Lightning VHF Polarization Imaging of Recoil Leaders

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Abstract

We proposed two kinds of location methods for an irregular VHF interferometer and found that a non-coplanar configuration can improve location precision. The theoretical distribution of the time uncertainty has been derived and the systematic time error can be calibrated for a non-coplanar array. Besides, we update our interferometer with a polarization detection function, and the polarization parameter can reveal more information about the breakdown process. A bolt-from-blue lightning was analyzed here, and there are several recoil leaders occurred at the later stage. The polarization parameter shows the breakdown direction of the recoil leader is nearly the same direction as the lightning channel.

1. Introduction

Lightning channels develop as bidirectional bipolar leaders in the cloud, and there is evident asymmetry on two ends[1]. The negative leader develops in a faster branching manner and produces wideband radio emissions, while the positive leader usually develops more smoothly and has very weak or non-detectable radio emissions[2]. The positive leader tends to decay and gets reactivated by the recoil leader; however, it rarely occurs for a decayed negative leader to initiate a recoil leader [3]. The recoil leader frequently occurs at the later stage of a negative cloud-to-ground (CG) discharge, and it could induce a subsequent negative return stroke (RS) when the recoil leader initiated on decayed positive leader arrived the negative leader to reach the ground[4]. The absence of recoil leaders on a decayed negative leader aligns with the lack of subsequent positive return stroke along the same stroke channel.

A lightning VHF interferometer is a vitally important tool in lightning research because it can map lightning channels with an unprecedented high resolution. It expanded our knowledge about lightning physics, especially the lightning initiation in the form of fast breakdown[5], [6], [7]. More recently, VHF polarization imaging has been introduced to investigate the lightning discharge process[8]. The polarization parameter shows the potential to reveal the orientation of the local electric field when it is linearly polarized. Though VHF polarization imaging can greatly enrich our understanding of lightning leaders, the related work has just started, and there is far more consensus on the lightning leader polarization result [9]. Here, we report our preliminary VHF polarization imaging result about a recoil leader of bolt-from-blue lightning.

2. Method

Location accuracy matters when explaining the very detailed lightning discharges. The traditional lightning interferometer consists of three antennas with two orthogonal equal-length baselines lying in the horizontal plane. In such a configuration, the elevation uncertainty is high at lower elevations, and the azimuth uncertainty is high near the zenith[10]. We have proposed two kinds of location methods based on an irregular short-baseline array[11]. The first is constrained optimization by mining the following goal equation:

$$f(\alpha,\beta,\gamma)=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\begin{pmatrix}\alpha\\ \beta\\ \gamma\end{pmatrix}^T\begin{pmatrix}x_j-x_i\\ y_j-y_i\\ z_j-z_i\end{pmatrix}-c\tau_{ij}\right)^2 \quad (1)$$

Where the α, β, and γ are the cosine of the angle between the direction of the source and the positive end of the x-axis, y-axis, and z-axis; τ_{ij} is the arrival time delay of antenna i and j; (x_i, y_i, z_i) is the location of the antenna i.

The second method is coordinate rotation. Any three antennas lie in the same plane. We divide a non-coplanar array into many coplanar arrays with different normal vectors. After obtaining the arrival direction of the radiation (α',β',γ') from the view of each subarray. Rotate the view back to the view from the horizontal plane using the following equation.

$$\begin{pmatrix}\alpha\\ \beta\\ \gamma\end{pmatrix}^T=\begin{pmatrix}\alpha'\\ \beta'\\ \gamma'\end{pmatrix}^T\begin{pmatrix}cos\theta & 0 & sin\theta\\ sin\varphi sin\theta & cos\varphi & -sin\varphi cos\theta\\ -sin\varphi sin\theta & sin\varphi & cos\varphi cos\theta\end{pmatrix} \quad (2)$$

Where the θ and φ are constant, which is determined by the angle between the inclined subarray and the horizontal plane.

We derived the angular uncertainty of elevation and azimuth for an inclined subarray as follows:

$$\delta_{EL}=\delta\sqrt{\sum\left(\frac{\partial EL}{\partial\tau_i}\right)^2}=\frac{\|(\alpha,\beta)M\|c\delta}{cos(EL)sin(EL)}$$
$$\delta_{AZ}=\delta\sqrt{\sum\left(\frac{\partial AZ}{\partial\tau_i}\right)^2}=\frac{\|(\beta,-\alpha)M\|c\delta}{cos(EL)^2} \quad (3)$$

Where M is the constant determined by the arrival direction and the array configuration; δ is the time uncertainty of each baseline; c is the light speed.

For method 2, after obtaining the arrival direction of the radiation using each combination, we can use the arithmetic average as the final location. However, our uncertainty analysis reveals that if the arithmetic average is used as the final location, the uncertainty is highly uneven on the whole cosine plane, as shown in Figure 1. The first method seems to have the same uncertainty as a coplanar horizontal plane. For the second method, after using the weighted average as the final location, the uncertainty of elevation at lower elevation and azimuth near the zenith can be improved near an order. Therefore, we highly recommend using a non-coplanar array for a VHF interferometer, and we have adopted such configurations in our later observation campaign.

As for the polarization analysis, we adopted a method similar to Shao et al.[8]. However, our imaging result is identical to Hare et al. [9] as shown in the late section.

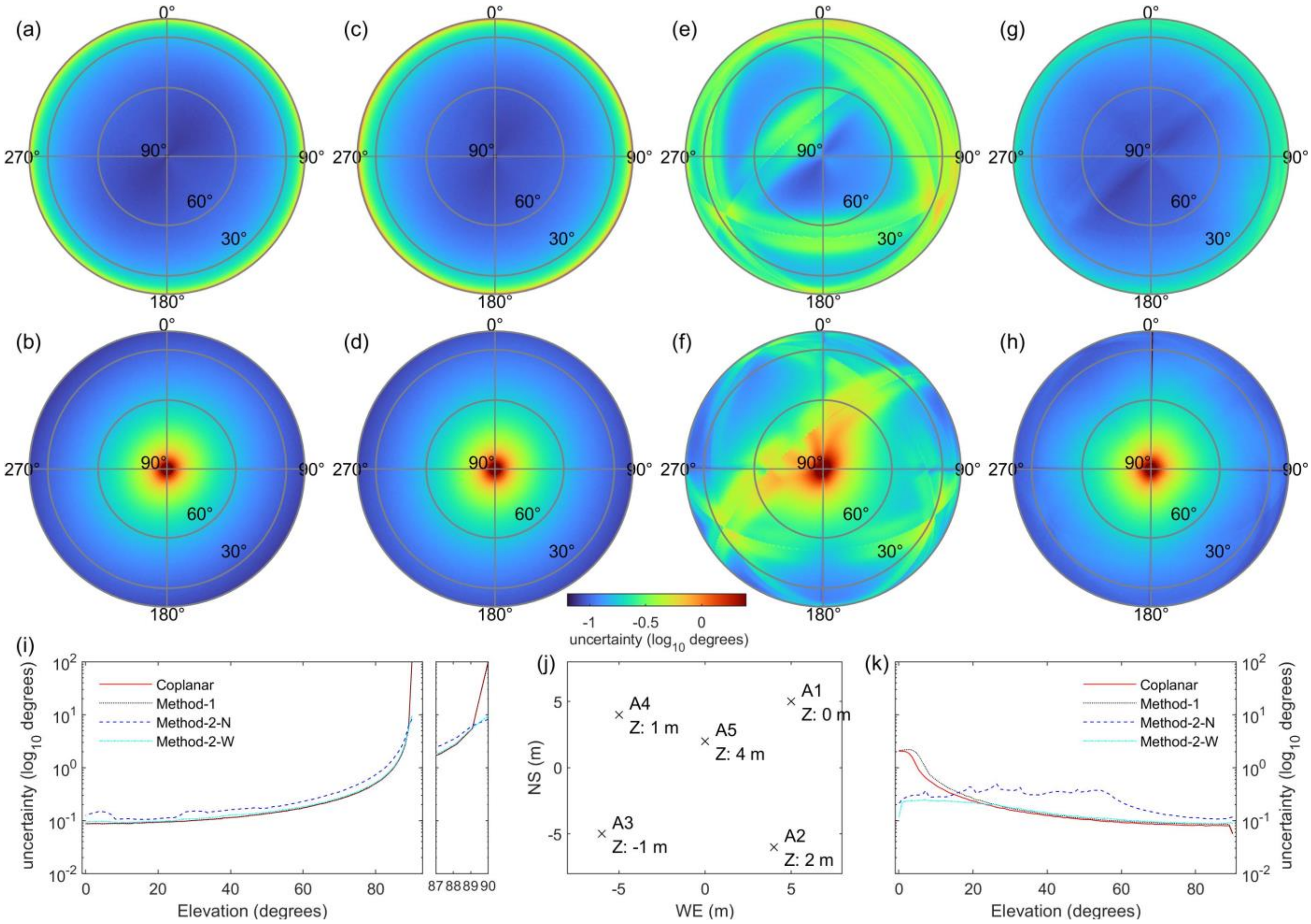

Figure 1. Comparison of uncertainty distribution of a five-antenna non-coplanar array using different methods. Elevation uncertainty (a) and azimuth uncertainty (b) for the coplanar array by setting the altitude of all five antennas as zero. The second column (c-d) is the angular uncertainty by Method 1 of constraint optimization. The third column (e-f) is the uncertainty distribution for Method 2 using the arithmetic average. The fourth column (g-h) is the result of Method 2 using weight average. Azimuth uncertainty (i) and elevation uncertainty (k) of different methods along the azimuth of 60°. (j) Configuration of the five-antenna non-coplanar array.

3. Results and discussions

Here, we imaged a bolt-from-blue lightning, as seen in Figure 2. The initial negative leader propagated upward then turned to propagate downward about 29 ms later initiation. The positive leader has few detectable radiations in this case. There are many recoil leaders after a return stroke. The first one was selected here to show details. It takes 118 μs for the recoil leader to reach the highest point with a speed of 2.6×10^7 m/s. Then, it propagated downward along the main negative leader with decreasing speed.

As seen in Figure 2d, the recoil leader shows a linear polarization, nearly with the same orientation as the lightning channel. We use a similar polarization antenna as Shao et al. (2018), who adopted the same method, but our preliminary results differed. Shao et al. [8], [12] find polarization from the recoil leader is almost perpendicular to the lightning channel. Hare et al. (2023) reported their 3D polarization of a dart leader (another term for recoil leader) with orientation nearly parallel to the channel in some sections; they found that the polarization shows similar variations with speed.

We should note that the processes we study are just the same, but the results show differences. Shao et al. confirmed their results using a two-station interferometer to obtain a 3D linear polarization orientation. Hare et al. use a different method to analyze the 3D polarization parameter using LOFAR, which has been rigorously calibrated. For now, we are still unsure whether there are some location errors or whether the polarization orientation of recoil leaders has different polarization features.

In this case, three recoil leaders initiated in the decayed positive branches have reached the negative leader, but it failed to attach the ground. Eventually, a positive recoil leader exited upward from nearly the far end of the previous negative recoil leader. The upward positive recoil leader is very strong, and it reaches the positive leader, exits new positive air breakdown, and gets mapped by the VHF interferometer.

Lighting VHF polarization imaging shows potential in revealing the orientation of the local electric field if they are linearly polarized or the energy of the radiations if they are eclipse polarized. The importance of polarization has not been understood. We have set up a synchronous observation campaign using lightning VHF polarization interferometer and high-energy detector array LHAASO. LHAASO has the excellent capability to image the cosmic ray shower in ns time errors[13].

Our preliminary results suggest at least some recoil leaders involving linear polarization. As for the percentage, we need to investigate more data. The relationship between high-energy particles and polarization patterns also requires further investigation.

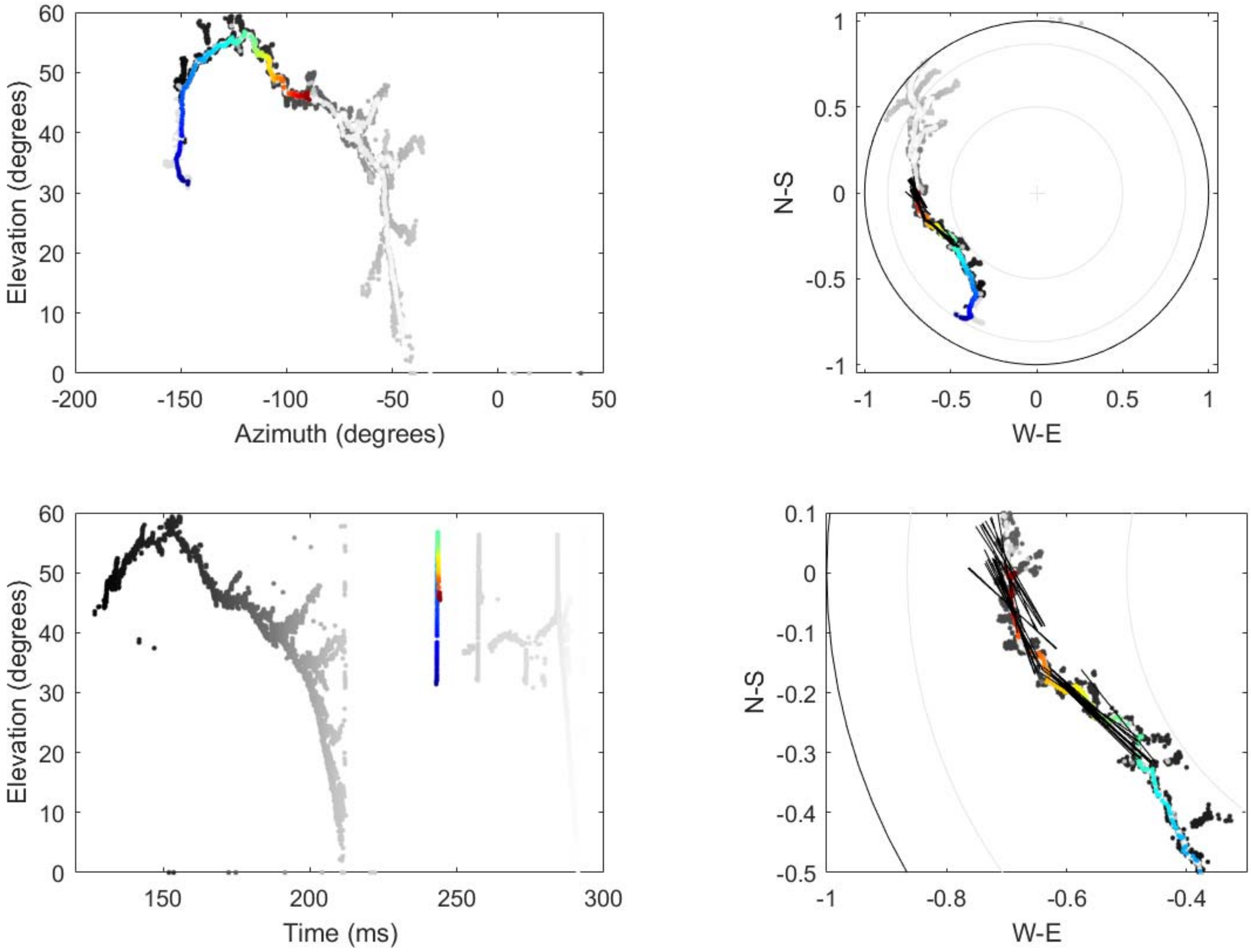

Figure 2. Lightning VHF polarization imaging result of bolt-from-blue lightning. (a) Elevation – azimuth view of this flash, (b) lightning projection in the cosine plane. (c) Variation of elevation with increasing time, (d) polarization imaging result of the recoil leader, where the polarization orientation is nearly parallel to the established lighting channel. Note: points are time-coded from black to white, and the recoil leader is time-coded from blue to red.

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