Research Article

Ultrawideband Discharge Source DOA Estimation Method Using Multiple Baseline Wideband Time-Domain Interferometry with Hilbert Transform

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The research interest of ultrawideband (UWB) discharge source location estimation has increased these years. In this paper, a direction of arrival (DOA) estimation method using multiple baseline wideband time-domain interferometry with Hilbert transform for UWB discharge source is proposed based on time-domain and frequency-domain characteristics of radiated RF electromagnetic pulses (EMPs) from discharge sources. Monte Carlo simulations are then carried out; the results indicate that, the proposed method provides a better performance in UWB discharge source DOA estimation than the traditional time-domain method, especially in low signal-to-noise ratio (SNR) conditions. Moreover, the influences of antenna array configurations and incident angles of radiated EMPs on the estimation precision are also studied. It has been shown that, the accuracy of both elevation angle and azimuth angle estimation improves with the increase of the antenna element number and baseline length. As for the influence of incident angles, the estimation accuracy of elevation angle enhances when real elevation angle increases, while that of azimuth angle tends to be opposite. Meanwhile, the real azimuth angle has little effect on the DOA estimation. Finally, an experimental setup for discharge source DOA estimation is introduced and the experiment results are illustrated.

1. Introduction

Gas discharge is a common phenomenon existing in nature and industrial fields and can bring inevitable interruption as well as serious damage to electronic equipment [1, 2]. However, the emission from gas discharge, especially the RF electromagnetic pulses (EMPs), has an extensive use in many applications, such as plasma density measurement, partial discharge detection, and lightning locating [3, 4]. Moreover, with the development of hypersonic technology in recent years, a great urge for passive detection of ultrawideband (UWB) discharge source such as hypersonic flight vehicle (HFV) has arisen [5]. In previous works, researchers have studied the radiation characteristics of weak gas discharge process [1, 6, 7], and in our last paper, the radiation characteristics in both time-domain and frequency-domain of spark discharge have also been studied and analysed [5]. Results show that EMPs radiated from discharge sources can present an UWB feature. Therefore, a locating method specially for UWB discharge source based on the radiation characteristics is worth studying.

Over the past decades, narrowband interferometry has been developed and implemented in radiation source locating, especially in lightning locating field [8–11]. Nevertheless, angle ambiguity is an inevitable problem in narrowband interferometry, and many algorithms have been proposed to eliminate the ambiguity [12–14]. However, the radiated EMPs of lightning and other discharge sources is a wideband signal, the frequency of which ranges from a few kHz to several GHz [1, 6]. Therefore, in order to make full use of the wideband information, Shao et al. proposed a one-spatial dimension wideband radio interferometry to observe
lightning and mentioned that wideband feature can be used to resolve the ambiguity [15]. Ushio et al. extended the basic interferometer into the two-dimensional system with orthogonal horizontal baselines and then developed this system further at Global Lightning and Spite Measurement mission (GLIMS) in Japan for detecting and locating the rocket triggered lightning in International Space Station [16–19]. And M. Stock and Krehbiel demonstrated that additional antenna can improve the accuracy of low amplitude source, which enables a larger number of sources to be observed during a single hybrid cloud-to-ground lightning flash [20].

As for the DOA estimation method, Bro proposed a 2-dimensional DOA estimation based on uniform squares array [21]. And Chen et al. came up with a new estimation method based on L-shape array [22]. It follows that the previous research studies mainly focus on observation of lightning, which is a high energy discharge process with an extremely high voltage and current. And the DOA estimation method is mainly for a unique antenna array. However, in real world UWB discharge source detection, such as HFV detection, the signal-to-noise ratio (SNR) is far lower than that in lightning location, and a simple random antenna array is necessary because of the complicated ground conditions. Therefore, it is of great significance to come up with a DOA estimation system specially for UWB discharge source under low SNR conditions based on a random antenna array.

In this paper, an UWB discharge source DOA estimation method based on multiple baseline wideband time-domain interferometry with Hilbert transform is proposed. The basic theory of operation will be described in Section 2. The analysis and the simulation results will be given in Section 3 under different signal-to-noise ratios (SNR) with different antenna array configurations and signal incident angles. Then, the experimental setup is introduced and experimental results are given in Section 4. Finally, conclusions are drawn in Section 5.

2. Basic Theory of Operation

2.1. Basic Principle of Interferometry. A single baseline interferometer is shown in Figure 1. Suppose that received signals $s_1(t)$ and $s_2(t)$ by antennas 1 and 2 are radiated EMPs from the same discharge source. A phase difference will appear between two antennas because of the path difference $\Delta l$ caused by distance $d$ as shown below:

$$\Delta \phi = \frac{2\pi}{\lambda},$$

$$\Delta l = \frac{2\pi f}{c} d \cos \theta,$$

where $d$ is baseline length, $\lambda$ is the wavelength of received signal, $f$ is the signal frequency, and $\theta$ is the incident angle. Equation (1) indicates that the unknown incident angle can be estimated by measurable phase difference, which can be obtained by interferometry.

The output of an interferometer $r_{12}(\tau)$ is the cross correlation between two input signals, in this case, $s_1(t)$ and $s_2(t)$:

$$r_{12}(\tau) = \int s_1^*(t)s_2(t + \tau)dt.$$  

(2)

Then, the discrete form of equation (2) can be written as follows:

$$r_{12}(m) = \sum_{n=1}^{N} s_1^*(n)s_2(n + m), \quad m = -N, \ldots, -1, 0, 1, \ldots, N,$$

and the cross-correlation coefficient is defined as the energy-normalized version of $r_{12}$:

$$\rho_{12}(m) = \frac{\sum_{n=1}^{N} s_1^*(n)s_2(n + m)}{\sqrt{\sum_{n=1}^{N} |s_1(n)|^2 \sum_{n=1}^{N} |s_2(n)|^2}}.$$  

(4)

In frequency domain, the cross correlation is expressed as follows:

$$R_{12}(f) = S_1^*(f)S_2(f),$$

where $S_1(f)$ and $S_2(f)$ are the Fourier transforms of $s_1(t)$ and $s_2(t)$, respectively. Because the two received signals are from the same target, $s_2(t)$ can be expressed as the delayed replica of $s_1(t)$, and equation (5) can be rewritten in

$$R_{12}(f) = |a|S_1(f)^2 e^{j2\phi},$$

(6)

where $a$ is a constant and $\Delta \phi$ stands for the phase difference between the two received signals, which can be obtained by the phase discriminator and finally be used to estimate the incident angle as follows:

$$\theta = \arccos\left(\frac{c}{2\pi f d} \Delta \phi\right).$$

(7)

2.2. Proposed Multiple Baseline Wideband Time-Domain Interferometry with Hilbert Transform. The radiated EMP from a far field point discharge source such as HFV is an ultrawideband signal with a limited SNR, the basic single baseline interferometer cannot meet its DOA estimation requirement due to angle ambiguity, and only the incident angle on the plane formed by the target and the baseline can be obtained by two antenna elements. Based on the specific
sition, a DOA estimation method for UWB discharge source based on multiple baseline wideband time-domain interferometry with Hilbert transform is proposed. As shown in Figure 2, an antenna array is located on the \( xoy \) plane, and the antenna elements are placed randomly, the coordinates of which are \((x_1, y_1, 0), (x_2, y_2, 0), \ldots, (x_n, y_n, 0)\), \ldots, \((x_m, y_m, 0)\), respectively. \( C_n^2 \) baselines are formed between each pair of antennas, and the baseline vector \( d_{mn} \) between the \( m \)th and the \( n \)th antenna element can be written in

\[
d_{mn} = (x_n - x_m, y_n - y_m, 0). \quad (8)
\]

Suppose that the elevation and azimuth angles of a far field target \( P \) are \( EI \) and \( Az \), as shown in Figure 2, then the direction vector from the antenna array to target can be calculated as follows:

\[
r = (\cos Az \cos El, \sin Az \cos El, \sin El) = (u, v, w), \quad (9)
\]

where \( u = \sin Az \cos El \), \( v = \cos Az \cos El \), and \( w = \sin El \) are the direction cosines of target \( P \). The path difference can be obtained by

\[
\Delta l_{mn} = d_{mn} \cdot r = (x_n - x_m)u + (y_n - y_m)v. \quad (10)
\]

Therefore, the phase difference can be calculated by equations (1) and (10) as follows:

\[
\Delta \phi_{mn} = \frac{2\pi f}{c} \Delta l_{mn} = \frac{2\pi f}{c} [(x_n - x_m)u + (y_n - y_m)v].
\]

(11)

It should be noted that, in a wideband interferometer, phase difference \( \Delta \phi_{mn} \) is linearly proportional to frequency \( f \), the slope \( k_{mn} \) of \( \Delta \phi_{mn} - f \) curve is an invariant constant, which can be obtained by curve-fitting algorithm. Meanwhile, according to equation (11), slope \( k_{mn} \) is related to direction cosines and antenna position as shown below:

\[
k_{mn} = \frac{2\pi f}{c} \Delta l_{mn} = \frac{2\pi f}{c} [(x_n - x_m)u + (y_n - y_m)v]. \quad (12)
\]

Equation (12) can be rewritten as follows:

\[
\left[
\begin{array}{cccc}
-x_1 & y_1 & 1 & 0 \\
-x_2 & y_2 & 1 & 0 \\
\vdots & \vdots & \vdots & \vdots \\
-x_n & y_n & 1 & 1 \\
\end{array}
\right]
\left[
\begin{array}{c}
x_1 \\
x_2 \\
\vdots \\
x_n \\
\end{array}
\right]
= \frac{c}{2\pi}
\left[
\begin{array}{c}
k_{12} \\
k_{13} \\
\vdots \\
k_{(n-1)n}
\end{array}
\right].
\]

Let \( A = \left[
\begin{array}{cccc}
x_2 - x_1 & y_2 - y_1 \\
x_3 - x_1 & y_3 - y_1 \\
\vdots & \vdots \\
x_n - x_{n-1} & y_n - y_{n-1}
\end{array}
\right] \) and \( B = \left[
\begin{array}{c}
k_{12} \\
k_{13} \\
\vdots \\
k_{(n-1)n}
\end{array}
\right], \)

where \( A \) stands for the antenna position parameters, which is a priori matrix, and \( B \) is the slope. Equation (13) is a linear equation set of the direction cosines and can be solved when the position information of at least three antenna elements are known. Therefore, when more than two baselines are used in the interferometer system, the direction cosines \( u \) and \( v \) can be solved with least square solution:

\[
\left[
\begin{array}{c}
u \\
v
\end{array}
\right]
= \frac{c}{2\pi}
\left(A^T A\right)^{-1} A^T B.
\]

(14)
Therefore, the elevation and azimuth angles can be obtained by

\[
El = \cos^{-1}\left(\sqrt{u^2 + v^2}\right),
\]
\[
Az = \tan^{-1}\left(\frac{v}{u}\right). \quad (15)
\]

Phase ambiguity of $\Delta \phi$ is an inevitable problem in the interferometer since the output angle of a phase discriminator is limited within $(-\pi, \pi)$. Specifically, in the wideband interferometer, the phase undergoing beyond $\pm \pi$ will be wrapped, as shown in Figure 3(a). However, due to the continuous frequency components of the radiated EMPs from the discharge source, the wrapped phase can be unwrapped with an appropriate algorithm design [23]. The unwrapped phase is shown in Figure 3(b), from which the slope of each baseline can be extracted and used in estimation.

However, the process of phase unwrapping and curve fitting in frequency domain can cause certain system error; in order to avoid this problem, equivalent operation will be accomplished in time domain directly. When signal arrives at the antenna array, the arrival time at each antenna element differs from others, as a result of the path difference shown below:

\[
\Delta t_{mn} = \Delta t_{mn}^c + \epsilon,
\]

where $\Delta t_{mn}$ is the time delay between antennas $m$ and $n$. Then, $k_{mn}$ can be calculated in time domain as follows:

\[
k_{mn} = \frac{2\pi}{c} \Delta l_{mn} = 2\pi \Delta t_{mn}, \quad (17)
\]

which means the matrix $B$ in equation (12) can be written as follows:

\[
B = 2\pi \begin{bmatrix}
\Delta t_{21} \\
\Delta t_{31} \\
\vdots \\
\Delta t_{2n} \\
\vdots \\
\Delta t_{n(n-1)}
\end{bmatrix}.
\]

The difference of time delay $\Delta t_{mn}$ can be obtained by cross correlating the two received signals. Suppose the received signals of antennas $m$ and $n$ are denoted as $s_m(t)$ and $s_n(t)$, respectively. Then, the cross correlation is defined as follows:

\[
r_{mn}(\tau) = E[s_m(t)s_n(t + \tau)], \quad (19)
\]

where $E[*]$ stands for the mathematical expectation. The peak of $r_{mn}(\tau)$ appears when $\tau = \Delta t_{mn}$; therefore, the time delay can be estimated by searching the peak position.

Specially, in UWB discharge source detection, radiated EMPs from the UWB discharge source tends to be high-frequency oscillating pulses, so the cross correlation will also oscillate at the similar frequency, which can generate false peaks under low SNR conditions and affect the estimation of time delay. As shown in Figure 4(a), the cross-correlation result $r_{1mn}$ oscillates at a high frequency, and the true peak point (marked as red circle) which corresponds to the correct time delay estimation is lower than a false peak (marked as red cross), which comes from noise and high-frequency oscillation. Peak search algorithm cannot distinguish the true peak from higher false peaks; therefore, an estimation error of time delay occurs. In order to mitigate this problem, the Hilbert transform is applied in our proposed method. Analytic form of received signals $s_m(t)$ and $s_n(t)$ can be calculated by the Hilbert transform as follows:

\[
s_m(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s_m(t)}{t-\tau} d\tau, \quad (20)
\]

\[
s_n(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s_n(t)}{t-\tau} d\tau,
\]

and be combined with $s_m(t)$ and $s_n(t)$, respectively, to form the complex signals. Cross correlation will be calculated upon those complex signals, so the interference peaks can be reduced effectively, as shown in Figure 4(b), and an obvious peak exists in cross-correlation result $r_{2mn}$. Nevertheless, due to the group delay of Hilbert transform, certain envelop location deviation may occur between the original cross-correlation function and the cross-correlation result after the Hilbert transform. Figures 4(a) and 4(b) illustrate that the true peak point occurs at time delay of 3.2 ns, while the peak point after the Hilbert transform occurs at 2.9 ns. However, this deviation is less than the time delay deviation between the false peak and correct peak by a considerable chance, which is 1.2 ns in Figure 4(a). Therefore, the estimation error of time delay can be reduced by precise peak point searching on $r_{1mn}$ within a search region, which is centered on the peak point after the Hilbert transform with proper radius, as shown in Figure 4(c).

3. Simulation and Numerical Results

To verify the performance of the proposed DOA estimation method, several simulations were accomplished and the numerical results will be exhibited in this section. A typical measured signal in our experiment, which will be introduced in Section 4, was used in simulations as a source signal. The entire DOA estimation flow is shown in Figure 5. The Hilbert transform is applied in the estimation of time delay, as described above in Section 2. After that, the direction of arrival can be calculated by the least square method with antenna position parameters and the time delay of each baseline.

In order to compare the estimation performance between the traditional time-domain method and proposed method, 1000 Monte Carlo trials under different SNR conditions were operated. In simulations, the azimuth angle and elevation angle were set to be 10° and 45°, respectively, the receiving array was formed by 4 antenna elements, and they were set on the corner of a square, the side length of which is 8 m. The relationship between the root mean square error (RMSE) of the DOA estimation and
the SNR of discharge source was calculated and demonstrated in Figure 6. RMSE in DOA estimation of both methods obviously declines when SNR of the received signal rises from $-10$ dB to 10 dB. It is because that the estimation of DOA is greatly influenced by the estimation error in time delay, and the standard deviation of time delay has a relationship with SNR as follows [24]:

$$\sigma^2_{\tau} \geq \frac{1}{2T \int_{f_1}^{f_H} \left(2\pi f d \sin \theta \right)^2 \left(1 + 2 \cdot \text{SNR}/\text{SNR}^2\right) f^2 df},$$

where $T$ is the integration time, $f_1$ and $f_H$ are the lower and upper bounds of the valid frequency band, and SNR is the signal-to-noise ratio. According to equation (21), the estimation in time delay is more accurate under higher SNR condition, which leads to a smaller RMSE in both estimation methods. And specifically, in low SNR situations, which is the common SNR circumstance in real discharge source locating, the DOA estimation precision is improved by the proposed Hilbert method compared to traditional time-domain method.

Furthermore, the effect of antenna array arrangement on DOA estimation RMSE were also studied. As shown in Figure 7(a) that with the increase of baseline length, the RMSE of estimation decreases obviously. The reason can be explained from the aspect of basic principle equation of interferometry. After derivation calculus on incident angle $\theta$ to the both sides of equation (1), the following equation can be obtained:

$$d\Delta \phi = \frac{2\pi f d \sin \theta d\theta}{c},$$

Equation (22) can be rewritten as follows:

$$\sigma^2_{\phi} = \frac{c}{2\pi f d \sin \theta} \sigma^2_{\Delta \phi}.$$
Figure 4: Peak search operation under low SNR conditions: (a) cross correlation $r_{1mn}$ of the received signal, (b) cross correlation $r_{2mn}$ after the Hilbert transform, and (c) true peak point location in $r_{1mn}$ within a proper region.

Figure 5: Flow diagram of the proposed method of UWB discharge source DOA estimation.
\[ \Delta \phi = \frac{2\pi f}{c} \left[ (x_n - x_m) \cos \theta + (y_n - y_m) \sin \theta \right] \sin \theta \cdot d\theta, \]
\[ \Delta \phi = \frac{2\pi f}{c} \left[ - (x_n - x_m) \sin \theta + (y_n - y_m) \cos \theta \right] \cos \theta \cdot d\theta. \]

(25)

Therefore, the RMS error of two arriving angles can be expressed as follows:

\[
\begin{align*}
\sigma_{\Delta \phi}^2 &= \frac{2\pi f}{c} \left[ (x_n - x_m) \cos \theta + (y_n - y_m) \sin \theta \right] \sin \theta \cdot d\theta, \\
\sigma_{\Delta \phi}^2 &= \left[ \frac{2\pi f}{c} \left[ - (x_n - x_m) \sin \theta + (y_n - y_m) \cos \theta \right] \cos \theta \cdot d\theta \right]^2.
\end{align*}
\]

(26)

where \( \sigma_{\Delta \phi}^2 \) and \( \sigma_{\Delta \phi}^2 \) are the RMS error of elevation and azimuth angle estimation and \( \sigma_{\Delta \phi}^2 \) is the error of phase difference, which is related to time delay measurement. According to

Figure 6: Monte Carlo simulation of the RMSE of DOA estimation using the proposed method and traditional time-domain method, respectively, as a function of SNR with the following parameters: azimuth angle = 10°, elevation = 45°, baseline length = 8 m, antenna number = 4, and 1000 realizations. (a) RMSE of azimuth angle estimation and (b) RMSE of elevation angle estimation.

Figure 7: Monte Carlo simulation of the RMSE of DOA estimation under different antenna array conditions: (a) simulation results under different baseline lengths with the following parameters: azimuth angle = 10°, elevation = 45°, SNR = 10 dB, antenna number = 4, and 1000 realizations and (b) simulation results under different antenna numbers with the following parameters: azimuth angle = 10°, elevation = 45°, SNR = 10 dB, baseline length = 8 m, and 1000 realizations.
equation (26), when elevation angle increases, the estimation accuracy of elevation angle is improved, while that of the azimuth angle declines. However, the change of the azimuth angle has little effect on the DOA estimation result; as illustrated in Figure 8(b), the RMS error of two incident angles presents an irregularly change within a very small range.

4. Experimental Setup and Results

Figure 9 illustrates the experimental setup to verify the proposed DOA estimation method. The antenna array consists of four ultrawideband D-dot antennas (Prodyn AD-70), the bandwidth of which ranges from 22 kHz to 1.4 GHz. Each antenna element was connected to a channel of a four-channel digital oscilloscope (DPO90604A) with a bandwidth of 6 GHz. When oscilloscope was triggered, all the channels started to record signals simultaneously and digitalize them at a rate of 10 GHz by built-in ADCs. During the entire experiment, the receiving antenna array was located at five different test points to investigate the performance of the proposed method under different incident angle conditions, and the position of antenna elements was changed three times on each test point to study the effect brought by changing the baseline length.

Features of receiving signals in our experiment under one typical condition will be demonstrated as an example below. In this condition, the antenna array arrangement is shown in Figure 10 that four antenna elements were set on the corner of a square with a side length of 4 m.

Figure 11 shows the characteristics of received signals from four antennas in both time domain and frequency domain. It can be seen from Figure 11(a) that four received signals differ in both time of arrival and signal intensity in time domain. Since the signal intensity imbalance is caused by antenna gain difference and has little impact on DOA estimation, it can be ignored during the angle estimation process. It is also clear that the received signal tends to be oscillating at a very high frequency, which is the feature of the radiated EMP pulse from the discharge source. The frequency characteristic is shown in Figure 11(b), four received signals share the similar spectrum distribution and obvious wideband characteristics emerge. The frequency band ranges from 200 MHz to 700 MHz, which indicates
that the wavelength of the equivalent narrowband component of the received wideband signal is within 0.43 m to 1.50 m. Therefore, phase ambiguity problem inevitably appears because the baseline lengths are all longer than the half-wavelength. Phase difference between antenna 1 and 2 is carried out and shown as a representation in Figure 12(a), and it is wrapped within $(-\pi, \pi)$ and so are the phase difference of other baselines as a typical phenomenon of phase ambiguity. After unwrapping and curve-fitting operations, obvious linear relation between phase difference and frequency of all the baselines can be observed, as shown in Figure 12(b), which confirms that the ambiguity in UWB discharge source DOA estimation can be avoided with wideband features.

The experiment result under different conditions will be demonstrated below. It should be pointed out firstly that the noise and other interferences in our experimental environment were relatively small, so measured results with large noise was hard to be collected. In order to investigate the DOA estimation performance under different SNR conditions, additional Gaussian noise was added to the received signals before the estimation progress. A comparison is made in Figure 13 for the DOA estimation performance of the traditional time-domain method and proposed method in different SNR circumstances, the SNR here stands for the ratio between the received signal power and the power of added Gaussian noise. It can be seen that the RMSE in both azimuth and elevation angle decreases when SNR increases, and the proposed method has better performance than the traditional method.

Estimation RMSE under different baseline lengths is shown in Figure 14. With the increase of baseline length from 1 m to 4 m, the RMSE of DOA estimation declines obviously, which is consistent with the simulation results. It
also can be seen that DOA estimation RMSE changes a lot sharper when baseline length increases from 1 m to 2 m, and it can be explained that mutual coupling effect exists between antenna elements, especially when two ultraband antennas are close to each other. Therefore, the increase of baseline length from a small value can lead to a rapid reduction in the estimation error of time delay and eventually improve the accuracy of DOA estimation.

Moreover, the influence of incident angle is exhibited in Figure 15; as the elevation angle changes from 18.23° to 24.92°, the RMSE of elevation angle estimation decreases from 7.14° to 1.88° and that of azimuth angle estimation increases 0.31° to 4.22°. As the azimuth angle changes, the RMSE of the elevation and azimuth estimation change in a random way, as shown in Figure 15(b). The aforementioned two observations also agree with the simulation results.
However, the DOA estimation RMSE in the experiment is relatively larger than that in the simulation. Possible reasons can be assumed as follows:

(a) Measurement error of the antenna position. In our experiment, certain measurement error occurred due to the circumstance of the test ground and measuring equipment. And the DOA of the target is estimated by the position information and the received signals in the proposed method, so the measurement error in antenna coordinates can degrade the estimation performance. Therefore, in order to obtain more accurate results, it is necessary to decline the measurement error.

(b) Coupling between antenna elements. Mutual coupling effect can affect the received waveform of each antenna. When two antennas are close to each other, besides the electromagnetic field generated by its own induced current, the two intersecting antennas are also affected by the electromagnetic field produced by the current in the other antenna, and the receiving performance of antennas is influenced. This effect becomes heavier when two antenna
elements are very close to each other and can cause serious distortion in the time-domain waveform of the received signal. Then, certain error will occur in the time delay estimation during cross-correlation process and eventually reduce the accuracy of DOA estimation.

(c) The imbalance among each antenna element.
(d) Multipath transmission effect by surrounding environment.

5. Conclusions

A multiple baseline wideband time-domain interferometer with Hilbert transform DOA estimation method for UWB discharge source locating is proposed in this paper. Simulations are then carried out and the influence of antenna array configurations and incident angles on DOA estimation performance are demonstrated and explained. The results of simulation confirm the improvement in DOA estimation of the proposed method and also explains the influence of antenna array configurations and incident angle on DOA estimation performance. Finally, a discharge source DOA estimation experiment setup is introduced and then the experimental results are exhibited and analysed. Both the simulation and experimental results share the same characteristics and agree very well. It has been shown that, with the increase of antenna element number and baseline length, the precision of DOA estimation will be improved obviously. As for the incident angle parameters, the higher elevation angle leads to a better estimation accuracy in the elevation angle and a lower accuracy in the azimuth angle, while the azimuth angle of a discharge source has little effect on DOA estimation.

Data Availability

The CSV data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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