Earth and Space Science

TECHNICAL REPORTS: METHODS
10.1029/2020EA001111

Huntsville Alabama Marx Meter Array 2: Upgrade and Capability

Yanan Zhu1, Phillip Bitzer1,2, Michael Stewart1, Scott Podgorny1, David Corredor1, Jeff Burchfield1, Lawrence Carey2, Bruno Medina2, and Michael Stock3

1Earth Systems Science Center, University of Alabama in Huntsville, Huntsville, AL, USA, 2Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, AL, USA, 3Earth Networks, Germantown, MD, USA

Abstract The Córdoba Argentina Marx Meter Array (CAMMA), consisting of 10 second-generation Huntsville Alabama Marx Meter Array (HAMMA 2) sensors, operated at Córdoba, Argentina, during the Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) field campaign in late 2018. Initial results obtained from the campaign demonstrate that the new sensor is able to provide a significantly more detailed depiction of various lightning processes than its first generation. The lightning flashes mapped by the CAMMA and a colocated Lightning Mapping Array (LMA) were compared. The overall flash structures mapped by the CAMMA and the LMA look similar for most of the flashes. However, comparisons at smaller time scale show that the majority of CAMMA and LMA sources are not concurrent, indicating that unmatched sources were possibly due to different physical processes in leader propagation dominating different frequencies and differences in data processing and location techniques.

1. Introduction

Various processes in lightning discharges emit electromagnetic waves ranging from several hertz to $10^{18}$ Hz (X-rays), in which the radio frequency band (3 kHz to 300 MHz) was widely used for most ground-based lightning locating systems (LLSs). Reviews on various LLSs can be found in Cummins and Murphy (2009) and Nag et al. (2015). By detecting very high frequency (VHF) emissions at 60–66 MHz, the Lightning Mapping Array (LMA) can depict the three-dimensional lightning channel development for both intracloud and cloud-to-ground lightning with high location accuracy (Rison et al., 1999; Thomas et al., 2004), which makes it a great tool to study severe storms and lightning physics (e.g., Goodman et al., 2005; Krehbiel et al., 2000). A number of short-baseline lightning locating networks operated in low-frequency (LF)/medium-frequency (MF) (30 kHz to 3 MHz) band have been developed in recent years (Bitzer et al., 2013; Karunarathne et al., 2013; Lyu et al., 2014; Shi et al., 2017; Wang et al., 2016; Wu et al., 2018; Yoshida et al., 2014). The lightning mapping in LF/MF seems to be less complete compared to LMA in terms of the number of sources located until Lyu et al. (2014) found that interferometric-time difference of arrival (TDOA) location technique can significantly improve the number of located sources. Such improvement can also be seen in works of Stock et al. (2016) and Wu et al. (2018), who applied similar cross-correlation techniques to their LF lightning locating networks, respectively.

The first generation of Huntsville Alabama Marx Meter Array (HAMMA 1) consists of seven electric field change meters with a typical baseline of 10–15 km. The HAMMA 1 sensor has a frequency response from 1 Hz to 400 kHz and a sampling rate of 1 MS/s. The lightning flashes mapped by HAMMA 1 largely resemble lightning images produced by the North Alabama Lightning Mapping Array (NALMA) (Bitzer et al., 2013). In this paper, the second generation of the HAMMA (HAMMA 2) sensor will be presented. The newly designed HAMMA 2 sensor and a new location algorithm empower the HAMMA 2 to map lightning discharges with far more detail.

A total of 10 HAMMA 2 sensors were deployed around Córdoba, Argentina, from October to December 2018 for Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) field campaign. Because of its service location, the network is referred to as Córdoba Argentina Marx Meter Array (CAMMA) thereafter in this paper. The CAMMA was deployed in a 100 km by 100 km area with typical baselines from 30–60 km. A total of 11 LMA stations
were also deployed in the same area, nine colocated with CAMMA stations. The locations for CAMMA and LMA stations are shown in Figure 1c. We will present some initial results of the CAMMA obtained from RELAMPAGO field campaign. Additionally, lightning flashes mapped by CAMMA and the colocated LMA will be compared.

2. Instrumentation

The HAMMA 2 sensor takes on a more compact and integrated design. A picture of the sensor is shown in Figure 1a. The HAMMA 2 sensor integrates antenna, front-end electronics, field programmable gate array (FPGA), Global Positioning System (GPS) module, and a compact computer into a standalone unit, which is the white inverted pot-like unit shown in the Figure 1a. The diameter of the unit is 40 cm. The sensor can be powered by an AC outlet or by solar energy. The integrated design provides more flexibility for sensor deployment at various locations. The HAMMA 2 sensor is equipped with two channels for measuring electric field changes produced by lightning at different frequency ranges. Figure 1b shows the bottom view of the sensor. The inner and outer annuli are the sensing plates for the slow and fast channels, respectively. The bandwidth for the slow channel is 1 Hz to 57 kHz with a time decay constant of 100 ms. The slow channel serves to keep the electrostatic change produced by lightning flashes without saturation for most nearby flashes, which can be used for charge retrieval analysis. The bandwidth for the fast channel is 1.6 kHz to
2.5 MHz with a time decay constant of 100 μs. The fast channel is designed to be very sensitive for lightning mapping. Note that the AM radio bands from 540 kHz to 1.6 MHz are within the bandwidth of our fast channel. To avoid noise from those bands, we only used 100 to 500 kHz frequency content of the fast-channel data for lightning mapping by applying a digital band-pass filter. The sensor is triggered when signals from the fast channel exceed a preset threshold. The signals from slow and fast channels were digitized with 16 bit at the sampling rates of 1 and 10 MS/s, respectively. The digitized data were written into a USB flash drive mounted on the compact computer. The record length of each record is 1 s with a 100 ns RMS timing error of the sensor mounted on the compact computer. The record length of each record is 1 s with a 100 ns RMS timing error of the sensor. Currently, the HAMMA 2 sensor is still under development. In the future, a cellular communication module will be installed on the sensor to remotely monitor the sensor status and provide the capability to show lightning locations in real time.

3. Location Algorithm

The algorithm developed to retrieve geolocation of lightning sources is referred to as the two-step cross-correlation time-of-arrival (TOA) algorithm, which is similar to the algorithm used by Lyu et al. (2014) but differs in several steps.

The recorded raw waveforms were first passed through a digital band-pass filter with passband from 100 to 500 kHz to remove AM radio noise. The station with the best signal/noise ratio was considered as the reference station, and the remaining stations were correlated against it. The filtered waveforms from each station were divided into the successive and overlapped 750-μs windows with 375-μs sliding steps. The selected window size is about twice larger than the largest possible time difference between each pair of stations, which is 376 μs, corresponding to the distance of 113 km between the southernmost station and the northeastern station shown in Figure 1c. The selection of long and overlapped windows ensures that the same prominent peaks are included in the windows for all stations, which is important for producing reliable cross-correlation results. Cross correlation was implemented to waveforms in each 750-μs window from all stations. Cross correlation of Signals A and B measures the similarity between Signal A and shifted copies of Signal B as a function of the shift. If more than four pairs of stations had maximum normalized cross-correlation coefficients greater than 0.3, this window is considered to have lightning pulses in it, and the shifts corresponding to the maximum correlation coefficients were used for waveform alignment. Windows of pure noise (no lightning pulses) have very noisy correlation curves, and the maximum correlation is usually below 0.2, which disqualifies them for further processing. After alignment, the 750-μs big windows will be divided into twenty-five 30-μs small windows, and the same cross-correlation alignment process was implemented to each 30-μs window again to further align the waveforms in small windows. Only the 30-μs windows with more than four stations having maximum correlation coefficients >0.7 will be used for the further TOA location. The arrival time difference between Stations i and j is given by \( \Delta t_{ij} = \Delta t_{ij \, \text{big}} + \Delta t_{ij \, \text{small}} \), where \( \Delta t_{ij \, \text{big}} \) and \( \Delta t_{ij \, \text{small}} \) are the time shifts taken from the 750-μs big-window and 30-μs small-window cross correlations, respectively. With arrival time differences available, the TDOA location technique can be used to retrieve the locations of lightning sources. However, no timing of lightning sources can be obtained from the TDOA technique. To solve this problem, we first determined the timing of the largest peak in the 30-μs waveform of the best station \( t_i \). The timings of the same peak in waveforms of other stations can be obtained using \( t_j = t_i + \Delta t_{ij} \). With the arrival times at all stations, the TOA algorithm can be implemented by sending the arrival times into a nonlinear minimizer using the Levenberg-Marquardt algorithm to retrieve the locations and timing of lightning sources. Only sources with reduced chi-square \( \chi^2 < 5 \) were kept as well located lightning sources. Note that the use of the overlapped window produces duplicated solutions. To remove the duplicates, we only allow one source per 30 μs (small window size), and only the source with lower \( \chi^2 \) will be kept.

In the following section, by showcasing two mapped flashes, we will demonstrate that the increased sensitivity from the hardware end of the new sensor, coupled with the fact that hybrid interferometric-TOA technique can locate continuous radiation sources (Lyu et al., 2014), gives the CAMMA the capability to locate substantially more lightning sources than its first generation.
4. Two Flashes Mapped by the CAMMA

In this section, we will present an intracloud lightning flash and a cloud-to-ground lightning flash mapped with five to six CAMMA stations. The two flashes were recorded by the CAMMA at the early stage of the field campaign when the CAMMA and LMA stations were not fully deployed. However, the CAMMA is still able to map these two flashes in detail with only five to six stations. The LMA data for the two flashes were not available. The physics sign convention, according to which the downward-directed electric field change vector produced by a negative return stroke is negative, is used throughout this paper.

4.1. An Intracloud Lightning Flash With Very Long K Process

Figure 2 shows an intracloud flash mapped by the CAMMA. The animation of this flash (Animation S1) and its location relative to the CAMMA network (Figure S1) can be found in the supporting information. The CAMMA 11 shown in Figure 1 was at the origin in Figures 2, 3, and 4. The flash appears to initiate at an altitude of 4.8 km and started to propagate bidirectionally at 172 ms (time is relative to the first CAMMA source shown in Figure 2). The inferred positive end was at the altitude of 6–7 km while the negative end was moving alternately down and up until it eventually reached the altitude of 5–7 km in another region that is about 25 km away from the positive end. The negative leader appears to propagate continuously during the period from 188 to 448 ms. In contrast to the negative leader, the positive end appears to be more stagnant when the negative leader was moving, and it started to reveal its branching structures via some small-scale K processes at 443 ms and became inactive at 600 ms. After a quiet period of 74 ms with few detected sources, a fast negative leader initiated at the position that was very close to the tip of remnants of the previous positive leader. The fast negative leader traversed the main channel of the preceding positive leaders and passed through the flash origin. Then it continued progressing along about three quarters of preceding main negative leader channel. This is similar to the VHF observations of K process in intracloud lightning flashes (Akita et al., 2010; Shao & Krehbiel, 1996). The average 3-D speed of the fast negative leader is 1.9 × 10⁶ m/s. The speed of negative recoil leaders in intracloud flashes were found on the order of 10⁶ to 10⁷ m/s (Akita et al., 2010; Shao & Krehbiel, 1996), consistent with our observation. The typical speed of a dart-stepped leader in negative cloud-to-ground lightning ranges from 1×10⁶ to 2×10⁷ m/s. (Rakov & Uman, 2003, chapter 1). The corresponding electric field (fast channel) signatures of this fast negative leader is very similar to regular pulse bursts reported in the literature but the 47-ms duration is significantly longer than the typical value of 1 ms for K process (Krider et al., 1975; Rakov et al., 1996; Zhu et al., 2014).

4.2. A Cloud-to-Ground Lightning Flash Containing Eight Return Strokes

Figure 3 shows a cloud-to-ground lightning flash with a preceding intracloud flash. The preceding intracloud flash is also shown because it was very close to the CG temporally and spatially. The animation of these two flashes (Animation S2) and their location relative to the CAMMA network (Figure S2) can be found in the supporting information. The initiation location of the preceding intracloud lightning flash is 7 km southwest of the origin of the CG flash. The intracloud lightning flash initiated at the altitude of 7 km and began with a clear downward negative stepped leader (labeled as IC IBPs in Figure 3a) and extended to an altitude of 4 km with an average speed of 4.5 × 10⁵ m/s, on the order of a typical negative stepped leader (e.g., Shao et al., 1995; Rakov & Uman, 2003, chapter 4.4). The upper positive end of the IC leader structure shows little movement. The CG flash was initiated at 88 ms (relative to the first source CAMMA source shown in Figure 3) with another downward stepped leader, as manifested by the second initial breakdown pulse sequence (labeled as CG IBPs) in Figure 3a. The stepped leader propagated for about 47 ms and ceased at an altitude of 3 km. About 10 ms later, a new bilevel leader (labeled in Figure 3b) started, utilizing parts of the remnants of the preceding CG stepped leader. The negative end of the bilevel leader started to show a clear downward movement at 205 ms and produced the first return stroke at 245 ms. It appears that all of the following seven subsequent leader/return stroke sequences utilized the same channel of the first stroke as one can see in Figure 3c that the overlapped source locations below 4 km that were produced by all leader/return stroke sequences. The sources of all the eight return strokes (marked by black triangles in Figure 3) were located. The standard deviations of the eight return-stroke locations are 26, 16, and 240 m with the maximum differences being 71, 50, and 640 m in X, Y, and Z, respectively. Out of the eight leaders preceding return strokes, four of them were clearly mapped. Reasons for the not clearly mapped leaders are (1) the amplitudes of pulses produced by the leader are too small and/or (2) the pulses produced by some other concurrent intracloud activities were larger than those produced by downward moving leaders,
which results in the “masking” effect (weak sources are masked by the strong ones in the same time window). It can be seen from Figure 3e that the other end (intracloud portion) of the CG flash progressed horizontally toward the southeast.

5. Comparison of CAMMA With LMA

Despite the difference by 2–3 orders of magnitude in frequency response, the lightning maps produced by the hybrid interferometric-TOA technique used in LF lightning mapping appear similar to those of VHF LMA (Lyu et al., 2014; Wu et al., 2018). Bitzer et al. (2013) compared the TOA-based lightning maps of
HAMMA 1 and NALMA and found source locations mapped by both systems were well correlated. Considering the improvements in both hardware and location algorithms, it is interesting to compare the CAMMA and LMA for the same lightning flashes. The fact that most of the stations of LMA and CAMMA were colocated in the field campaign provides a great opportunity to do the comparative analysis. Unlike the flashes presented in the previous section, the flashes used for comparative analysis in this section were recorded at the later stage of the field campaign, when LMA and CAMMA stations were fully deployed. For both CAMMA and LMA, a minimum of six detecting stations and a maximum reduced chi-square value of 5 are required to locate a source. Sources over a typical LMA network are located with an uncertainty of several tens of meters (Koshak et al., 2004; Thomas et al., 2004).

Figure 3. Electric field waveforms and the 3-D mapping for the cloud-to-ground lightning flash including it preceding intracloud lightning (about 7 km away from the CG flash). The plot layout is the same as Figure 2. The return stroke terminations were marked by black triangles in panels b, c, and f.
The comparison of lightning source locations mapped by the CAMMA and LMA for an intracloud flash is given in Figure 4. The timing in Figure 4 is relative to the first CAMMA source. A total of eight CAMMA stations and nine LMA stations were active during this flash. The flash structures mapped by two networks look generally similar in the plan view. The flash started with a negative leader ascending from 5 km and propagating through an inferred positive charge region roughly at the altitude of 5-8 km. Many CAMMA sources were located below 4 km after 200 ms of the flash. By looking at the corresponding electric field waveforms recorded at the close stations, all the sources located below 4 km are produced by K processes manifested by a sequence of pulses that appear similar to regular pulse bursts. We speculated that the positive breakdown was not mapped by the CAMMA but its structure is partially revealed by mapped K processes that occurred in the remnants of positive leaders. Note these K processes were not mapped by the LMA, which possibly because the LMA sometimes cannot pick up the same peak in 80-μs windows for all stations. As demonstrated by Kolmašová et al. (2018) for initial breakdown processes, the LMA could have a large number of intense VHF radiation in a single 80-μs window. However, the largest peaks selected for locating for different stations sometimes do not correspond to each other, leading to no located source. The number of CAMMA sources located for this flash is twice that located by the LMA. Several other possible factors contributing to the difference in the number of located sources were listed as follows: (1) The window length used for locating for CAMMA (30 μs) is smaller than that of the LMA (80 μs). This factor can be addressed in the future by comparing sources of CAMMA and the LMA operating in the mode with shorter window length. (2) The baseline for both the CAMMA and LMA in this campaign is relatively long (30 to 60 km), in which VHF signals suffer from more attenuation than LF signals. Several short-baselined LMAs showed the capability to detect thousands of sources for a typical lightning flash (e.g., Edens et al., 2012; Pilkey et al., 2013; Thomas et al., 2004). (3) The CAMMA uses the interferometric-TOA hybrid technique while the peak-finding-TOA technique was used for the LMA.
The lightning sources located by the CAMMA and the LMA in a 30-min period from 19:30 to 20:00 UTC on 5 December 2018 were compared. All the lightning flashes recorded in the 30-min period are within 50 km of the closest CAMMA sensor with the majority of them were within the network. The locations of lightning sources in the 30-min period relative to both networks are given in Figure S4. In the 30-min period, a total of 45420 CAMMA sources and 67716 LMA sources were located, respectively. The number of CAMMA sources is smaller mainly due to the fact that the LMA sensors were more frequently triggered than the CAMMA sensors and that results from the fixed trigger threshold of the CAMMA versus the dynamic trigger threshold of LMA.

The CAMMA sources recorded in the 30-min period were first grouped into flashes. The grouping algorithm is similar to what was described by Cummins et al. (1998). Sources are added to any active flash if the source is within 20 km of any previous sources in the flash and the time interval from the previous source is less than 500 ms. Only flashes with more than 30 CAMMA sources were kept. The CAMMA sources were grouped into 145 flashes, and then corresponding LMA sources were searched in the same time periods for each of these flashes. We produced figures (not shown) for each of the 145 flashes like what was shown in Figure 4, from which we confirmed that both networks observed the same lightning flash with similar structures in each. For the 145 sorted flashes seen by both networks, 44,540 CAMMA sources and 13,105 LMA sources were located. Similar to what has been shown in Figure 4, the structures of lightning maps produced by the CAMMA and the LMA look similar for most of the 145 flashes. The CAMMA detected more sources than the LMA for the majority (126/145) of the flashes.

Spatial differences between close LF and VHF sources of the 145 flashes were determined. Within the ±20 μs and 2-km radius of each CAMMA source, the LMA sources were searched for a match. If a matched source could be found, the location difference was computed. For the rare cases in which multiple matched sources were found in the searching window, only the temporally closest source was kept. Out of 44,540 CAMMA sources, 2610 (6%) of them have matched LMA sources. On the other hand, 20% (2,610/13,105) of the LMA sources have matched CAMMA sources. For the matched sources, the histograms of location differences in X, Y, and Z are given in Figure S5. The median location differences (CAMMA relative to LMA) are 40, 28, and −156 m in X, Y, and Z, respectively. The corresponding standard deviations are 157, 139, and 488 m in X, Y, and Z, respectively. The timing error produces larger uncertainty in Z than those in X and Y due to the planar array effect. Factors that contribute to the fact that the CAMMA sources are generally lower than LMA sources by a median of 156 m are not clear at the time of this writing and will be the topic for future study. The differences are similar to what reported for the difference between HAMMA 1 and NALMA (Bitzer et al., 2013). Different spatial thresholds ranging from 0.5 to 5 km were also used for source matching. The number of matched sources and location differences between matched sources for different thresholds can be found in Table S1.

Although the overall structures look similar for most of the flashes, the comparison of CAMMA and LMA sources at smaller time scale (±20 μs) shown above indicates that the many CAMMA and LMA sources were not concurrent, revealing that unmatched LF and VHF sources were possibly produced by different physical processes dominating different frequencies. It is known that large transient current in relative long and pre-established channels produces powerful emissions in LF/VLF while the radiation produced by the development of streamers in breakdown processes dominate VHF (Cummins & Murphy, 2009; Shi et al., 2016). A study on initial breakdown processes found that 47% of broadband initial breakdown pulses are accompanied by VHF pulses and many VHF pulses have no associated broadband initial breakdown pulses. These observations indicate that the initial lightning leader extends very fast at multiple time scales ranging from submicrosecond to several tens of microseconds (Kolmasova et al., 2019). It was speculated that the VHF radiation is produced by small corona streamers that give rise to the negative breakdowns at a larger scale that are manifested by initial breakdown pulses (Marshall et al., 2019). While the study of Kolmasova et al. (2019) focused on comparisons of LF/VHF radiation produced by lightning during the initial breakdown process, our flash-to-flash comparison was looking at LF/VHF radiation sources produced by propagating leaders from initiation to termination. If the simultaneous VHF/LF observations by Kolmasova et al. (2019) do suggest the initial leader extends at multiple time and spatial scales, then this study shows this happens throughout the leader processes of the flash, not just during the initial stage of leaders. It is also
quite possible that some of the unmatched sources are due to the limitations in data processing or location techniques of either system. Some possible factors were given earlier in this section.

6. Summary

The newly designed HAMMA 2 sensor was presented in this paper. The new sensor is a standalone unit with all the components integrated, which makes it more flexible for deployment. A total of 10 new sensors were deployed around Córdoba, Argentina, during the RELAMPAGO field campaign from October to December 2018. Some initial results from the RELAMPAGO field campaign demonstrated that the upgrades in hardware and location technique give the CAMMA the capability to map various lightning processes (e.g., K processes, subsequent leaders, initial breakdowns, and return strokes). The lightning flashes mapped by the CAMMA and the colocated LMA were compared. For 2,610 matched sources using the ±20-μs window and 2-km spatial threshold, the median location differences (CAMMA relative to LMA) are 40, 28, and −156 m in X, Y, and Z, respectively. Although the overall flash structures mapped by the CAMMA and the LMA look similar, comparisons at individual source time scale show that the majority of CAMMA and LMA sources are not concurrent, indicating that unmatched LF and VHF sources were possibly due to different physical processes in leader propagation dominating different frequencies and differences in data processing and location techniques.

Acknowledgments

This research was supported in part by NSF Grants AGS-1654576 and AGS-1661785. The authors thank Timothy Lang for providing the LMA data and Jacquelyn Ringhausen, Lena Heuscher, Shaina Wilburn, Kecly Brunner, Sarah Paiman, and Shane Pendleton for testing sensors and collecting the data in the field campaign. This study complies with the AGU data policy; the presented data are available online (at https://figshare.com/articles/CAMMA_and_LMA_data/9820625/1). Comparison of CAMMA with LMA for more flashes can be found at figshare (http://figshare.com/articles/CAMMA_LMA_figures_reprocessing/11944413). The authors thank the two anonymous reviewers for their constructive comments.

References

Akita, M., Nakamura, Y., Yoshida, S., Morimoto, T., Ushio, T., Kawasaki, Z., & Wang, D. (2010). What occurs in K process of cloud flashes? Journal of Geophysical Research, 115, D07106. https://doi.org/10.1029/2009JD012016

Biter, P. M., Christian, H. J., Stewart, M., Burchfield, J., Podgorny, S., Corredor, D., et al. (2013). Characterization and applications of VLF/LF source locations from lightning using the Huntsville Alabama Marx Meter Array. Journal of Geophysical Research: Atmospheres, 118, 3120–3138. https://doi.org/10.1002/jgrd.50271

Cummins, K. L., & Murphy, M. J. (2009). An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN. IEEE Transactions on Electromagnetic Compatibility, 51(3), 499–518. https://doi.org/10.1109/TEMC.2009.2023450

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., & Pifer, A. E. (1998). A combined TOA/MDF technology upgrade of the US National Lightning Detection Network. Journal of Geophysical Research, 103(D8), 9035–9044. https://doi.org/10.1029/98JD00153

Edens, H. E., Eack, K. B., Eastvedt, E. M., Trueblood, J. J., Winn, W. P., Krehbiel, P. R., et al. (2012). VHF lightning mapping observations of a triggered lightning flash. Geophysical Research Letters, 39, L19807. https://doi.org/10.1029/2012GL053666

Goodman, S. J., Blakeslee, R., Christian, H., Koshak, W., Bailey, J., Hall, J., et al. (2005). The North Alabama Lightning Mapping Array: Recent severe storm observations and future prospects. Atmospheric Research, 76(1–4), 423–437. https://doi.org/10.1016/j.atmosres.2004.11.035

Karunarathne, S., Marshall, T. C., Stolzenburg, M., Karunarathna, N., Vickers, I. E., Warner, T. A., & Orville, R. E. (2013). Locating initial breakdown pulses using electric field change network. Journal of Geophysical Research: Atmospheres, 118, 7129–7141. https://doi.org/10.1029/2013JD049441

Kolmasova, I., Marshall, T., Bandara, S., Karunarathne, S., Stolzenburg, M., Karunarathne, N., & Siedlecki, R. (2019). Initial Breakdown Pulses Accompanied by VHF Pulses During Negative Cloud-to-Ground Lightning Flashes. Geophysical Research Letters, 46, 5592–5600. https://doi.org/10.1029/2019GL082488

Kolmas’kova, I., Santolík, O., Defer, E., Risen, W., Coquillat, S., Pedebey, S., et al. (2018). Lightning initiation: Strong pulses of VHF radiation accompany preliminary breakdown. Scientific Reports, 8(1), 3650. https://doi.org/10.1038/s41598-018-21972-z

Koshak, W. J., Solakekivicz, R. J., Blakeslee, R. J., Goodman, S. J., Christian, H. J., Hall, J. M., et al. (2004). North Alabama Lightning Mapping Array (LMA): VHF source retrieval algorithm and error analyses. Journal of Atmospheric and Oceanic Technology, 21(4), 653–558. https://doi.org/10.1175/1520-0426(2004)021<0653:NLMAIV>2.0.CO;2

Krehbiel, P. R., Thomas, R. J., Rison, W., Hamlin, T., Harlin, J., & Davis, M. (2000). GPS field interferometric lightning mapping system reveals lightning inside storms. Eos, Transactions American Geophysical Union, 81(3), 21. https://doi.org/10.1029/99EO00014

Krider, E. P., Redd, G. J., & Noggle, R. C. (1975). Regular radiation field pulses produced by intracloud lightning discharges. Journal of Geophysical Research, 80(27), 3801–3804. https://doi.org/10.1029/JC080i027p03801

Lyu, F., Cummer, S. A., Solanki, R., Weinert, J., McBride, L., Katko, A., et al. (2014). A low-frequency near-field interferometric-TOA 3-D Lightning Mapping Array. Geophysical Research Letters, 41, 7777–7784. https://doi.org/10.1002/2014GL061963

Marshall, T., Bandara, S., Karunarathne, N., Karunarathne, S., Kolmasova, I., Siedlecki, R., & Stolzenburg, M. (2019). A study of lightning flash initiation prior to the first initial breakdown pulse. Atmospheric Research, 217, 10–23. https://doi.org/10.1016/j.atmosres.2018.10.013

Nag, A., Murphy, M. J., Schulz, W., & Cummins, K. L. (2015). Lightning locating systems: Insights on characteristics and validation techniques. Earth and Space Science, 2(4), 65–93. https://doi.org/10.1002/2014EA000051

Pilkey, J. T., Uman, M. A., Hill, J. D., Ngin, T., Gamerota, W. R., Jordan, D. M., et al. (2013). Rocket- and wire-triggered lightning in 2012 tropical storm Debby in the absence of natural lightning. Journal of Geophysical Research: Atmospheres, 118, 13,158–13,174. https://doi.org/10.1002/2013JD020501

Rakov, V. A., Uman, M. A., Hoffman, G. R., Masters, M. W., & Broek, M. (1996). Bursts of pulses in lightning electromagnetic radiation: Observations and implications for lightning test standards. IEEE Transactions on Electromagnetic Compatibility, 38(2), 156–164. https://doi.org/10.1109/15.494618

Rakov, V. A., & Uman, M. A. (2003). Lightning: Physics and effects. New York: Cambridge University Press.
Rison, W., Thomas, R. J., Krehbiel, P. R., Hamlin, T., & Harlin, J. (1999). A GPS-based three-dimensional lightning mapping system: Initial observations in Central New Mexico. *Geophysical Research Letters*, 26(23), 3573–3576. https://doi.org/10.1029/1999GL010856

Shao, X. M., & Krehbiel, P. R. (1996). The spatial and temporal development of intracloud lightning. *Journal of Geophysical Research*, 101(D21), 26,641–26,668. https://doi.org/10.1029/96JD01943

Shao, X. M., Krehbiel, P. R., Thomas, R. J., & Rison, W. (1995). Radio interferometric observations of cloud-to-ground lightning phenomena in Florida. *Journal of Geophysical Research*, 100(D2), 2749–2783. https://doi.org/10.1029/94JD01943

Shi, D. D., Zheng, D., Zhang, Y., Zhang, Y. J., Huang, Z. G., Lu, W. T., et al. (2017). Low-frequency E-field Detection Array (LFEDA)—Construction and preliminary results. *Science China Earth Sciences*, 60(10), 1896–1908. https://doi.org/10.1007/s11430-016-9093-9

Shi, F., Liu, N., & Rassoul, H. K. (2016). Properties of relatively long streamers initiated from an isolated hydrometeor. *Journal of Geophysical Research: Atmospheres*, 121, 7284–7295. https://doi.org/10.1002/2015JD024580

Stock, M., Wu, T., Akiyama, Y., Ushio, T., Kawasaki, Z., Nakamura, Y., et al. (2016). Improvements to the BOLT lightning location system. In 2016 33rd International Conference on Lightning Protection (ICLP) (pp. 1–4). IEEE. https://doi.org/10.1109/ICLP.2016.7791365

Thomas, R. J., Krehbiel, P. R., Rison, W., Hunyady, S. J., Winn, W. P., Hamlin, T., & Harlin, J. (2004). Accuracy of the lightning mapping array. *Journal of Geophysical Research*, 109, D14207. https://doi.org/10.1029/2004JD004549

Wang, Y., Qie, X., Wang, D., Liu, M., Su, D., Wang, Z., et al. (2016). Beijing Lightning Network (BLNET) and the observation on preliminary breakdown processes. *Atmospheric Research*, 171, 121–132. https://doi.org/10.1016/j.atmosres.2015.12.012

Wu, T., Wang, D., & Takagi, N. (2018). Lightning mapping with an array of fast antennas. *Geophysical Research Letters*, 45, 3698–3705. https://doi.org/10.1002/2018GL077628

Yoshida, S., Wu, T., Ushio, T., Kusunoki, K., & Nakamura, Y. (2014). Initial results of LF sensor network for lightning observation and characteristics of lightning emission in LF band. *Journal of Geophysical Research: Atmospheres*, 119, 12,034–12,051. https://doi.org/10.1002/2014JD020665

Zhu, B., Zhou, H., Thottappillil, R., & Rakov, V. A. (2014). Simultaneous observations of electric field changes, wideband magnetic field pulses, and VHF emissions associated with K processes in lightning discharges. *Journal of Geophysical Research: Atmospheres*, 119, 2699–2710. https://doi.org/10.1002/2013JD021006