHz to 20 MHz," *Geophys. Res. Lett.*, vol. 8, no. 8, pp. 931–934, 1981.

[78] M. J. Murphy and K. L. Cummins, "Two-dimensional and three-dimensional cloud discharge detection," presented at the Int. Lightning Detection Conf., Tucson, AZ, Preprints, Nov. 1998.

[79] M. J. Murphy, N. W. S. Demetriades, R. L. Holle, and K. L. Cummins, "Overview of capabilities and performance of the U.S. National Lightning Detection Network," in *Proc. 12 Conf. Aviation, Range, Aerosp. Meteorol. 2nd Conf. Meteorol. Appl. Lightning Data, Preprints*. Atlanta, GA: Amer. Meteorol. Soc., Jan. 29–Feb. 2. 2006.

[80] V. Cooray, M. Fernando, T. Sörensen, T. Götschl, and A. Pedersen, "Propagation of lightning generated transient electromagnetic fields over finitely conducting ground," *J. Atmos. Terres. Phys.*, vol. 62, pp. 583–600, 2000.

[81] K. C. Weins, T. Hamlin, J. Harlin, and D. M. Suszcynsky, "Relationships among narrow bipolar events, "total" lightning, and radar-inferred strength in great plains thunderstorms," *J. Geophys Res.*, vol. 113, p. D05201, 2008. DOI: 10.1029/2007JD0099400.

[82] H.-D. Betz, K. Schmidt, B. Fuchs, W. P. Oettinger, and H. Höller, "Cloud lightning: Detection and utilization for total lightning measured in the VLF/LF regime," *J. Lightning Res.*, vol. 2, pp. 1–17, 2007.

[83] H.-D. Betz, K. Schmidt, and W. P. Oettinger, "LINET—An international VLF/LF lightning detection network in Europe," in *Lightning: Principles, Instruments and Applications*, H.-D. Betz, U. Schumann, and P. Laroche, Eds. Dordrecht, NL: Springer-Verlag, 2008, ch. 5.

[84] X. M. Shao, M. Stanley, A. Regan, J. Harlin, M. Pongratz, and M. Stock, "Total lightning observations with the new and improved Los Alamos Sferic Array (LASA)," *J. Atmos. Ocean. Tech.*, vol. 23, pp. 1271–1288, Oct. 2006.

[85] E. M. Thomson, P. J. Medelius, and S. Davis, "System for locating the sources of wideband dE/dt from lightning," *J. Geophys. Res.*, vol. 99, pp. 22793–22802, 1994.

[86] K. Shimizu, M. Ishii, J. Hojo, and K. Shinjo, "Observation of multiple-stroke flashes through electromagnetic field," (in Japanese), *Trans. IEE Jpn.*, vol. 118-B, no. 2, pp. 164–169, Feb. 1998.

[87] M. Ishii, J. Hojo, K. Shimizu, K. Sato, and K. Shinjo, "Height of radiation sources associated with lightning discharges," in *Proc. 11th Int. Conf. Atmos. Electr.*, Guntersville, AL, Jun.1999, pp. 10–13.

[88] H. J. Christian, R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, "Global frequency and distribution of lightning as observed from space by the optical transient detector," *J. Geophys. Res.*, vol. 108, no. D1, p. 4005, 2003. DOI: 10.1029/2002JD002347.

[89] H. J. Christian, "Geostationary lightning mapper (GLM)," presented at the 12th Conf. Aviation Range Aerosp. Meteorol., Atlanta, GA, Jan. 30–Feb. 2, 2006.

[90] A. R. Jacobson, S. O. Knox, R. Franz, and D. C. Enemark, "FORTE observations of lightning radio-frequency signatures: Capabilities and basic results," *Radio Sci*, vol. 34, pp. 337–354, 1999.

[91] W. Boeck, D. M. Suszcynsky, T. E. Light, A. R. Jacobson, H. J. Christian, S. J. Goodman, D. E. Buechler, and J. L. L. Guillen, "A demonstration of the capabilities of multi-satellite observations of oceanic lightning," *J. Geophys. Res.*, vol. 109, p. D17204, 2004. DOI: 10.1029/2003JD004491.

[92] A. Pessi, S. Businger, K. L. Cummins, N. W. S. Demetriades, M. Murphy, and B. Pifer, "Development of a long-range lightning detection network for the pacific: Construction, calibration, and performance," *J. Atmos. Ocean. Tech.*, vol. 26, pp. 145–166, 2009.

[93] X.-M. Shao and A. R. Jacobson, "Model simulation of very low-frequency and low-frequency lightning signal propagation over intermediate ranges," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 519–525, Aug. 2009.

[94] J. R. Wait, "Theory of the terrestrial propagation of VLF electromagnetic waves," in *Advances in Electronics and Electronic Physics*, L. Marton, Ed. San Francisco, CA: Academic, 1965.

[95] T. G. Chronis and E. N. Anagnostou, "Error analysis for a long-range lightning monitoring network of ground-based receivers in Europe," *J. Geophys. Res.*, vol. 108, no. D24, p. 4779, 2003. DOI: 10.1029/2003JD003776.

[96] T. G. Chronis and E. N. Anagnostou, "Evaluation of a long-range lightning detection network with receivers in Europe and Africa," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 6, pp. 1504–1510, Jun. 2006.

[97] A. C. L. Lee, "Bias elimination and scatter in lightning location by the VLF arrival time difference technique," *J. Atmos. Ocean. Tech.*, vol. 7, pp. 719–733, 1990.

[98] J. Nash, N. C. Atkinson, E. Hibbett, G. Callaghan, P. L. Taylor, P. Odhams, D. Jenkins, S. Keogh, C. Gaffard, and E. Walker, "The new met office ATDNET lightning detection system," presented at the WMO Tech. Conf. Instrum. Observing Methods, Geneva, Switzerland, Dec. 4–6, 2006.

[99] C. Gaffard, J. Nash, N. Atkinson, A. Bennett, G. Callagha, E. Hibbett, P. Taylor, M. Turp, and W. Schulz, "Observing lightning around the globe from the surface," presented at the 20th Int. Lightning Detection Conf., Tucson, AZ, Preprints, Apr. 21–23, 2008.

[100] C. J. Rodger, J. B. Brundell, and R. L. Dowden, "Location accuracy of VLF World Wide Lightning Location (WWLL) network: Post-algorithm upgrade," *Ann. Geophys.*, vol. 23, pp. 277–290, 2005.

[101] C. J. Rodger, S. W. Werner, J. B. Brundell, N. R. Thomson, E. H. Lay, R. H. Holzworth, and R. L. Dowden, "Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study," *Ann. Geophys.*, vol. 24, pp. 3197–3214, 2006.

[102] A. R. Jacobson, R. Holzworth, J. Harlin, R. Dowden, and E. Lay, "Performance assessment of the World Wide Lightning Location Network (WWLLN), using the Los Alamos Sferic Array (LASA) as ground truth," *J. Atmos. Ocean. Tech.*, vol. 23, pp. 1082–1092, 2006.

[103] E. H. Lay, A. R. Jacobson, R. H. Holzworth, C. J. Rodger, and R. L. Dowden, "Local time variation in land/ocean lightning flash density as measured by the World Wide Lightning Location Network," *J. Geophys. Res.*, vol. 112, p. D13111, 2007. DOI: 10.1029/2006JD007944.

[104] R. E. Orville and H. Songeter, "The east coast lightning detection network," *IEEE Trans. Power Del.*, vol. PWRD-2, no. 3, pp. 899–907, Jul. 1987.

[105] R. E. Orville, "Lightning ground flash density in the contiguous United States—1989," *Mon. Weather Rev.*, vol. 119, pp. 573–577, 1990.

[106] R. E. Orville, "Development of the National Lightning Detection Network," *Bull. Amer. Meteorol. Soc.*, vol. 89, no. 2, pp. 180–190, Feb. 2008.

[107] V. P. Idone, D. A. Davis, P. K. Moore, Y. Wand, R. W. Henderson, M. Ries, and P. F. Jamason, "Performance evaluation of the U.S. National Lightning Detection Network in eastern New York. 1. Detection efficiency," *J. Geophys. Res.*, vol. 103, pp. 9045–9055, 1998.

[108] V. P. Idone, D. A. Davis, P. K. Moore, Y. Wand, R. W. Henderson, M. Ries, and P. F. Jamason, "Performance evaluation of the U.S. National Lightning Detection Network in eastern New York. 2. Location accuracy," *J. Geophys. Res.*, vol. 103, pp. 9057–9069, 1998.

[109] K. L. Cummins, R. B. Pyle, and G. Fournier, "An integrated North American lightning detection network," in *Proc. 11th Int. Conf. Atmos. Electr., Preprints*, Guntersville, AL, Jun. 7–11, 1999, pp. 218–221.

[110] R. E. Orville, G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins, "The North-American Lightning Detection Network (NALDN)—First results: 1998–2000," *Mon. Weather Rev.*, vol. 130, no. 8, pp. 2098–2109, Aug. 2002.

[111] C. J. Biagi, K. L. Cummins, K. E. Kehoe, and E. P. Krider, "NLDN performance in Southern Arizona, Texas and Oklahoma in 2003–2004," *J. Geophys. Res.*, vol. 112, p. D05208, 2007. DOI: 1029/2006JD007341.

[112] M. J. Murphy, N. W. S. Demetriades, and K. L. Cummins, "The value of cloud lightning in probabilistic thunderstorm warning," in *Proc. 16th Conf. Probability Stat. Atmos. Sci., Preprints*, Orlando, FL, Jan. 13–17, 2002, pp. 134–139.

[113] J. Jerauld, V. A. Rakov, M. A. Uman, K. J. Rambo, D. M. Jordan, K. L. Cummins, and J. A. Cramer, "An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket-triggered lightning," *J. Geophys. Res.*, vol. 110, no. D19, p. D19106, 2005.

[114] N. G. Parker and E. P. Krider, "A portable PC-based system for making optical and electromagnetic measurements of lightning," *J. Appl. Meteorol.*, vol. 42, pp. 739–751, 2003.

[115] K. E. Kehoe and E. P. Krider, "NLDN Performance in Arizona," in *Proc. 18th Int. Lightning Detection Conf., Preprints*. Helsinki, Finland: Vaisala, 2004.

[116] N. W. S. Demetriades, M. J. Murphy, and K. L. Cummins, "Early results from the Global Atmospherics, Inc. Dallas-Fort Worth Lightning Detection and Ranging (LDAR-II) research network," presented at the AMS, 6th Symp. Integr. Observing Syst., Orlando, FL, Preprints, Jan. 13–17, 2002.

[117] C. D. Carey and S. A. Rutledge, "Characteristics of cloud-to-ground lightning in severe and nonsevere storms over the central United States from 1989-1998," *J. Geophys. Res.*, vol. 108, no. D15, p. 4483, 2003. DOI: 1029/2002JD002951.

[118] R. E. Orville and G. R. Huffines, "Cloud-to-ground lightning in the continental United States: NLDN results in the first decade, 1989–1998," *Mon. Weather Rev.*, vol. 129, pp. 1179–1193, 2001.

[119] S. A. Fleenor, C. J. Biagi, K. L. Cummins, E. P. Krider, and X.-M. Shao, "Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the great plains," *Atmos. Res.*, vol. 91, pp. 333–352, 2009.

[120] M. Murphy and A. E. Pifer, "Network performance improvements using propagation path corrections," presented at the Int. Lightning Detection Conf., Tucson, AZ, Preprints, 1998.

[121] N. Honma, F. Suzuki, Y. Miyake, M. Ishii, and S. Hidayat, "Propagation effect on the field waveforms on relation to TAO technique in lightning location," *J. Geophys. Res.*, vol. 103, pp. 14141–14146, 1998.

[122] W. Schulz and G. Diendorfer, "Evaluation of a lightning location algorithm using a elevation model," presented at the 25th Int. Conf. Lightning Protection, Rhodes, Greece, Sep. 2000, Paper 2.3.

Kenneth L. Cummins (S'73–M'78–SM'99) received the B.S. degree in electrical engineering from the University of California, Irvine, in 1973, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1974 and 1978, respectively.

He was engaged in research on digital and statistical signal processing and physiological modeling. Until 1989, he was involved in the field of neurosciences as a Research Scientist at Stanford Medical Center and the Veterans' Administration, and then, as a Staff Scientist at Nicolet Instrument. From 1989 to 2005, he was the R&D Manager and the Chief Scientist at the Thunderstorm Business Unit, Vaisala (formally Global Atmospherics, Inc.), Tucson, AZ. He is currently a Research Professor with the Institute of Atmospheric Physics, University of Arizona, Tucson. He is the author or coauthor of more than 70 scientific papers, and holds eight U.S. patents.

Martin J. Murphy received the B.S. degree in meteorology from Pennsylvania State University, University Park, in 1992, and the M.S. and Ph.D. degrees in atmospheric sciences from the University of Arizona, Tucson, in 1994 and 1996, respectively

He was involved in the field of thunderstorm electrification and lightning detection. He is currently with Vaisala, Inc., Tucson, AZ, where he was a Staff Scientist and a Software Engineer. He is currently engaged in research in organic chemistry with an emphasis on carbon capture and storage. He has authored or coauthored several scientific papers, and holds four U.S. patents.