Short-Baseline Time-Difference of Arrival Observations on Lightning Discharge

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ABSTRACT: A lightning VHF radiation location system based on short-baseline time-difference of arrival (TDOA) technology has been developed. With the improvement on the system sensitivity and data recording method, the system successfully realized the continuous or sequential signal acquisition over the entire duration of a lightning flash. The temporal and spatial development characteristics of a rocket-triggered lightning and two nature lightning flashes are discussed, combining with simultaneous observations of high-speed camera images and fast/slow electric field changes. The results indicate that the TDOA technique provides an effective approach to describe the progression of lightning discharge in two dimensions with high temporal and spatial resolution.

INTRODUCTION

Lightning breakdown processes emit the broadband electromagnetic radiation in the range of VHF/UHF, which can be located to reproduce the lightning channels development and to realize the detection of both cloud-to-ground lightning and intra-cloud lightning. A new lightning VHF radiation location system based on a technique of short-baseline time-difference of arrival (TDOA) technology has been developed since 2009, and has been applied in the SHandong Artificially Triggering Lightning Experiment (SHATLE) [Qie et al.,2009] in the last 4 years. A great deal of data on natural and rocket-triggered lightning discharges was documented by using the TDOA location system. In this work, a brief summary of the TDOA location system is presented, and radiation sources location results of a rocket-triggered lightning and two nature lightning flashes are also analyzed in detail.

SHORT-BASELINE TDOA SYSTEM

The basic principle of the location technology is the TDOA estimations for the lightning broadband VHF radiation signals received by a pair of antennas, and the location of lightning radiation sources in two dimensions (elevation and azimuth) can be determined by using independent non-collinear baselines in an orthogonal antenna array, as shown in the Figure 1. To weaken influence of noise and improve estimation accuracy of TDOA estimation, a generalized cross correlation time delay estimation algorithm based on direct correlation method and wavelet analysis algorithm technique was proposed. In addition, a parabolic

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interpolation algorithm was adopted in the fractional delay estimation to improve the time resolution of the location system.

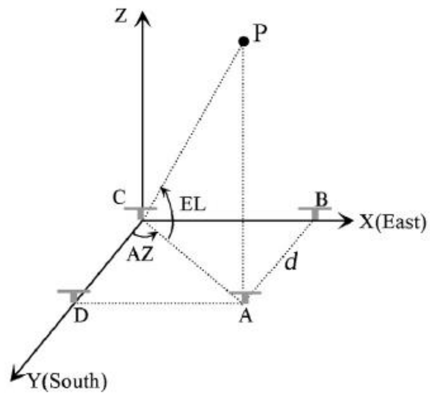

Figure 1 Antenna array configuration of the TDOA location system.

Block diagram of TDOA location system components is shown in Figure 2. The short-baseline TDOA location system consisted of four identical broadband discone antennas to receive the lightning VHF radiation signals. The received signals were processed through the band-pass filter and preamplifier sequentially, and then transmitted to the data acquisition equipment through the four coaxial cables with the same length and frequency response. Meanwhile, a fast antenna and a slow antenna were used to measure the lightning electric field changes with different bandwidth and decay time constant, and the electric signals were sampled by an analog-to-digital converter (ADC). In practice, the VHF signals acquisition was externally triggered by the ADC, and the trigger time was provided by the high-time accuracy GPS for a cooperating analysis with other observations.

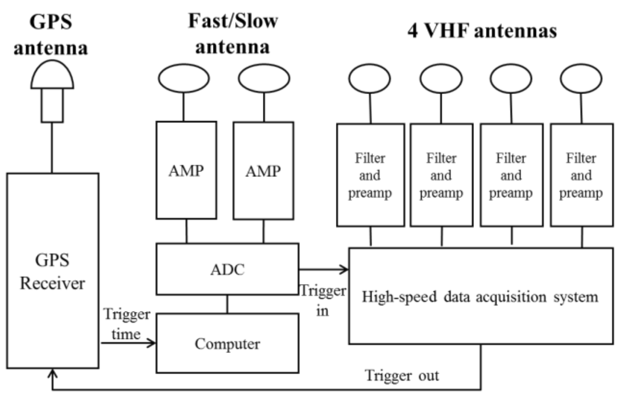

Figure 2 Block diagram of the TDOA location system

In the early stages of the short-baseline TDOA location system (system 1), the bandwidth of the band-pass filter is about 125–200 MHz, and VHF signals were acquired by a LeCroy oscilloscope at a sampling rate of 1 GS/s with an 8-bit vertical resolution. Due to the so high sampling rate and the device memory limit, sequential record mode is used. In order to enhance the detection efficiency, the location system has been improved in the summer of 2013, and another new system has also been designed for the continuous lightning signals acquisition. Specific parameters of the sequential and continuous location systems were illustrated in the table 1.

Table 1 Specific parameters of the short-baseline TDOA location systems

	System 1(2010-2012)	System 2(2013)	System 3 (2013)
Filter	125-200 MHz	140-300 MHz	140-300 MHz
Preamp	20 dB	27 dB	27 dB
Acquisition	oscilloscope	oscilloscope	high-capacity waveform digitizer
Acquisition mode	sequential	sequential	continuous / sequential
Sampling rate	1 GS/s	1 GS/s	1 GS/s
Vertical resolution	8 bits	12 bits	8 bits
Record length	2 µs *4,000 Segs	2 µs *10,000 Segs	1 s
Intersegment time	~6 µs	~2 µs	-
GPSDO time accuracy	50 ns	25 ns	25 ns
Fast/Slow E-field bandwidth	5 MHz/ 2MHz	2 MHz/ 0.5 MHz	2 MHz/ 0.5 MHz,
Fast/Slow E-field time constant	1 ms/ 3s	0.1 ms/ 220 ms,	0.1 ms/ 220 ms

For both the system 2 and system 3 in the year 2013, the orthogonal baseline length was decreased from 10 m to 8 m due to the space restraint. The gain of preamplifier was raised to 27 dB, and the bandwidth of the band-pass filter was expanded to 140-300 MHz. So, the ability of capturing small signals in a broadband frequency range was enhanced. The system 2 received the lightning broadband VHF radiation signals using a high-performance LeCroy oscilloscope, with a 12-bit vertical resolution and up to 10,000 segments number. Meanwhile, the intersegment time was also declined to 2 µs. In the continuous acquisition location system (system 3), the mass memory waveform digitizer was applied for the data acquisition over about 1s. The data sampling rate is 1 GS/s and the data vertical resolution is 8 bits.

In addition, the time accuracy of GPS Disciplined Oscillator (GPSDO) was increased and specifications of the fast/slow electric field change were also modified as shown in Table 1. By convention, the remove of negative charge in the cloud is defined to produce a positive electric field change in this paper.

ANALYSIS AND RESULTS

A rocket-triggered lightning

Figure 3 shows the 2-D VHF radiation source locations of discharge channel for a triggered lightning flash together with one frame from high-speed camera images. The straight part of the lightning channel was the trajectory of the metal wire after evaporation, and elevation of its top end was about 20.8° with a height of 256 m. The upper curved channel was corresponding to the natural discharge. The top of the visual channel outside the thundercloud corresponds to an elevation of approximately 37°. Up to the elevation of 35°, the shape and the height of the channel showed certain consistency with the optical observation, showing the good performance of the system in mapping the progression of lightning radiation sources in 2 dimensions. The high speed camera couldn't capture the channel with elevation from

35 ° to 76 ° for cloud shielding effect, while VHF radiation source locations show the advantage of depicting in-cloud lightning channel.

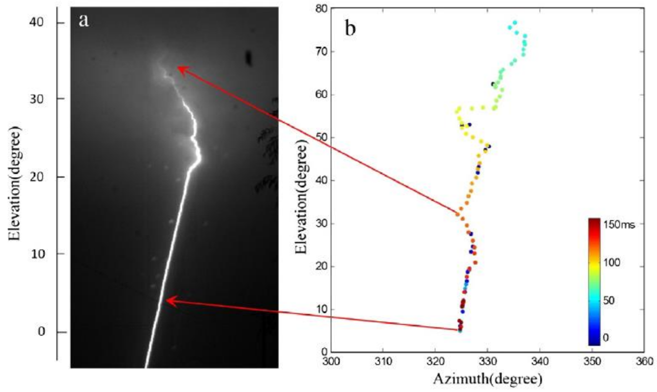

Figure 3 The 2-D VHF radiation source locations of discharge channel of a triggered lightning compared with one frame from high speed video images. The north direction is the reference azimuth with increasing clockwise. Color changes with time from blue to red.

A cloud-to-ground (CG) lightning

Figure 4(a) shows the electric field changes of a negative single-stroke CG lightning and the VHF radiation field detected by the short-baseline TDOA location system. It can be found that the VHF radiation mainly concentrated in the phases before the return stroke and near the times of K processes. The lightning started from the position S, and developed the preliminary breakdown channels simultaneously with a large horizontal component in two different directions, as labeled by arrows *a* and *b* in Figure 4(b). The stepped leader was directly converted from one of branches of the preliminary breakdown process, and spread downward to the ground with branches progressing simultaneously. The K processes might initiate from the start region of the lightning or a new negative region in cloud and transferred negative charges along the channel established by preceding breakdowns. The propagation velocities of K changes were about 10^6~10^7 m/s, which were typical of those reported by other investigators [Shao et al.,1996; Akita et al., 2010].

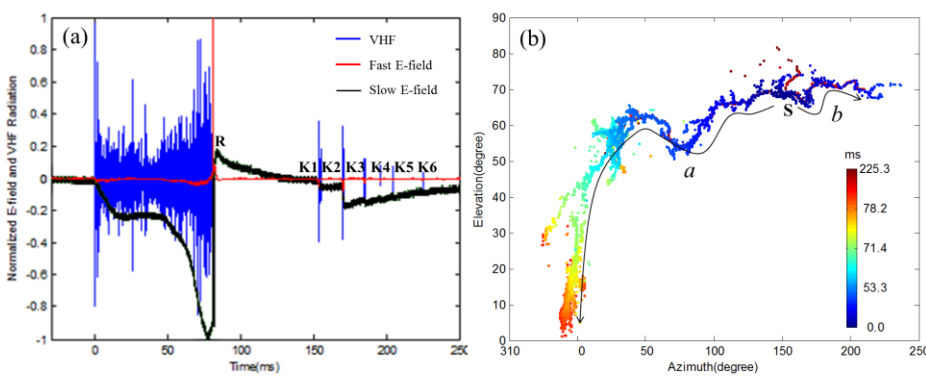

Figure 4 (a) The electric field changes and VHF radiation field, and (b)2-D VHF radiation source locations of the whole CG lightning flash

An intra-cloud (IC) lightning

Figure 5 shows the electric field changes and 2-D VHF radiation source locations of an IC lightning. The IC lightning lasted about 380 ms, and had relatively simple electric field change waveforms. During the first 84 ms, the slow electric field change increased negatively in a slow rate. The lightning started from the position S, as marked in Figure 5(b), and progressed upward in elevation with time. It can be indicated that the IC lightning extended the channel horizontally toward the observation site. From 84 to 168 ms, the lightning produced a rapid negative electric field changes, and microsecond-scale pluses on the fast electric field change became frequently. The lightning channels split into numerous small branches, and spread simultaneously with an extensive horizontal extension. The results indicate that the location system has a good performance in depicting multiple simultaneous streamers.

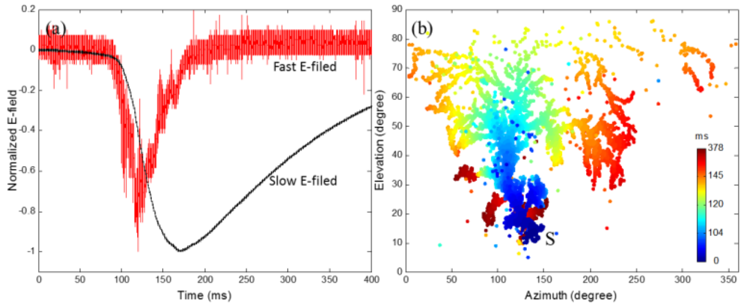

Figure 5 (a) The electric field changes and (b)2-D VHF radiation source locations of the whole IC lightning flash

CONCLUSIONS

The development of the lightning VHF radiation location system based on short-baseline time-difference of arrival (TDOA) technology was summarized in this paper. Radiation sources location results of a rocket-triggered lightning had a good agreement with the high-speed video camera images. The results of both rocket triggered lightning and nature lightning flashes indicated the location system could effectively map the lightning radiation sources, and visually reproduced the development of lightning occurring inside the cloud.

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