2018 25th International Lightning Detection Conference & 7th International Lightning Meteorology Conference
March 12 - 15 | Ft. Lauderdale, Florida, USA

Interferometric Radio Imaging of the Initiation and Propagation of In-Cloud Lightning Leaders

Steven A. Cummer and Fanchao Lyu
Electrical and Computer Engineering Department
Duke University
Durham, NC USA
cummer@duke.edu

Zilong Qin and Mingli Chen
Department of Building Service Engineering
The Hong Kong Polytechnic University
Hung Hom, Hong Kong

***Abstract*—This paper describes the design and application of a very high frequency (VHF, 30-300 MHz) radio interferometric lightning imaging system built at Duke University. Here we report measurements and imaging of processes associated with lightning flash initiation. We see clear examples of previously reported fast positive breakdown that appears to be responsible for the initiation of some flashes. We observe many examples, however, of flashes that do not exhibit fast positive breakdown process at initiation, and we attempt to distinguish and quantify these two populations.**

***Keywords*—lightning; radio imaging; interferometry; VHF; fast positive breakdown**

I. Introduction

Radio emissions continue to provide the clearest (and sometimes only) view into many of the most interesting and least understood lightning processes. These include terrestrial gamma-ray flashes [Dwyer et al., 2012], some and perhaps all of which are produced during the upward development of new in-cloud lightning leaders; and lightning initiation itself, which at least sometimes appears to involve a newly discovered but largely unknown process termed fast positive breakdown [Rison et al., 2016; Stock et al., 2017].

Here we describe the development of a very high frequency (VHF, 30-300 MHz) interferometric lightning imaging system built at Duke University. We also present recent measurements made by this system, with a primary scientific focus on detection and imaging of fast positive breakdown at the initiation of lightning flashes.

II. VHF Lightning Imaging System

We designed, built, and operated our VHF interferometer near Duke University in the summer of 2017. This system is based on three flat plate electric field sensors on two 50 meter orthogonal baselines, a sampling frequency of 125 MHz, and an overall bandwidth of roughly 0.1 to 55 MHz. The overall system design is very similar to the VHF interferometer built and

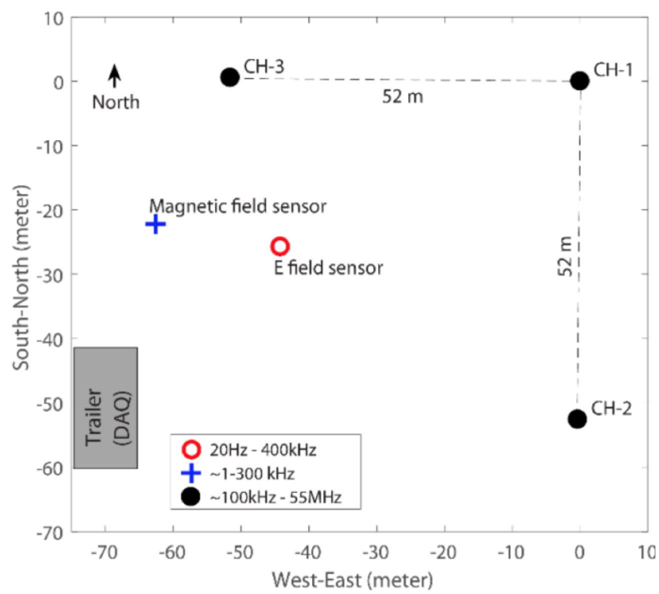

Fig. 1. Plan view of the VHF sensors that comprise our interferometer system along with several collocated lower frequency sensors.

operated by researchers at New Mexico Tech [Stock et al., 2014]. The Duke VHF interferometer system began operation in May 2017 and has since recorded radio emissions from lightning flashes in dozens of individual storms. The wide bandwidth enables us to process and image different frequency ranges separately to gain insight into the spatial and temporal relationship of lightning processes that radiate at different frequencies. Fig. 1 illustrates the geometry and physical layout of our VHF interferometer system.

III. PROCESSING AND EXAMPLE IMAGES

Our data processing approach is essentially the same as that developed and described by Stock et al. [2014], and it is illustrated in Fig. 2. The waveforms are processed in pairs. Short time windows of roughly 1 µs are interpolated and cross correlated to measure the time difference of the signal across the two sensor baseline. Time differences from windows in which the two signals are sufficiently coherent, i.e. time-shifted but otherwise similar, are kept as source points. Each sensor pair then delivers a time sequence of time differences with a precision of several nanoseconds.

This time difference corresponds to a specific end-fire viewing angle for the particular source point. The two orthogonal baselines then yield the equivalent of the azimuth and elevation of the source point. Note that source range is not generally detectable because the source point is in the far field of the array. Nevertheless, the sky map of source points in azimuth and elevation, as show in Fig. 2, yields a very detailed view of the spatial and temporal development of the lightning flash. Tens of thousands of individual source points are typically found for a single lightning flash, creating an almost continuous view of the channel development.

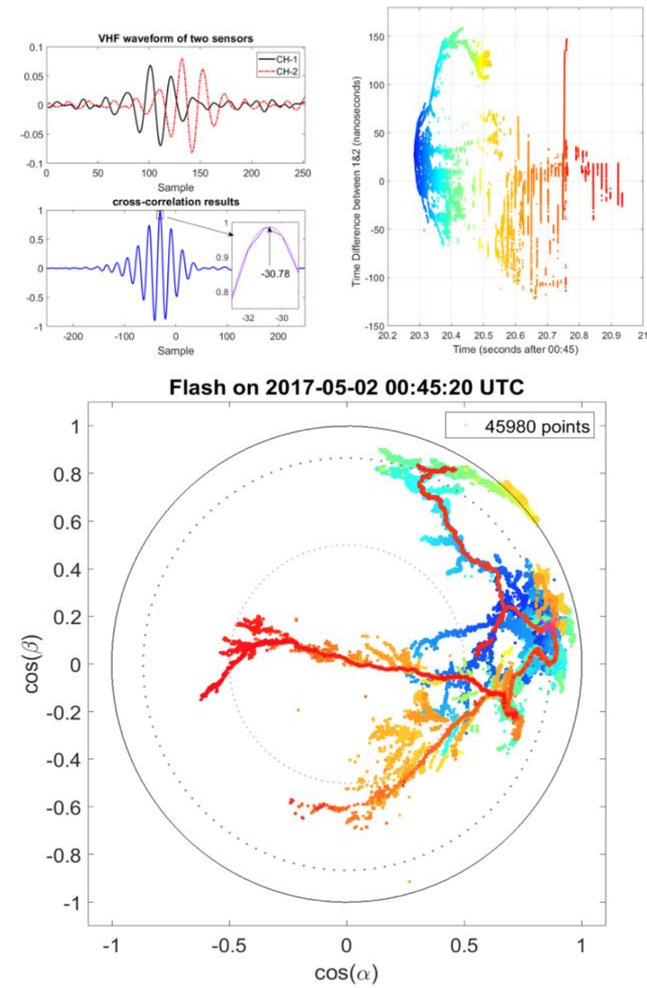

Fig. 2. Top left: Sample short windows of data from two VHF sensors, showing how the time difference between the two signals can be measured from signal cross correlation. Top right: The whole flash yield a nearly continuous distribution of signal time differences. Bottom: The time differences from orthogonal baselines map to azimuth and elevation, which yield a detailed view of the spatial and temporal development of the flash.

IV. MEASUREMENTS OF FAST POSITIVE BREAKDOWN

During the summer and fall of 2017, three storms that produced lightning flashes passed close to our VHF imaging system on July 08, August 12 and October 24. Among all of the flashes recorded during these three close storms that were reported by NLDN, 26 occurred with initial lightning events within 10 km from the interferometer site. This short range is close enough for high quality interferometer observation and good vertical resolution of the flash development.

Additionally, in examining the VHF data during these three storms, there also were five flashes that initiated with very high amplitude burst-like VHF emissions and were also associated with very strong narrow bipolar LF signals with a time scale of 10-20 µs. These features suggest that they were conventional narrow bipolar events (NBEs), and the VHF data for these events are also high quality despite the slightly longer range (15-20 km) and lower source elevation (~20°). They are included here for a more comprehensive study of fast positive breakdown and the VHF emission of lightning initiation events.

The resulting dataset is a total of 31 lightning initiation events, including 26 events within 10 km and another 5 known NBE events at 15-20 km from the interferometer. For every flash in this study, the flash initiation event was identified to be the first detectable VHF emission with an amplitude at least twice the background noise level and that is located in the region from where the first leader eventually originates. The background noise is defined as the standard deviation of the VHF emissions during the period without any lightning signals.

We find that the 31 lightning initiation events in this dataset naturally divide into two populations based on the timescale of the initial VHF emissions. The initial VHF emissions in one group were an approximately 10 µs continuous burst that is essentially identical with those described recently as FPB events [Rison et al., 2016]. Not surprisingly, four of the five NBEs in our data set fell in this category and also displayed the clear down-up motion associated with recently identified FPBs [Rison et al., 2016], Fig. 3 shows data for an example of a close-by event that was clearly initiated with the fast positive breakdown process. Exactly what FPB is remains a mystery, but we can confirm that it looks in our interferometer system exactly as those events reported by Rison et al. [2016].

But the initial VHF emissions in the second group, which includes the majority of the events in our dataset, contained only very short duration pulse-like VHF emissions with a time scale 1 µs or shorter. These lightning initiation events do not appear to contain FPB events, unless it is extremely weakly emitting at VHF. This suggests that while in some cases it appears clear that FPB is the process that initiates a lightning flash, in many cases it is not.

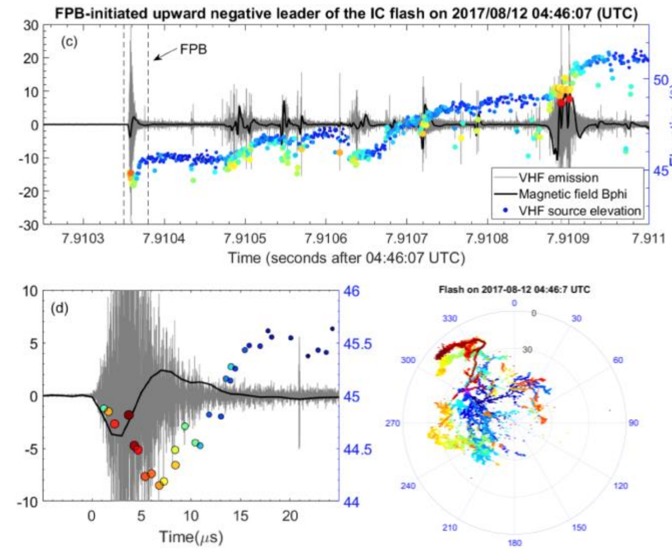

Fig. 3. Top: VHF waveform at flash initiation overlaid with the source elevation versus time. Bottom left: Zoom-in on the first VHF emissions of the flash, clearly showing the duration and fast down-up motion associated with fast positive breakdown. Bottom right: Overall VHF emission map of the flash, showing the space-time structure of a standard IC flash.

V. SUMMARY

We have developed a VHF interferometric lightning imaging system at Duke University. Overall performance is good and yields detailed images of lightning VHF source locations. We have a number of examples of clear, downward-moving fast positive breakdown that occurs as the first VHF emissions of the lightning flash, in very close agreement with the measurements reported by Rison et al. [2016]. But the majority of the observed flashes that initiated close to our VHF system do not show fast positive breakdown VHF emissions at flash initiation. Although it does seem nearly certain that some lightning flashes initiate with a fast positive breakdown event, our data suggest that a large fraction of flashes also do not initiate with a fast positive breakdown event. Clearly more measurements and modeling are needed to sort out the role the fast positive breakdown plays in lightning initiation.

REFERENCES

Dwyer, J. R., D. M. Smith, and S. A. Cummer (2012), High-energy atmospheric physics: terrestrial gamma-ray flashes and related phenomena, Space Science Review, doi: 10.1007/s11214-012-9894-0.

Rison, W., P. R. Krehbiel, M. G. Stock, H. E. Edens, X.-M. Shao, R. J. Thomas, M. A. Stanley, and Y. Zhang, Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms, Nature Comms., doi:10.1038/ncomms10721.

Stock, M. G., M. Akita, P. R. Krehbiel, W. Rison, H. E. Edens, Z. Kawasaki, and M. A. Stanley (2014), Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm, J. Geophys. Res., doi:10.1002/2013JD020217.

Stock, M. G., P. R. Krehbiel, J. Lapierre, T. Wu, M. A. Stanley, and H. E. Edens (2017), Fast positive breakdown in lightning, J. Geophys. Res., doi:10.1002/2016JD025909.