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Kenneth L. Cummins, Martin J. Murphy, Jeffrey V. Tuel
Global Atmospherics, Inc. Tucson Arizona, U.S.A

LIGHTNING DETECTION METHODS AND METEOROLOGICAL APPLICATIONS

1. Introduction

Lightning discharges range from low current intracloud events that can have sub-kilometer lengths, to large cloud-to-ground (CG) return strokes with peak currents of several hundred kA and channel lengths greater than 10 km. In general, this range of events cannot be detected and located using a single technique. In this presentation, three detection technologies and location methods that employ networks of radiation-field sensors are summarized. These three technologies are distinguished by both their frequency ranges of operation (VLF, LF and VHF), and by their spatial extent and resolution. In addition, basic meteorological applications of lightning information are presented.

2. Background

2.1 Cloud Flashes

A cloud flash acts to equalize or neutralize charge between two charge regions within or between clouds. The most common intracloud flashes occur between a main region of negative charge, located where ambient air temperatures are between –10 and –20C, and a region of positive charge above the negative [1]. The *active phase* of the flash begins with a negative *initial breakdown streamer* moving upward at a speed of about 10^5 m/s [2], [3]. The initial breakdown creates a conducting channel through which current can flow. On the basis of broadband fields [4], it appears that pulses of current frequently follow immediately after an extension of the vertical channel by the breakdown process. Often, the largest low-frequency emissions, associated with current-carrying processes, occur just following the initial breakdown portion of a cloud flash [5]; [6]. When the initial breakdown reaches its full vertical extent after about 20-50 msec, horizontal breakdown develops outward from the top of the vertical channel. Later, horizontal breakdown also begins to occur within the negative charge region. Throughout the active phase of a flash, upward breakdown processes recur in the initial vertical channel, with periods of continuous current flow in between [3]. The upward current eventually stops after a time on the order of hundreds of msec, when the negative charge around the base of the vertical channel is sufficiently depleted or has been replaced by an excess positive charge. At that point, the activity consists mostly of lower altitude, horizontal *K-streamers* that transport negative charge into the depleted region. During this *final stage* of the cloud flash, some of the streamers go up the single vertical channel into the upper part of the flash [3].

2.2 *Cloud-to-Ground Flashes*

The majority of CG flashes begin with an intracloud (IC) discharge that is called the *preliminary breakdown*. After about a tenth of a second, the *stepped-leader* appears below the cloud base and propagates downward in a series of intermittent steps. Most leaders effectively deposit negative charge along the leader channel; however, a few percent of leaders are positive. After a few tens of milliseconds, when the tip of the leader gets to within several tens of meters above ground, the electric field under the tip becomes large enough to initiate one or more upward *connecting discharges (streamers)*, usually from the tallest object(s) in the local vicinity of the leader. When an upward discharge contacts the leader, the first *return stroke* begins. The return stroke is basically an intense wave (positive wave of ionization) that propagates upward and discharges the leader channel at about half the speed of light. After a pause of 40 to 80 ms, another leader, the *dart-leader*, may propagate down the previous return-stroke channel and initiate a *subsequent return stroke*. A typical CG flash contains several strokes and lasts about half a second. In roughly 30–50% of all flashes to ground, the dart-leader propagates down just a portion of the previous return-stroke channel and then forges a different path to ground. In these cases, the flash actually strikes ground in two (or more) places.

2.3 *Frequency-Time Characteristics of Lightning*

From the discussion of IC and CG discharges provided above, it is clear that both types of lightning emit RF energy over a wide range of frequencies. During breakdown and ionization processes (mostly from leaders and streamers), there are strong emissions in the VHF range. When high currents occur in previously ionized channels (mostly from return strokes and the active stage of cloud flashes), the most powerful emissions occur in the LF and VLF ranges. Figure 1, presented originally by Malan [7], illustrates the electrostatic field changes and radiation field pulse activity in the VLF, LF, HF, and VHF bands. Pierce [8] also contains a good summary of the radiation produced by lightning in these bands. In the VLF and LF, cloud-to-ground return strokes completely dominate the VLF and LF radiation fields produced by lightning because of their channel length and large currents. Consequently, there are only a few large pulses per flash. Cloud flashes produce tens to hundreds of small pulses (~ 5% of the median amplitude of return strokes) in the LF, but apparently produce pulses of comparable magnitude to return strokes only occasionally [9], [10]. In the VHF, by contrast, there are approximately 100 times as many pulses as in the LF and VLF, and the amplitudes of the pulses produced by cloud flashes are comparable to those of cloud-to-ground flashes. The VHF radiation is produced by breakdown processes with dimensions on the order of tens to hundreds of meters and small currents [11]. Usually, relatively little VHF pulse activity is associated with high-current components such as return strokes, as shown in Figure 1.

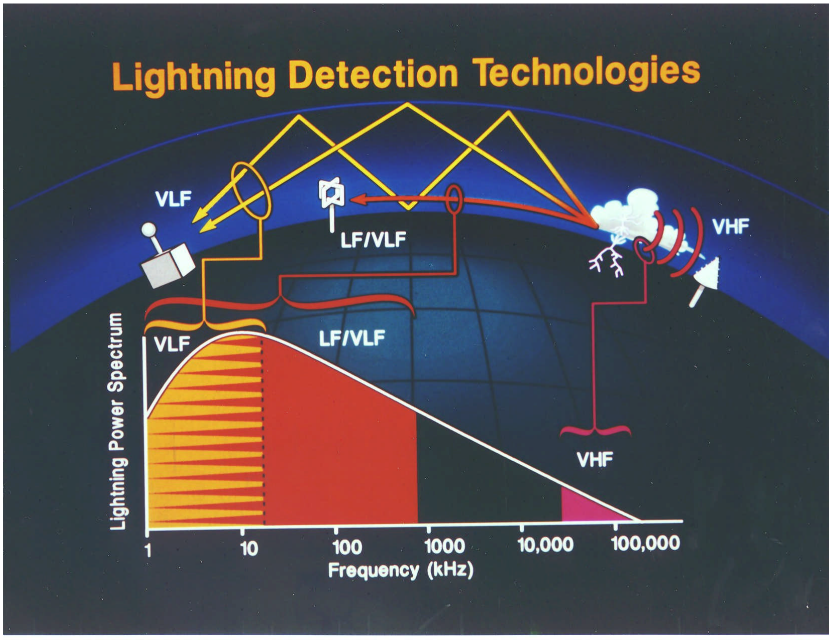

Figure 1. Relationship between frequency and lightning detection method. See text for details.

Given the differences between pulse rates and amplitudes, different techniques are better suited for detecting different processes within cloud and cloud-to-ground flashes. Figure 2 depicts the three detection methods that we will describe in greater detail in this paper. Low-frequency and VLF signals that propagate along the surface of the earth have been used to detect and locate the return strokes in cloud-to-ground flashes for many years. Sensors that operate in the LF can also be used to locate cloud flashes, although, as described above, the signals are normally much smaller than those due to return strokes. The same existing sensor technology has been applied to the detection of purely VLF signals from cloud-to-ground return strokes that propagate thousands of kilometers by reflections from the ionosphere and ground. This allows some cloud-to-ground lightning to be located in remote areas where sensors cannot be installed. Systems that operate in the VHF are equally sensitive to most processes in both cloud and cloud-to-ground flashes. Because of the line-of-sight propagation of VHF signals, these systems have a limited range. However, the line-of-sight propagation, together with the fact that VHF impulses are of short duration, allows VHF sources to be modeled as point sources and located in three dimensions as described later in this paper. In addition, the large number of pulses per flash in the VHF means that flashes can be mapped in great detail.

3. Detection Methods

Methods for detecting lightning processes at VLF, LF, and VHF are described in this section. An overview of network-based (multi-sensor) methods and systems is presented. The detection methods employed by Global Atmospherics are discussed in detail.

3.1 Early History

Before the development of weather radars, a variety of sferics detection systems were the primary means of identifying and mapping thunderstorms at medium and long ranges [12]. In the 1920s, Watson-Watt and Herd [13] developed a cathode-ray direction finder (CRDF) that utilized a pair of orthogonal loop antennas tuned to a frequency near 10 kHz, where propagation in the earth-ionosphere waveguide is relatively efficient, to detect the horizontal magnetic field produced by lightning. The azimuth angle to the discharge was obtained by displaying the north-south and east-west antenna outputs simultaneously on an *x-y* oscilloscope, so that the resulting vector pointed in the direction of the discharge [14]. Two or more CRDFs at known positions were sufficient to determine the location of a discharge from the intersection of simultaneous direction vectors. Various low frequency CRDF systems were used up to and during World War II in many regions of the world.

3.2 Low Frequency Methods

CG discharges are typically detected using VLF/LF detection and waveform discrimination of fields propagated along the earth's surface or in the earth-ionosphere waveguide. The sensors in these systems are typically separated by 50-400 km. The CG discharges are located in terms of their ground strike points using various forms of direction finding, time-of-arrival (TOA), and combinations thereof.

3.2.1 Gated, Wideband Magnetic Direction-Finders (DFs)

In 1976, an improved magnetic DF system was developed for locating cloud-to-ground lightning within a range of about 500 km [15], [16]. This system operated in the time-domain (i.e., covering the LF and VLF bands from about 1 to 500 kHz) and was designed to respond to field waveforms that were characteristic of the return strokes in CG flashes [16]. When such a field was detected, the magnetic direction was sampled (in both a north-south loop and an east-west loop) just at the time of the initial field peak. The resulting direction vector pointed as closely as possible to the onset of the stroke and to the place where the stroke struck ground. The electric field was also sampled at this time to determine the stroke polarity. When employed in a network of DFs, the

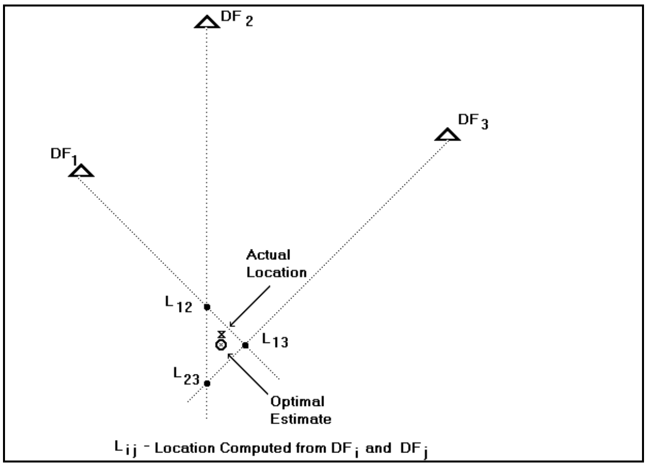

Figure 2 Optimal location algorithm for direction finding.

location of the stroke could be determined by triangulation using two sensors, and the peak current could be estimated from the measured peak field. When three or more sensors report a discharge, an optimization which minimizes the "angle disagreement" between the reporting sensors can be employed. This process is illustrated in Figure 2. The three points (L$_{12}$, L$_{13}$, and L$_{23}$) show the possible “triangulated” locations that would be computed if only two sensors were to report the discharge. The use of gated field measurements and multi-sensors optimization results in significant improvements in location accuracy for CG lightning.

There are certain conditions where the geometrical relationship between direction-finding sensors and the lightning discharge produce poor results. Specifically, if the discharge occurs along a line between two sensors, and these sensors are the only ones to see the discharge, then errors in azimuth measurement can result in significant errors in location. In some circumstances, the measurements may not produce an intersection at all. Because of this baseline problem, practical networks have at least three sensors.

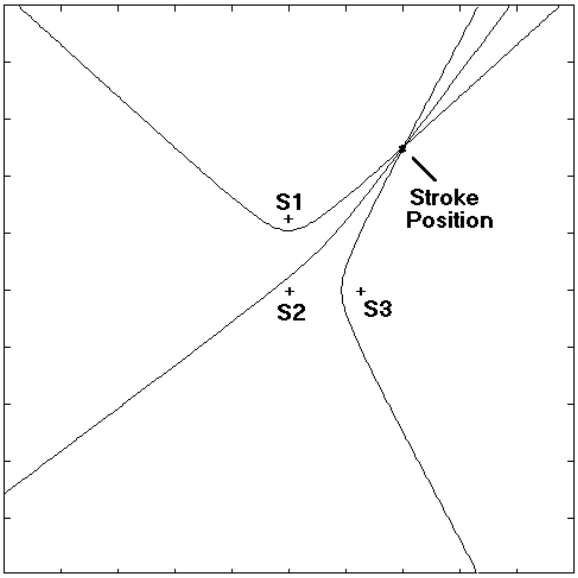

Figure 3a Hyperbolic intersection method for locating lightning using three sensors.

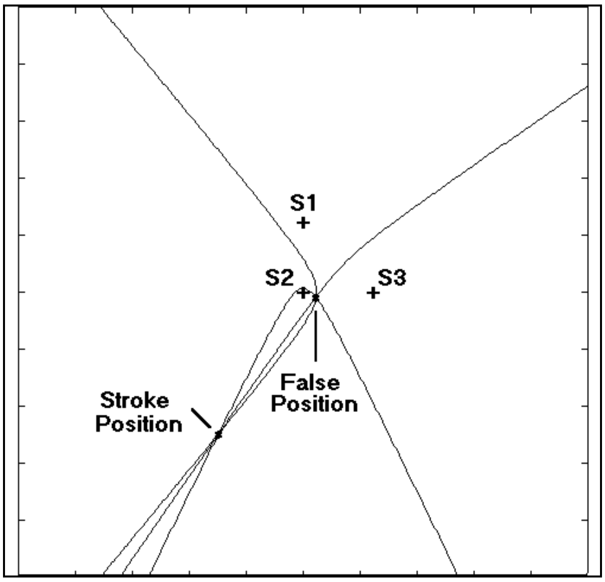

Figure 3b Example of an ambiguous location for a three-sensor hyperbolic intersection.

3.2.2 Time-of-Arrival (TOA) Sensors

Lewis et al. [17] have described a method for locating lightning that is based on measurements of the time-of-arrival of a radio pulse at several stations that are precisely synchronized. A constant difference in the arrival time at two stations defines a hyperbola, and multiple stations provide multiple hyperbolas whose intersections define a source location. This technique is illustrated in Figure 3a. Under some geometrical conditions, curves produced from only three sensors will result in two intersections, leading to an ambiguous location as shown in Figure 3b. This problem is avoided if four sensors detect the discharge. A detailed theoretical analysis of this early methodology, collectively referred to as location by *hyperbolic intersections*, was performed by Lewis [17]. Time-of-arrival (TOA) methods can provide accurate locations at long ranges [18], and if the antennas are properly sited, the systematic errors are minimal. Casper and Bent [19] have developed a wideband TOA receiver (termed the Lightning Position and Tracking System or LPATS) that is suitable for locating lightning sources at medium and long ranges using the hyperbolic method [20].

3.2.3 Improved Accuracy Using Combined Technology (IMPACT)

In the early 1990's, Global Atmospherics developed a method for combining direction-finding and time-of-arrival to produce yet another lightning location method which we refer to as the IMPACT method. In this approach, direction finding provides azimuth information and absolute arrival time provides range information. These measurements produce three estimated parameters -- latitude, longitude, and discharge time. Thus the IMPACT method has redundant information which allows for an optimized estimate of location even when only two sensors provide both timing and angle information. The combined MDF and TOA location algorithm offers many advantages over either a DF or TOA method taken alone. For example, a discharge that occurs along the baseline between two IMPACT sensors will be more accurately located by the intersection of two direction vectors and two "TOA range circles" than by the direction intersection alone [21].

The IMPACT algorithm can utilize information from any combination of direction finding, TOA, or combined (DF/TOA) sensors. Figure 4 shows a typical lightning stroke in Florida that was detected by five sensors in the U.S. National Lightning Detection Network™ (NLDN) – three IMPACT and two LPATS sensors. The direction measurements are shown as straight-line vectors, and range circles centered on each sensor represent the TOA measurements. Further details regarding the NLDN and its uses can be found in [22], [23].

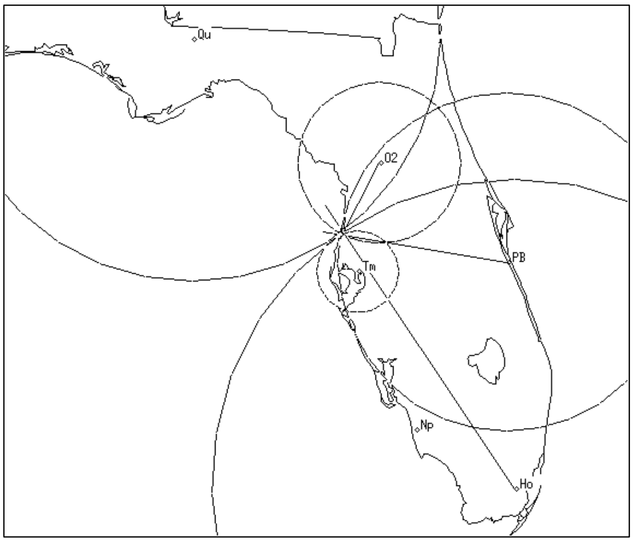

Figure 4. Example of the IMPACT location algorithm using three LPATS TOA sensors and 2 IMPACT sensors.

Cloud discharges can also be detected and roughly located using the same broadband VLF/LF signals employed in CG lightning location systems. These systems employ sensor baselines that are somewhat shorter than CG detection systems and typically provide a single location that is associated with a non-specific point along the path of the discharge. The practical benefits of these systems include their ability to provide information about both IC and CG discharges using the same instrumentation (lower cost) and the fact that VLF/LF signals propagate well through mountainous terrain (no line-of-sight constraint).

3.3 Long-range VLF Detection

Since the sensors discussed above are responsive to electromagnetic fields at both LF and VLF frequencies, they are capable of detecting VLF "spherics" produced by very distant cloud-to-ground lightning. These signals propagate thousands of kilometers by ionospheric reflection, as illustrated in Figure 1. Standard LF/VLF sensors can be simultaneously employed for their conventional use and for this long-range application. For this long-range application, the sensor information is processed in a manner that identifies and employs ionospherically-propagated electromagnetic signals produced by distant lightning, rather than the "normal" ground-wave propagated signals. An evaluation of GAI's approach to long-range detection has been carried out by Cramer and Cummins [24]. An alternate VLF "sferics" locating system based on arrival-time differences is described by Lee [18].

Although this technique only detects a small fraction of the lightning discharges in a storm, it is capable of reliably reporting convective thunderstorms in areas where sensors cannot be placed. This technology has been used by GAI for the last five years, providing the Aviation Weather Center of the U.S. National Weather Service with a tool to forecast convective SIGMETS over the oceans.

3.4 Two- and Three-Dimensional VHF Detection

By using higher-frequency components of the lightning discharge (UHF/VHF), it is possible to reconstruct the path (map) of the cloud discharge in two or three dimensions using TOA or direction-finding location methods. In these UHF/VHF "lightning mapping" systems, one focuses on detailed discharge structure, but loses broad-area coverage and information about polarity, charge, and current magnitudes. Today it is clear that these VHF methods offer great promise, both for early warnings and for research, particularly in local regions and for those phases of the discharge that occur within the cloud. These systems have the ability to provide a tremendous amount of information regarding storm stage, intensity, and configuration, which may prove to be valuable parameters related to storm severity.

3.4.1 Direction Finding Based on VHF Interferometry

Hayenga and Warwick [25] showed that a radio interferometer could be used to measure the azimuth and elevation angles of lightning sources at VHF frequencies. Rhodes et al. [26] and Shao et al. [27] have developed this technique further and have used single-station interferometers to improve our understanding of the development of both IC and CG lightning. These were single-station systems that provided a "projection" of lightning onto a plane. Richard et al. [28], and [29] have developed multiple-station networks of interferometers that can locate and map the sources of VHF radiation in two- or three-dimensions with high time resolution. A commercial version of this system is available commercially and is reported to locate both IC and CG flashes [30], [31]. As with LF/VLF direction finding systems, the location accuracy of these systems is somewhat limited and dependent on sensor spacing, particularly in three dimensions.

3.4.2 TOA Methods Operating at VHF

Proctor [11] showed that when the difference in the time of arrival of each RF pulse is measured at four stations that are precisely synchronized, the locations of the sources can be mapped in three dimensions. This location method is a direct extension of the two-dimensional hyperbolic intersections method discussed in Section 3.2.2. In recent years, the NASA Kennedy Space Center has developed a Lightning Detection and Ranging (LDAR) System that is capable of providing three-dimensional locations of more than a thousand RF pulses within each lightning flash [32], [33]. This system is similar to that of Proctor, but the data acquisition is automatic, and the data displays are generated in real-time. In order to facilitate the support of this system, which had been the only one of its kind, NASA entered into a technology transfer agreement with GAI to build a COTS version of the system in 1997. The following year, the New Mexico Institute of Mining and Technology (NMT) began work on a portable lightning mapping system that was designed for research only and did not have any real-time capability. Their system was first deployed in Oklahoma in 1998 [34] and then in central New Mexico [35]. GAI has operated its first system (LDAR-I) at KSC in parallel with the components of the original LDAR system and has successfully tested it against the original system over the past year. In addition, GAI and NMT have collaborated over the past year, and are currently working together on the commercialization of LDAR-II. Many of the concepts of the NMT system are being incorporated into GAI's commercial version of the system (LDAR-II) with its real-time capability.

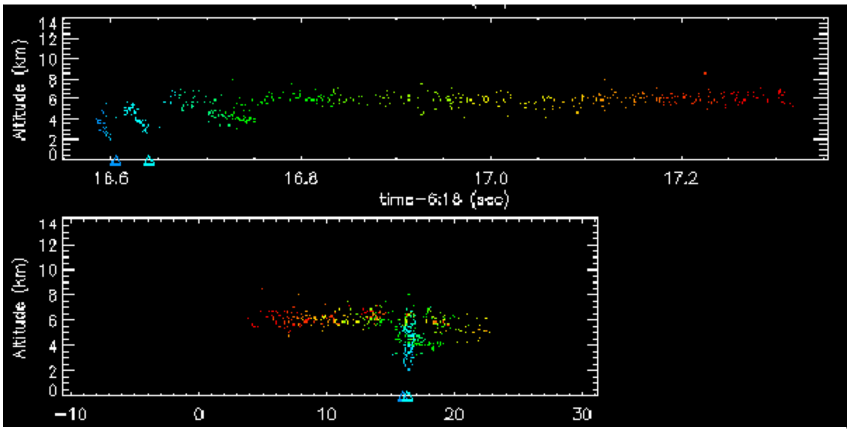

Figure 5 Three-Dimensional Projections of a Cloud-to-ground Lightning Flash. Upper panel is a time-height representation of the breakdown events. The lower panel displays events as a function of height and horizontal distance, looking North.

Figure 5 shows elements of a negative cloud-to-ground (CG) flash detected by the NMT research system. Several hundred VHF sources were produced by this flash. The top panel of this display is an altitude vs. time plot of about 800 msec of data. Each point in this plot is a radiation source that was located in three dimensions and represents breakdown processes in this lightning flash. The color changes denote the time sequencing of the located events. Note that the mapping system detected two leaders that began at an altitude of about 5 km and propagated to ground. Both leaders were followed by return strokes that were detected by the U.S. National Lightning Detection Network (triangles plotted at zero altitude). Following the two strokes, charge rearrangement occurred in the cloud, mainly in a single stratified charge region at about 6 km altitude, for nearly 700 ms. The lower panel in Figure 5 shows an altitude vs. distance plot of this flash, looking from the South to the North. Note that the rearrangement of charge occurred over a 20 km extent that was limited to altitudes in the range of 5-8 km.

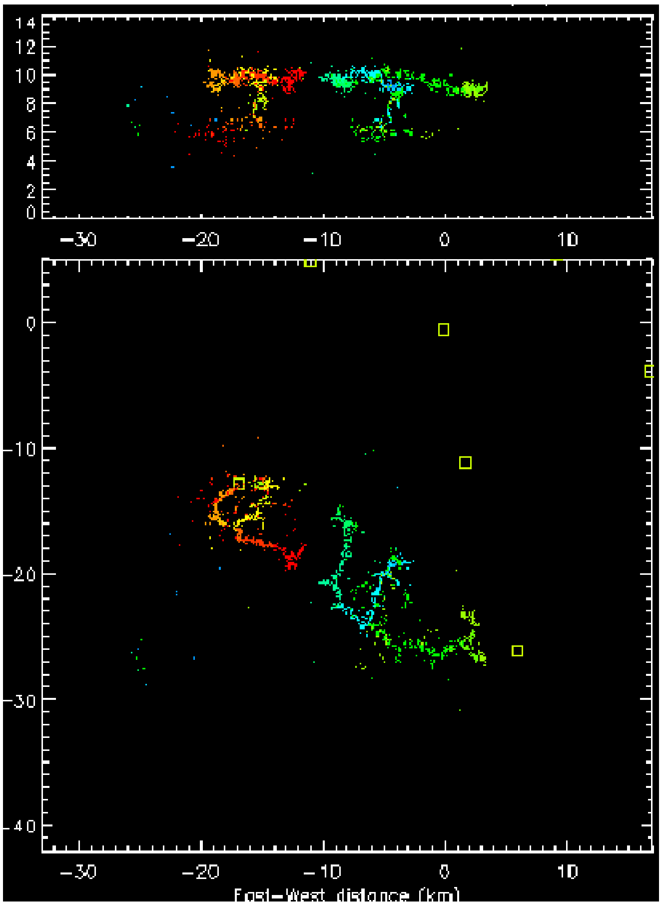

Figure 6. Three-dimensional representation of two cloud lightning flashes. See text for details.

Figure 6 shows an example of two cloud flashes that were detected by the NMT research network. The top panel of this display is the same North-looking projection as shown in the lower panel of Figure 5. The large plot in the lower panel is a plan view. These two flashes occurred in a 3-minute time interval. The color changes denote the time sequencing of the located events. Both flashes shown in this figure are typical bi-level intracloud flashes occurring between an inferred negative charge region at an altitude of about 6 km and a positive charge region at an altitude of about 10 km, similar to flashes described by Shao and Krehbiel [3]. Each flash produced more than 500 detected VHF impulses. The greatest rates of pulse emission in lightning discharges occurs in the VHF [8], and there can be as many as a few thousand pulses produced by a single flash.

Meteorological Applications

In the remainder of this paper, we briefly discuss the applications of total lightning detection for the early warning of thunderstorms (and specifically CG lightning) and severe weather phenomena. The tracking and early warning of thunderstorms and CG lightning is a common application of lightning data, but a statistical characterization was only recently performed by Murphy and Cummins [36]. In the area of severe weather, recent investigations involving total lightning have accompanied an increase in available VHF time-of-arrival technology. In this section, we provide an overview of some studies of severe weather-lightning relationships.

Early warning of Thunderstorms and CG Lightning

The early warning of CG lightning and thunderstorms was recently characterized by Murphy and Cummins [36]. They assumed that the first CG flash within 5 km of a known point of interest constituted a risk, and they computed cumulative distributions of the probability of successfully averting the risk as a function of lead time. Cloud-to-ground lightning data from greater distances and nearby cloud lightning data were used to anticipate the risk. Figure 7 shows the cumulative distributions of lead times for a low-frequency network in Hong Kong for three warning categories: cloud flashes within 15 km of the center of the network, CG flashes between 5-15 km of the center, and total lightning (the aggregate of the first two). The Hong Kong network has a CG flash detection efficiency of 90% and a cloud flash detection efficiency of about 10%. Negative time values in figure 7 denote lead times, that is, advance warning. At least 5 minutes of advance warning were available in 70-80% of storms, not only in this network but in others studies as well. Note that the cloud flash and CG flash categories produced about the same distributions despite the large difference in detection efficiency between cloud and CG flashes. The total lightning distribution lies slightly above the other two, indicating that a modest improvement is possible by combining data sets. In order to evaluate the sensitivity of the distributions to the cloud flash detection efficiency of the network, Murphy and Cummins [36] performed the same analysis using a combination of the Kennedy Space Center LDAR system and the U.S. National Lightning Detection Network (NLDN). By comparing the LDAR result with the Hong Kong cloud discharge distribution, they found that the LDAR outperformed the LF total lightning data for all lead times, but not by a large amount. They concluded that the additional benefit of cloud flashes, even if 100% are detected, is limited to a typical range of 5-10 minutes because (1) most thunderstorms approach from a distance and are already producing CG lightning when they arrive, and (2) when thunderstorms do develop overhead, the time from the first cloud flash to the first CG is usually a few minutes [37].

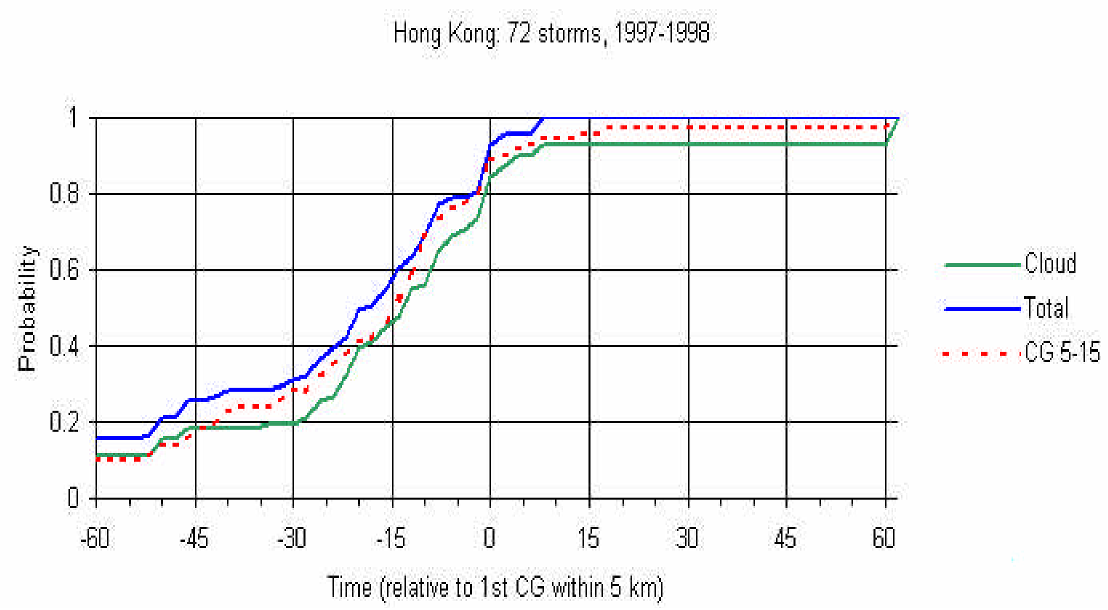

Figure 7. Probability of warning for cloud-to-ground lightning at a point of interest. Cumulative distributions of lead (negative) and lag (positive) times for 72 storms in Hong Kong.

Severe Weather

Because of the availability of CG lightning detection networks for a long time, many studies have been carried out to look for relationships between CG lightning activity and severe weather. For example, in storms producing tornadoes, Perez et al. [38] found a general pattern of a peak in CG flash rate prior to the tornado, a relative minimum in CG rate at about the time of the tornado, and a second peak in rate following the tornado. Sometimes, the percentage of positive CG flashes near the time of the relative minimum in CG flash rate [39], [40], [41]. In addition, often more than 50% of CG flashes are positive prior to or during periods of large hail in some storms [41], [42], [43], [44]. Recently, more studies have used "total lightning," the combination of cloud and CG lightning rather than CG information alone. These have employed VHF detection systems because of their equal sensitivity to cloud flashes and the in-cloud components of CG flashes. Early studies using total lightning information found that cloud flashes can far outnumber CG flashes during severe weather [45], [46]. Total lightning information seems to have useful applications, as shown by Williams et al. [47] and Laroche et al. [48], in which cloud lightning rates peaked several minutes before microbursts at the surface in some storms. The LDAR system at Kennedy Space Center [32] was used by Williams et al. [49] to study 30 severe storms in Florida. They observed rapid increases in lightning flash rate that, in almost all cases, preceded the severe weather event. These events included tornadoes, large hail, and straight-line winds. The rapid jumps in total lightning rate were dominated by cloud flashes, which consistent with the other studies.

The location accuracy of VHF time-of-arrival systems (≤ 50 m RMS three-dimensional over the network for radiation source altitudes ≥ 4 km MSL) and detection rates (up to 10^4 pulses/sec) are sufficient for the structure of severe storm lightning activity to be analyzed with great detail and precision. Krehbiel et al. [34] observed very high-altitude lightning activity at altitudes of 16-20 km MSL in several storms, once in conjunction with a lightning-free region within a supercell thunderstorm. For one storm that produced tornadoes, they also saw lightning structures that were shaped like hook echoes in radar imagery and lightning discharges that appeared to delineate the wall cloud of the storm. Although many studies show encouraging correlations between severe weather events cloud lightning rates, there are still many questions to be answered regarding the uniqueness of these correlations. Global Atmospherics is currently collaborating with several research key meteorological groups in a effort to evaluate further the benefit of 2-dimensional and 3-dimensional total lightning information for severe weather detection and classification.

Lightning data can be a useful proxy for radar data where radar beams are blocked by mountainous terrain, but care must be taken when employing VHF detection systems. This is because both microwave-frequency radar beams and the VHF emissions from lightning are blocked by mountainous terrain. LF and VLF emissions from lightning can propagate over such terrain, making networks of LF/VLF sensors particularly useful in this application. Good spatial and temporal correlations between CG lightning and precipitation were found by Cheze and Sauvageot [50], Soula et al. [51], and Molinie et al. [52] for storms in mountainous areas of France and Spain, including two that produced flash floods. Cheze and Sauvageot [50] suggest that radar-derived rain rates correlate better with CG flash rate than with total lightning rate in cases where both were available. The quantitative use of lightning to determine rain rate is complicated, however Tapia [53] and Petersen and Rutledge [54] showed that the amount of rain per CG flash varies over several orders of magnitude depending on geographical location. Furthermore, they and Lopez et al. [55] showed that even the prevailing meteorological conditions can cause this quantity to vary by a factor of 10-100 at any one location. Some compensation for this has been found by Sheridan et al. [56], who found that the percent positive tends to be higher where the rain-to-CG flash ratio is high (*e.g.,* in the stratiform regions of mesoscale convective systems). By using locally-derived information, and including seasonal and storm-type information, it is likely that lightning information, particularly CG information derived from LF systems, will be a significant tool on flash flood forecasting in areas with poor radar coverage.

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