IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 3, 2020, accepted October 12, 2020, date of publication October 16, 2020, date of current version October 29, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3031810

Lightning Mapping: Techniques, Challenges, and Opportunities

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This work was supported by the Universiti Tenaga Nasional through BOLD2025 Fund.

ABSTRACT Despite the significant progress in the understanding of the phenomenon of lightning and the physics behind it, locating and mapping its occurrence remain a challenge. Such localization and mapping of very high frequency (VHF) lightning radiation sources provide a foundation for the subsequent research on predicting lightning, saving lives, and protecting valuable assets. A major technical challenge in attempting to map the sources of lightning is mapping accuracy. The three common electromagnetic radio frequency-based lightning locating techniques are magnetic direction finder, time of arrival, and interferometer (ITF). Understanding these approaches requires critically reviewing previous attempts. The performance and reliability of each method are evaluated on the basis of the mapping accuracy obtained from lightning data from different sources. In this work, we review various methods for lightning mapping. We study the approaches, describe their techniques, analyze their merits and demerits, classify them, and derive few opportunities for further research. We find that the ITF system is the most effective method and that its performance may be improved further. One approach is to improve how lightning signals are preprocessed and how noise is filtered. Signal processing can also be utilized to improve mapping accuracy by introducing methods such as wavelet transform in place of conventional cross-correlation approaches.

INDEX TERMS Interferometer, lightning mapping, magnetic direction finder, time of arrival.

I. INTRODUCTION

Lightning is a natural phenomenon in which electrical discharges occur between two objects with different polarities. It may occur between clouds and the ground, between two clouds, or within a cloud. When discharges are generated, electromagnetic (EM) radiations over frequencies ranging from ultra-low frequency to ultra-high frequency, are produced [1]. Lightning discharges are mainly categorized into two types, namely, cloud-to-ground (CG) discharges (i.e., downward negative, upward negative, downward positive, and upward positive) and in-cloud discharges (i.e., intra-cloud (IC), cloud-to-cloud (CC), and cloud-to-air)[2]–[6].

Although the physics behind lightning initiation remains unclear, many hypotheses have been proposed in the literature. Two candidate theories about lightning initiation have been considered, and they are hydrometeor-initiated positive streamers and cosmic ray-initiated runaway breakdown [7]. When the electric field between charges becomes sufficiently large, lightning is initiated. The massive amount of electromagnetism generated makes lightning a major cause of EM interference that can affect various electronic systems. Lightning is also one of the major causes of death in various countries around the world. Hence, different lightning mapping systems have been introduced long ago to protect humans and valuable assets. However, these old systems have problematic processing times because they are implemented offline [4], [8]–[11]. With the technological advancements in

The associate editor coordinating the review of this manuscript and approving it for publication was Amedeo Andreotti.

signal processing, these systems have made positive progress in the real-time detection of lightning strikes and the mitigation of the impact of lightning.

Lightning mapping is generally categorized into three-dimensional (3D) mapping, e.g., lightning mapping arrays (LMAs)) and two-dimensional (2D) mapping (e.g., interferometer (ITF)) [12]. LMA systems are usually composed of 6 to 20 very high frequency (VHF) antennas that are separated by a distance of kilometers and operate at different frequency ranges. ITF systems are composed of 3–4 VHF antennas that are separated by a distance of several meters and operate at selected frequency ranges [9], [12]. ITF is superior to LMAs because of its capability of scanning more lightning events than LMA and performing continuous and quasi-continuous emission mapping from lightning pulses for enhanced 2D visualization [4]. Modern lightning mapping systems have been designed to operate in different frequency bands ranging from extremely low frequency (ELF) to VHFs. VHF lightning mapping was traditionally performed using the time of arrival (TOA) technique [13], which was developed in Florida to achieve accurate 3D measurements for locating radio frequency (RF) radiation sources [14]–[16]. The method uses the time difference of arrival (TDOA) technique that requires a minimum of four to five antennas. Meanwhile, the use of ITF in determining difference of arrival (DOA) has been developed and enhanced by many researchers over the past 40 years [17]–[21]. Hence, current lightning mapping that uses ITF methods allow for a highly accurate mapping of lightning. ITF can locate a source of VHF impulses on the basis of the digital interferometric technique. In the latest development of ITF [9], the system receives VHF signals from different antennas that work as an array within a specific distance of a few wavelengths (10–20 m and higher). The system can capture the electric field changes caused by lightning discharges in VHF bands. The system consists of three resistively coupled flat plate antennas that are arranged to form two equally spaced orthogonal baselines along with a fourth antenna to record the time series data. This system enables the 3D mapping of sources in the azimuth and elevation angles.

VLF has been used in a wide range of research areas, including magnetic direction finder (MDF) and TOA. In MDF, the objective is to find the location from which the lightning initiated. However, the accuracy of the conventional VLF-MDF in detecting less distant lightning (below 200 km) is relatively poor, and it depends on the spacing of sensors [22]. Several attempts to use the gated technique have been proposed to improve the accuracy of narrowband VLF-MDF at short ranges. Krider *et al.* [23] introduced the first commercial gated wideband MDF system to overcome the problem of large errors in narrowband MDF. The gated wideband DF provides azimuthal errors with a mean value of 1° and a standard deviation of 2° [23].

The key factors in differentiating between mapping techniques include the number of sensors (i.e., antennas) required to find lightning locations, the baselines between sensors, network geometry, and the type of sensors deployed [24]–[26]. Some systems use a combination of two mapping techniques to improve accuracy and cover wide mapping distances (in kilometers) with a minimal number of sensor (e.g., antennas) baselines [22]. Kawasaki [27] attempted to provide a clear image and summary of the TOA lightning techniques compared to the ITF and how they are equivalent. The study distinguished both systems from different perspectives on the basis of pulse radiation procedures linked to lightning discharges and their locations by discussing the principles of each system accurately. However, the combination of TOA/ITF is still in the development stage and is far from being applicable in real-time.

II. SOURCES AND METHODS

Figure 1 shows a summary of the commonly used lightning mapping methods, which are reviewed in this work. The methods are further categorized according to the number of antennas, type of baselines, number of dimensions to which lightning is mapped, and frequency bands. This classification enables readers to understand the taxonomy used throughout this work.

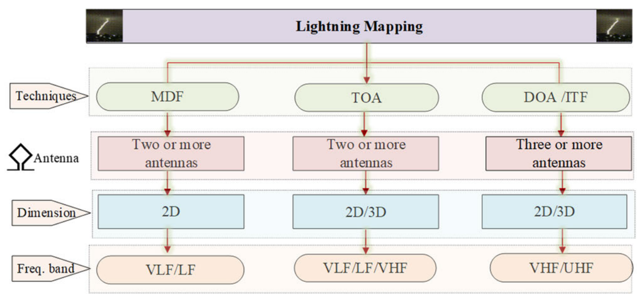

FIGURE 1. Lightning mapping methods.

The two most common techniques used for lightning geolocation in ground-based lightning stations are TOA and MDF. Currently, 3D VHF–TOA lightning mapping systems can provide complete records of the spatial and temporal development of lightning channels. However, the use of broadband ITF has shown significant improvement in lightning mapping despite its ongoing development. Dozens of lightning locating networks are being operated worldwide. Table 1 summarizes some of the existing systems categorized according to the operating frequency band. Further details are available in the reviews by [28]–[31] and in the references therein.

III. MAGNETIC DIRECTION FINDER

The basic principle of the MDF is the use of two vertical orthogonal loops with planes oriented at the north–south and east–west (EW) directions. Each loop measures the magnetic field from a given vertical radiator and can be used to obtain the direction to the source. However, the MDF uses a single station with one loop antenna, which can only determine the azimuth angle of a lightning source [32]. Moreover, the MDF

TABLE 1. Summary of existing lightning detection/mapping systems.

System	Frequency	Band	Antennas	Distance	Method
LMA	60–66 MHz	VHF	10–15 stations	15–20 km	NA
NLDN	400 Hz–400 kHz	VLF/LF	>100 stations	300–350 km	TOA and MDF
LINET	1–200 kHz	VLF/LF	NA	≤200–250 km	TOA
USPLN	1.5–400 kHz	VLF/LF	100 sensors	NA	VLF/LF TOA
ENTLN	1 Hz–12 MHz	ELF/HF	NA	NA	TOA
WWLLN	6–18 kHz	VLF	57 sensors	>1000 km	TOGA
GLD360	300 Hz–48 kHz	VLF	NA	NA	TOA and MDF
LDAR	66 MHz	VHF	7 stations	8-9 km	TOA
ONERA-3D	110-118 MHz	VHF	2 stations	40 km	ITF

LMA: Lightning Mapping Array, NLDN: National Lightning Detection Network, LINET: Lightning Detection Network, USPLN: US Precision Lightning Network, ENTLN: Earth Networks Total Lightning Network, WWLLN: World Wide Lightning Location Network, GLD360: Global Lightning Dataset, TOGA: Time of Group Arrival, NA: not available

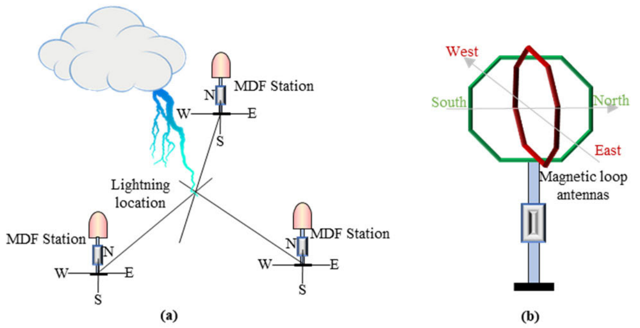

FIGURE 2. Lightning detection using MDF. (a) Multistation MDF; (b) orthogonal magnetic antenna.

method requires at least two stations to determine lightning location sources. The azimuth angle is calculated between the station, the south–north (SN) plane, and the direction where the lightning strikes. A line is drawn from the station to cross the unknown lightning strike point. At least two lines are then drawn from two stations, with the intersection between these two lines representing the exact lightning strike location, as shown in Figure 2. Therefore, several stations are required to reduce the errors in the estimation of lightning strike locations. In the MDF method, some cases could involve a lightning strike hitting a point on a line between stations; determining the location of such lightning strike is difficult. In this situation, at least three stations are required to observe the lightning strike location.

The MDF method uses magnetic field to locate, track, and measure the intensity of lightning emissions. It is mainly used to find the azimuth angle of the return stroke in CG lightning. MDF systems are implemented using a vertical magnetic loop or cross-loop antenna [33], [34]. The MDF technique requires at least two sensors to determine the location of a lightning strike. These sensors can detect the azimuth angle, which is located between the north direction and the direction of the lightning strike [22].

MDF has been applied to estimate the peak of lightning that strikes from the main radiating sources to pinpoint retriggering flashes. However, due to the errors in previous measurements for estimating return strike points in early versions of the MDF, other researchers [35] have proposed minimizing measurement errors by implementing two baselines with a sampling frequency of 1 kHz to 1 MHz based on VLF bands. However, the close ranges between VLF measurements result in poor accuracy. Orville [36] attempted to optimize the accuracy of MDF of CG lightning flashes at a frequency range of 10 kHz to 3 MHz. The statistical analysis was based on the geometrical property of the magnetic finder. The system is able to reduce the detection error by 80% relative to previous measurements [36]–[38]. Sonnadara *et al.* [37] studied the reconstruction of lightning strike locations on the basis of CG lightning flashes by using two wideband MDF stations. The direction finder's uncertainty localization accuracy of ±5 km within a 100 km radius was successfully optimized.

Orville [36] used MDF to estimate the peak current of return strokes triggered by CG flashes in Georgia and Florida by estimating and calculating the exact radiated lightning. The system comprised six magnetic direction finders, each of which had an orthogonal magnetic loop, a flat plate antenna, and a bandwidth range of 1–350 kHz. The lightning locations and protection of 18 triggered lightning return strokes were continuously measured in the span of four years. The peak current of each lightning stroke was estimated on the basis of the normalized signal strength amplitude. The estimation of lightning peak showed sensitivity of 2%. The study also suggested that the MDF technique could become a suitable method for enhancing the estimation of lightning return strokes in 2D with the improved estimation of distance, rise time, and peak current.

Yang *et al.* [39] suggested a number of improvements to the MDF technique in terms of the measurement of closed magnetic fields in the triggering of flashes in 2D. The study focused on the statistical distribution of the used channel and base currents to effectively analyze the closed magnetic field. The authors used numerical methods to examine the effects of different parameters, such as current rise time, return stroke speed, distance, and peak current, on the closed magnetic field. They concluded that the radiation components of the total magnetic field peaks depend on the assumption of the current rise time and return stroke speed. Generally, the magnetic field peak does not depend on the peak current but strongly depends on the distance from the radiation source. The effects of distance on the time variation in the radiation components are considerably different from those of return stroke speed and current rise time. In this case, increased distance and rise time causes a decrease in the field peak value.

With the development of technology, Tao and Lihua [38] investigated two MDF stations operating on the basis of two baselines to reconstruct the position of CG lightning flashes. They performed numerical simulations to find the relation between errors in the calculated lightning striking points and the locations of the stations. They found that the locations of stations are heavily dependent on the orientation of striking points. Mehranzamir *et al.* [40] extended the basic MDF technique for measuring a magnetic field to obtain the direction of lightning sources. An MDF with three stations working with VLF sensors at a frequency range of 3–30 kHz was used. The system was based on two types of magnetic loops: a single crossed loop to investigate the horizontal magnetic field component and orthogonal and vertical loops to obtain the lightning direction in the SN–EW directions. With these components, the system could detect the source of a magnetic field by measuring the ratio of the induced voltages in the two orthogonal magnetic loops. CG lightning flashes are generally only detected when the return strokes reach a height of a few hundred meters. In the MDF method, the antenna loop is sensitive to the magnetic field but not to the electric field. Therefore, in using MDF alone, at least two sensors should be used to determine the location, but the position error is subject to distance-dependent growth. Moreover, the site errors affecting the azimuth angle measurements should be corrected. In the study, the MDF direction for the crossed loop antenna had 20° bearing errors in both directions of the incoming signal. Overall, the MDF method still yields high location errors due to the sensitivity of antennas, metal objects, and tall structures that increase site errors in the MDF system.

In another study, Cai *et al.* [41] focused on measuring the current waveform of return strokes via the classical rocket triggering of lightning flashes. The study focused on different measurements, such as return strokes and M-components. For each measurement, the errors in rise time, half peak, and charge transfer, as well as CG flashes, were tested. The system was operated to measure lightning currents using a magnetic sensor with a specific range of 40–800 kHz and a limited bandwidth of 3 dB from a distance of 130 m away. The system was able to measure the lightning current without natural lightning flashes or direct current measurements near the rocket triggering of the 48RS and 40 M-components. The magnetic field sensors were applied to the measurement of return stroke currents in natural CG lightning at close ranges and upward lightning from the highest objectives. Close

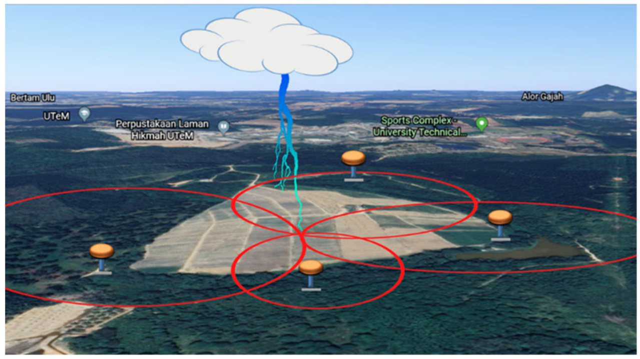

FIGURE 3. Time of arrival (TOA) lightning localization technique.

ranges were calculated using Maxwell equations while considering the highest lightning as a constant (in an improved version of the MDF). An increase in distance or current rise time produced an increase in the width of the magnetic field of the half-peak current. The triggering lightning flash efficiency reflected by the rise time error varied from 30% to 90%. The error in the measurement of the magnetic field was based on a few microseconds. Therefore, the system still needs to be improved further to avoid errors in rise time, half-peak, charge transfer, and M-components. A single station still does not provide accurate measurements for triggering lightning flashes.

Table 2 summarizes the MDF-related methods that have been reviewed. The table shows the details of the configurations and parameters of the design of MDF systems. The table also presents the advantage and disadvantages of each

IV. TIME OF ARRIVAL (TOA)

Generally, lightning mapping systems use the TOA technique to map lightning strikes through the recorded VHF pulses associated with lightning discharges. These systems can be divided into three levels: (1) the very short-baseline technique operating at a distance of tens to hundreds of meters, (2) the short-baseline technique operating at a distance of hundreds to thousands of kilometers [42], [43], and (3) the long baseline technique operating at a distance of hundreds to thousands of kilometers with a VLF/LF band [44].

The basic principles of the TOA method require at least three widely separated stations (few to tens of kilometers) to determine lightning locations. Adding more than three stations ensures a precise analysis of the measured arrival times of impulsive VHF events. Figure 3 illustrates a simplified setup of a TOA locating system. In this example, four lightning stations are used (stations 1 to 4), with each station independently recording lightning events and using a peak detector to determine the instantaneous times of these events. This setup could lead to different recorded times at each station and ultimately degrade localization performance.

The TOA technique generally involves multiple stations that utilize the information obtained from the TOA data to construct a 3D mapping of lightning flashes. The TOA

TABLE 2. Summary of MDF methods from the literature.

Ref.	Description/Parameters	Merits/Remarks 1	Demerits\Remarks 2
[35]	• The authors focused on solving the error of the nonvertical lightning channel of the MDF. • The study focused on CG lightning flashes at VLFs of 10–30 kHz; the wideband was sampled by 1 kHz to 1 MHz.	• The accuracy of magnetic direction detection is optimized. • Detection error is reduced by 80%. • Cross product technique is used to determine the direction of the magnetic field.	• Some polarization errors due to the use of nonvertical sources in the development stage still remain. • Errors due to the locations of lightning channels remain. • Orientation channels cause errors in lightning beyond 10 km.
[36]	• The study attempted to measure the peak currents of triggered lightning return strokes. • CG lightning flashes were observed on the basis of six magnetic direction finders, each with an orthogonal magnetic loop and a flat plate antenna with a bandwidth of 1–350 kHz.	• A total of 18 triggered lightning return strokes were collected in four years. • The peak currents of triggered lightning return strokes were estimated using detection finders with specific coefficients of 0.53–0.93.	• The error in the estimation of lightning peak current was 2%. • The estimation of the lightning peak current requires further improvements. • Some locations of the triggered flashes were not triggered due to the direction finders' azimuthal errors.
[1]	• The study was conducted to measure the closed magnetic fields in triggering flashes. • A system was operated to locate CG lightning flashes of two different limited bandwidths of 0.9 Hz to1.5 MHz for the current monitor and 0–3.2 MHz for the channel base current.	• The combination of MDF/TOA sensors improves the collected data from the NLDN. • For accuracy measurements, two observation sites are used: Site 1 for the control room located 60 m away and Site 2 for the main observation site located 550 m away.	• An increase in distance or current rise time increases the width of the magnetic field's half-peak value. • Flash detection efficiency varies from 80% to 90% due to regional effects for expected locations of 0.5 km. • Location accuracy is limited to the range of 0.5–1 km.
[37]	• CG lightning flashes were located on the basis of two wideband MDF stations. • Two MDF stations operated on the basis of two orthogonally looped antennas with a distance of 65 km.	• The reconstruction of lightning strike locations with an accuracy of 10 km was proposed. • Localization accuracy of ±5 km within a 100 km radius was achieved.	• The optimization of the MDF instruments is uncertain. • The system recorded 50% of the flashes with the same multiplicity; 25% showed a difference of ±1. • Errors in locating stations require further reconstruction improvements.
[38]	• The study focused on CG lightning flashes. • The system consisted of two simulated MDF stations with two crossed loop antennas that were spaced 2.985 km apart and had a sampling rate of 10 MHz.	• Location accuracy depends on return strike point orientations. • MDF location is observed in the range of a few hundred meters.	• The approach to locating return strike points is usually related to location positioning errors. • Estimation errors at the angle level need further improvements.
[40]	• The study extended the MDF technique by using a VLF (3–30 kHz) band and a minimum of three stations. • The system consists of a single crossed loop and orthogonal and vertical loops in the SN–EW directions to measure lighting directions.	• The system can detect sources using the ratio of the induced voltages in the two orthogonal magnetic loops. • The system can detect CG lightning flashes at heights of a few hundred meters.	• Using MDF alone requires a minimum of two sensors, and the position error is subject to distance-dependent growth, which necessitates post corrections. • Measurements contain high location errors due to the sensitivity of the antennas.
[41]	• The study focused on measuring the current waveform of return strokes via rocket-triggering flashes. • The system was operated at 40–800 kHz and a distance of 130 m.	• The magnetic field sensors are applicable to the measurement of return stroke currents in natural CG lightning at close ranges and upward lightning from the highest objectives.	• System efficiency in terms of rise time error varies from 30% to 90% in a few microseconds. • The poor accuracy in observing the triggered lightning flashes indicates that the system needs further improvements.

technique was first developed in Florida by [15]; the technique works only with single, short baselines and can provide the time for some portions of lightning EM field signals. Lennon and Maier [16] used the same system as in Proctor [45] and attempted to locate lightning sources from CG and in-cloud flashes in 3D. Two different systems were operated at a frequency range of 60–300 MHz with an initial operating frequency of 63 MHz for the first system and 255 MHz for the second. Hence, the system was built on the basis of two independent antenna arrays to provide rapid data quality check in real time. The intention was to design a lightning detection and ranging system for the location mapping of CG and in-cloud flashes and to provide the 3D locations of RF pulses for each lightning flash. This type of system could provide more than a thousand 3D locations within each lightning flash. It is similar to the system introduced by Proctor [15], but its data acquisition is automatic, and the data displayed are generated in real time [17].

Cummins *et al.* [1] continued the study of the TOA technique. However, their system was aimed at upgrading the design and implementation of the National Lightning Detection Network (NLDN) with data from TOA/MDF studies. The main objective was to improve system location accuracy, system efficiency, and detection, as well as to estimate the peak currents of all strokes in ground flashes to meet the needs of all-electric utilities. In this system, the delivery of stroke and flash information in real time is the main focus. The combination of TOA and MDF led to a noticeable improvement in lightning detection efficiency and produced better reliability than NLDN. Hence, this study preferred to use the two techniques to measure the arrival times and directions of all strokes. Further studies require changes in the way data are interpreted. Cummins *et al.* [46] explored the combination of the two methods on the basis of typical lightning strokes in Florida, which were detected using five sensors of the NLDN. The combination of MDF and TOA was used as the primary method for lightning localization to obtain extensive information about azimuth angle, area, altitude, and discharge time.

Thomas *et al.* [47] upgraded the system of TOA measurement of lightning in South Africa by adopting measurements based on 3D mapping. The study focused on the detailed breakdown of individual lightning discharges on the basis of five station arrays. Perpendicular baselines were implemented for the study of the breakdown of individual lightning discharges. Therefore, the center frequency was set to 60–66 MHz. The system was first tested in New Mexico Tech LMA, with the time of uncertainty empirically found to have a root mean square (RMS) of 30, which corresponds to source location accuracies as good as 10 m RMS. Given the different numbers of station arrays, location uncertainties could not be eliminated from the TOA measurements, and location accuracy was treated in some events outside the network. Therefore, systematic errors in lightning observations for LMA were found, with the RMS of the defined pulse shape being 43 ns.

Amir and Ibrahim [48] introduced a multistation system by using a short baseline for VHF and TOA techniques. This study focused on the connectivity of three antennas with a distance of 10 m through a national instrument data acquisition connection to a personal computer. The main aim was to display collected data to determine and calculate azimuth and elevation incident angles. Another objective was to determine the exact location of lightning strokes. To determine the incident angle, the authors added a third antenna through two baselines perpendicular to each other. This setup enabled them to monitor signals on a personal computer and save the filtered signals to estimate the incident angles in LabVIEW software. A short baseline was applied to measurements based on the TOA method and converted into 2D. Hence, the CG lightning strike data detected from the antenna plate could be analyzed and defined. The localization of the short multistation baseline of the alarm system was carried out using three broadband antennas. As the speed of data acquisition was slow, their system could only provide a short recording time. Therefore, measurements required a relatively long time to record the collected data.

Liu *et al.* [49] conducted a study in the northern region of Jiangsu Province, China, by using the TOA technique. The authors proposed a 3D VHF lightning mapping system that uses a waveform cross-correlation technique. The time difference of 10 μs was adopted for effective TOA positioning. Structural improvement was made in the K-process and two overlapped K-processes for the TOA system to achieve a high location accuracy under a limited speed of $1.1 \times 10^7 m/s$. The system's VHF bandwidth was 5 MHz, and the center frequency could be adjusted according to the local VHF EM environment. The system operated on the basis of five substations with a center frequency of 63 MHz. The sixth antenna operated at a center frequency of 53 MHz owing to local interference. The system was limited to a low sampling rate of 20 MS/s, and additional sensors were required to increase measurement accuracy. The waveform TOA method was used to analyze the lightning cases of interest.

Chen *et al.* [50] provided updated TOA measurements from his study in the Chinese Academy of Meteorological Sciences. The authors introduced a new 3D technique called the Low Frequency E-field Detection Array (LFEDA). The LFEDA method combines TOA and time reversal (TR) methods. This combination was applied to identify the best method for producing reliable positioning points for detecting lightning return strokes and CG lightning flashes. Wang *et al.* [51] were the first to apply the TR technique to an ITF lightning system to achieve 3D azimuth and elevation positioning. The method was proved effective in distinguishing multisource radiation. LFEDA is also capable of locating lightning mapping in 3D with multistation waveform data and a signal-to-noise ratio (SNR) of 5 dB. The system yielded continuous lightning positioning with a minimum of four antennas and a 500 ns time error relative to the LF signal TOA–3D positioning method. The study proved the method's anti-interference ability with low requirements and its time accuracy with

45 return strokes and more positioning points than the TOA method. Therefore, the TOA technique is useful in obtaining initial solutions, whereas the TR method can be used to obtain the final spatial locations to fit time discharges. To the best of the author's knowledge, the TOA–TR combination can enhance lightning positioning systems. However, previous results showed that the vertical error of the TOA method with less than four stations is larger than that of the TOA–TR method. Positioning errors and the effects of combining TOA and TR methods still need smoothening as both are still at the infancy stage. Hence, they require further tests on altitude lightning triggering for detecting CG flashes and position points of return strokes. Nevertheless, TOA measurements should be combined with other lightning mapping methods to comprehensively observe positioning locations.

Table 3 summarizes the studies related to TOA lightning mapping. The table includes the purpose and description of each method. The contribution and main limitations for each method are also highlighted.

The new measurements based on TDOA mainly use short baselines, and the real difference depends on the number of antennas. Sun *et al.* [6] introduced a new localization system by using four extra fast/slow antennas to measure the electric field changes applied to a global positioning system (GPS) system. TOA systems accurately measure the arrival times of impulsive VHFs at numerous ground locations, and they are widely spaced over distances as high as tens of kilometers. TOA fails to produce accurate estimations of lightning radiation when short baselines are used. By contrast, the combined TOA/TDOA improves the configuration of the antenna system and allows the use of short baselines. Unlike TOA, TDOA does not require the implicit recording of the arrival time of lighting radiation; instead, it uses signal processing methods to estimate the time delay of two received signals at each baseline (short baseline) [52].

For a very short-baseline system, TOA usually operates at a VHF band with a frequency range of 30–300 MHz and with a receiving frequency range of approximately 30–100 MHz [53]. The very short-baseline system consists of two or more VHF–TOA receivers with a spacing and time difference between arrivals of individual VHF pulses of approximately 1–100 μs. Hence, although multiple antennas are used to detect VHF pulses, the pulses could become challenging to distinguish. This issue can be addressed by applying the very short-baseline technique, which uses closely spaced antennas that have almost identical positions and receive all pulses. Meanwhile, the short baseline of the TOA technique for 3D locations requires at least four antennas to obtain a high imaging accuracy for lightning sources. Overall, the very short-baseline technique is useful for estimating azimuth and elevation of VHF sources. By contrast, the short-baseline technique is useful for developing two independent systems and providing EM images to develop channels for any type of lightning flash [27], [54]. Lewis stated that by using a long baseline, the TOA system could operate at a VLF/LF with a bandwidth of 4–45 kHz, separated by over 100 km and spread over four stations. The problem with the long baseline system, however, is the difficulty in identifying the same pulse features in the signal received by different antennas.

V. INTERFEROMETER (ITF)

The basic principle of the ITF system is to estimate the phase difference of VHF EM emissions detected by closely spaced pairs of antennas. The TDOA of incident EM pulses is estimated for every two antennas (baseline) separated by distance d. As shown in Figure 4, the pair of antennas BC and BD are used to calculate the phase difference between the implemented antennas; antenna B is the reference. The azimuth and elevation angles of the radiation sources can then be derived from the ITF geometry.

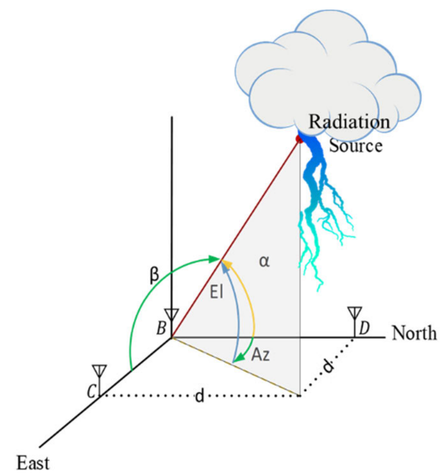

FIGURE 4. Two-orthogonal baseline schematic diagram of 2D ITF lightning location system.

The existing lightning ITF systems can be categorized into two types according to their operating frequency: the narrowband ITF and broadband ITF. The broadband ITF is superior to the narrowband ITF as it can record lightning emissions in a higher resolution and thus provides more information on temporal lightning events. A single broadband ITF station can provide continuous lightning mapping in 2D, through which a synchronous multistation system can visualize the lightning progression in 3D maps [55]. The broadband lightning ITF method was developed in the field of localization and is considered a novel tool in lightning discharge investigations [2], [56], [57]. The basic idea of broadband ITF is to estimate the phase difference at various frequency components of the Fourier spectra between a pair of broadband antennas.

Warwick *et al.* [21] were the first to implement lightning ITF on the basis of a single baseline operating over a narrowband with a center frequency of 34 MHz and two VHF antennas spaced 80 m apart. The authors found that the instrument was useful in tracking the motion of lightning by using the quadrature phase detection method to determine the phase DOA. However, working with only a single-baseline ITF, the system was not able to produce maps or images of the lightning source and some fringes with electric field

TABLE 3. Summary of studies related to TOA.

Ref.	Description/parameters	Merits (Remarks 1)	Demerits (Remarks 2)
[15]	• The study was the author's first exploration of the TOA lightning mapping technique in Florida. • The study mapped out the location of lightning in-cloud flashes in 3D. • The system operated with five antennas at center frequencies of 253 and 355 MHz and a short baseline in the range of 10–30 km.	• The proposed system is the first to map out a location radiation source using TOA. • The system was able to locate a large number of radio noise sources for each pulse flash. • Three Cartesian coordinate position sources were identified by measuring the TOA of each noise pulse.	• Noise was emitted from different sources, such as triggered DL, recoil streamers, and positive pulses. • Given the effects of noise = [$10\mu s$ to $about$ 5 ms], achieving high accuracy requires the careful selection of source positioning. • The system works with only single-short baseline, which can provide the time for some portions of the lightning EM field signal.
[16]	• The author implemented the same system used by Proctor [15]. • The study attempted to locate lightning location sources from CG and in-cloud flashes in 3D. • Two different systems were used with limited bandwidth antennas of 60–300 MHz and different centered frequencies of 63 MHz for the first system and 255 MHz for the second system.	• The data were generated in real time. • The LDAR system for in-cloud and CG discharges was able to provide the 3D locations of RF pulses for each lightning flash. • The study enhanced the understanding of using LDAR to locate lightning in a real-time operating system.	• The system is similar to the system introduced by Proctor [15], with the difference being the real-time and automatic data acquisition. • The LDAR system did not allow the researcher to locate lightning by using the VHF burst pulses because of the K-change processes and recoil streams.
[1]	• The author aimed to map out lightning on the basis of the different data collected from several sensors in CG. • The study was based on a single dimension with a distance of 15 km for the first stroke and 500 m for the time interval.	• The study is the first to use the TOA/MDF combination to map lightning locations. • The study used the same short baselines of the MDF.	• The result varied slightly by region, leading to a peak current of less than 5 kA. • The system proved less efficient than its counterparts due to an unknown current distribution.
[52]	• The study focused on lightning physics and mapping of VHF radiation sources in 2D (azimuth and elevation). • A TDOA detection system was designed on the basis of a 10 m short baseline operated at a center frequency of 280 MHz with a bandwidth of 6 MHz.	• The 2D location of lightning radiation sources was performed. • The peak seeking technique was used to determine time differences. • Details about lightning physics were provided in the study.	• The system's detection efficiency in observing lightning sources was considerably low. • The system yielded large errors in elevation angle, and thus, the short baseline should be improved further. • The system was sensitive to the use of wideband signals at the VHF range.
[47]	• The study focused on TOA techniques and the development of an LMA, which could locate lightning sources in 3D. • The LMA had a limited bandwidth in the range of 60–66 MHz; operated under control and center frequencies of 25 and 300 MHz, respectively; and had two pairs of baselines.	• Sources over the network could be located with an uncertainty of 6–12 m RMS in the horizontal direction and 20–30 m RMS in the vertical direction, resulting in a 3D location of less than 100 m. • The LMA was investigated using a sounding balloon measurement and via storm observations.	• Given the systematic baseline, timing errors of 15 m were observed, along with a fractional error in the 16 km baseline length. • Systematic and effective errors in lightning observations for the LMA were found, with the RMS of the defined pulse shape being 43 ns. • The accuracy of the locations was treated in some events outside the system network.
[48]	• The study proposed a TOA system with multistation VHFs with short baselines. • The study attempted to determine the location of a lightning strike in 2D with the estimated azimuth and elevation angles. • The study employed a short baseline with three separate antenna connectivities at a distance of 10 m.	• Using the TOA technique can determine location sources using multiple stations in 2D, but the baselines are separated. • The TOA technique with a short baseline is a capable approach to determining lightning locations at long ranges.	• The data acquisition was slow; speed thus needs to be improved. • The system can only provide short recording times; thus, the system is still imperfect, and its recording of data needs to be prolonged. • A separation of the baselines was required to collect the captured data and thus indicated different time events.
[58]	• The study conducted an LMA observation of upward positive leaders developed from triggered flashes in a storm in Central New Mexico. • The study was based on a short baseline operated with a limited bandwidth of 60–66 MHz in 3D and a specific distance of 1.8 km from the triggering site.	• TOA was represented in LMA to understand the normal polarity tripolar charge structure with an upper positive charge. • TOA showed a good agreement with the LMA and produced an accurate location.	• Not all the flashes of the VHF emissions could be captured along the positive leader channels. • The LMA located weak VHF sources at a high altitude, closer to the tip of the positive leaders.
[27]	• The author provided a summary of the VFH pulse radiation procedure linked to lightning discharges and their locations. • The study aimed to distinguish the TOA and ITF systems from different perspectives.	• A good compression was achieved between the TOA and ITF systems, and how both systems are equivalent was understood. • Each system had different numbers of antennas and data collection methods.	• A real-time operational system remains under development. • The TOA (LMA) and digital ITF are still imperfect in terms of providing a clear view of lightning images as the two systems are ultimately equivalent to each other in the lightning field.
[6]	• The study aimed to locate lightning VHF radiation in 2D on the basis of a short-baseline TDOA. • The system was equipped with four identical broadband flat plane antennas with an orthogonal distance of 10 m. • The baselines operated at a bandwidth of 125–200 MHz with a sampling rate of 1 GS/s.	• A rocket-triggering lightning discharge and cloud lightning were detected with TDOA in 2D (azimuth and elevation). • Generalized cross correlation with parabolic interpolation was used to improve noise reduction and accurately determine the time delay. • The system was validated using a high-resolution video camera.	• The use of short baseline and VHF–TDOA remains imperfect. • The error of the azimuth angle estimation is relatively large. • TDOA can only estimate the time delay in the time domain, and it does not consider the phase difference estimation in the frequency domain. • The enhanced compression of lightning locations between rocket triggering and IC requires different lightning case studies.
[50]	• The author focused on the 3D location of lightning using low frequencies and combined the TOA and TR algorithms requiring at least four stations (antennas).	• The combined method requires the deployment of a minimum number of stations relative to the conventional TOA. • The combined method can determine 3D locations under low SNR conditions.	• The study focused on VLF/LF bands and showed that errors could be reduced by combining TOA and TR; however, the combination requires further improvement.
[49]	• The study aimed for 3D VHF lightning mapping. K-processes with a limited speed of 1.1×10^7 m/s were run, and the 3D velocities of the K-processes were measured. • Different sets of 3D standards of two different 3D axes ($\sigma x = 20\,m, \sigma y = 19\,m, and\ \sigma z = 5\,m$) with limited bandwidth of 5 MHz were used.	• A new waveform cross-correlation technique was introduced, but the TOA system remains imperfect. • The time difference was computed with a small range at 10 μs. • The length of each trigger was 1 ms, and the pretrigger length was 0.3 ms.	• The system is limited to a low sampling rate of 20 MS/s. • The system requires a large number of positioning points as the VHF system is used. • Additional sensors are required to increase the accuracy of the system. In addition, waveform cross correlation is still an open question in the TOA lightning field.

recorded by lightning flashes. Therefore, the ITF system is still imperfect and requires further improvements in terms of locating extended portions of the radiation emitted by lightning. Hayenga and Warwick [18] conducted another study on a system that estimates lightning mapping in 2D (azimuth and elevation) locations on the basis of ITF with $2.5\mu s$ resolution. The system operates at 34.3 MHz narrowband (3.4 MHz) with two pairs of antennas spaced 15 m apart. Instruments were implemented perpendicular to the crossed baseline instead of a single baseline. The azimuth and elevation incidence angles were determined at this point. However, due to the large number of errors in the phase difference measurements, the authors employed a baseline length of 2λ to enhance the localization. Therefore, the findings showed a breakdown progression during lightning flashes, but it did not improve the ITF technique. Nevertheless, the study was the first to apply a 2D ITF. The system was found to be susceptible to phase ambiguities, and fuzzy maps of lightning flashes and multiple baselines are required to eliminate these ambiguities and provide comprehensive source information (e.g., [59], [60]).

In general, the methods for mapping lightning using broadband digital ITF can be classified into the following three types according to the processing technique: linear fit method (phase fitting), wavelet transform-based techniques, and cross-correlation-based techniques. Rhodes and Krehbiel [17] continued the study on ITF lightning by providing more advanced measurement configuration with an increased operating frequency of 34–274 MHz. Two pairs of baselines, namely, a short baseline of 1/2λ and a long baseline of 4λ, were used instead of a single pair of crossed baselines of 2λ to improve the angular uncertainty and to avoid fringe ambiguity. The study focused on CG lightning and used similar narrowband mixers. The results included measurements on 2D (azimuth and elevation) with $1\mu s$ time resolution direction of arrival in the radiation source. The long baseline produced noticeably high accuracy results, whereas the short baseline was not useful as it only determined some portion of the flashes.

Shao and Krehbiel [2] studied an improved version of the ITF system used by [20]. The antenna configurations of short and long baselines were changed to 1λ and 4.5λ, and the limited broadband was set to 40–350 MHz. The authors also attempted to use integer arithmetic to convert phase measurements to azimuth and elevation values. Given the noise immunity of the system, the baselines were combined by an automated process. The comparative analysis of the CG and IC flashes of lightning with increasing spacing between antennas helped to resolve fringe ambiguity. Real-time lightning locations could also be displayed by focusing on broadband ITF. In 1995–1996, the authors concentrated on the development of an ITF with a full description of CG and CC/IC flashes on the basis of an advanced and affordable broadband ITF. However, the study was not able to identify all the features of the IC discharges, and the short-baseline measurements showed minor errors.

Mazur *et al.* [61] proposed two different systems, namely, lightning detection and ranging ''LADR'' interferometric system (TOA) and French office national d'etudes et de Recherches Aerospatiale ''ONERA-3D'' (ITF), to locate CG lightning sources at 2D (azimuth and elevation) maps. LDAR operated at a center frequency of 66 MHz, and ONERA-3D operated at a center frequency of 110–118 MHz. The bandwidth of LDAR data was 6 MHz, and that of ONERA-3D data was only 1 MHz. The study focused on the comparative and simultaneous lightning mapping of the same storm using the LDAR and ONERA-3D systems. IC and CG lightning events were analyzed. ONERA-3D mapped best the fast intermittent processes and dart leaders, whereas LDAR mapped best the continuously developing IC processes. Therefore, the LDAR (TOA) system failed to detect positive leaders and showed a slow negative breakdown. Moreover, the LDAR system did not perform well in mapping radiation sources associated with stepped and dart leaders propagating toward the ground. LDAR is similarly inadequate in mapping K-changes inside the cloud. By contrast, the ONERA-3D (ITF) system did not map radiation from continuous positive leaders.

Shao and Krehbiel [2] introduced a new technique called linear fit, which focuses on the change of phase difference with frequency. The technique is based on a single vertical baseline to obtain further detailed measurements of the descent of a leader toward the ground. Data were recorded continuously for short durations just before the return strokes. With these procedures, the manufactured ITF was able to locate and reconstruct lightning progression in a one-spatial dimension. To provide a proof of concept, the study presented a new method for determining the time difference between antennas.

Ushio *et al.* [56] used the same linear fit technique by extending the antenna system with a pair of orthogonal horizontal baselines. The two baselines allowed the lightning to be mapped in 2D (azimuth and elevation). Given the relatively high digitization rate, the broadband ITF faced difficulties in recording the emitted radiation from the lightning discharge. Therefore, the authors developed triggering techniques to effectively record radiation. The VHF broadband digital ITF was developed with measurements correlated with the amplitude and phase of the signals received by antenna pairs.

The earliest instruments for reconstructing CG lightning discharges were developed in Australia in December 1997 to address the significant lightning spectrum bandwidths and the limitation of digitized memory storage. Further improvements were made in [62], which used triggering techniques to record EM pulse data with a frequency of 0–250 MHz. The focus was on the location of fast EM radiations emitted from lightning discharges and on acquiring data on the emitted flashes of lightning. The ITF technique was able to estimate and extract the phase difference at variable frequencies using a discrete Fourier transform. The signal was delivered in the frequency domain of the incidence of EM pulses at two antennas. Therefore, the azimuth and elevation angles were resolved, and strong EM pulses were detected along with the lead progression. The best reconstruction of CG lightning discharges was displayed in two dimensions and in time sequences.

Mardiana and Kawasaki [62] attempted to solve the issues of large lightning frequency bandwidths due to the limitation of digitized memory capacity by using a high digitization rate and equational triggering techniques. Several attempts were made to solve this problem by increasing the frequency range from 25 MHz to 250 MHz using the same perpendicular baselines and the same mathematical techniques. This study added another antenna to calculate the azimuth and elevation incidence angles using cross-correlation and Fourier transform techniques between two antennas. The changes resulted in notable success in recording data for broadband fast-moving EM and in reconstructing CG lightning discharges. Moreover, that broadband ITF was found to be more useful than the narrowband ITF in locating heavy lightning.

Dong *et al.* [63] used a new comparison to investigate emitted radiation and the development of decisive leaders in artificially triggering lightning by using a power spectrum with a high-pass filter frequency of 25 MHz. Different frequencies of a positive leader ranging from 25 MHz to 30 MHz and negative breakdown processes of 60–70 MHz were tested. Narrowband and broadband ITF systems were implemented to identify which one could achieve the best emitted radiation detection. The result revealed that the narrowband ITF system produced the strongest IC. As a result of the intermittent sampling of the broadband, the ITF was not able to record the entire radiation by triggering lightning. The authors claimed that using a high-pass filter close to lightning produces radiation from the positive leader rather than the broadband ITF. Therefore, recording at a high sampling rate was recommended for the enhanced resolution of radiation signals from antennas.

Kawasaki *et al.* [64] conducted a study to improve the broadband ITF of CG discharges and focused on changing the bandwidth range (10–250 MHz) by implementing two orthogonal baselines with a specific length of 10 m. The study was based on two pairs of antennas with two independent baselines and amplifiers equipped with antennas digitized at a sampling rate of 500 MHz and 8-bit resolution. To obtain 3D lightning, they developed a broadband ITF for imaging lightning channels and identified the positive charge distribution inside thunderclouds. Different charges of thunderclouds were observed, but they were not fully identified due to insufficient data for preparing advanced broadband ITF with high spatial and temporal resolutions.

Mardiana *et al.* [57] used the same baselines as those used in[64] for data digitization at 500 MHz with the same baseline length of 10 m. The focus of their study was on IC temporal development observed by VHF broadband ITF. The IC flashes were characterized to be at the active and final stages, as indicated by streamer breakdown at the low-level channel. The main idea was to observe the most robust radiation sources in the lower part of the storm toward the positive charge region. A 2D method was applied to observe IC lightning discharges via the VHF broadband system. A few bidirectional IC discharges were also represented, but not all features of the IC lightning discharges were reported.

Qiu *et al.* [19] carried out a study by using an algorithm based on new and advanced techniques. The authors focused on reducing the phase noise of VHF radiation. Effective noise reduction was achieved during system implementation. As a result of the phase difference spectra, some of the random noise was added to the system with noticeable effects on accuracy and reliability. Hence, several algorithms were applied; these algorithms included phase filtering algorithms characterized by circular correlation and translation invariants. These algorithms addressed the problem of simulated and experimental data being distorted by extra noise and resolved the incident angles. The wavelet transform based on the Myere wavelet function was also used to remove or reduce noise. The experimental results showed that compared with conventional approaches, the proposed approach achieved better accuracy and reliability in phase noise reduction and higher location accuracy in incident angle resolution. However, the use of wavelet transforms remains debatable in the localization field.

Cao *et al.* [65] studied an ITF system operating at 125–200 MHz and consisting of four perpendicular broadband flat antennas separated horizontally by 10 m. Fast and slow antennas were used to capture lightning electric fields. The system was equipped with two GPS receivers to provide an accurate trigger time. Differences in arrival times and phase differences were calculated using the geometric model and fast Fourier transform approach, respectively. The system achieved the 2D lightning discharge mapping of CG flashes with multiple strokes. Fourier filtering and Symlet wavelet denoising were applied to suppress the unwanted high frequencies (>200 MHz). Data were stored using a LeCroy oscilloscope with a 1 GHz sampling rate. The sequential triggering technique was used to reduce the data samples. The system used what is referred to as the short-baseline time of arrival (improved version of TOA) with ITF antennas, noise reduction to improve lightning source detection, and measurements limited to single CG flashes. The system did not provide a clear direction for lightning flashes.

The cross-correlation technique is a well-established technique and was first used in lightning mapping by [10], [66]. The authors contributed to the study of VHF broadband digital ITF systems by locating the impulsive VHF radiation sources of lightning discharges [66]. Akita *et al.* [10] introduced further upgrades to the digital ITF system with a new processing method for phase difference distribution analysis to effectively locate lightning-related radiation sources. The measurements were taken using two ITF systems to calculate the location of lightning flashes in 3D. Hence, the azimuth and elevation angles of the radiation sources were derived. Moreover, the measurements concentrated on recording the ground to estimate the charge distribution occurring inside a cloud. A two-ITF mapping system was deployed approximately 15 km apart. The system reconstructed lightning charges by recording the 3D locations of sources. The results proved the system's ability to measure the 3D propagation speed of fast-moving ionization waves called the K-change.

The best ITF measurement study involved implementing changes in frequency bandpass filters installed inside antennas from 20–125 MHz to 20–80 MHz to avoid contaminated aliasing [10]. The authors developed a new phase fitting technique to continuously record radiation observations with a digital ITF and processing algorithms for enhanced lightning detection. Stock *et al.* [67] developed another common technique called cross-correlation. Motivated by the lack of any useful findings of scientific interest, the authors continued their attempts at different measurements and data collection to obtain new results. Stock and Krehbiel [9] redesigned the antenna system by moving it farther from noise generation with an extended baseline at a specific distance of 10–16 m; each antenna was reconnected to a single cable. A fourth channel was added to improve the VHF ITF recording during the use of multiple baselines. In this case, the number of flashes recorded increased from three during the 2012 storms to over a thousand in 2013. Overall, high quality results were obtained, and the triggering mechanism for detecting lightning discharges was improved.

Akita *et al.* [66] used a VHF digital ITF system [56] to investigate the progression of the K-processes (K-type breakdowns) of cloud flashes. The 3D localization of radiation sources was achieved by using two stations of the conventional 2D ITF and by considering the arrival times. The entire system comprised two-ITF systems 5.2 km apart and implemented in two different sites; one of the ITF systems included a slow E-field antenna. The analysis of two cloud flashes using phase difference estimation revealed further details about K-process visualization and progression. However, lightning map validation was not possible due to the lack of real images of in-cloud channels. Hence, most studies implement cross-correlation techniques rather than phase fitting techniques for lightning mapping.

Nakamura *et al.* [68] built an ITF system on the basis of a VHF broadband (25–80 MHz) of three antennas with a sampling rate of 200 MS/s and one additional antenna for triggering signals. A low frequency system of a single fast antenna called broadband observational network for lightning and thunderstorms (BOLT) (500 Hz–500 kHz) was used for lightning localization in 3D. The comparative analysis of ITF and BOLT was conducted on the basis of lightning detection. The ITF system was able to detect small lightning EM waves. By contrast, the BOLT system requires very long baselines and thus failed to detect huge EM waves in a short time. Hence, the system requires a huge memory to store data.

Stock *et al.* [9] proposed a hybrid approach involving a broadband (20–80 MHz) ITF and TOA Langmuir LMA. The ITF consists of three flat plate antennas situated 10.2 m apart and another fourth antenna for triggering recording. Continuous ITF data were recorded with a sampling rate of 180 MS/s to observe the entire lightning activity. A generalized cross correlation in the frequency domain with windowing functions was used to determine the segmental TDOA between the implemented antennas. They combined 2D ITF maps with 3D LMA to provide a quasi-3D lightning map. The use of LMA with ITF provided a superior 3D spatial resolution and did not require multiple stations. Overall, ITF and LMA are sensitive to environmental noise levels and require post-processing to eliminate noise and nonvalid localizations. The use of windowing ($1.52\mu s$) with an overlap of 98% to obtain time delays showed an estimated angular uncertainty of 0.82° for the azimuth angles and 0.63° for the elevation angles.

Abeywardhana and Fernando[69] aimed to locate VHF radiation sources in 2D (azimuth and elevation). A VHF broadband (10–80 MHz) ITF system comprised three flat circular capacitive antennas that were arranged orthogonally and spaced 10 m apart; the center frequency was 45.5 MHz. Tektronix MDO-3034 oscilloscope was used to digitize and store the data with a sampling rate of 250 MS/s. The fourth antenna was added to record the fast-electric field. The cross-correlation method was used to map the lightning progression. The system yielded a 2D lightning source, and the maps were validated with visible events of CG flashes using a high-resolution camera. Data recording length was limited to 40 ms only due to the high storage requirements. This ITF system thus still requires improvements to eliminate the noise with minimum information loss to enhance lightning maps.

Liu *et al.* [55] attempted to measure the 3D location based on VHF broadband lightning ITF. The study introduced a 3D lightning location method based on a two-station broadband ITF located at Canghua District, Guandong Province, China. The measurements of the two sites included a VHF antenna array placed on the square shape of both sites and operated at baselines of 16 and 15 m, respectively. In a recent study, broadband ITF based on a theodolite wind measurement method was applied. Simulation was also performed to assess the method's accuracy. The system was able to detect different types of lightning flashes, including 1 IC and 61 CG lightning flashes. The study confirmed that using the two-station ITF produced high accuracy because of the connection between the sites. The 3D location of the two-station ITF was found suitable for observing lightning at a close range and at a high elevation angle in a small area. However, the implemented system produced the same results as those of the existing TDOA method. Moreover, increasing the distance of the broadband ITF–VHF system could affect the location accuracy of the radiation source and the stations used, as well as decrease location accuracy. Therefore, a locating method for lightning mapping in 2D or 3D could be used to improve and perfect this method.

Zhang *et al.* [70] continued the measurements of a lightning mapping system based on a single station. The measurements included a microphone installed in a 3D steel frame. The study used an improved version of the ITF system to detect and determine EM and thunder signals using a broadband DOA estimation technique for lightning observations. The proposed system operated with four elementary arrays and a limited bandwidth of 0.1–500 MHz with a sensor node located at the center of a 45 m distance. Thunder signals were detected at a frequency range of 800–1200 Hz by using an array element. Several lightning flashes, including four CG flashes, were observed; two of these CG flashes were comparable to those of a high-speed 3D camera. Different branches of the same lightning were also distinguished. DOA considers the calculation of the distance of a thunder source specifically between acoustic and EM signals. Less comprehensive information is produced, and thus, few stations are required. Moreover, different return strikes appeared in the same lightning, and different lightning flashes occurred almost simultaneously. Therefore, using a single station to detect EM and thunder signals still needs improvement and perfecting. The system is also affected by contaminated noise from the atmospheric environment; this aspect also needs to be improved.

Puricer *et al.* [71] proposed using a new accurate test for lightning VHF–ITF based on artificial CC pulse generation. The study used a VHF–ITF system operating on three antennas separated by a distance of 6 m with a short baseline and a limited bandwidth of 20–60 MHz to determine the DOA and TDOA from captured signals. Angle-of-arrival techniques were applied to determine the errors in estimating the DOA of CC pulses. The system was found capable of reducing some of the errors in the linear distortion of the received lightning signals. Furthermore, the location accuracy depended on the best-tested installation of the ITF location system, to which a preprocessing technique could be introduced to achieve enhanced performance. Therefore, this system could implement many enhancements related to the accuracy of the ITF. This implementation depends on the discovery of an optimal installation location. The short baseline and estimation of the TDOA are still imperfect, and the effectiveness of noise reduction from different VHF–ITF installation locations requires further improvement. The study suggested the use of preprocessing and cross-correlation techniques to improve and perfect the ITF system.

Wang *et al.* [51] were the first to develop an electromagnetic time reversal (EMTR) system for locating lightning return strike points. The study used the EMTR technique to further investigate lightning VHF localization. The system operated on two different broadband frequency ranges, namely, 25M Hz–90 MHz and 110–150 MHz, for the localization algorithms. The authors used multisource localization in their field experiments to achieve good VHF source-emitted lightning localization. As the continuous recording of VHF lightning localization could provide rich information about VHF sources, the authors attempted to use the EMTR technique with multiple VHF sensors. The EMTR can produce a continuous recording system without estimating the phase difference or TDOA. The study also determined the performance of the multiantenna array versus the three-element array. The system yielded two classical triggering flashes. EMTR was unable to estimate the phase difference between the captured signals. Moreover, when calculating the TDOA, the system heavily overlapped due to contaminated noise that required filtering. Furthermore, DOA could still be estimated using other methods.

Wang *et al.* [72] used an alternative to EMTR that was used previously by Wang *et al.* [38] but modified it by using the same broadband frequency ranges. Multiple signal classification (MUSIC)–VHF algorithms were applied to improve the mapping quality discharge processes and to estimate the DOA of the lightning sources. Seven omnidirectional antennas based on 9 m "L"-shaped baselines were used together with eight LeGory channels under a recording mode with 500 MHz sampling rate. The instruments proved useful in comparing return strikes, K-events, dart leaders, and ITF–VHF radiation sources for subsequent return strokes. Furthermore, a numerical simulation was run to investigate the performance of the MUSIC–VHF method in locating VHF sources and in terms of its localization accuracy. The results were compared with those of EMTR–VHF and revealed that both systems could estimate lightning mapping with exceptionally detailed information. MUSIC–VHF still requires improvement, especially in observing bidirectional leader development for lightning mapping initiation. The number of antennas used in simulations could also be increased, and the results can be compared with those ITF–VHF because the proposed method is limited to classical triggering lightning flashes. The continuous broadband VHF lightning mapping system by Wang *et al.* [38] could still be employed as an instrument, but it needs improvements.

As lightning VHF multisource localization has been the subject of numerous research on the ITF system, Yan *et al.* [73] extended the studies in this field and estimated DOA by using multiple-baseline widebands (TD, FD-ITF) and a Hilbert transform for wideband RF discharge lightning sources. The system operated on single-baseline ITF with two antennas. The antennas were separated by a distance of 8 m. Other multiple-baseline ITFs with four antennas were set at the corner of a square with a side length of 4 m and a frequency band of 200–700 MHz. In doing so, thee antenna array consisted of four ultra-wideband D-dot antennas (Prodyn AD70) and had a bandwidth ranging from 22 kHz to 1.4 GHz. Each antenna element was connected to a channel in a four-channel digital oscilloscope (DPO90604A) with a bandwidth of 6 GHz. Improved DOA estimation was obtained using the UWB discharge source relative to the traditional TD method, especially in low SNR conditions. The accuracy of the elevation angle and azimuth angle estimation improved with the increase in the antenna element number and baseline length. The cross-correlation technique was used to estimate the TDOA by using a single ITF system. The resulting system showed that the real azimuth angle had a small effect on the DOA estimation and that the single-baseline ITF could not meet the DOA estimation requirement due to angle ambiguity, the errors occurring due to the ground measuring equipment, and the low accuracy due to the cross correlation in estimating time delays. All these issues eventually reduced the accuracy of the DOA estimation. Therefore, ITF–VHF can still be improved.

Some of the advantages of using ITF systems from the aspect of TOA are described here. First, these systems do not require the identification of individual pulses because the ITF measures the phase difference between narrowband signals corresponding to the noise-like bursts received by two or more closely spaced sensors [53]. Second, only a few antennas spaced closely apart are used to estimate the TDOA or phase differences between the correlated signals arriving at two antennas. With regard to the use of the advanced broadband ITF technology, "this trend is made possible by the advantage of affordable broadband RF and digital signal processing electronics" as the ITF needs to be integrated over windowing [2], [9], [62]. Third, the ITF system is generally used to determine the directions of radiation sources from a combination of phase measurements in a relatively small or wide bandwidth. The antenna system is made up of an array of dipoles that are connected to an ITF receiver to determine the phase differences of received observations. The phase difference is usually obtained by comparing the received signals from several antennas or by comparing these signals with those of a standard local oscillator. The accuracy of phase measurements is then achieved by integrating the desired time resolution. Through post-processing, the phase differences are obtained for the radiation source to produce the 2D or 3D map (azimuth and elevation). The radiation triangulation mechanism is determined in the central processor for radiation event localization using the information received from several sensors [34].

Table 4 summarizes the studies on ITF and depicts how ITF has rapidly developed amid different lightning measurements. The main difference between current ITF systems and previously proposed ITF systems depends on the range of the bandwidth used, the type of baseline (vertical, orthogonal, or short), the wavelength of each measurement (the most changeable parameter), the number of antennas, and the distance between the implemented and designed antenna. Some of the similarities cluster around with the ITF technique for lightning localization, which can locate VHF sources more successfully than previous non-ITF methods. The table also details the dimensions in which the ITF was employed, along with the number of antennas used in each mapping system. For each study, Table 4 includes remarks to reflect the newly implemented methods and system advantages. Other remarks pertaining to limitations and disadvantages are also illustrated. Most authors proposed different lightning mapping methods and various solutions to achieve good lightning localization based on different setups with different data collected. Finally, the broadband ITF currently in use presents a significant improvement over other lightning ITFs in terms of TOA.

VI. DISCUSSION AND OPEN ISSUES

A major challenge in using conventional methods to map lightning sources is their dependence on preprocessing steps. Their performance in estimating lightning mapping of ITF systems may still be improved if effective preprocessing techniques are utilized. One key element of preprocessing improvements is the use of reliable methods to remove unwanted noise and obtain a precise estimation of TDOA. The following suggestions are made:

1. First, lightning signals can be filtered and prepared for further signal processing. This step requires the use of various filters to completely remove the noise that is superimposed on lightning signals during data collection and can induce a TDOA estimation error, which will affect mapping performance. Therefore, a possible research direction that we intend to follow is to investigate and benchmark the use of various filtration techniques by introducing wavelet transform, Kalman filter, and bandpass filter, each with its own mathematical representation [74].
2. Second, different cross-correlation methods can be compared in three domains: time domain, frequency domain, and wavelet domain. Each cross-correlation method is implemented using interpolation and resampling techniques. Previous studies achieved remarkable accuracy by using cross correlation for better lightning mapping. According to Stock *et al.* [9], cross correlation is the primary technique to map VHF lightning signals, although it has a relatively poor performance (60% accuracy) in estimating lightning mapping. This deficiency opens the door for further improvement through the introduction and application of new cross-correlation methods (e.g., wavelet-based cross correlation). The signals obtained using these cross-correlation techniques may not mimic the natural behavior of real lightning or lead to an optimal estimation of lightning maps. Furthermore, lightning mapping has many graphical shapes and representations, and judging the accuracy of a representation of real lightning is difficult without a validation source. A high-speed camera can be used to validate the lightning results that are presented in elevation and azimuth x–y axis coordination.
3. Finally, observations of broadband VHF pulses associated with lightning discharges by multiple antennas and/or sites are applicable for TOA and ITF to locate source positions. In estimating TOA, the cross-correlation method is occasionally adopted, and interpreting the mechanism of lightning progression offers many contributions [4], [61].
   The authors highly respect and appreciate these contributions indeed, but they are faced with a serious question: "Does cross correlation always give the correct time difference among VHF pulses?" However, the shape of recorded broadband pulses consists of several peaks that resemble an oscillation, and some of the peaks show nearly the same amplitude. If we simply apply the cross-correlation method, the estimated

TABLE 4. Summary of studies related to ITF.

Related Work	Description/Parameters	Merits /Remarks 1	Demerits/Remarks 2
[21]	• This study was the first interferometric study on lightning reported in 1979. • The system was operated at a narrowband of 34 MHz with two VHF antennas spaced 80 m apart. • Quadrature phase detection method was to determine the phase DOA.	• The instrument was useful for tracking the motion of lightning sources. • The ITF was capable of estimating lightning mapping. • The system provided one-spatial dimension of lightning detection with 5 µs.	• Working with only a single-baseline ITF, the system was not able to produce maps or images of lightning. • Some fringes with electric field were recorded from lightning flashes. • The ITF is still imperfect and thus requires further improvements.
[18]	• The system was operated at 34.3 MHz narrowband (3.4 MHz) with two pairs of antennas spaced 15 m apart. • The study implemented perpendicularly crossed baselines rather than a single baseline. • Additional phase reference data are recorded.	• The system was the first to estimate lightning mapping in 2D (azimuth and elevation) location based on ITF with 2.5 µs time resolution. • Results showed the progression of breakdown during a lightning flash.	• The system was susceptible to phase ambiguity. • Fuzzy maps of lightning flashes were generated. • Multiple baselines were required to eliminate the ambiguities and provide comprehensive source information. • The ITF system still requires further improvement.
[17]	• The study was conducted with an operating frequency of 34–274 MHz. • Two pairs of baselines, namely, short baseline of 1/2λ and long baseline of 4λ instead of 2λ, were used to improve the angular uncertainty and thereby avoid fringe ambiguity.	• Lightning mapping in 2D (azimuth and elevation) was realized with a 1 µs time resolution. • The study focused on CG lightning using similar narrowband mixers.	• Compact baselines and few radiation sources were observed. • A short baseline was not useful as it could only determine some portion of flashes relative to the long baseline, which gives high accuracy results.
[20]	• The system was operated at 274 and 6 MHz BW. • Five antennas were used to form orthogonal short baselines (0.2 λ) and long (4λ) baselines. • Quadrature phase detectors were employed to measure phase differences from phase measurements recorded on a magnetic tape.	• 2D mapping (azimuth and elevation) was achieved. • The ITF could estimate lightning mapping. • Lightning data were digitized and stored with a sampling rate of 10 MHz. • New interactive graphics analysis could be carried out.	• A single station was used to locate the radiation sources of IC and CG lightning flashes. • The errors in phase measurements tended to have constant values in the phase plane, which lead to large elevation errors. • Phase ambiguities were manually removed.
[75]	• The ITF system is similar to that of [20] with an additional high-speed camera. • Loop antennas were used for the magnetic field derivative. • An optical sensor was used to trigger the camera. • The RF radiation receiver was operated at 290 MHz.	• A high-speed video camera was used. • The study focused on IC and CG discharges by using a narrowband to determine the lightning sources in 2D. • Maps provided the direction of motion in various lightning flash processes.	• The system failed to completely distinguish the K-processes from the M-processes and dart leaders, although the former did not propagate all the way to ground.
[25]	• The ITF system was similar to that of [20]. • Measurements of phase differences between pairs of antennas were carried out to determine the source directions. • The fast-electric field was recorded and digitized on a magnetic tape.	• The study detailed the phenomena of negative polarity CG discharges, including dart leaders, attempted leaders, and M- and K-events. • Fringe ambiguities were automatically removed using interactive graphics software.	• Ambiguities were not fully resolved. • Some lightning phenomenon details, which are required for the improvement of antenna configurations, were not provided.
[2]	• The study used an improved version of the ITF system used by [20]. • The antenna configurations involving short and long baselines were respectively changed to 1λ and 4.5, and the limited broadband was set to 40–350 MHz. • Integer arithmetic was performed to convert phase measurements to azimuth and elevation values.	• The study mainly focused on VHF radiation events during IC flashes. • CG and IC flashes were comparatively analyzed. • Increased spacing between antennas reduced the ambiguities.	• Artifacts added to the azimuth and elevation angles during the phase conversion. • The study identified a number but not all of the features of IC discharges. • Small errors were noted in the short-baseline measurements.
[61]	• LADR (TOA) and ONERA-3D (ITF) systems were adopted to locate CG lightning sources at 2D maps. • LDAR operated at a frequency of 66 MHz, and ONERA-3D operated at a frequency of 110–118 MHz. • The bandwidth of LDAR data was 6 MHz, whereas that of ONERA-3D was only 1 MHz.	• The simultaneous lightning mapping of the same storm using the LDAR and ONERA-3D systems was investigated, and the results were compared. • IC and CG lightning events were analyzed. • ONERA-3D mapped fast intermittent processes and dart leaders best while LDAR mapped continuously developing IC processes best.	• The LDAR (TOA) system failed to detect positive leaders and slow negative breakdown. • LDAR did not perform well in mapping radiation sources associated with stepped and dart leaders propagating toward the ground. • LDAR was also inadequate to map K-changes inside a cloud. • The ONERA (ITF) system did not map the radiation from continuous positive leaders.
[56]	• The system consisted of four broadband (10–200 MHz) flat plane antennas arranged in square orthogonal baselines spaced 5 m apart. • The slow antenna was used to record the electrostatic field. • Discrete Fourier transform was used to extract the phase differences.	• A 2D broadband ITF lightning mapping system was developed. • Data were stored using Tektronix digital storage oscilloscope and digitized with a 500 MHz sampling rate. • A sequential triggering method was proposed to solve the limited storage memory.	• The ITF system was still limited by recoding time, allowing only certain pulses to be in a lightning flash. • The study included an analysis of rocket-triggered lightning discharges but not real lightning flashes. • Only two types of triggered discharges were analyzed.

TABLE 4. ***(Continued)*** **Summary of studies related to ITF.**

[65]	• The ITF system was operated at 125–200 MHz and consisted of four perpendicular broadband flat antennas spaced 10 m apart horizontally. • Fast and slow antennas were used to capture the lightning electric fields. • The system was equipped with two GPS receivers to provide accurate trigger times. • Differences in arrival times and phase differences were calculated using a geometric model and the fast Fourier transform approach, respectively.	• 2D lightning discharge mapping of CG flashes of multiple strokes was achieved. • Fourier filtering and Symlet wavelet denoising were applied to suppress the unwanted high frequencies (>200 MHz). • Data were stored using a LeCroy oscilloscope with a 1 GHz sampling rate. • The sequential triggering technique was used to reduce the data samples.	• The system used the short-baseline time of arrival (improved version of TOA) with ITF antennas. • Noise reduction effectiveness improved the lightning source detection stage. • The study was limited to a single CG flash. • Results did not provide a clear direction of the lightning flash.
[66]	• Two sets of ITF systems similar to that in [56] were installed in two sites separated by a 5.2 km distance. • Methodologies similar to those in [56] were applied.	• The 3D localization of lightning radiation sources was accomplished by the triangulation of 2D mappings. • The measurement focused on the lightning location of the IC flashes, including the visualization of K-changes.	• Lightning map validation was not possible due to the lack of real images of in-cloud channels. • Most studies used cross-correlation techniques rather than phase fitting.
[6]	• An ITF system with four identical broadband (125–200 MHz) flat plane antennas separated 10 m apart was used. • An additional high-speed camera and fast/slow electric field antennas were adopted. • The system used a high-time accuracy GPS for time synchronization. • A wavelet-based generalized cross correlation was used to find the TDOA.	• The 2D localization system was achieved by integrating an improved TDOA with ITF. • Experiments were conducted IC lightning, and the results were validated by rocket-triggered lightning. • Data were recorded using the LeCroy oscilloscope at 1 GS/s. • The system achieved a localization accuracy within 50 ns of absolute time.	• The TDOA approach was mainly used in TOA-based systems with previous knowledge of arrival times; it tended to fail in noisy environments. • The methodology of using wavelet and segmental cross correlation was not detailed to show the effects of noise, windowing, and numerical localization errors. • Interpolation of cross correlation was suggested to tackle the time resolution.
[9]	• Two systems were used: a broadband (20–80 MHz) ITF, and TOA Langmuir LMA. • The ITF consisted of three flat plate antennas spaced 10.2 m apart and another fourth antenna for record triggering. • Generalized cross correlation in the frequency domain with windowing functions was used to determine the segmental TDOA.	• The study combined 2D ITF maps with 3D LMA to provide a quasi-3D lightning map. • Continuous ITF data were recorded with a sampling rate of 180 MS/s to observe the entire lightning activity. • The use of LMA with ITF instead of using multiple ITF stations provided superior 3D spatial resolutions.	• BITF and LMA are sensitive to environmental noise levels. • Postprocessing was required to eliminate the noisy and nonvalid localizations. • The use of windowing (1.52 µ) with an overlap of 98% to obtain the time delays showed an estimated angular uncertainty of 0.82° for the azimuth angles and 0.63° for the elevation angles.
[68]	• A VHF broadband (25–80 MHz) ITF system of three antennas and one additional antenna for triggering signals was proposed. • A low frequency system of a single fast antenna called BOLT (500 Hz–500 kHz) was used for 3D low frequency lightning localization.	• ITF and BOLD were comparatively analyzed in terms of lightning detection. • The system sampling rate was increased up to 200 MS/s. • The ITF system was able to detect small lightning EM waves.	• BOLT shows blurred lightning horizontal projection paths compared to ITF. • BOLT system requires very long baselines, which fails to detect huge EM waves in a short time. • It requires huge memory to store the data.
[69]	• A VHF broadband [10-80 MHz] ITF system with three flat circular capacitive antennas arranged orthogonally and spaced by 10 m. • Fourth antenna to record fast-electric field. • The cross-correlations method was used for mapping the lightning progression.	• The 2D lightning source maps were validated with the visible events of CG flashes using a high-resolution camera. • Tektronix MDO-3034 oscilloscope was used to digitize and store the data with a sampling rate of 250 MS/s.	• Data recording length was limited to 40 ms due to high storage requirements. • The ITF system still requires improvements to eliminate noise with minimum information loss to enhance lightning maps.
[51]	• The authors were the first to develop an EMTR system for locating lightning return strike points. • The system operated on the broadband frequency ranges of 25–90 MHz and 110–150 MHz for the localization algorithms.	• The system was capable of continuously recording VHF lightning localization. • Two triggered flashes were analyzed. • The advantage of this method is that it does not require any preprocessing of the detected waveforms.	• EMTR was unable to estimate the phase difference between the captured signals. • In calculating the TDOA, the system heavily overlapped due to contaminated noise. • The system is still employed as a prototype instrument.
[55]	• The author attempted to measure the 3D location of the VHF broadband lightning ITF by introducing a theodolite wind measurement method as a reference. • The system was operated at two sites with VHF antenna arrays placed on the square-shaped sites with two baselines of 16 and 15 m and distances of 18.5 km.	• The system was capable of detecting different types of lightning flashes, including 1 IC and 61 CG lightning flashes. • The 3D location of the two-station ITF was found suitable for observing lightning at a close range and at a high elevation angle in a small area.	• The study produced the same results as those of an existing TDOA method. • Increasing the distance of the broadband ITF–VHF system could affect the location accuracy of the radiation source and decrease the location accuracy due to the height of the radiation sources. Therefore, the system needs further improvements.
[71]	• The author proposed a new test for lightning VHF–ITF based on artificial CC pulse generation. • The system consisted of three antennas separated by a distance of 6 m with a short baseline and a limited bandwidth of 20–60 MHz to determine the DOA and TDOA from captured signals.	• Angle-of-arrival techniques were applied to determine the errors in estimating the DOA of CC pulses. • The system was found capable of reducing some errors in the linear distortion of the received lightning signals.	• The system showed that using a short baseline for the estimation of TDOA is still imperfect. • The noise reduction effectiveness from different VHF–ITF installation locations also requires improvement.
[72]	• MUSIC–VHF algorithms were applied to improve lightning mapping. • The system consisted of seven antennas based on 9 m "L"-shaped baselines operating at 25–90 and 110–150 MHz and a sampling rate of 500 MHz.	• The instruments can be useful in comparing return strikes, K-events, dart leaders, and ITF–VHF radiation sources for return strokes. • The numerical simulation was performed to evaluate the performance of MUSIC–VHF relative to the EMTR method.	• The proposed method was limited to classical triggering lightning flashes, which were not compared with the actual lightning of ITF–VHF. • The continuous broadband lightning system required more antennas and could be employed as an instrument, but it still needs to be improved.

TABLE 5. Comparative summary of selected lightning detection and mapping systems.

Method	Ref.	Antenna #	Frequency	Lightning Type	Performance	Baseline
MDF	[35]	2 loop antennas	1 kHz – 1 MHz	99 CGs	18° polarization error	NA
	[36]	6 loop antennas	1–350 kHz	118 triggered RS	~ 2% error	NA
	[1]	100 sensors	400 Hz–400 kHz	7 triggered RS	90% DE	NA
	[37]	2 loop antennas	1 kHz–400 kHz	10 CG flashes	Accuracy of ±5 km	NA
	[38]	2 stations	NA	2 CG flashes	Accuracy ~ 100's meters	2.985 km
	[40]	3 stations	3 to 30 kHz	CG (unknown #)	20º error	NA
	[41]	2 loop antennas	40–800 kHz	8 triggered flashes	NA	130 m
TOA	[16]	2 antennas	60–300 MHz	1 CG	Efficiency of 75%	NA
	[47]	13 stations	60–66 MHz	Balloons VHF Pulses	6–12 m RMS	5–10 km
	[48]	3 antennas	NA	76 CG strikes	NA	10 m
	[58]	3 antennas	300 kHz	NA	NA	300 m
	[6]	4 antennas + Cam	125–200 MHz	9 triggered RS & 1 IC flash	NA	10 m
	[50]	10 substations	160 Hz–600 kHz	7 triggered flashes with 45RS	500-ns time error	6– 66 km
	[49]	6 stations	61.5–65.5 MHz	1 IC flash	Accuracy of < 224 ns	10–30 km
	[18]	2 pairs of antennas	34.3 MHz	6 CG flashes	Positioning error of 2º	NA
	[17]	2 pairs of antennas	34–274 MHz	1 CG flash	NA	NA
	[20]	5 antennas	271–277 MHz	IC & CG (unknown #)	Large El error	0.5–4λ
	[75]	5 antennas	271–277 MHz	6 CG flashes	NA	0.5–4λ
ITF	[25]	5 antennas	27–277 MHz	5 CG Strokes	NA	0.5–4λ
	[2]	5 antennas	27–277 MHz	6 IC & unknown # of CGs	NA	0.5–4λ
	[56]	4 antennas	10–200 MHz	2 triggered flashes	NA	5 m
	[65]	4 antennas	125–200 MHz	1 CG flash	NA	10 m
	[66]	2 stations	10–200 MHz	2 IC flashes	NA	10 m
	[6]	4 antennas	25–200 MHz	1 IC and 1 triggered flash	Accuracy within 50 ns	10m
	[9]	3 antennas	20–80 MHz	IC & CG (Unknown #)	0.82° Az error, 0.63° El	10.2 m
	[68]	4 antennas	25–80 MHz	3 lightning events	NA	5 m
	[69]	4 antennas	10–80 MHz	1 CG flash	NA	10 m
	[51]	4 antennas	50–300 MHz	1 CG flash	Error < 1°	12.5 m
	[55]	4 antennas	50–300 MHz	1 IC flash	200 m (simulation)	NA
	[71]	3 antennas	20–60 MHz	2 lightning events	NA	6 m
	[72]	7 antennas	0–200 MHz	2 triggered flashes	CR: 0.23 (min)	9 m

Az: azimuth, Cam: camera, CC: cloud-to-cloud, CG: cloud-to-ground, CR: coherence ratio, DE: detection efficiency, IC: intracloud RS: return stroke, El: elevation, RMS: root-mean-square, NA: not available, #: number.

time difference may not always be correct despite the smoothness of the main estimation. From the aspect of science, these estimation errors may create confusion in the lightning physics field, especially in the imaging of the progression of positive breakdowns.

Despite the widespread success achieved by the MDF, researchers in the field of lightning mapping do not always pursue it. This reluctance to continue the research into MDF may be attributed to the tremendous development and success of new methods, such as the TOA and ITF. Table 5 summarizes the design, type and performance of lightning detections and mapping systems.As for the development opportunities of the TOA, given the tremendous progress that it has reached, researchers may consider its use in specific applications. For example, one can consider deploying TOA to study the phenomenon of negative lightning breakdowns and visualize bidirectional leader processes.

As for the possibility of research in the field of ITF, the technology may be developed further from aspects such as real-time mapping. Previous studies on lightning mapping were carried out offline due to the limitation of storage capacity and the high computational cost of high sampled lightning data. Considering the rapid technological advancements in digital signal processing techniques and storage devices, a real-time processing of lighting signals has become possible. The current use of static temporal window (i.e., fixed-length window) could fail in accurately mapping the low burst of peak power, i.e., positive breakdown. Thus, an adaptive windowing procedure could effectively solve this problem and improve the lightning mapping accuracy. In complex discharge processes, such as winter lightning, EM waves are thought to arrive frequently at the same time, thus leading to multiple sources being present in the same window and resulting in failure of lightning mapping. A similar problem-solving approach is called the "CLEAN method" in the VLBI of the same passive radar [76]. As a different approach, compression sensing can also be applied.

VII. CONCLUSION

Lightning mapping is crucial in lightning monitoring, tracking, detection, and mapping of CG and IC flashes. This review presents an intensive discussion of the studies that are most related to lightning detection methods. We discuss the common methods used for lightning mapping, namely, MDF, TOA, and ITF. We conclude that the following points are essential for lightning mapping systems: measurement improvements of radiation sources to produce accurate mapping, especially for weak sources; increasing the accuracy of the measurements of current amplitude and lightning mapping efficiencies; and distinguishing the types of flashes. From this review, we also conclude that VHF is the most common frequency band used for lightning mapping as it provides more information on broader frequency components and allows for more accurate mapping in comparison with other frequency bands.

Some of the methods studied in this work perform better when combined with other methods to form hybrid systems. Such improvement is noted in the combination of MDF and TOA methods. We also conclude that achieving highly accurate mapping using the TOA method requires installing a large number of sensors, which can be costly. By contrast, ITF could accurately map lightning signals with three to four antennas only. ITF is one of the most promising techniques in mapping signals, and we note that with improved signal processing, the ITF method can achieve high accuracy in mapping lightning discharges. One advantage of ITF is that it is not sensitive to noise that is captured along with recorded lightning signals.

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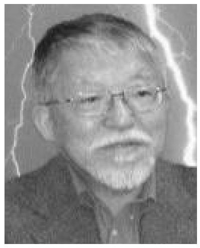

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