SECTION: Cover green

Guide to Instruments and Methods of Observation

Volume III – Observing Systems

Chapter 6. Methods of Lightning Detection

CHAPTER 6. METHODS OF LIGHTNING DETECTION

6.1 INTRODUCTION

There are many individual physical processes in cloud and ground lightning flashes. Each of these processes is associated with characteristic electric and magnetic fields. Lightning is known to emit significant electromagnetic energy in the radio-frequency range from below 1 Hz to near 300 MHz, with a peak in the frequency spectrum near 5 to 10 kHz for lightning at distances beyond 50 km or so. Further, electromagnetic radiation from lightning is detectable at even higher frequencies, for example, in the microwave (300 MHz to 300 GHz) and, obviously, in visible light (roughly 10^{14} to 10^{15} Hz). At frequencies higher than that of the spectrum peak, the spectral amplitude varies roughly inversely proportional to the frequency up to 10 MHz or so and inversely proportional to the square root of frequency from about 10 MHz to 10 GHz. Also, lightning is known to produce X-rays (up to 10^{20} Hz or more), although at ground level they are usually not detectable beyond a kilometre or so from the source. In general, any observable electromagnetic signal from a lightning source can be used to detect and locate the lightning process that produced it. In addition to electromagnetic radiation, lightning produces the acoustic radiation that can be also used for lightning location. The acoustic locating techniques, acoustic signal time of arrival and acoustic ray tracing are not further discussed here.

6.2 LIGHTNING DISCHARGE

Lightning can be defined as a transient, high-current (typically in the kiloamperes range) electric discharge in air whose length is measured in kilometres. As for any discharge in air, the lightning channel is composed of ionized gas, that is, of plasma, whose peak temperature is typically 30 000 K (during the so-called return-stroke stage), about five times higher than the temperature on the surface of the Sun. Lightning was present on Earth long before human life evolved, and it may even have played a crucial role in the evolution of life on our planet. According to climatologists of total lightning flash rates observed by the spaceborne Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) instruments, the mean global flash rate from the merged climatology is 46 flashes per second varying from 35 to 60 flashes per second depending on the season (Cecil et al., 2014). Each year, some 25 million cloud-to-ground lightning discharges (note that, on average, about three quarters of lightning discharges are confined to the cloud, that is, do not involve ground) occur in the USA alone. Because of increased awareness of lightning safety, among other factors, lightning now kills fewer people in the USA than flooding, hurricanes, tornadoes, and extreme heat. Lightning initiates many forest fires, and over 30% of all electric power line failures are lightning related. Each commercial aircraft is struck by lightning on average once a year. A lightning strike to an unprotected object or system can be catastrophic.

6.2.1 Lightning types, processes and parameters

About 90% or more of global cloud-to-ground lightning is accounted for by negative (negative charge is effectively transported to the ground) downward (the initial process begins in the cloud and develops in a downward direction) lightning. Other types of cloud-to-ground lightning include positive downward, negative upward, and positive upward discharges. There are also bipolar lightning discharges sequentially transferring both positive and negative charges during the same flash. The basic elements of the negative downward lightning discharge are termed component strokes or just strokes. Each flash typically contains 3 to 5 strokes, the observed range being 1 to tens of strokes. Roughly half of all lightning discharges to Earth strike ground at more than one point, with the spatial separation between the channel terminations being up to many kilometres. The two major lightning processes comprising a stroke are termed the leader and the return stroke, which occur as a sequence with the leader preceding the return stroke. The following discussion considers lightning discharges in more detail. Rakov and Uman (2003) and references therein contain more details.

Two photographs of a negative cloud-to-ground discharge are shown in Figures 6.1(a) and 6.1(b). The image in Figure 6.1(a) was obtained using a stationary camera, while the image in Figure 6.1(b) was captured with a separate camera that was moved horizontally during the time of the flash. As a result, the latter image is time-resolved showing several distinct luminous channels between the cloud and ground separated by dark gaps. Each luminous channel corresponds to an individual stroke, and the dark gaps represent time intervals which are typically of the order of tens of milliseconds. These dark time intervals between the strokes explain why lightning often appears to the human eye to flicker. The first stroke being on the far right (time advances from right to left). The first two strokes are branched, and the downward direction of branches indicates that this is a downward lightning flash.

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Figure 6.1. Lightning flash which appears to have at least 7 (perhaps as many as 10) separate ground strike points. Image (a) is a still photograph and image (b) a streaked photograph. Some of the strike points are associated with the same stroke having separate branches touching ground, while others are associated with different strokes taking different paths to ground. Adapted from Hendry (1993)

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Sketches of still and time-resolved images of the three-stroke lightning flash are shown in Figures 6.2(a) and 6.2(b), respectively. A sketch of the corresponding current at the channel base is shown in Figure 6.2(c). In Figure 6.2(b), time advances from left to right, and the timescale is not continuous. Each of the three strokes in Figure 6.2(b), represented by its luminosity as a function of height above ground and time, is composed of a downward-moving process, termed a leader, and an upward-moving process, termed a return stroke. The leader creates a conducting path between the cloud charge source region and ground and distributes negative charge from the cloud source region along this path. The return stroke traverses that path moving from ground towards the cloud charge source region and neutralizes the negative leader charge. Thus, both leader and return-stroke processes serve to effectively transport negative charge from the cloud to ground. As seen in Figure 6.2(b), the leader initiating the first return stroke differs from the leaders initiating the two subsequent strokes (all strokes other than the first are termed subsequent strokes). In particular, the first-stroke leader appears optically to be an intermittent process, hence the term “stepped leader”, while the tip of a subsequent-stroke leader appears to move continuously. The continuously moving subsequent-stroke leader tip appears on streak photographs as a downward-moving dart, hence the term “dart leader”. The apparent difference between the two types of leaders is related to the fact that the stepped leader develops in virgin air, while the dart leader follows the pre-conditioned path of the preceding stroke or strokes. Sometimes a subsequent leader exhibits stepping while propagating along a previously formed channel; in which case it is referred to as a dart-stepped leader. There are also so-called chaotic subsequent-stroke leaders. All types of leaders produce bursts of X-ray emission with energies typically up to 250 keV (twice the energy of a chest X-ray) (Dwyer, 2005).

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Figure 6.2. Drawing showing the luminosity of a three-stroke ground flash and the corresponding current at the channel base. Figure (a) is a still-camera image, (b) a streak-camera image, and (c) a channel-base current.

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The electric potential difference between a downward-moving stepped-leader tip and ground is probably some tens of megavolts, comparable to or a considerable fraction of that between the cloud charge source and ground. The magnitude of the potential difference between two points, one at the cloud charge source and the other on ground, is the line integral of electric field intensity between those points. The upper and lower limits for the potential difference between the lower boundary of the main negative charge region and ground can be estimated by multiplying, respectively, the typical observed electric field in the cloud, 10^5 V/m, and the expected electric field at ground under a thundercloud immediately prior to the initiation of lightning, 10^4 V/m, by the height of the lower boundary of the negative charge centre above ground, 5 km or so. The resultant range is 50 to 500 MV.

When the descending stepped leader attaches to the ascending leader and then ground, the first return stroke begins. The first return-stroke current measured at ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The return stroke effectively lowers to ground the several coulombs of charge originally deposited on the stepped-leader channel including all the branches.

Once the bottom of the dart-leader channel is connected to the ground, the second (or any subsequent) return-stroke wave is launched upward, which again serves to neutralize the leader charge. The subsequent return-stroke current at ground typically rises to a peak value of 10 to 15 kA in less than a microsecond and decays to half-peak value in a few tens of microseconds.

The high-current return-stroke wave rapidly heats the channel to a peak temperature near or above 30 000 K and creates a channel pressure of 1 MPa or more, resulting in channel expansion, intense optical radiation and an outward propagating shock wave that eventually becomes the thunder (sound wave) we hear at a distance.

The impulsive component of the current in a return stroke (usually subsequent) can be followed by a continuing current which has a magnitude of tens to hundreds of amperes and a duration of up to hundreds of milliseconds. Continuing currents with a duration in excess of 40 ms are traditionally termed long continuing currents. According to flashes detected by LIS, about 7% of all flashes contain long continuing currents, and 25 – 40 % of them show only intracloud pulses (Bitzer, 2017). Current pulses superimposed on continuing currents, as well as the corresponding enhancements in luminosity of the lightning channel, are referred to as M-components.

There is a special type of lightning that is thought to be the most intense natural producer of HF-VHF (3–300 MHz) radiation on Earth. It is referred to as compact intracloud discharge (CID). CIDs were first reported by Le Vine (1980) and received their name (Smith et al., 1999) due to their relatively small (hundreds of metres) spatial extent. They tend to occur at high altitudes (mostly above 10 km), appear to be associated with strong convection (however, even the strongest convection does not always produce CIDs), tend to produce less light than other types of lightning discharges, and produce single bipolar electric field pulses (narrow bipolar pulses or NBPs) having typical full widths of 10 to 30 μs and amplitudes of the order of 10 V/m at 100 km, which is comparable to or higher than for return strokes in cloud-to-ground flashes. As an illustration of intensity of wideband electromagnetic signature of CIDs, 48 CIDs examined in detail by Nag et al. (2010) were recorded by 4 to 22 (11 on average) stations of the United States National Lightning Detection Network (NLDN), whose average baseline is 300–350 km.

6.2.2 Lightning electromagnetic signatures

Both cloud-to-ground and cloud lightning discharges involve a number of processes that produce characteristic electromagnetic field signatures. Salient characteristics of measured electric and magnetic fields generated by various lightning processes at distances ranging from tens to hundreds of kilometres are briefly reviewed below. The emphasis is put on those processes which produce substantial microsecond- and submicrosecond-scale field variations.

The table below summarizes essentially all identifiable lightning radiation field signatures as recorded at ground. Note that apparently there is no characteristic microsecond-scale field signature associated with lightning K- and M- processes. Besides return strokes (the first row) and CIDs (the last row), the pulses produced by lightning processes represented in the table occur in sequences with submillisecond-interpulse intervals. Leader pulses (second and third rows) are presumably emitted by the lower portion of the channel to ground just prior to the initiation of a return stroke, while both initial breakdown pulses (fourth and fifth rows) and regular pulse bursts (sixth row) are produced by lightning processes occurring inside the cloud. Characterization given below concerns both the overall pulse sequences and individual pulses.

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Characterization of microsecond-scale electric field pulses associated with various lightning processes (adapted from Rakov, 1999)

TABLE: Table horizontal lines

Type of pulses	*Dominant polarity (atmospheric electricity sign convention)*	*Typical total pulse duration (µs)*	*Typical time interval between pulses (µs)*	*Comments*
Return stroke in negative ground flashes	Positive	30–90 (zero-crossing time)	60 x 10^3	3–5 pulses per flash
Stepped leader in negative ground flashes	Positive	1–2	15–25	Within 200 μs just prior to a return stroke
Dart-stepped leader in negative ground flashes	Positive	1–2	6–8	Within 200 μs just prior to a return stroke
Initial breakdown in negative ground flashes	Positive	20–40	70–130	Some milliseconds to some tens of milliseconds before the first return stroke
Initial breakdown in cloud flashes	Negative	50–80	600–800	The largest pulses in a flash
Regular pulse burst in both cloud and negative ground flashes	Both polarities are about equally probable	1–2	5–7	Occur later in a flash; 20–40 pulses per burst
CID (narrow bipolar event)	Both polarities occur, with negative being more frequent	10–30	–	Typically not preceded or followed by any other lightning process within hundreds of milliseconds

Notes:

a Polarity refers to the polarity of the initial half cycle in the case of bipolar pulses.

b According to the atmospheric electricity sign convention, a downward-directed electric field vector is assumed to be positive.

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Negative ground flashes

The typical microsecond-scale pulse structure of naturally occurring negative ground discharges, as observed at ground, includes an initial sequence of pulses (usually called initial or preliminary breakdown pulses) followed, typically some milliseconds to some tens of milliseconds later, by 3 to 5 relatively large return-stroke pulses spaced several tens of milliseconds apart. The duration of the initial sequence of pulses is typically a few milliseconds. Individual pulse waveforms characteristic of the preliminary breakdown in negative ground flashes are shown in Figure 6.3(a). The initial polarity of the preliminary breakdown pulses is usually the same as that of the following return-stroke pulse. The initial breakdown pulses can have amplitudes comparable to or even exceeding that of the corresponding return-stroke pulses. Just prior to the first return-stroke pulse and prior to some subsequent return-stroke pulses there are pulse sequences, in the former case associated with the stepped-leader process and in the latter case with dart-stepped (regular pulse train) or chaotic (irregular pulse train) leader processes. These pulse sequences have been observed to last for a few milliseconds, and the pulse amplitudes are one to two orders of magnitude smaller than the corresponding return-stroke pulse amplitude. The stepped-leader pulses are seen just prior to the return-stroke pulse in Figure 6.4(a), before $t = 0$. A rather irregular pulse train, indicative of chaotic leader, is seen prior to the subsequent return-stroke pulse (before $t = 0$) in Figure 6.4(b). Usually there is a relatively quiet millisecond-scale gap between the preliminary breakdown pulse sequence and the beginning of pronounced stepped-leader pulses. The intervals between the return-stroke pulses, and the interval of some tens of milliseconds following the last return-stroke pulse, contain regular pulse bursts of relatively small amplitude and some other, usually irregular, pulse activity. Pulse peaks in regular pulse bursts are approximately two orders of magnitude smaller than return-stroke initial field peaks in the same flash. As seen in the table, the regular pulse bursts are very similar in their characteristics to the pulse sequences associated with dart-stepped leaders. The geometric mean initial electric field peak normalized to 100 km for negative first strokes, about 6 V/m, is about a factor of two larger than for negative subsequent strokes, about 3 V/m. The geometric mean time interval between return-stroke pulses is 60 ms.

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Figure 6.3. Examples of electric field (E) pulse waveforms characteristic of (a) the initial breakdown in negative ground (CG) flashes, (b) the initial breakdown in cloud (IC) flashes, and (c) compact intracloud discharges (CIDs). Positive electric field (atmospheric electricity sign convention) deflects upward. (Adapted from Rakov, 1999)

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Figure 6.4. Examples of electric field pulse waveforms for (a) the negative first stroke, (b) the negative subsequent stroke, and (c) the positive first stroke. All three events have been detected by NLDN, and their NLDN-reported characteristics (estimated peak current I_p, and distance R) are given on the plots. See also caption of Figure 6.3. (Adapted from Rakov, 1999)

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Positive ground flashes

Positive flashes usually contain a single return stroke (although up to four strokes per flash have been observed) whose microsecond-scale electric and magnetic field waveforms are similar to those characteristic of negative first return strokes, except for the initial polarity. An example of positive return-stroke electric field waveform is given in Figure 6.4(c). Small pulses seen before $t = 0$ in Figure 6.4(c) are indicative of a stepped-leader process. As opposed to negative first strokes, these pulses are detected only in about one third of field waveforms. The mean initial electric field peak normalized to 100 km for positive first strokes is about a factor of two larger than for negative first strokes. Positive strokes to ground can be initiated in a way similar to how negative lightning flashes are initiated (see above) or they can be by-products of extensive cloud discharges.

Cloud flashes

The typical pulse structure that is observed in naturally occurring cloud discharges includes an initial sequence (or sequences) of pulses of relatively large amplitude, spaced some hundreds of microseconds apart and occurring within the first several to a few tens of milliseconds, followed by a number of regular pulse bursts of significantly smaller amplitude. Pulses within the burst are several microseconds apart, with each burst lasting for some hundreds of microseconds. Individual pulse waveforms characteristic of the initial breakdown in cloud flashes are shown in Figure 6.3(b). The initial polarity of these pulses tends to be opposite to that of the initial breakdown pulses in negative ground flashes. There are also microsecond-scale pulses, with amplitudes appreciably lower than those of the initial breakdown pulses, which are dispersed, as opposed to clustering in bursts, throughout the flash. Some of these smaller and often irregular pulses are associated with step-like K changes (field signatures of K-processes). K changes typically occur in the late stage of the cloud flash and are separated by many tens of milliseconds.

Compact intracloud discharges

An example of electric field signature of CIDs (also called narrow bipolar events) is given in Figure 6.3(c). These pulses have peaks and peak time derivatives comparable to those of return strokes in ground flashes.

6.2.3 Key terminology

Atmospheric electricity sign convention. Electric field sign convention according to which a downward-directed field vector is defined as positive.

Bipolar lightning. Lightning discharges sequentially transferring both positive and negative charges to ground during the same flash.

Cloud flash. Flash that does not contact the ground.

Cloud-to-ground (CG) flash, ground flash. Flash that contains at least one return stroke.

Cloud lightning. Lightning discharges that do not involve ground.

Compact intracloud discharge (CID). A small-spatial-scale (typically hundreds of metres) lightning discharge in the cloud that is thought to be the most intense natural producer of HF-VHF (3–300 MHz) radiation on Earth.

Continuing current. A steady current immediately following some return-stroke current pulses.

Discharge. Often used synonymously with “flash”.

Downward CG lightning. Lightning discharges to ground initiated by descending leaders from the cloud.

Event. Specific part of a flash, typically any isolated signal measured during a flash. Note that event is also used for the illuminated pixel-level data in the optical lightning detection.

Flash, lightning flash. Complete neutralization process that involves many processes (leaders, strokes, K-processes, continuing currents, and the like) within a time interval of typically about 1 s; refers to a cloud flash or a ground flash. It can be defined as a transient, high-current (typically tens of kiloamperes) electric discharge in the air whose length is typically measured in kilometres.

Ground flash density. The number of ground flashes per unit area per unit of time (usually per square kilometre per year).

K-processes. Transient processes occurring in a previously conditioned (heated) lightning channel that is not connected (or lost its connection) to ground. They can occur in both ground and cloud flashes.

Leader. Lightning process that creates a conducting path between the cloud charge source region and ground (in the case of downward CG lightning) and distributes charge from the cloud source region along this path.

M-components. Transient processes occurring in a grounded lightning channel while it carries continuing current.

Negative lightning. Lightning discharges that effectively lower negative charge from the cloud to ground.

Positive lightning. Lightning discharges that effectively lower positive charge from the cloud to ground.

Return stroke, CG stroke. Lightning process that traverses the previously created leader channel, moving from ground towards the cloud charge source region, and neutralizes the leader charge.

Rocket-triggered lightning. Lightning discharges artificially initiated from natural thunderclouds using the rocket-and-wire technique.

Sferic, or atmospheric. Very Low Frequency (VLF) radio frequency emissions from lightning in the atmosphere that can travel over long distances and affect up to HF (3-30 MHz) frequencies and beyond depending on strength.

Thunderstorm cell. A unit of convection, typically some kilometres in diameter, characterized by relatively strong updraughts (>10 m/s). The lifetime of an ordinary cell is of the order of 1 h.

Upward CG lightning. Lightning discharges to ground initiated by ascending leaders from grounded objects.

6.3 PRINCIPLES OF LIGHTNING LOCATION

6.3.1 General

For the three most common multi-station electromagnetic radio-frequency locating techniques – magnetic direction finding (MDF), time of arrival (TOA) and interferometry – the type of locating information obtained depends on the frequency f (or on the wavelength $\lambda = c/f$, where c is the speed of light) of the radiation detected (Rakov and Uman, 2003). For detected signals whose wavelengths are very short compared to the length of a radiating lightning channel, for example, the VHF range where f = 30 to 300 MHz and λ = 10 to 1 m, the whole lightning channel can, in principle, be imaged in two or three dimensions. For wavelengths that exceed or are a significant fraction of the lightning channel length, for example, the very low-frequency (VLF) range where f = 3 to 30 kHz and λ = 100 to 10 km and the low-frequency (LF) range where f = 30 to 300 kHz and λ = 10 to 1 km, generally only one or a few locations can be usefully obtained for each lightning channel. In the case of a single location for a CG return stroke, it is usually interpreted as some approximation to the ground strike point. The best electromagnetic channel imaging methods at VHF have location accuracies in the order of 100 m or even less with the Lightning Mapping Array systems (LMA) described in 6.3.3. The best high precision locating techniques at VLF and LF achieve similar location accuracies of around 100 m with sensor distances between 10 and few hundred kilometres depending on the system design. On the other end of the accuracy scale, long-range VLF systems detect lightning at distances up to thousands of kilometres and have uncertainties in locating individual lightning flashes on the kilometre scale with sensor distances of several thousand kilometres. These latter systems are typically called global lightning detection systems.

Table: Frequency bands (excerpt) according to International Telecommunication Union (ITU)

		Frequency bands	Wavelength
ELF	Extremely low frequency	3 – 30 Hz	100.000 – 10.000 km
SLF	Super low frequency	30 – 300 Hz	10.000 – 1.000 km
ULF	Ultra low frequency	300 – 3000 Hz	1.000 – 100 km
VLF	Very low frequency	3 – 30 kHz	100 – 10 km
LF	Low frequency	30 – 300 kHz	10 – 1 km
MF	Medium frequency	300 – 3.000 kHz	1.000 – 100 m
HF	High Frequency	3 – 30 MHz	100 – 10m
VHF	Very high frequency	30 – 300 MHz	10 – 1m

For those electromagnetic locating techniques involving the measurement of field change amplitudes at multiple stations, the bandwidth of the measurement is not directly related to the locating accuracy. It is only necessary to have a measurement system that can faithfully reproduce the field changes of the process of interest. Hence, for example, from measuring the electrostatic field change in the frequency range from a fraction of a hertz to a few hertz at multiple stations, one can locate an average position for the charge source of a complete CG flash. And with a system bandwidth from a few hertz to a few kilohertz, so as to be able to resolve electrostatic field changes on a millisecond timescale, one can locate the charge sources for individual strokes in the flash as well as for continuing current. Lightning location using the return-stroke electric or magnetic radiation field peaks, similar to using the electrostatic field change, only requires that the system faithfully reproduces those peaks. The electric and magnetic field amplitude lightning locating techniques are not further discussed here.

Accurate lightning locating systems, whether they image the whole lightning channel or locate only the ground strike points or the cloud-charge centres, necessarily employ multiple sensors. Single station surface-based sensors, such as the lightning flash counters, detect the occurrence of lightning, but cannot be used to locate it on an individual flash basis. Nor are they designed to do so because of the wide range of amplitudes and wave shapes associated with individual events. Nevertheless, with single-station sensors one can assign groups of flashes to rough distance ranges if data are accumulated and averaged for some period of time. There are many relatively simple, commercially available single-station devices that purport to locate lightning. Most operate like AM radios, with the amplitude of the radio static being used to gauge the distance to the individual lightning flashes – a technique inherently characterized by large errors. In addition to field amplitude detectors, some commercial single-station devices employ optical detectors, magnetic direction finders and/or characteristics of lightning waveforms to allow estimates of the distance of CG return strokes from the sensor.

Single-station optical sensors on Earth-orbiting satellites detect the light scattered by the volume of cloud that produces the lightning and hence cannot locate to an accuracy better than about 10 km – about the diameter of a small cloud. Additionally, satellite-based sensors cannot distinguish between cloud and ground discharges. The next-generation series of geostationary satellites like Geostationary Operational Environmental Satellites (GOES-R and GOES-S), Feng-Yun 4A (FY-4A and FY-4C) and Meteosat Third Generation (MTG-I) carries monitor lightning continuously over a wide field of view (see paragraph 6.3.6).

The following subsections discuss how individual sensors measuring various properties of the lightning electromagnetic radiation have been combined into systems to provide practical lightning locating. More details can be found in the reviews by Rakov and Uman (2003), Cummins and Murphy (2009), and Nag et al. (2015) and in the references therein.

In general, there are three principal ground-based lightning detection methods: magnetic direction finding (MDF), time-of-arrival (TOA), and interferometry. The MDF and long-baseline TOA systems usually use the VLF/LF range and detect one location per lightning event, with multiple events usually detected per lightning flash. The shorter-baseline (tens of kilometres or less) TOA systems and interferometry usually use VHF ranges and detect multiple events per lightning. The systems using MDF and TOA methods can detect many events per lightning flash even with the baseline of 200 to 300 km. The MDF, TOA, and interferometric methods are described in 6.3.2, 6.3.3, and 6.3.4, respectively. In addition, lightning detection systems operating on a global scale typically extract source information from electromagnetic signals dominated by ionospheric reflections or utilize optical information for satellite-based lightning detections. These are described in 6.3.5 and 6.3.6, respectively.

6.3.2 Magnetic field direction finding

Two vertical and orthogonal loops with planes oriented north-south and east-west, each measuring the magnetic field from a given vertical radiator, can be used to obtain the direction to the source. This is because the output voltage of a given loop, by Faraday's law, is proportional to the cosine of the angle between the magnetic field vector and the normal vector to the plane of the loop. For a vertical radiator the magnetic field lines are circles that are coaxial with respect to the source. Hence, for example, the loop whose plane is oriented north-south receives a maximum signal if the source is north or south of the antenna, while the orthogonal east-west loop receives no signal. In general, the ratio of the two signals from the loops is proportional to the tangent of the angle between north and the source as viewed from the antenna.

Crossed-loop magnetic direction finders (DFs) used for lightning detection can be divided into two general types: narrowband (tuned) DFs and gated wideband DFs. In both cases the direction-finding technique involves an implicit assumption that the radiated electric field is oriented vertically and the associated magnetic field is oriented horizontally and perpendicular to the propagation path.

Narrowband DFs have been used to detect distant lightning since the 1920s. They generally operate in a narrow frequency band with the centre frequency in the range of 5 to 10 kHz, where attenuation in the Earth-ionosphere waveguide is relatively low and where the lightning signal energy is relatively high. Before the development of weather radars in the 1940s, lightning locating systems were the primary means of identifying and mapping thunderstorms at medium and long ranges.

A major disadvantage of narrowband DFs is that for lightning at ranges less than about 200 km, those DFs have inherent azimuthal errors, called polarization errors, of the order of 10°. These errors are caused by the detection of magnetic field components from non-vertical channel sections, whose magnetic field lines form circles in a plane perpendicular to the non-vertical channel section, and by ionospheric reflections – skywaves – whose magnetic fields are similarly improperly oriented for direction finding of the ground strike point.

To overcome the problem of large polarization errors at short ranges inherent in the operation of narrowband DFs, gated wideband DFs were developed in the early 1970s. Direction finding is accomplished by sampling (gating on) the north-south and east-west components of the initial peak of the return-stroke magnetic field, that peak being radiated from the bottom hundred metres or so of the channel in the first microseconds of the return stroke. Since the bottom of the channel tends to be straight and vertical, the magnetic field is essentially horizontal. Additionally, a gated DF does not record ionospheric reflections since those reflections arrive long after the initial peak magnetic field is sampled. The operating bandwidth of the gated wideband DF is typically from a few kilohertz to about 500 kHz. Interestingly, although an upper-frequency response of many megahertz is needed to assure accurate reproduction of the incoming radiation field peak, particularly if the propagation is over saltwater, practical DFs only need an upper-frequency response of a few hundred kilohertz in order to obtain an azimuthal error of about 1°. This is because the ratio of the peak signals in the two loops is insensitive to the identical distortion produced by the identical associated electronic circuits of the two loops. Thus, the gated wideband DF can operate at frequencies below the AM radio band and below the frequencies of some aircraft navigational transmitters, either of which could otherwise cause unwanted directional noise.

Gated wideband DFs, as well as narrowband DFs, are susceptible to site errors. Site errors are a systematic function of direction but generally are time-invariant. These errors are caused by the presence of unwanted magnetic fields due to non-flat terrain and nearby conducting objects, such as underground and overhead power lines and structures, being excited to radiate by the incoming lightning fields. In order to eliminate site errors completely, the area surrounding a DF must be flat and uniform, and without significant conducting objects, including buried ones, nearby. These requirements are usually difficult to satisfy, so it is often easier to measure the DF site errors and to compensate for any that are found rather than to find a location characterized by tolerably small site errors. Once corrections are made, the residual errors have been reported (using independent optical data) to be usually less than 2° to 3°, and typically around 1° in the case of wide-band DFs.

Since it is not known a priori whether a stroke to ground lowers positive or negative charge, there is an 180° ambiguity in stroke azimuth from the measurement of only the orthogonal magnetic fields. That ambiguity is resolved in all wideband DF systems by the measurement of the associated electric field whose polarity indicates the sign of the charge transferred to ground.

6.3.3 Time-of-arrival technique

A single time-of-arrival (TOA) sensor provides the time at which some portion of the lightning electromagnetic field signal arrives at the sensing antenna. TOA systems for locating lightning can be divided into three general types: (a) very short baseline (tens to hundreds of metres), (b) short baseline (tens of kilometres), and (c) long baseline (hundreds to thousands of kilometres). Very short- and short-baseline systems generally operate at VHF, that is, at frequencies from 30 to about 300 MHz, while long-baseline systems generally operate at VLF and LF, 3 to 300 kHz. It is generally thought that VHF radiation is associated with air breakdown processes, while VLF signals are due to current flow in conducting lightning channels. Short-baseline systems are usually intended to provide images of lightning channels and to study the spatial and temporal development of discharges. Long-baseline systems are usually used to identify the ground strike point, cloud lightning events in predominantly vertical channels, or the average location of the flash.

A very short-baseline (tens to hundreds of metres) system is composed of two or more VHF TOA receivers whose spacing is such that the time difference between the arrival of an individual VHF pulse from lightning at those receivers is short compared to the time between pulses, which is some microseconds to hundreds of microseconds. The locus of all source points capable of producing a given time difference between two receivers is, in general, a hyperboloid, but if the receivers are very closely spaced, the hyperboloid degenerates, in the limit, into a plane on which the source is found. Two-time differences from three very closely spaced receivers yield two planes whose intersection gives the direction to the source, that is, its azimuth and elevation. To find source location, as opposed to determining the direction to the source, two or more sets of three closely spaced receivers, the sets being separated by tens of kilometres or more, must be used. Each set of receivers is basically a TOA direction finder, and the intersection of two or more direction vectors yields the location.

Short-baseline TOA systems are typically networks of 5 to 15 stations that make use of time-of-arrival information for three-dimensional (3D) mapping of lightning channels. A portable version of such system has been developed by researchers at the New Mexico Institute of Mining and Technology. This system is presently referred to as the Lightning Mapping Array (LMA) and has recently become a major tool for both lightning research and operational applications. The short-baseline VHF TOA systems provide electromagnetic images of the developing channels of any type of lightning flash.

The first long-baseline (hundreds to thousands of kilometres) TOA systems operated at VLF/LF. For example, one of them employed a pair of receiving stations in Massachusetts with a bandwidth of 4 to 45 kHz and separated by over 100 km (the overall network was composed of four stations) to compare differences in the times of arrival of the signals at each station and hence determine directions to the causative lightning discharge in western Europe. The two-station system was basically a direction finder similar to the very short-baseline systems described above but operating at lower frequencies and with a longer baseline. The resultant directions compared favourably with the locations reported by the UK Meteorological Office’s narrow-band DF network. Spherical geometry was used to account for propagation over the Earth's surface in finding the locus of points for a constant measured arrival time difference between receivers.

Another long-baseline TOA system, called the Lightning Position and Tracking System (LPATS), was developed in the 1980s. The LPATS, operating at LF/VLF, used electric field whip antennas at stations 200 to 400 km apart to determine locations via the measured differences between signal arrival times at the stations. In the frequency band used, return-stroke waveforms were generally the largest and hence most easily identified. In principle, responses from four stations (three-time differences) are needed to produce a unique location since the hyperbolae on the Earth’s surface from only two time differences can, in general, intersect at two different points. For CG lightning near or within the network, there is often only one solution, in which case the three-station approach suffices.

The Los Alamos Sferic Array (Smith et al. 2002) with two subarrays (New Mexico/Texas and Florida) with baselines of 160 to 240 km also belongs to the category of long-baseline TOA systems.

6.3.4 Interferometry

In addition to radiating isolated pulses, lightning also produces noise-like bursts of electromagnetic radiation lasting tens to hundreds of microseconds. These bursts are hard to locate using TOA techniques due to the difficulty in identifying the individual pulses. In the case of interferometry, no identification of individual pulses is needed, since the interferometer measures phase difference between narrowband signals corresponding to these noise-like bursts received by two or more closely spaced sensors. The simplest lightning interferometer consists of two antennas some metres apart, each antenna being connected via a narrowband filter to a receiver. The antennas, filters and receivers are identical. The outputs of the two receivers are sent to a phase detector that produces a voltage that is proportional to the difference in phase between the two quasi-sinusoidal signals. The phase difference defines, as does the time difference in very short-baseline TOA systems, a plane on which the source is located, that is, one direction angle to the VHF source. To find the azimuth and elevation of a source, three receiving antennas with two orthogonal baselines are needed at minimum. To locate the source in three dimensions, two or more synchronized interferometers are needed, each effectively acting as a direction finder and separated by a distance of the order of 10 km or more. The principles of interferometric lightning location are described in detail by Lojou et al. (2008).

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, it may not provide the highest possible signal-to-noise ratio and it places a specific limitation in the spacing of the antenna array elements to avoid arrival-time (phase) ambiguity. There is a recent trend towards using broadband interferometry (Shao et al., 1996; Mardiana and Kawasaki, 2000; Morimoto et al., 2004). This trend is made possible by the advent of affordable broadband radio frequency and digital signal processing electronics.

6.3.5 Global lightning detection using VLF signals

The VLF signals emitted by lightning are reflected by the ionosphere and, thus, propagate in the earth-ionosphere waveguide. Consequently, signals with higher amplitudes can be detected over large distances of several thousand kilometres. This is exploited by global lightning locating systems which typically operate in the VLF range. These systems use a comparably small number of sensors (some tens or less) to cover big parts of the globe, and the sensor baselines are in the order of thousands of kilometres. Two exemplary location methods are described in hereafter.

6.3.5.1 Time-of-Group-Arrival (TOGA) technique

The TOGA method takes advantage of the fact that VLF signals experience dispersion, where the higher-frequency components arrive earlier than the lower-frequency components (for example, Dowden et al. 2002). From the measured waveform the TOGA is derived, which depends on the travel distance of the VLF signal. This lightning detection method is used by the World Wide Lightning Location Network (WWLLN).

6.3.5.2 MDF and TOA Methods Combined with a Lightning Waveform Recognition Algorithm

Lightning locations are obtained using MDF, long-baseline TOA methods, and a lightning waveform recognition algorithm. The waveform recognition algorithm relies on a set of ‘‘canonical’’ waveforms corresponding to propagation distances (Said et al. 2010). This method is implemented in the Global Lightning Dataset (GLD360).

6.3.6 Space-based optical lightning detection

Lightning detection by optical means (see the Guide to Instruments and Methods of Observation (WMO-No. 8), Volume IV, Part III, 3.2.10) bases on the observation of the radiation of light, which is emitted from the hot lightning channel and propagates subsequently through the atmosphere and clouds, where it is mainly affected by scattering, until it reaches an observer above the clouds (Finke 2009). The optical spectrum of lightning in the visible and near infrared range is made of spectral lines of the excited and ionized gases of the air. The optical spectrum of lightning in the visible and near infrared range is made of spectral lines of the excited and ionized gases of the air (Orville and Henderson, 1984).

Lightning detection by optical means from satellites provides a globally uniform observation of lightning. Prototypes of optical detectors were operated by NASA on low orbit satellites from 1995 to 2015 and then again on ISS from 2017 to present. For the next generation of geostationary satellites optical lightning detection sensors are already utilized like Geostationary Operational Environmental Satellites (GOES-R and GOES-S), Feng-Yun 4A (FY-4A and FY-4C) and planned on Meteosat Third Generation (MTG-I) establishing a geostationary ring of lightning detection. These instruments monitors lightning continuously for the full field of view (Rudlosky et al., 2019, Yang et al., 2017, Holmlund et al., 2021) delivering near-real-time information on total lightning of intercloud and cloud to ground lightning.

6.4 PERFORMANCE CHARACTERISTICS

Generally, a modern VLF-medium frequency (MF) lightning locating system is expected to record (in separate categories) and locate over a certain area CG strokes of either polarity, as well as cloud discharges. Also expected for each discharge is a measure of its intensity, usually in the form of peak current inferred from measured electric or magnetic fields. Accordingly, the system’s performance can be evaluated using the following characteristics, noting that these are relative values and may not be directly comparable between different systems or geographical areas:

(a) CG flash detection efficiency;

(b) CG stroke detection efficiency;

(c) Cloud flash detection efficiency;

(d) Percentage of misclassified events (particularly cloud discharges assigned to the positive or negative CG stroke category);

(e) Location accuracy (or location error);

(f) Peak current estimation error.

In general, the detection efficiency is the fraction (usually expressed in percent) of the total events occurred that are detected by the system and is ideally equal to 100%. While the CG stroke detection efficiency can be readily defined (since these strokes involve a unique and observable feature – the luminous channel to ground – and the total number of occurred events can be better determined), the cloud flash detection efficiency concept is rather uncertain. Indeed, there are many cloud discharge processes (some of them poorly understood) occurring on different spatial scales and timescales and apparently exhibiting no unique and readily observable features. As a result, the total number of occurred events is generally unknown. In practice, if all cloud discharge events are accepted as counts, the number of detected cloud discharges may be largely determined by the local noise level and the system's signal transmission rate limit.

In defining the CG flash detection efficiency, which is probably the most important performance characteristic for lightning locating systems used for determining ground flash density, a flash is considered to be detected if at least one stroke of the flash is detected. A similar approach could be applied to cloud flashes, although one would need to decide if a single count constitutes a flash and how to assign multiple counts to individual flashes. In practice, Lightning Mapping Arrays (see 6.3.3) can be used to identify individual cloud flashes during low lightning flash-rate periods, and these can be compared against the data provided by other lightning locating systems to determine the cloud flash detection efficiency of the latter.

The location error is the distance between the actual location and that reported by the system. In general, the location error consists of random and systematic components. The latter in some cases can be accounted for (for example, site errors in MDF systems). Location accuracy can be assessed using discharges occurring at a precisely known location equipped with a current-measuring device (tall tower or lightning-triggering facility). Additionally, high-speed video observations showing multiple CG strokes taking the same path to ground can be used to assess the location accuracy by way of the differences in locations of those strokes.

The peak current estimation error is the difference between the actual peak current value and that reported by the system, and is usually expressed in per cent of the actual peak current. Peak currents are estimated by lightning locating systems using either an empirical or model-based field-to-current conversion equation. There are reasonable field-to-current conversion equations for CG strokes, but not for cloud discharge processes.

In order to evaluate the performance characteristics listed above, independent (ground-truth) data are needed. For example, discharges occurring at a precisely known location equipped with a current-measuring device (tall tower or lightning-triggering facility) can be used for estimating the location accuracy and peak current estimation error. Detection efficiencies and percentage of misclassified events are usually estimated based on time-resolved optical recordings. Sometimes lightning-related damage to various objects (buildings, trees, and the like) is used in estimating location errors, although identification of the causative lightning event in this approach is uncertain due to insufficient accuracy of timing information (usually not known within better than a minute). Less definitive evaluations of lightning locating systems' performance characteristics are possible via modelling or comparison with a more accurate system operating in the same area. As of today, only a limited number of ground-truth studies have been performed, particularly for first strokes in negative CG flashes, positive CG flashes and cloud discharges.

In some applications (for example, tracking of thunderstorm cells), the tracking ability may be more important than detection of individual lightning discharges. Performance of the systems intended primarily for such applications is often tested against radar or infrared satellite imagery, with a good correspondence between detected lightning and regions of high radar reflectivity or low cloud-top temperatures being viewed as the system's output validity criteria. For early warning, the ability to detect the first lightning is probably the most important performance characteristic.

It is not clear how to define the performance characteristics for VHF lightning channel imaging systems. Surely, they cannot locate all the VHF sources in the cloud. Limitations in sensitivity prevent these systems from regularly detecting and mapping positive leaders. Thus, the resultant VHF images are necessarily partial. Further, supplementary information about return strokes is usually needed to reliably distinguish between cloud and CG flashes, because the VHF radiation directly associated with subsequent return strokes is limited and difficult to detect. Also, no peak current estimates are possible. Nevertheless, VHF lightning channel imaging systems represent a very valuable tool for studying detailed lightning morphology and evolution, particularly inside the cloud, and are often used in testing other types of lightning locating systems.

6.5 EXAMPLES OF MODERN GROUND-BASED LIGHTNING LOCATING SYSTEMS

One VHF lightning channel imaging system (LMA), three VLF/LF (NLDN, LINET and USPLN), one ELF/VLF/LF/MF/HF (ENTLN), and three VLF (the World Wide Lightning Location Network (WWLLN), GLD360 and ATDnet) systems are briefly reviewed here as representative examples of modern lightning locating systems. The systems have been chosen because they are good examples of each type of system, but their inclusion should not be taken to imply that they are better than others or are recommended over the use of other systems not discussed here. Information about these and other systems can be found in Rakov and Uman

(2003), Cummins and Murphy (2009), Betz et al. (2009) and references therein. There are more than 60 lightning locating networks worldwide that operate in the VLF/LF range.

Besides a general characterization of each system, the available information on its performance characteristics is given with emphasis on those based on formal ground-truth studies published in the peer-reviewed literature. Generally, the amount of such information for “older” systems is greater than for more recent ones.

6.5.1 Lightning Mapping Array, 60–66 MHz

LMA networks typically consist of 10–15 stations separated by 15–20 km and connected by wireless communication links to a central location (Thomas et al., 2004). Each station receives the lightning signals (from both cloud and CG flashes) in a locally unused television channel (usually TV channel 3, 60–66 MHz). A typical time resolution (the measurement time window) is 80–100 μs. A larger time window, typically 400 μs, is used for real-time processing and display.

The location accuracy of the New Mexico LMA has been investigated experimentally using a sounding balloon carrying a VHF transmitter, airplane tracks, and observations of distant storms (Thomas et al., 2004). Simple geometric models for estimating the location uncertainty of sources both over and outside the network have also been developed. The model results were found to be a good estimator of the observed errors. Sources over the network at altitudes ranging from 6 to 12 km were located with an uncertainty of 6–12 m rms in the horizontal and 20–30 m rms in the vertical, resulting in less than a 100-metre 3D error for most located sources. Outside the network the location uncertainties increase with distance.

6.5.2 United States National Lightning Detection Network, 400 Hz–400 kHz

The NLDN consists of more than 100 stations separated typically by 300–350 km and covering the contiguous USA. A combination of TOA and gated wide band MDF locating techniques is employed to facilitate uniform detection efficiency. Both cloud and CG lightning discharges are reported. Classification is accomplished by applying field waveform criteria. Peak currents are estimated from measured fields using an empirical formula based on rocket-triggered lightning data, with the field peaks being adjusted to account for expected propagation effects (stronger than the inverse proportionality distance dependence). Further information on the evolution of the NLDN and its system updates, its enabling methodology and applications of NLDN data can be found in Rakov and Uman (2003, Chapter 17), Orville (2008), Cummins and Murphy (2009), Murphy et al. 2021 and references therein.

CG stroke and flash detection efficiencies (DE) have been investigated, using video cameras, and matching electric field measurements (Zhu et al. 2016), showing a CG stroke DE of 92%. Earlier work in southern Arizona, Oklahoma and Texas (Biagi et al., 2007) showed a stroke detection efficiency in southern Arizona of 76% (N = 3 620), and in Texas/Oklahoma it was 85% (N = 885). The corresponding flash detection efficiencies were 93% (N = 1 097) and 92% (N = 367). Additionally, classification of lightning events as cloud or CG discharges was examined in this study, as well as in a similar study (but additionally using independent electric field waveform measurements) in the Colorado/Kansas/Nebraska region (Fleenor et al., 2009).

CG stroke and flash detection efficiencies have been also investigated, using rocket-triggered lightning as the ground truth, in the Florida region (Jerauld et al., 2005; Nag et al., 2011). From the latest study (2004–2012, Mallick et al. 2014), the CG stroke and flash detection efficiencies were found to be 75% (N = 326) and 94% (N = 78), respectively. Strokes in rocket-triggered flashes are similar to regular subsequent strokes (following previously formed channels) in natural lightning, and hence the 76% stroke detection efficiency is applicable only to regular negative subsequent strokes in natural lightning. The flash detection efficiency derived using rocket-triggered lightning is expected to be an underestimate of the true value for natural negative lightning flashes, since first strokes typically have larger peak currents than subsequent ones.

Nag and Rakov (2012) examined electric field waveforms produced by 45 positive flashes containing 53 strokes. Out of these 53 strokes, the NLDN located 51 (96%), of which 48 (91%) were correctly identified and 3 return strokes were misclassified as cloud discharges.

The cloud flash DE of the NLDN, after its 2013 system-wide upgrade, was validated by Murphy and Nag (2015) using data from Lightning Mapping Arrays during low flash-rate situations. The DE generally ranged from 45-65% in most cases. Zhu et al. (2016), using video and field measurements taken in Florida, found a post-upgrade detection efficiency of 33% for all IC events, and of 73 % for IC events only belonging to IC flashes. Wilson et al. (2013) stated that the NLDN typically reports 1–3 cloud pulses per flash, although more recently, that has increased to about 4-5 pulses per flash on average. Nag et al. (2010) examined wideband electric fields, electric and magnetic field derivatives, and narrowband VHF (36 MHz) radiation bursts produced by 157 CIDs before the 2013 upgrade. The NLDN located 150 (96%) of those CIDs, and correctly identified 149 (95%) of them as cloud discharges.

The most recent validation of the location accuracy of the NLDN was carried out by Zhu et al. (2020), by identifying lightning clusters associated with known locations of more than 1400 towers located around the continental USA In the period after the 2013 NLDN upgrade (2014-2017 in the study), the median location accuracy was estimated to be 84 meters. The Euclid network in Europe which uses the same sensor technology as the NLDN was also recently validated for its location accuracy. Paul et al. 2020 compared the current pulses measured by an instrumented tower in Germany and found a location error of 161 m (geometric mean) for 199 measured events. High-speed video observations and electric field measurements were used by Schwalt et al. (2020) to evaluate the locations accuracy of 1527 negative CG strokes in the years 2015, 2017, and 2018. Here the median location errors are in the range 90 – 130m.

Prior to the 2013 updated, Nag et al. (2011) estimated, from comparison of NLDN-reported locations with the precisely known locations of triggered lightning ground attachment points, the median absolute location error to be 308 m, with the largest error being 4.2 km (N = 105). These results are applicable only to regular negative subsequent strokes in natural lightning. Peak current estimation errors have been estimated from comparison of NLDN-reported peak currents with directly measured currents at the triggered-lightning channel base. In 2004-2009, the median absolute value of current estimation error was 13% (N = 96). The current estimation errors never exceeded 129% in absolute value (60% if two outliers are excluded). These results are applicable only to regular negative subsequent strokes in natural lightning.

6.5.3 Lightning Detection Network, 1–200 kHz

The basic location method used in the Lightning Detection Network (LINET) is TOA, although the magnetic field sensors provide arrival-angle information that is employed as a plausibility check on computed locations. Classification between CG strokes and IC discharges, and determination of their heights is accomplished by evaluation of the travel time differences of VLF signals to the sensors depending on their source height (Betz et al., 2004, near-ground locations are assumed to be associated with CG strokes and elevated ones with all the other processes).

LINET can report several locations per flash including height information (for example, Stolzenburg et al. 2012, Marshall et al 2012, Smith et. al 2018), and, hence, can even operate as a rudimentary imaging system. This requires baselines of 200–250 km or less. Emphasis is placed on detection of low-amplitude signals of both cloud and CG lightning. Peak currents for processes in cloud flashes and for in-cloud processes (for example, preliminary breakdown) in CG flashes and CG strokes are estimated assuming direct proportionality between the peak current and peak magnetic (or electric) field and inverse distance dependence of field peak. More information about LINET can be found in Betz et al. (2009), Höller et al. (2009) and references therein.

CG stroke detection efficiency has been reported using high speed video cameras in Florida (Stolzenburg et al., 2012). The DE was 96-97% for 450 return strokes. Like for VHF channel imaging systems, it is not clear how to define the detection efficiency for LINET, which in a sense also maps the evolution of lightning channels, although with a considerably smaller number of located sources per flash compared to VHF. But still the IC discharge height information is beneficial for a number of applications, such as cell tracking, and detection and classification of severe weather. The random location error is approximately 150 m, but the existence of systematic errors is acknowledged. Betz et al. (2009) showed an example of 58 located strokes terminated on an instrumented tower with an average location error of less than ~100 m, after compensating systematic errors.

Peak current estimation errors for LINET are unknown (no comparison with ground-truth data has been published to date).

6.5.4 United States Precision Lightning Network, 1.5–400 kHz

The USPLN employs the VLF/LF TOA technique and consists of 100 electric field sensors covering the continental USA and other parts of North America. No formal performance testing studies regarding this system have been reported, but the operators of the system claim, apparently from the network simulation analysis, 95% stroke detection efficiency and 250-metre typical location error throughout most of North America (>80% detection efficiency and <1 km location error in key deployment areas elsewhere in the world).

Differentiation between cloud and CG processes is apparently accomplished by examining the frequency content and amplitude of the received signals. The field-to-current conversion procedure has not been formally described, nor is any information available about testing its validity.

6.5.5 Earth Networks Total Lightning Network, 1 Hz–12 MHz

The Earth Networks Total Lightning Network (ENTLN) sensors operate in a frequency range from 1 Hz to 12 MHz (spanning the ELF, VLF, LF, MF and HF ranges), and the TOA method is used to detect both cloud and CG lightning discharges. According to Heckman and Liu (2010), the whole electric field waveforms are transmitted from the sensors to the data-processing unit and used in locating the lightning events and differentiating between cloud and CG processes. Strokes (or individual cloud events) are clustered into a flash if they are within 700 ms and 10 km of the first detected stroke (or cloud event). A flash that contains at least one return stroke is classified as a CG flash, otherwise it is classified as a cloud flash. For cell tracking and thunderstorm alert generation, only flashes (which are less likely than strokes to be missed by the system) are used. The sensors are installed worldwide.

The operators of the system claim 40%–50% cloud flash detection efficiency across much of the United States and up to 95% in the United States Midwest and East (Heckman and Liu, 2010). Maximizing the detection efficiency for cloud flashes appears to be the primary focus of this system. Peak currents are estimated assuming direct proportionality between the peak current and peak electric field, and distance dependence of field peak.

Using triggered-lightning data acquired at Camp Blanding, Florida in 2009–2012, the flash and stroke detection efficiencies has been estimated 89 % and 67 %, respectively (Mallick et al., 2013). The median location error was 687 m, and the median absolute current estimation error was 17 %. All events were used for the evaluation, regardless of their classification. 52 % of the triggered-lightning return strokes (all negative) were misclassified as cloud discharges (51 %) or positive return strokes (1 %).

Bitzer et al. (2016) evaluated the worldwide performance of ENTLN in relation to combination of GLD360 and NLDN, and WWLLN for data from 2014 to 2015. By using Bayesian techniques, they estimated the upper limit of the absolute detection efficiency of each system. On a global scale, ENTLN detected 56.8% of all discharges, the combined Vaisala networks (GLD360 + NLDN) detected 59.8%, and WWLLN detected 7.9%.

6.5.6 World Wide Lightning Location Network, 6–18 kHz

The WWLLN utilizes the time-of-group-arrival (TOGA) method to locate lightning strikes (see 6.3.5). As of February 2021, the WWLLN employed 70 sensors located on all continents, although, according to Dowden et al. (2002), global coverage could be in principle provided by as few as 10 sensors. Distances between the sensors are of the order of thousands of kilometres. Presently, only those lightning events that triggered at least five sensors and that had residuals (uncertainties in the stroke timing) less than or equal to 30 μs are regarded as located with acceptable accuracy.

In their study of WWLLN performance characteristics, Abarca et al. (2010) used NLDN data as the ground truth and found that the CG flash detection efficiency increased from about 3.9% in 2006–2007 to 10.3% in 2008–2009, as the number of sensors increased from 28 in 2006 to 38 in 2009. For events with NLDN-reported peak currents of 130 kA or higher, the detection efficiency was 35%. The average location error was estimated to be 4–5 km. Hutchins et al. (2012a) developed a model to compensate for the uneven global coverage of the WWLLN.

Interaction of lightning signals with the ionosphere spectrally distorts the field waveform, so that it is not straightforward to infer the peak current and even polarity of lightning. Nevertheless, Hutchins et al. (2012 b) developed a method to convert the stroke radiated power in the 6–18 kHz band to peak current. Errors involved in such conversion are presently unknown.

6.5.7 Global Lightning Dataset, VLF

The Global Lightning Dataset (GLD360), also referred to as the Global Lightning Detection Network, employs an unspecified number of VLF sensors strategically placed around the world. As described in 6.3.5, locations are obtained using both TOA and MDF methods in conjunction with a lightning waveform recognition algorithm. At least three sensors are necessary to detect a lightning event. In 2020, the system was updated so that it now also distinguishes between ground and cloud lightning events.

Demetriades et al. (2010) evaluated the GLD360 performance characteristics using NLDN data as the ground truth and found that the CG flash detection efficiency was 86% to 92%, and the median location error was 10.8 km. From a similar study, but using the Brazilian lightning detection network, Naccarato et al. (2010) reported the CG flash detection efficiency of 16% and a mean location error of 12.5 km. The performance of GLD360 was compared to the networks participating in the European Cooperation for Lightning Detection (EUCLID) for Europe in May–September 2011 by Pohjola and Makela (2013).

Using electric field measurements and high-speed video recordings, Poelman et al. (2013) estimated the flash and stroke detection efficiencies to be 96 and 70 % for 210 strokes in 57 negative CG flashes in Belgium. The median location error was estimated 1.3 km (N = 134) compared to EUCLID. Said et al. (2013) estimated the ground flash detection efficiency to be 57 %, and the median location error to be 2.5 km, using NLDN data as reference. Said and Murphy (2016) evaluated GLD360's performance against NLDN again after an algorithm update in 2015. In this comparison the median location error of matched CG strokes was 1.8 km and the 90th percentile location error was 6.4 km. The relative CG flash DE was 81%, and GLD360 detected 44% of all cloud pulses reported by NLDN in the evaluation window.

The GLD360 also reports the peak current and polarity. Relative to the NLDN, Said et al. (2013) found the arithmetic and geometric mean peak current magnitude error for the GLD360 to be 21% and 6%, respectively. GLD360 reported the same polarity for 96% of the matched strokes as the NLDN.

6.5.8 Arrival Time Difference network

The Arrival Time Difference network (ATDnet) long-range lightning location system (LLS) is the current version of the UK Met Office's VLF LLS that has been in operation since 2007. It follows from a major system update of the ATD VLF LSS that had been operational since 1987. The network currently consists of 10 sensors across Europe that contribute to the main network. It is primarily designed for lightning location in Europe. However, it is capable of regularly detecting lightning in Africa and South America. The sensors, referred to as outstations, detect VLF (sferic) signal waveforms and transmit waveform data to a central processor at the UK Met Office, where a waveform correlation technique is used to determine the arrival time differences of the waveforms across the network. These arrival time difference data are used to locate lightning.

Poelman et al. (2013) found the random location error of ATDnet to be on the order of 1 km, with a CG flash detection efficiency of 88%. The actual median location uncertainty of CG flashes across Europe is likely to be on the order of 2 to 5 km, although this requires verification in peer-reviewed literature. ATDnet does not currently provide information on stroke polarity, type (CG/IC) or power/peak current. ATDnet's successor, LEELA, will become operational in 2022 replacing ATDnet.

6.5.9 Lightning Electromagnetic Emission Location via Arrival time differencing

Lightning Electromagnetic Emission Location via Arrival time differencing (LEELA) is the UK Met Office's next generation long range VLF LLS. It is due to become operational in 2022 replacing ATDnet. The LEELA network currently consists of 10 VLF receivers referred to as nodes. These are deployed across the UK and Europe and send a constant stream of VLF data to a central processing and archiving system. The central processor extracts the VLF lightning waveforms (sferics) from the VLF data streams. A waveform correlation technique is used to firstly group and then extract precise arrival time differences between sferic waveforms from nodes across the network. These arrival time differences are then used to locate the position of the lightning.

The network focuses on detecting lightning over Europe. In addition, it can detect lightning over Central and Southern America, Africa, and central Asia. Due to it being a relatively new system no peer-reviewed comparisons with other LLS have been made at the time of writing. However, in development benchmarking against ATDnet it has been found that LEELA's detection efficiency and location accuracy is as good as or better than ATDnet.

Polarity, current, and (CG/IC) classification capabilities are intended for addition in further system updates. LEELA can also observe sudden ionospheric disturbances, by monitoring sudden changes in received signal strength from VLF transmitters in its archive.

6.5.10 Global Lightning Detection Network

The Global Lightning Detection Network (LINETglobal) is a new lightning detection network which operates on a global scale. Several tens of sensors are installed as equidistant as possible over the whole globe and all continents, for example, also using extremely remote Islands in Atlantic, Indian, and Pacific Oceans to cover the world with optimal uniform detection efficiency and location accuracy.

The globally distributed sensors measure the magnetic field in the VLF frequency range and transmit the recorded signals via internet to a central processing unit, where a time-of-arrival algorithm evaluates the information in real time. The algorithm uses the arrival times of the signals together with waveform information, and applies correction factors to compensate for different effects, for example, ionospheric reflections and the general varying ionospheric conditions depending on daytime and season.

The network was just recently installed and became operational in July 2022. No peer-reviewed publications with comparisons to other systems are available so far. Earlier comparisons of a prototype network in 2021 and recent comparisons of the just finished LINETglobal network to data from the Lightning Detection Network LINET (6.5.3) show a relative flash DE of around 80% and relative location errors in the range of 1 km. The LINET global system provides in addition to location and time information the lightning type (CG/IC) and amplitude of the lightning.

6.6 UTILIZATION OF LIGHTNING LOCATION SYSTEMS BY METEOROLOGICAL SERVICES

Lightning data have utility in different areas of importance to public and private meteorological service organizations. Typically, national meteorological agencies use LLS data to help accomplish their national duties to protect life and property, and commercial entities use lightning data to provide improved severe weather warnings, forecasts, damage analysis, and guidance to clients for specialized applications including aviation, agriculture, energy and mass media.

6.6.1 Storm recognition and alarms for severe weather

One of the important duties of the meteorological services is to provide reliable warnings for severe weather conditions. As a rule, the best severe weather forecast skill and lowest false-alarm rates are achieved when several data sources are exploited, but since thunderstorm-related severe weather is typically accompanied by an increase of IC, LLS data alone can usually serve as a very clear indicator of the strength and extent of storm cells. This points to the importance of total lightning networks, since CG detection alone will not suffice for this application.

Although an alarm can be issued as soon as a stroke occurs in the vicinity of an instrumented area, a more reliable procedure involves the definition of a storm cell and tracking it as it moves inside or towards an area of interest. Some LLS allow for short-term extrapolation (nowcasting) of cell displacements on the order of 1 h or so. Monitoring the total flash rates and the rate changes makes it possible to identify lightning cells with the potential to produce severe weather. When a cell is identified and the total lightning rate exceeds a given threshold, an alert can be generated.

Except for certain storms generated along frontal boundaries, forecasting over longer durations with acceptable skill requires the use of NWP models. Finally, it may be pointed out that lightning, in combination with cell tracking, not only indicates the initiation of heavy thunderstorm activity but also signals the end of a threat in a given area.

Although storm reports from spotters on the ground or in the air are an invaluable source of information during severe weather, information derived from remote-sensing techniques (including lightning detection) is becoming more important all the time. One can now use radar reflectivity, cloud images, passive microwave brightness temperatures and lightning data (alone or in combination) to identify thunderstorm activity with high accuracy and reliability even in remote regions. Of all these techniques, global and/or local networks of LLS systems and stand-alone detectors on the ground or in aircraft are clearly the most definitive when it comes to identifying significant thunderstorm activity for the reasons discussed above. While the simple detection of a thunderstorm is feasible with any LLS, more complete measurements require advanced systems and techniques that are capable of providing early detection and identification of thunderstorm activity while at the same time reducing false alarms to an acceptable level.

6.6.2 Nowcasting, forecasting and derived products

Nowcasting is a widely used technique for very short-range weather forecasting. A nowcast starts with information about the current (weather) state of the atmosphere as expressed by one or more observed parameters, and then uses an estimate of their movement to predict their location and extent a short time in the future. Nowcast accuracy depends on the validity of the assumption that the weather associated with the observed parameter(s) will persist during that period without significant change. Of course, certain lightning parameters are indicative of the phase of a storm's life cycle and this may also be exploited for nowcasting. The above assumption is reasonable for short (~1 h) periods, but its validity diminishes with time. As a consequence, extrapolations over periods longer than about 1 h require the use of data assimilation and NWP techniques.

Qualitative evaluations of LLS data commonly involve the display of lightning data on maps (with or without other information) in real or near-real time. These products can be used for many purposes, such as localizing or limiting an area likely to be affected by a storm and aiding in the decision to issue an alarm. Beyond qualitative evaluation, high-quality LLS data are highly amenable to quantitative treatment including statistical evaluations of stroke rates to estimate storm intensity, which can greatly enhance their utility.

A number of projects are under way that are aimed at developing automated procedures for thunderstorm cell tracking and the evaluation of lightning parameters in these areas. Refined interpretations, analysis and animations of results from cell tracking should greatly enhance the nowcasting potential of LLS data. The combination of cell tracking involving both lightning and radar represents another type of potentially useful derived product.

Finally, lightning data, as well as other observations such as radar reflectivity, can be used to generate model output statistics for objective forecasting (Glahn and Lowry, 1972; Knüpffer, 1996) that are appropriate for use in probabilistic post-processing techniques like those described for the hourly Rapid Refresh NWP model developed by the NOAA Earth System Research Laboratory (Weygandt et al., 2008).

6.6.3 Lightning and climate

Recent climate studies have noted the connection between lighting and climate change (Williams, 2005; Price, 2006, 2009). As surface and lower tropospheric temperatures rise, lightning rates are predicted to increase in the range of 10%–100% for every one degree of surface warming, depending on the model and assumptions used. There is also a clear relationship between temperature, water vapour and lightning activity; thunderstorms carry large amounts of water vapour into the upper troposphere and lower stratosphere, and this in turn influences the greenhouse effect on the Earth's climate. Further, lightning discharges produce nitrogen oxides that influence the production of the greenhouse gas ozone. It must be recognized, however, that even though the underlying mechanisms linking global climate change to lightning are well understood, different processes may dominate in unanticipated ways. For example, climate simulations by Grewe (2008) suggest that global warming can actually lead to the worldwide occurrence of fewer but more intense convective events. As such, lightning decreases in total flash frequency, but individual storms are predicted to produce more lightning.

In any case, lightning activity is one of the factors that should be taken into account in any detailed climate model or predictions of climate change. Consequently, it is important to monitor lightning activity at different scales over large areas and establish or extend the database of lightning events over long time periods. Relationships are also studied on short timescales, ranging from daily and diurnal variations, five-day waves, intra-seasonal, semi-annual and annual to longer periods. To achieve this goal, local high-precision LLS should be expanded, global LLS must be completed and standards for lightning detection must be introduced and implemented.

6.6.4 Verification of lightning-induced ground damage

An early motivation for the development of LLS was to have an objective way to verify the cause of lightning-induced damage in legal disputes, and most insurance companies use lightning data to verify or reject lightning damage claims. To be useful in this regard, LLS must exhibit both excellent detection efficiency and location accuracy at all thresholds. Location accuracy should be better than ~1 km so that a reliable correlation between lightning and damage can be demonstrated, and relatively weak strokes must be detected because even a 5 kA stroke can produce significant damage or over-voltage. Even higher location accuracy is needed for the power industry to determine if the interruption of a high-voltage transmission line could have been caused by a lightning stroke. Since heavy storms can produce high stroke rates and lightning flashes may be composed of many strokes with differing strike points, an accuracy of 100–200 m is desired for the establishment of a reliable spatial correlation. Of course, this requirement is relaxed when precise event timing of both the power failure and the strokes are available, and tools for automatic recognition of these incidents are now available commercially.

SECTION: Chapter

Chapter title in running head: CHAPTER 6. ELECTROMAGNETIC METHODS OF L…

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