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Lightning Localization Based on VHF Broadband Interferometer Developed in Sri Lanka.

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***Abstract*— A basic broadband digital interferometer was developed, which is capable of locating Very High Frequency (VHF) radiation sources in two spatial dimensions and time. Three antennas sensed the time series of broadband electromagnetic (EM) signals and digitized with 4 ns sampling interval for a duration of several milliseconds. A technique based on cross-correlations has been implemented for mapping lightning source locations. A map of the first return stroke (RS) and the preceding stepped leader was mapped successfully, using the system with a time resolution of few milliseconds. The result was compared with the visible events of the ground flash to validate the system.**

Keywords- lightning, lightning locating, inteferometer, EM source localization

I. INTRODUCTION

Lightning is a natural phenomenon consisting of intense electrical discharges. Scientific knowledge of lightning is not complete, mainly because most of the lightning initiate within clouds. If the initiating process of lightning inside clouds could be visualized, scientists can improve their understanding of initiating and prediction of thunderstorms.

Lightning discharges produce EM radiation over a broad spectrum from ULF to UHF and higher [1]. The VLF/LF EM radiations are radiated during the RS. The VHF/UHF EM waves are emitted from small-scale breakdown activities during the evolution of breakdown such as leader process [2]. Since VHF radiations (30-300 MHz) can penetrate through a cloud, VHF radiation can assist in investigating lightning discharges within thunderclouds.

Lightning mapping techniques have been developed in many stages within the last few decades to improve the understanding of the lightning process. There are two main streams of lightning mapping techniques; the Interferometer technique and the Time of arrival (TOA). The TOA technique measures the arrival time of EM radiation from three or more stations separated by several kilometers [1, 3, 4, and 5]. The broadband lightning interferometer technique was initially designed by the Osaka University lightning research group [6, 7, and 8]. Later, New Mexico Institute of Mining and Technology have independently developed a technique [9], and observed intra-cloud lightning activities in two dimensions(2D). Mardiana et al. [10] reported the development of an interferometer technique to map lightning propagation in three dimensions and time. In this technique, two broadband interferometers were used in two different sites. Considering the drawbacks of using two different sites to locate VHF source, Elbaghdady et al. [11] designed a single station technique capable of reconstructing lightning channel in three dimensions.

This paper presents a study on the development of broadband lightning interferometer system. After discussing the experimental technique and the lightning source localizing process, the paper next presents the initial observations from the broadband digital interferometer. The primary objective of this study is to confirm the capability of locating lightning sources. Thus, the study is limited to localize the source in 2D. The constructed 2D map of the lightning source location is compared with visual observations captured with a high-resolution video camera, to validate the results from the interferometer.

II. VHF BROADBAND INTERFEROMETER

The basic idea of broadband digital interferometer technique is to estimate the phase differences between two EM signals observed by two separated antennas. Phase differences are directly related to the incident angle of the EM signal against the baseline of antennas. The broadband interferometer can locate a continuous radiation source in microsecond time resolution. Thus, it can be used to study intra-cloud lightning activities such as preliminary breakdown, leader process, and

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narrow bipolar pulse. The simplest radio interferometer consists of two antennas [Fig. 1(a)] that gives the location of the source in one dimension, the incident angle. The incident angle of EM signal (α) is given by (1). Here, 'd' is the baseline of antennas, 'Δφ' is the phase difference between signals received from two antennas, and 'λ' is the wavelength. The same result for the incident angle can be derived using the time delay (Δt) of the signal between two antennas (1).

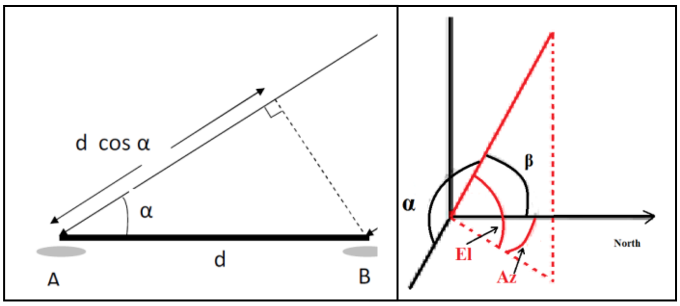
$$d \cos \alpha = \frac{\lambda \Delta\phi}{2\pi} = c\,\Delta t \qquad (1)$$

Fast Fourier transformation (FFT) can be applied to calculate each Fourier component and corresponding phase of the received EM signal. The phase difference between two antennas (Δφ) is a function of the incident angle of the signal against the baseline. Δt can be derived using the cross-correlation method. Therefore, the incident angle of VHF signal can be realized using both methods.

Using two pairs of antennas and two independent baselines, an EM source can be located in 2D, namely *azimuth* and *elevation*. Three antennas that equipped at three apexes of a right-angled triangle can help to find the 2D location of a radiation source. If the two baselines are orthogonal, as shown in Fig. 1(b), azimuth and elevation angles could be calculated from two incident angles using the relationships given in (2) and (3).

$$\cos \alpha = \sin(\mathrm{Az}) \cos \mathrm{El} \qquad (2)$$

$$\cos \beta = \cos(\mathrm{Az}) \cos \mathrm{El} \qquad (3)$$



(a) (b)

Figure 1. (a) The simplest radio interferometer with two separate antennas that can be used to find the incident angle ; (b)Two-demensional spatial location using two pairs of antennas. Azimuth and elevation angles can be derived from two incident angles against each baseline using (2)and (3).

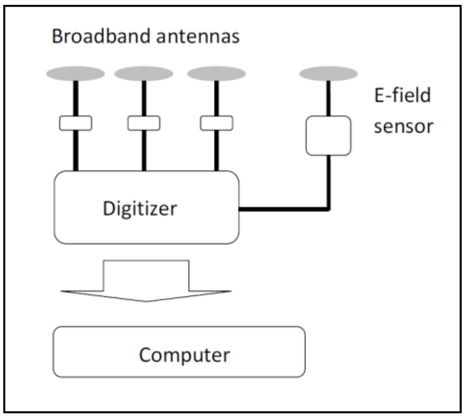


Figure 2. VHF broadband digital interferometer data acquisition system.

I. EXPERIMENTAL SETUP

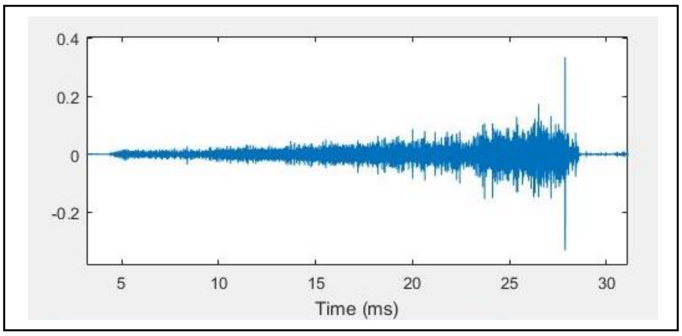
The VHF broadband interferometer developed in the University of Colombo consists of three identical flat circular capacitive antennas with a 30cm diameter. The antenna sensed broadband electric field derivative (dE/dt) and the signal was band limited to 10-80 MHz. The Antennas were arranged at three apexes of a right-angled triangle that makes two orthogonal baselines of 10 m. The antenna at the right-angled apex was common for both baselines. The sensed signals from each antenna were transmitted to four-channel digitizer via a 50 Ω coaxial cable with 30 m length. Broadband dE/dt signals were digitized at the rate of 250 MS/s, and 8-bit resolution by Tektronix MDO 3034. A sampling rate of 250 MS/s fulfills the Nyquist criteria and avoids aliasing effect. Signals were recorded continuously with a 50% pre-trigger delay. The signal length was limited to 40 ms due to the continuousness and high sampling rate. The digitized signals were stored in a personal computer. Further, a sensor was equipped for measuring fast field signature [Fig. 2] that is useful for verifying the lightning event. Visual aid was required to compare the interferometer result with an independent measurement. For this purpose, three wide-angle action cameras were operated to record a high-resolution video of the sky.

II. RESULT AND OBSERVATION

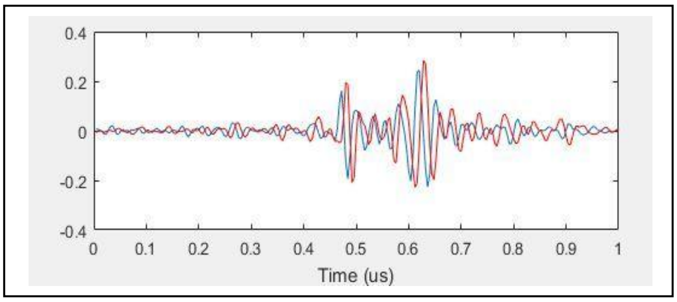
A. Localizing Algorithm

Fig. 3(a) shows a measured dE/dt signal related to a lightning flash triggered at 15:57:09 (+5:30 GMT) on 15 December 2017. According to the BIL approach of preliminary breakdown introduced by Baharudin et al. [12], this window of dE/dt signal is relevant to the discharge process of the first return stroke and preceding stepped leader. In Fig. 3(b), the blue colored illustration represents a time expanded window of 1 µs (250 sample) in Fig. 3(a), while the red color represents the signal received by the second antenna, installed 10 m away. By observing the two signals, a clear phase shift or a time lag between signals could be easily identified.

FFT has been applied in many broadband lightning interferometers to calculate the Fourier component of the signal and their phase [6, 7, and 8]. The time lag between two signals can also be derived by the generalized cross-correlation method [9]. Using any of these techniques, the incident angle of VHF radiation on each baseline could be uncovered with equation (1). In this study, the cross-correlation technique has been used to calculate the lightning source direction.



(a)



(b)

Figure 3. (a) EM signal relevant to 1st return stroke of a cloud to ground discharge process, received by the central antenna; (b)Time expanded window of the same signal(blue) and the EM radiation received by the antenna to the north in the same time window(red).

Measured dE/dt signal corresponding to the first RS and preceding stepped leader was extended around for a period of 24 ms (≈6 x10^6samples), and the digital signal was divided into windows of 100 samples points (1.0 μ s). Successive windows were over-lapped by 50 samples, so that the false solution caused by the impulse at the edge of the window can be eliminated. Time lag between each pair of antennas was calculated for every window using the cross-correlation technique. Fig (4) illustrates the cross-correlation of the two signals with a peak near zero offsets. Time at the peak gives the time lag between the two signals. Since the sampling interval of the recorded EM signal is 4ns, the accuracy of calculated time lag is ±2 ns. Parabolic fitting was used on cross-correlation coefficients after up-sampling to increase the accuracy.

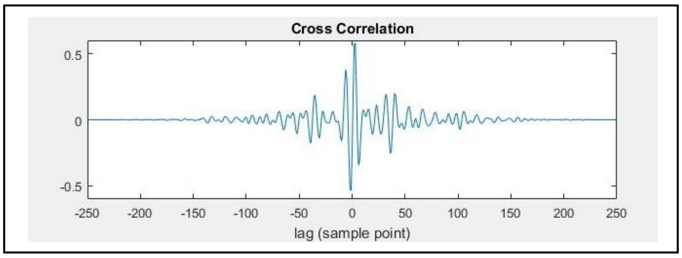


Figure 4. Cross correlation between two signals received by the central antenna and the antenna to the north.

The main challenge of source localization is to identify the radiation emitted by the source out of noisy signal received by the measuring system. Various methods are used in interferometers and other signal processing appliances to confront this issue. Windows below 4.7 dB signal to noise ratio (SNR) were neglected for the cross-correlation method. Closer phase is a technique used in radio astronomy to eliminate the background noise. When three antennas receive EM signal from the same source, the closer phase is defined as,

$$\phi_{Cl} = \Delta\phi_{12} + \Delta\phi_{23} + \Delta\phi_{31} \quad (4)$$

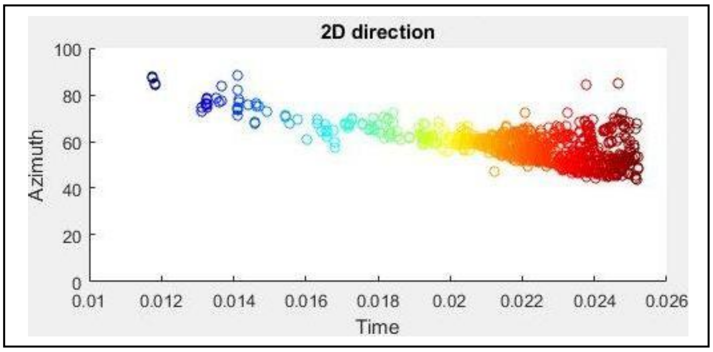
If EM radiation is a distant point source, the closer phase reaches zero. Closer time follows the same principle, considering the relationship between time lag and the phase difference between antennas. Since the baseline is 10 m maximum, the minimum time lag between two antennas has to be ± 33.3 ns (±d /c). Thus, this standard, along with the closer time principle and SNR principle, was useful in eliminating outliers of source location.

B. 2D Location

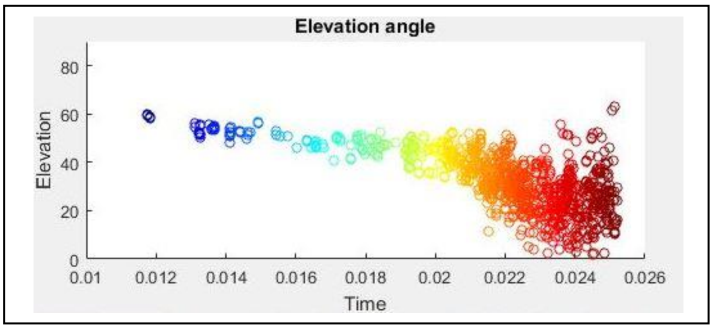
First, the VHF interferometer technique was applied to the data measured by the antenna system, and azimuth and elevation angles were calculated. The azimuth angle of EM source slightly decreases over the duration of stepped leader and RS [Fig. 5(a)]. However, Fig. 5(b) exhibit a decline of elevation angle with time. Elevation angle decreases slowly for the first 20 ms and change rapidly for the last 5 ms prior the RS. The 2D location of EM source can be mapped using the elevation together with the azimuth angle.

Fig. 6 presents the constructed map of the lightning source location over the period of stepped leader and RS. For studying discharge propagation against time, the event was divided into sub time windows, and a map was reconstructed (Fig. 7). The duration associated with maps were unevenly selected. In Fig. 7(a), the discharge process within the first 16ms had concentrated in above elevation of 40^0 with a minor change in elevation angle. For the next 4 ms, as shown in Fig. 7(b), it had change the propagation direction to form a shape of the downward channel and continued for the last 4 ms before RS [Figs. 7(c) and7(d)].

A high-resolution camera made the visual confirmation of the flash. Fig. 8 shows a frame of the video captured during the same lightning event. A Wide-angle camera can cover a 2π/3 horizontal angle and π/3 vertical angle. The center of the camera was directed towards the azimuth of π/2. The video frame displays only the visible part of the lightning flash attached to the ground. Azimuth and elevation of the visible lightning channel were calculated using direction and angle of view of the camera. According to Fig 8., the visible fragment of the channel extends between 50 to 60-degree azimuth and 22 degrees of elevation. However, the frame rate of the camera was insufficient to differentiate the stepped leader process. Although the result map of lightning source extends to 60^0 of elevation angle, the visible lightning channel limited to 20 degree. Those visible part of the lightning channel matches with the result of interferometer.



(a)



(b)

Figure 5. elevation angle variation in time.

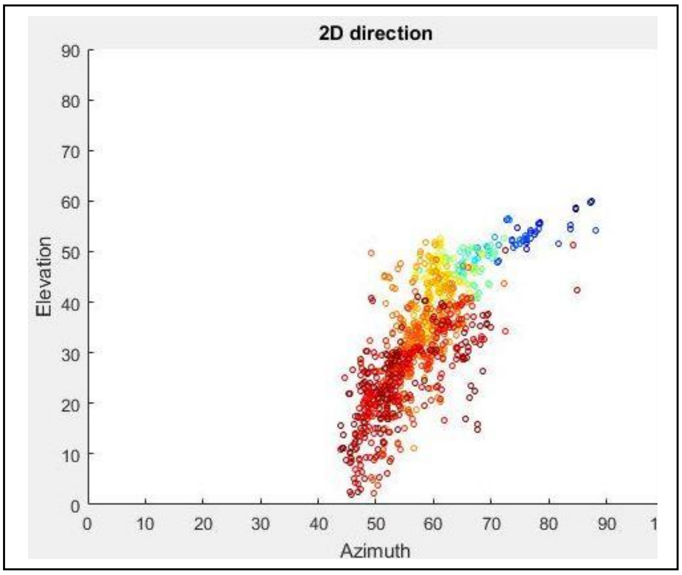
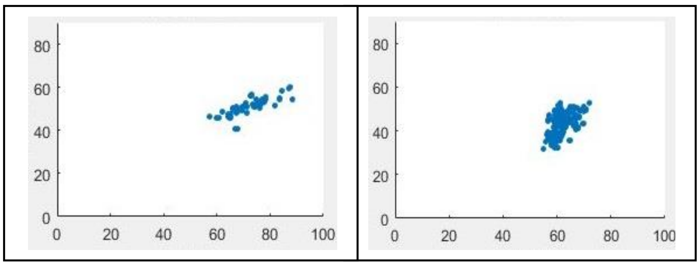
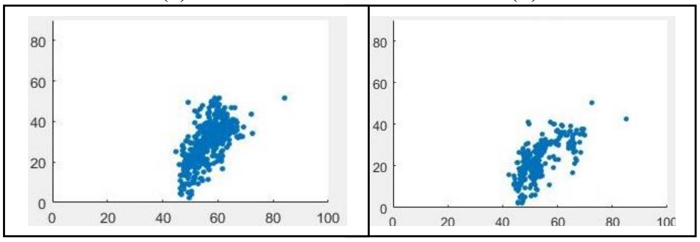


Figure 6. 2D location of stepped leader and the firstreturn stroke occurred at 17:57:15 (+5:30 GMT) December 15, 2017.



(a) (b)



(c) (d)

Figure 7. 2D location of lightning discharge for a small time window: (a) First 16 ms of the event from Fig. 3(a); (b) 4 ms started from 13th millisecond of the event; (c) Last 3 ms before the RS; (d) 1 ms time windows including the RS.

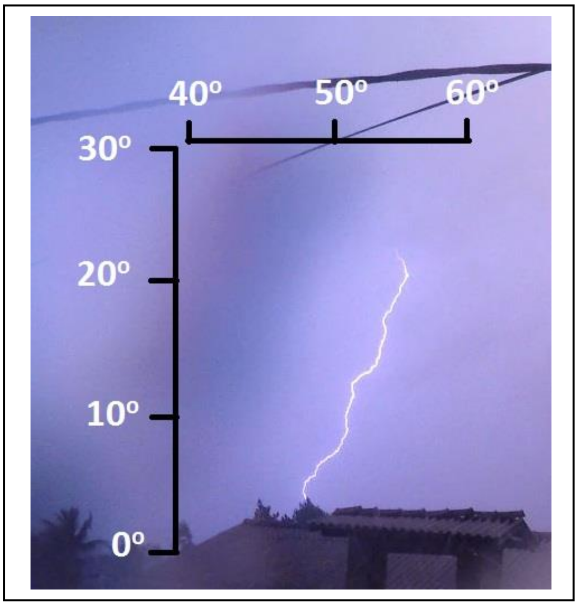


Figure 8. The visual confirmation of the RS flash recorded with a high-resolution video camera. Leader propagation cannot be differentiated due to the low frame rate.

III. CONCLUSION

In this study, we have presented an overview of the VHF broadband digital interferometer system developed by the University of Colombo, Sri Lanka. The system capability was tested using natural lightning and realized that the developed system is competent of mapping lightning progression in two spatial dimensions with high-time resolution. A stepped leader and a first RS development were reconstructed using the interferometer. According to the result map of lightning location, discharges in lower elevation (below elevation of 30^0) start to appear around 5 ms prior to RS. The system has exhibited a potential of localizing EM sources with high-time resolution. The measured visual channel fragment of the lightning using a video camera have verified the interferometer result.

This paper describes the first result of a 2D lightning observation made with a digital broadband interferometer, along with the capability of the system. However, the system needs further improvements to eliminate noise with a minimum information loss.

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