Direction Finding Using Uniform Circular Array of Horizontal Log-Periodic Dipole Antennas

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Abstract **─** Direction finding (DF) using the uniform circular array composed of horizontal log-periodic dipole antennas (UCA-LPDA) is studied in this paper. One advantage of the UCA-LPDA is that it has a reasonable effective radius for broadband DF. Compared with the previous works which usually focused on isotropic antennas, the UCA-LPDA has higher gain and higher angular resolution for the direction of arrival estimation. The spatial response of the UCA-LPDA and the direction of arrival (DOA) estimation algorithms are discussed. The proposed polarized MUSIC (Pol-MUSIC) method can obtain the DOA of signals with any unknown polarizations while no search of the polarizations is required. Based on the theoretical analysis, the actual signal DF experiment which uses a UCA-LPDA with 24 elements was carried out. The DF experiments results demonstrate the effectiveness and accuracy of using UCA-LPDA with Pol-MUSIC method.

Index Terms **─** Log-periodic dipole antenna, multiple signal classification (MUSIC) algorithm, radio direction finding, uniform circular array.

I. INTRODUCTION

Most of the radio DF systems adopt several identical antennas (including amplitude, phase, polarization, etc.) to form linear array, circular array, or L-shaped array, and so on. Usually vertical monopole or dipole antenna is employed as the element in DF array antennas, and then a single-polarized antenna system can be formed for DF. According to the simple relationship of geometric phase between array elements, the DOA is estimated by means of related interferometer and MUSIC, which have been widely applied in many DF systems [1-3]. The DF algorithms of the circular arrays with directional array elements are considered in [4, 5]. The Cramer-Rao Lower Bound of the DOA estimation by using directional antenna is analyzed in [6]. These studies mainly focus on the radiation pattern of directional antenna and obtaining good DF results. However, the polarization characteristics of the antenna are rarely discussed.

In order to estimate the DOA for unknown polarization of signals, the polarization-sensitive array is proposed [7-9]. These arrays are often composed of orthogonal dipole antennas, triad antennas and six dimensional electromagnetic vector sensors. These DF systems require at least two channels for each space sampling point, and the system equipment's are large in size and expensive in cost. Heterogeneous array with only one element at each point of the spatial sampling is proposed in [10].The directions of arrival are estimated for two known polarized waves using active loop antennas with eight different polarized states. Furthermore in [11], the unknown polarized signal DF operated on six art ferrite load dipole with titled forward different direction, which constituted a heterogeneous array. Although, the heterogeneous array needs only one channel in each space sampling point, and it can be used to estimate the direction of arrival for unknown polarized signals. However, the gains of these elements are low, which make them difficult to be applied to high sensitivity DF system.

In order to implement high sensitivity direction-finding for HF wave signals in the range of 0-360 degrees, the direction finding using a novel UCA-LPDA is studied in this paper. 24 horizontal log-periodic dipole antennas (LPDA) are arranged in a circle with certain angle in the XOY plane to form a uniform circular array. The beam of each antenna points to the center of the circle. Because of the relationship between the phase center of the LPDA and the operating frequency [12], the effective radius of the UCA-LPDA is reasonable. The effective radius of the DF array is defined as the horizontal distance between the phase centre of the LPDA and the center of the circle. At lower frequency, the array has a long effective radius, and at high frequency, it has a short effective radius. This ensures a reasonable effective radius for broadband direction

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finding using interferometer or MUSIC method [13].

In addition, the UCA-LPDA is a heterogeneous array, in which the elements have different polarized states. For the UCA-LPDA, a polarized MUSIC (Pol-MUSIC) method is proposed for unknown polarized signal while no search of the polarizations is required. Because of the polarization-sensitivity, the UCA-LPDA has lower spatial correlation than isotropic antennas and can obtain a higher angular resolution. The effectiveness and robustness of the DOA estimation for unknown polarized signals using UCA-LPDA are demonstrated by simulation and experiment in this paper.

II. DOA ESTIMATE WITH UCA-LPDA

A. Spatial response of LPDA

Log-periodic dipole antenna (LPDA) is composed of multiple dipoles arranged according to a certain scale factor. Current distributions on the antenna can be obtained by using computer simulations based on the method of moment (MOM). Once the current distributions are determined, it is easy to calculate the radiation vector $\boldsymbol{a}$ of LPDAs in far area [14]. In spherical coordinate, the general expression is as follows:

$$\boldsymbol{a} = (|a_\theta| \mathrm{e}^{\mathrm{j}\delta} \hat{\boldsymbol{\theta}} + |a_\phi| \mathrm{e}^{\mathrm{j}\zeta} \hat{\boldsymbol{\phi}}) \, , \qquad (1)$$

where $|a_\theta|$ and $|a_\phi|$ represent the magnitude of the $\hat{\boldsymbol{\theta}}$ component and the $\hat{\boldsymbol{\phi}}$ component of the electric field, respectively. δ and ζ represent the phase.

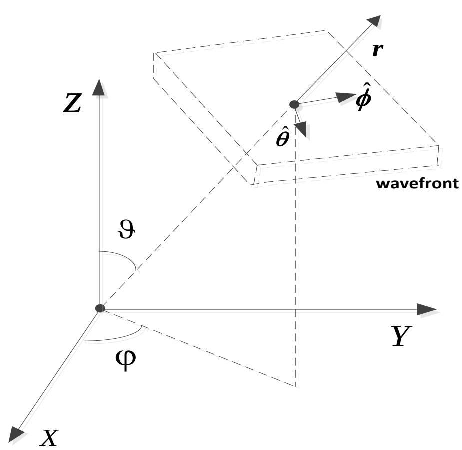


Fig. 1. The unified coordinate system.

Formula (1) can be further rewritten as follows:

$$\boldsymbol{a} = f(\vartheta, \varphi) \mathrm{e}^{\mathrm{j}\zeta(\vartheta,\varphi)} (\cos\gamma \mathrm{e}^{\mathrm{j}\eta} \hat{\boldsymbol{\theta}} + \sin\gamma \hat{\boldsymbol{\phi}}) \, . \qquad (2)$$

$$\cos\gamma = \frac{|a_\theta|}{\sqrt{|a_\theta|^2 + |a_\phi|^2}} \, , \sin\gamma = \frac{|a_\phi|}{\sqrt{|a_\theta|^2 + |a_\phi|^2}} \, , \eta = \delta - \zeta \, ,$$

$$f(\vartheta, \varphi) = \sqrt{|a_\theta|^2 + |a_\phi|^2} \, .$$

Where $\gamma \in [0, \pi/2]$ and $\eta \in [-\pi, \pi]$ represent the magnitude ratio and the phase between the two polarization components [15]. When γ=0°, represents the vertical polarization, when γ=90°, represents the horizontal polarization. For a horizontal LPDA, there is only horizontal components $\hat{\boldsymbol{\phi}}$ at pitch angle $\vartheta = 90°$; however, there are both the horizontal components $\hat{\boldsymbol{\phi}}$ and vertical components $\hat{\boldsymbol{\theta}}$ at other pitch angles. The definition of the coordinate system is shown in Fig. 1.

Let $\boldsymbol{U} = (\cos\gamma \mathrm{e}^{\mathrm{j}\eta} \hat{\boldsymbol{\theta}} + \sin\gamma \hat{\boldsymbol{\phi}})$, then

$$\boldsymbol{a} = f(\vartheta, \varphi) \mathrm{e}^{\mathrm{j}\zeta(\vartheta,\varphi)} \boldsymbol{U} \, . \qquad (3)$$

Formula (3) represents the full spatial response of the LPDA, including amplitude, phase, and polarization. $\boldsymbol{U}$ represents spatial polarization, which is a function of the angle of space observation (ϑ, φ).

The LPDA with N elements are arranged into an "inward-looking" circular array with a certain angle in the XOY plane. The schematic diagram is shown in Fig. 2. The main radiation direction of each element is toward the center of the circle. So the array with small size is obtained. Besides, the DOA within the range of 0-360° can also be achieved and the electrical effective radius of the UCA-LPDA can be remained in a wide frequency range because of its phase center movement toward the center of the array.

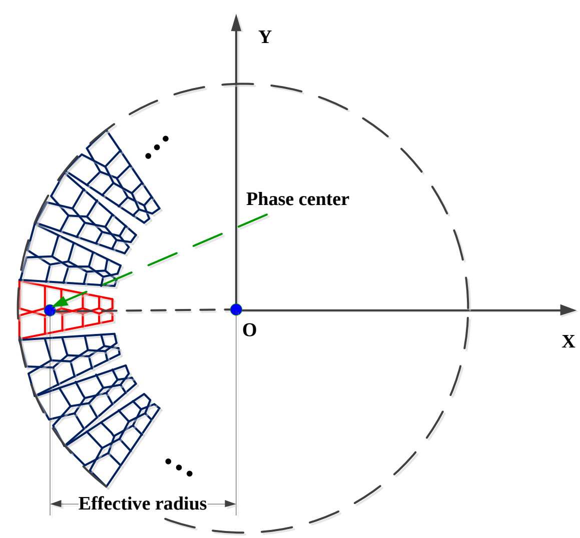


Fig. 2. The schematic diagram of the UCA-LPDA.

The spatial response of the array can be written as follows:

$$\boldsymbol{a}(\vartheta,\varphi) = \begin{bmatrix} \boldsymbol{a}_\theta & \boldsymbol{a}_\phi \end{bmatrix} = \begin{bmatrix} a_1^{\theta}(\vartheta,\varphi) & a_1^{\phi}(\vartheta,\varphi) \\ a_2^{\theta}(\vartheta,\varphi) & a_2^{\phi}(\vartheta,\varphi) \\ \vdots & \\ a_N^{\theta}(\vartheta,\varphi) & a_N^{\phi}(\vartheta,\varphi) \end{bmatrix} = \begin{bmatrix} f_1(\vartheta,\varphi)\mathrm{e}^{\mathrm{j}\zeta_1(\vartheta,\varphi)}\boldsymbol{U}_1 \\ f_2(\vartheta,\varphi)\mathrm{e}^{\mathrm{j}\zeta_2(\vartheta,\varphi)}\boldsymbol{U}_2 \\ \vdots \\ f_N(\vartheta,\varphi)\mathrm{e}^{\mathrm{j}\zeta_N(\vartheta,\varphi)}\boldsymbol{U}_N \end{bmatrix} . \qquad (4)$$

The spatial response of the array includes the amplitude, phase, and polarization, whose dimension is

$N\times 2$. Because the elements point to different orientations, $\boldsymbol{U}_1 \neq \boldsymbol{U}_2 \neq \cdots \neq \boldsymbol{U}_N$, the UCA-LPDA is a heterogeneous array.

Considering that the incoming wave of signal is a fully polarized wave, the polarization state is $\hat{\boldsymbol{u}}$. $\hat{\boldsymbol{u}} = \hat{\boldsymbol{\theta}}\cos\gamma_0 + \hat{\boldsymbol{\phi}}\sin\gamma_0 e^{j\eta_0}$, $\gamma \in [0, \pi/2]$ and $\eta \in [-\pi, \pi]$ represent the magnitude ratio and the phase between the two polarization components. γ=0° represents the vertical polarization while γ=90° the horizontal polarization. According to the antenna receiving theory, the amplitude of the ith element receiving the unit field strength is:

$$V_i = \boldsymbol{a}_i \bullet \hat{\boldsymbol{u}}^* .$$

Where the sign (*) represents conjugate. Then the manifold of the UCA-LPDA is:

$$\boldsymbol{A}(\vartheta,\varphi,\gamma_0,\eta_0) = \underbrace{\begin{bmatrix} f_1(\vartheta,\varphi)e^{j\zeta_1(\vartheta,\varphi)} \\ f_2(\vartheta,\varphi)e^{j\zeta_2(\vartheta,\varphi)} \\ \vdots \\ f_N(\vartheta,\varphi)e^{j\zeta_N(\vartheta,\varphi)} \end{bmatrix}}_{N\times 1} \odot \underbrace{\begin{bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_2 \\ \vdots \\ \boldsymbol{U}_N \end{bmatrix}}_{N\times 2} \underbrace{\begin{bmatrix} \cos\gamma_0 \\ \sin\gamma_0 e^{-j\eta_0} \end{bmatrix}}_{\boldsymbol{u}^H:\ 2\times 1} . \quad (5)$$

Where the sign ($\odot$) represents the Schur-Hadamard.

From formula (5), it can be seen that the manifold of the UCA-LPDA is relation to the polarization state of the incoming wave because of the different polarization states of the LPDAs.

Now, we consider the spatial correlation coefficient of two incident waves impinging upon the UCA-LPDA. Let the directions of the two incoming waves in space are $\psi_1 = (\vartheta_1, \varphi_1)$ and $\psi_2 = (\vartheta_2, \varphi_2)$, respectively, and the corresponding polarized states are respectively $\boldsymbol{u}_1$, $\boldsymbol{u}_2$ respectively. Then, the spatial correlation coefficient of the two incident waves is:

$$\begin{aligned}\rho &= \frac{[\boldsymbol{a}(\psi_1)\boldsymbol{u}_1^H]^H[\boldsymbol{a}(\psi_2)\boldsymbol{u}_2^H]}{\|[\boldsymbol{a}(\psi_1)\boldsymbol{u}_1]\| \bullet \|[\boldsymbol{a}(\psi_2)\boldsymbol{u}_2]\|} \\ &= \frac{\sum_{i=1}^{N} f_i(\psi_1) f_i(\psi_2) e^{j[\zeta_i(\psi_1)-\zeta_i(\psi_2)]}[\boldsymbol{u}_1\boldsymbol{U}_i^H(\psi_1)\boldsymbol{U}_i(\psi_2)\boldsymbol{u}_2^H]}{\sqrt{\sum_{i=1}^{N}\left|f_i(\psi_1)\boldsymbol{u}_1\boldsymbol{U}_i^H(\psi_1)\right|^2} \bullet \sqrt{\sum_{i=1}^{N}\left|f_i(\psi_2)\boldsymbol{u}_2\boldsymbol{U}_i^H(\psi_2)\right|^2}} . \quad (6)\end{aligned}$$

When the antennas are omni-directional and have same polarized states (such as vertical dipoles), the spatial correlation coefficient is:

$$\rho = \frac{\sum_{i=1}^{N} e^{j[\varphi_i(\psi_1)-\varphi_i(\psi_2)]}}{N} . \quad (7)$$

Obviously, for UCA-LPDA, the correlation coefficients are related to wave polarized state. Two waves have different polarized states and their spatial angles are close to each other, the correlation coefficient is less than 1 according to Schwartz inequality. However, for the isotropic antenna, its correlation coefficient is approximately equal to 1. The spatial correlation decreases in the UCA-LPDA, which provides favorable conditions for distinguishing two signals in space. The smaller the spatial correlation coefficient, the more favorable distinguishing signals will be [16].

The spatial response of UCA-LPDA is more complex than the isotropic antenna. Usually it is not an analytical expression. A feasible method is that spatial response of the element in the whole array including mutual coupling is calculated using MOM, or measured accurately. The spatial response obtained is stored into the direction-finding receiver in the term of tables.

B. DOA estimation algorithms

Considering that the UCA is composed of N LPDAs with the same parameters in the XOY plane. Assuming that there are D signals illuminating upon, and the signal is narrow-band, and the noise obeys Gaussian white noise distribution. Then the time domain signal received by the elements can be written as follows:

$$\boldsymbol{X} = \boldsymbol{AS}(\boldsymbol{t}) + \boldsymbol{N}(\boldsymbol{t}) , \quad (8)$$

where $\boldsymbol{N}(\boldsymbol{t})$ is Gaussian white noise. $\boldsymbol{A} = [\boldsymbol{a}(\psi_1)\boldsymbol{u}_1^{\boldsymbol{H}}, \boldsymbol{a}(\psi_2)\boldsymbol{u}_2^{\boldsymbol{H}}, \ldots \boldsymbol{a}(\psi_{\boldsymbol{D}})\boldsymbol{u}_{\boldsymbol{D}}^{\boldsymbol{H}}]$ is the manifold [17]. $\boldsymbol{S} = [\boldsymbol{s}_1(\boldsymbol{t}), \boldsymbol{s}_2(\boldsymbol{t}), \ldots \boldsymbol{s}_{\boldsymbol{D}}(\boldsymbol{t})]^{\boldsymbol{T}}$. $\psi_1, \psi_2, \ldots \psi_{\boldsymbol{D}}$ are the directions of the D signals, respectively, which including the two dimension direction (ϑ, φ). $\boldsymbol{u}_1, \boldsymbol{u}_2 \ldots \boldsymbol{u}_{\boldsymbol{D}}$ are the polarization of the D signals.

Then the covariance matrix of the receiving data is:

$$\boldsymbol{R}_{xx} = \boldsymbol{AR}_s\boldsymbol{A}^{\boldsymbol{H}} + \sigma^2\boldsymbol{I} , \quad (9)$$

$\boldsymbol{R}_s$ is the covariance matrix of the signals. When the signals are uncorrelated, $\boldsymbol{R}_s$ is a diagonal matrix. σ^2 is the power of the noise.

According to the MUSIC subspace method [18], the span of the eigenvectors corresponding to the N-D small eigenvalues of $\boldsymbol{R}_{XX}$ is the noise subspace $\boldsymbol{E}_{KC}$, and the span of the eigenvectors corresponding to the D large eigenvalues of $\boldsymbol{R}_{XX}$ is the signal subspace.

Using the orthogonal principle of signal subspace and noise subspace, the entire signal subspace including polarized space is projected into the noise subspace. In the true direction of the signal, the following equation holds on:

$$\boldsymbol{ua}^H\boldsymbol{E}_{KC} = 0 . \quad (10)$$

Further,

$$\boldsymbol{ua}^H\boldsymbol{E}_{KC}\boldsymbol{E}_{KC}^H\boldsymbol{au}^H = 0 . \quad (11)$$

If DOA estimation is carried out directly using above equation, it is necessary to conduct a four-dimensional traversal searching in the whole polarization domain and spatial domain. In fact, this process can be simplified. For heterogeneous array, $\boldsymbol{a}$ is a full rank matrix with dimension of $N\times 2$. Whatever the true polarization of the signal is, making (11) holds on in the true direction of the signal, the matrix $\boldsymbol{a}^H \boldsymbol{E}_{KC} \boldsymbol{E}_{KC}^H \boldsymbol{a}$ whose dimension is 2×2 must be rank deficient. Namely,

$$\det\left\{\boldsymbol{a}^H \boldsymbol{E}_{KC} \boldsymbol{E}_{KC}^H \boldsymbol{a}\right\} = 0 . \quad (12)$$

Operator symbol $\det\{\bullet\}$ represents the determinant of matrix.

Therefore, the spatial spectral function of the polarized MUSIC (Pol-MUSIC) can be constructed as below:

$$P(\vartheta,\varphi) = \frac{1}{\det\left\{\boldsymbol{a}^H(\vartheta,\varphi)\boldsymbol{E}_{KC}\boldsymbol{E}^H{}_{KC}\boldsymbol{a}(\vartheta,\varphi)\right\}} . \quad (13)$$

The DOA is obtained from the angle corresponding to the maximum spectral peak. Thus, the searching in polarization space can be avoided, and $\boldsymbol{a}(\vartheta,\varphi)$ is given by formula (4), which is the spatial response of the LPDA. The proposed method does not need to know the polarization state of incoming wave beforehand.

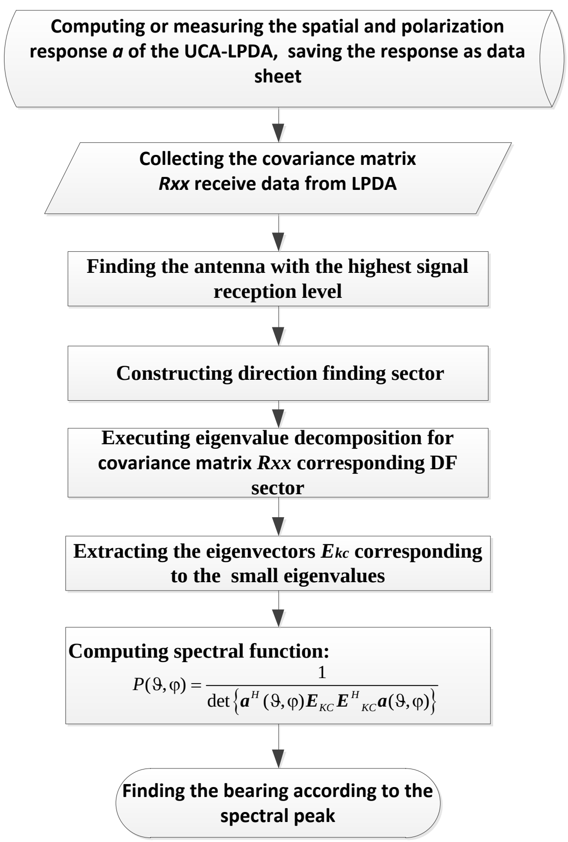


Fig. 3. Algorithm flow chart.

In (13), $\boldsymbol{a}(\vartheta,\varphi)$ is a vector composed of spatial response of LPDAs in the unified coordinate system. The spatial response contains $\hat{\boldsymbol{\theta}}$ component and the $\hat{\boldsymbol{\phi}}$ component. It can be obtained by electromagnetic calculation. Because of the directional pattern of the LPDA, spatial response should been normalized. $\boldsymbol{a}(\vartheta,\varphi)$ is replaced by $\boldsymbol{a}(\vartheta,\varphi)/\left\|\boldsymbol{a}(\vartheta,\varphi)\right\|_2$.

If ignoring the polarization in the spatial response of the LPDA, only consider the amplitude and phase, then,

$$\boldsymbol{a}_{\phi}(\vartheta,\varphi) = f(\vartheta,\varphi)\mathrm{e}^{\mathrm{j}\zeta(\vartheta,\varphi)} .$$

The spatial spectral function is:

$$P(\vartheta,\varphi) = \frac{1}{\boldsymbol{a}_{\phi}{}^H(\vartheta,\varphi)\boldsymbol{E}_{KC}\boldsymbol{E}^H{}_{KC}\boldsymbol{a}_{\phi}(\vartheta,\varphi)} . \quad (14)$$

This is the traditional MUSIC method. In fact, only when the polarization of the incoming wave signal is horizontal polarization or all elements in the array are same, $\boldsymbol{U}_1 = \boldsymbol{U}_2 = ...\boldsymbol{U}_N$ (homogeneous array), formula (14) holds on. Direction of arrival estimation for unknown polarization signal using UCA-LPDA, the polarization states of the antennas must be included in the manifold.

Because the phase center of LPDA only exists in main beam [19]. When DF array employs UCA-LPDA, not all LPDAs can be used. There is a DF sector in the array. The DF sector employs a LPDA with highest signal reception level.

The proposed Pol-MUSIC applying to UCA-LPDA algorithm flow chart is shown in Fig. 3.

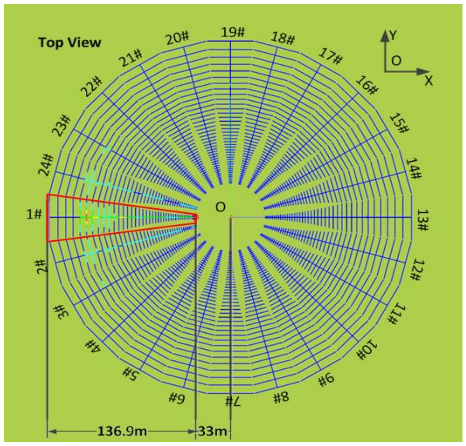
III. SIMULATION AND EXPERIMENTAL RESULTS

In order to illustrate the previous method, three simulation examples using UCA-LPDA are conducted for HF direction finding. The circular array is composed of 24 horizontal elements with an interval of 15 degrees which are disposed in XOY plane. The total number of the dipoles is 40 in each LPDA. The diameter of the UCA-LPDA is 340 meters. Because HF antenna is affected by the ground, the LPDA needs to have an angle of inclination to ensure that the electric height of the antenna above the ground doesn't change drastically in a wide frequency band. The projected length of the LPDA is 136.9m. The model of the UCA-LPDA is shown in Fig. 4. The parameters of the LPDA is shown in Table 1.

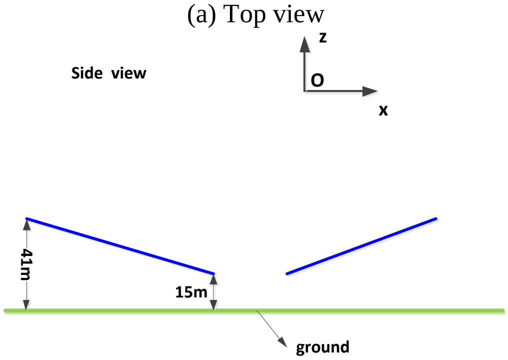
Table 1: The parameters of the LPDA

Parameter	**Value**	**Parameter**	**Value**
N	40	l_1	44.9m
τ	0.92	l_{40}	2.9m
σ	0.077	H1	41m
Projected **length**	136.9m	**H2**	15m

N: the total number of the dipoles in LPDA. τ is the scale factor and the σ is spacing factor. l_1 is the length of the longest dipole and l_{40} is the length of shortest dipole.



(a) Top view



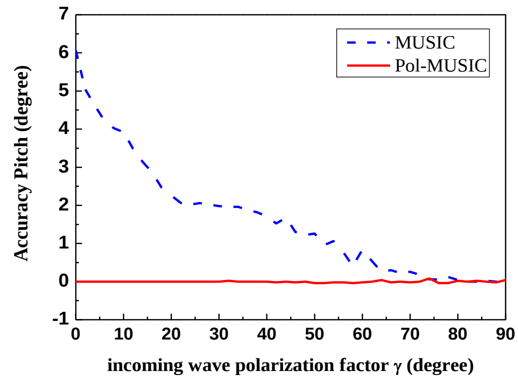
(b) Side view

Fig. 4. The model of UCA-LPDA.

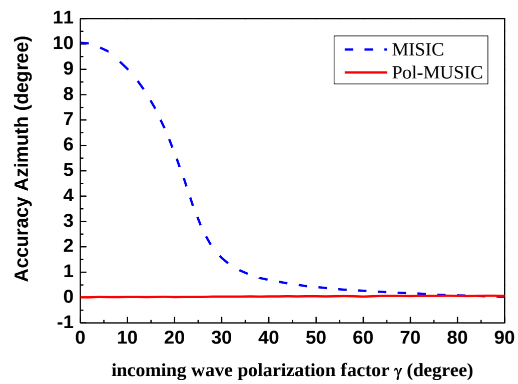
The spatial responses of the LPDA are calculated by FEKO. In order to take account of the mutual coupling between the antennas, the simulated element is excited while other elements are connected to standard loads.

In the first example, only one incident signal is received by the UCA-LPDA. The azimuth angle of the signal is 153° and elevation angle is 30°. The polarization parameter γ changes continuously from 0° to 90° with a step of 2° and η is -120°. In the simulation process, it is assumed that the noise power of each element is the same and independently distributed. The max signal-to-noise ratio (SNR) is set to be 20dB and the noise bandwidth is set to be 3 KHz. The frequency of signal is 6MHz. The total number of samples is 1024. We conduct 300 times Monte-Carlo simulations to estimate the azimuth and the pitch. Figure 5 shows the estimation results of Pol-MUSIC method using formula (13) compared with the general MUSIC method ignoring the polarization of the LPDA using formula (14).

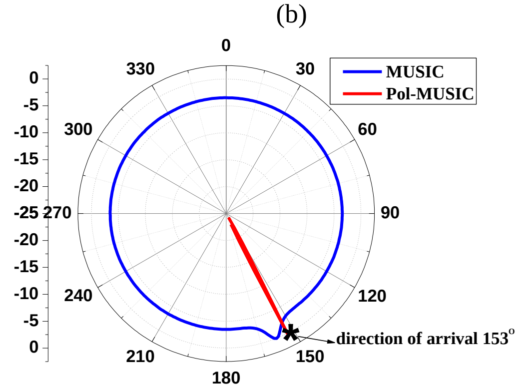
The DF results show that the Pol-MUSIC can obtain accurate result whatever the incoming polarization varies. The proposed Pol-MUSIC method is effective. The accuracy of estimation is less than 1 degree. However the general MUSIC estimates wrong result, especially when polarization of incoming wave is close to vertical polarization. If only the polarization state of the signal is close horizontal polarization, the general MUSIC method can obtain accurate result. This is because the general MUSIC method does not take into account the wave polarization effect. And the UCA-LPDA is a heterogeneous array, which is a polarization-sensitive array. Because of the ionosphere, the polarization state of incoming wave is often elliptical polarization. So the polarization of the DF antenna should been contained in the DF processing. The Pol-MUSIC method should be employed.



(a)



(b)



(c)

Fig. 5. The DF precision varies with the polarization using UCA-LPDA. SNR=20dB, in the noise bandwidth of 3 kHz, 1024 samples. Operating frequency is 6MHz. (a) Pitch estimation, (b) azimuth estimation, and (c) the beam tracking of direction finding, γ=30.

In the second example, the DF precision of full HF band is simulated. Incoming wave polarization state is elliptical polarization, γ=30°, and η=-120°. Figure 6 shows the DF precision of general MUSIC method and Pol-MUSIC method with 20dB of SNR. It is obvious that Pol-MUSIC method is superior to general MUSIC method in the full frequency band.

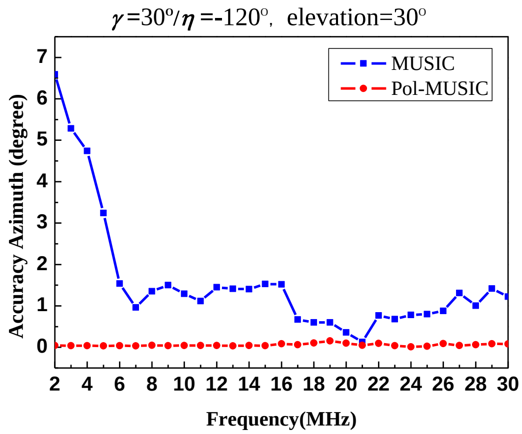


Fig. 6. DF precision varies with operation frequency in all HF frequency band. SNR=20dB.

Figure 7 shows the DF precision with different SNR in all HF bands. With the improvement of signal-to-noise ratio, the direction finding accuracy is improved. Figure 8 shows the variation curve of the estimation accuracy of Pol-MUSIC method with the SNR at 6MHz. The estimation results are close to the CRLB.

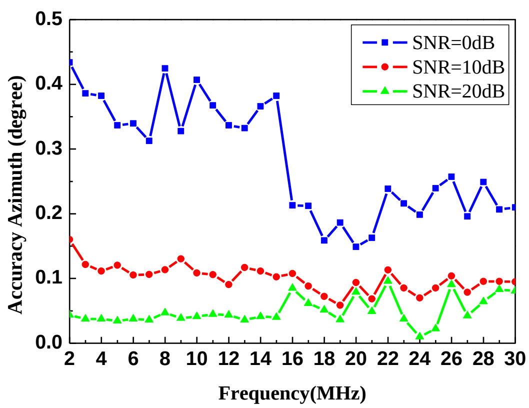


Fig. 7. The DF precision varies with operation frequency with different SNR.

In the third example, the angle resolution of two non-correlated signals with a small angular were simulated using uniform circular array composed of LPDAs, isotropic antennas, and orthogonal dipole antennas. The two signals are different polarization state. To make a fair comparison , the electrical effective radiuses of the three arrays are same as 1.25 λ. Because the equivalent diameter of the UCA-LPDA varies with operating frequency, we choose the operating frequency at 6MHz. Its effective radius (the distance from phase center to the center of the circle) is 62.5m (1.25 λ). The effective radius of the LPDA is as show in Fig. 9.

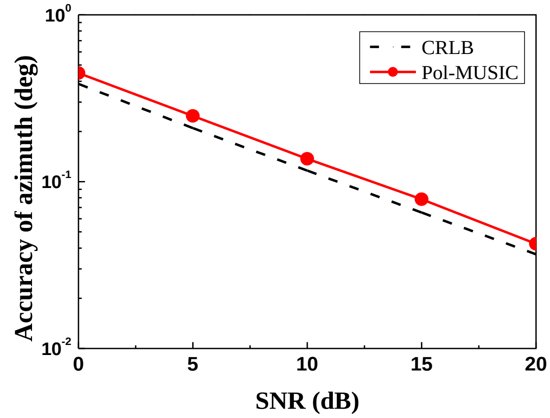


Fig. 8. Precision of DOA estimation of Pol-MUSIC.

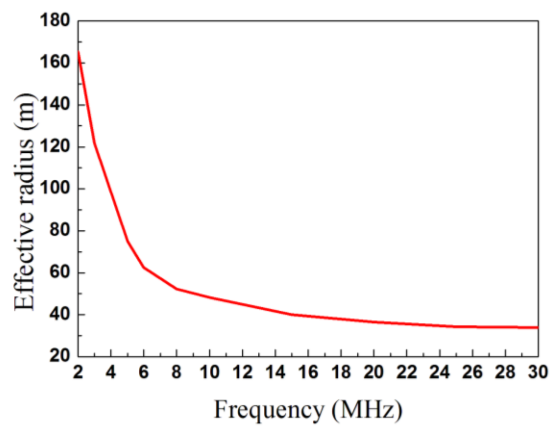
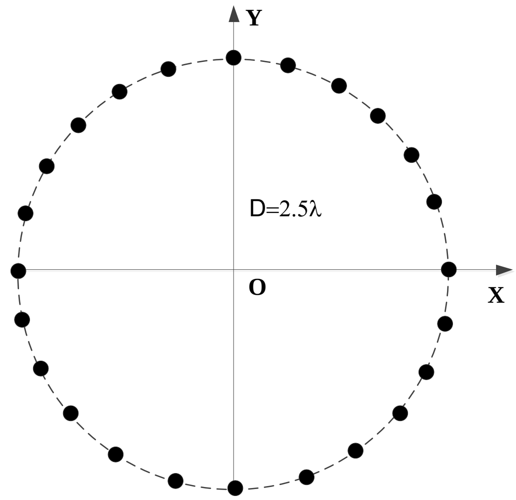


Fig. 9. The effective radius of the LPDA.

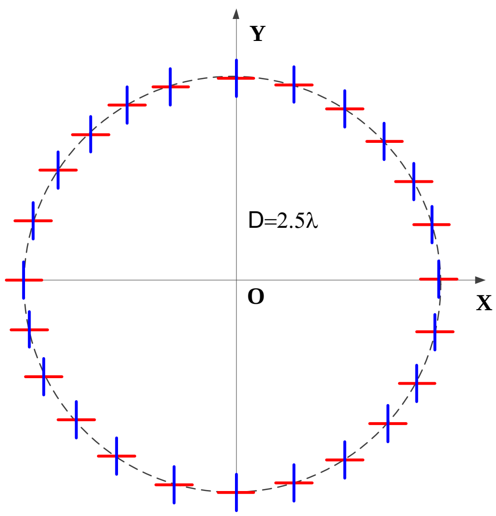
The parameters of the two simulation signals are presented in Table 2. The SNR is of 10dB. The orthogonal dipole antennas are composed of X antenna and Y antenna. The orientations of all elements in the array are parallel to the X-axis and Y-axis. The uniform circular arrays composed of isotropic antennas and orthogonal dipole antennas are indicated in Fig. 10.

Table 2: The simulation parameters of two signals

Parameters	Signal 1	Signal 2
Elevation	30°	36°
Azimuth	153°	157°
Polarization	γ=30°, η=120°	γ=60°, η=-60°



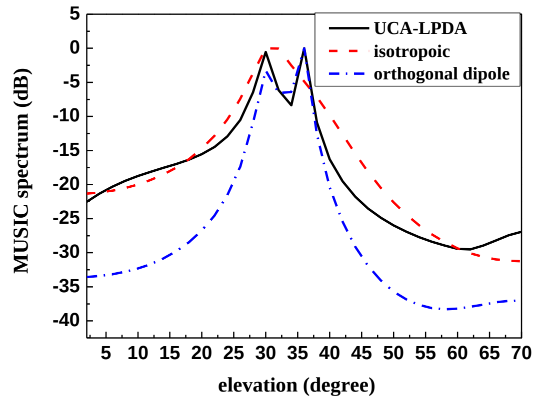
(a)



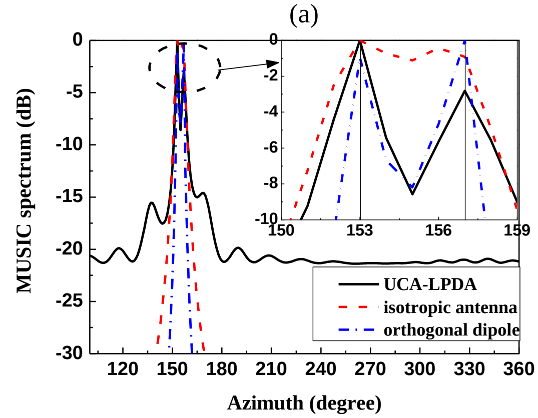
(b)

Fig. 10. (a) 24-element isotropic antennas UCA. (b) 24-element orthogonal antennas.

Figure 11 displays the MUSIC spectrums of the three arrays. The UCA-LPDA can accurately distinguish the angles of two signals with a small angular separation in the space, but the isotropic antennas cannot. DF results have higher angular resolution while using UCA-LPDA than isotropic antenna. The spatial correlation of UCA-LPDA is decreased with the use of polarization information of two signals. This feature is good for distinguishing signals from two approaching angles. However, the isotropic antennas have no polarization information, the spatial correlation is close to 1 (see formula (7)). So the isotropic array cannot distinguish signals from two approaching angles. Because of polarization sensitivity, the orthogonal dipoles can also distinguish two different polarized signals. However, the numbers of the required DF channels of the orthogonal dipole antennas are doubled, and its gain is lower than LPDA.



(a)



(b)

Fig. 11. Comparison of spatial spectrums for the three uniform circular array: LPDAs, isotropic antennas, and orthogonal dipole. SNR=10dB, in the noise bandwidth of 3 kHz, 1024 samples. (a) MUSIC spectrum of elevation, and (b) MUSIC spectrum of azimuth.

On the basis of simulations, one UCA-LPDA was fabricated for DF experiments. The array consists of 24 elements, with an angle of 15°. The parameters of the fabricated UCA-LPDA are the same as the simulated ones. The UCA-LPDA is connected to a 24 channel direction-finding receiver through the exchange matrix. The UCA-LPDA is shown as Fig. 12.

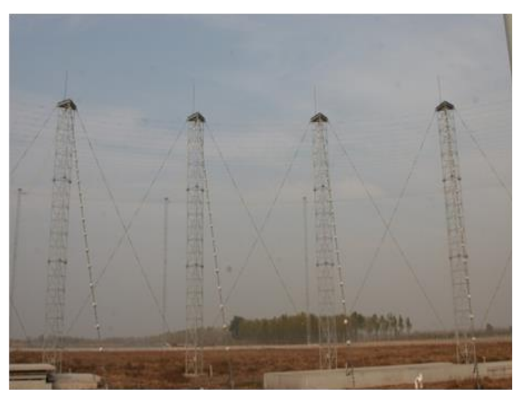
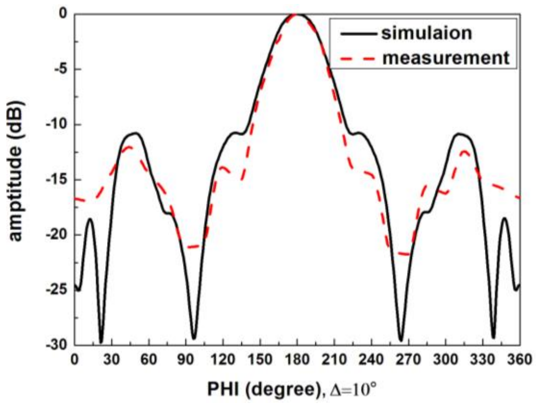
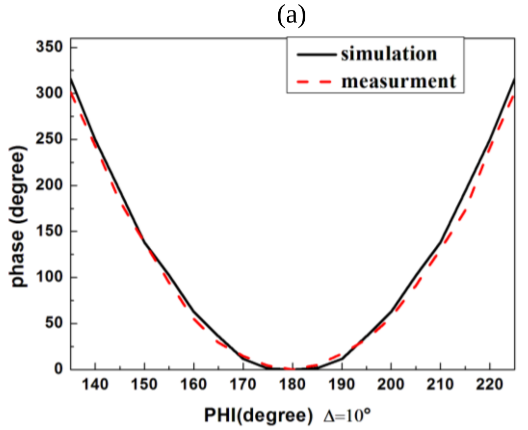


Fig. 12. The UCA-LPDA for direction finding.

The magnitude and phase spatial response of the element in the array are measured at 10° of elevation. The test results show a good agreement between the measured and simulated, as shown in Fig. 13. Because of the good agreement, the spatial response of full space adopts the theoretical calculation value in FEKO and saved into the DF receiver.



(a)

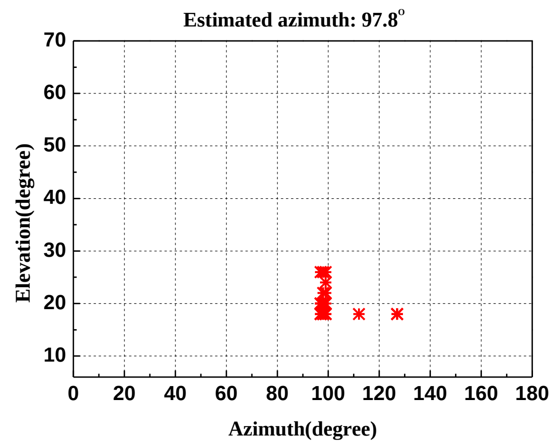


(b)

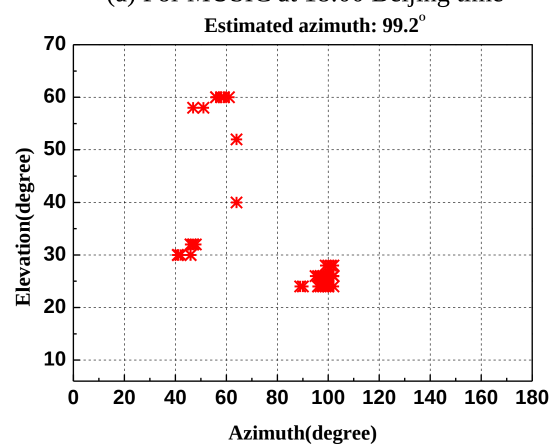
Fig. 13. Spatial response measured of the LPDA in the circular array at 6MHz: (a) the magnitude response, and (b) the phase response.

The DOA was estimated by 1024 sampling data of HF signal at 6.03MHz in 24 July, 2017. Due to the influence of the instrumental errors and actual non-ideal channel of the propagation, the DOA was estimated 100 times. The final direction finding result is given by the statistical median. The actual signal was at the azimuth of 96° with unknown polarization state. For HF signals, because of the Faraday rotational properties, after ionosphere reflection, the polarization characteristic of received signals is usually elliptical polarization. However, its polarization parameters are unknown [20].

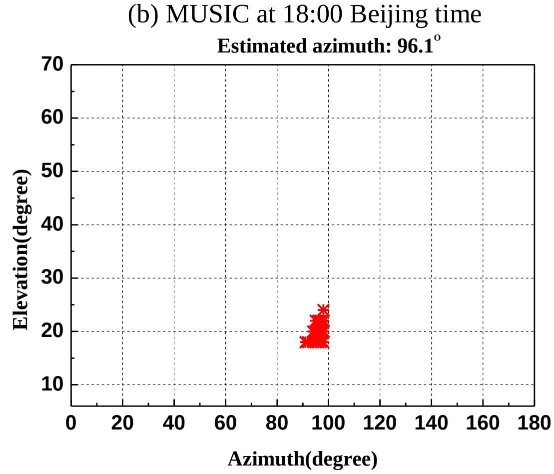
The DF experiments are conducted at 18:00 and 19:45 Beijing time, respectively. We estimate the DOA of actual HF signal using Pol-MUSIC method and general MUSIC method. Figure 14 illustrates the DF results of the signal. We can obviously see that the DOAs estimated are drifting at 18:00 from Fig. 14. This is caused by the ionosphere. When Pol-MUSIC method is used, the DF result is robust. This is because the Pol-MUSIC method takes into account the polarization characteristics of the signal. The direction of incoming wave is easier to identify and capture. DF experiments demonstrate the effectiveness and robustness using UCA-LPDA with Pol-MUSIC method.



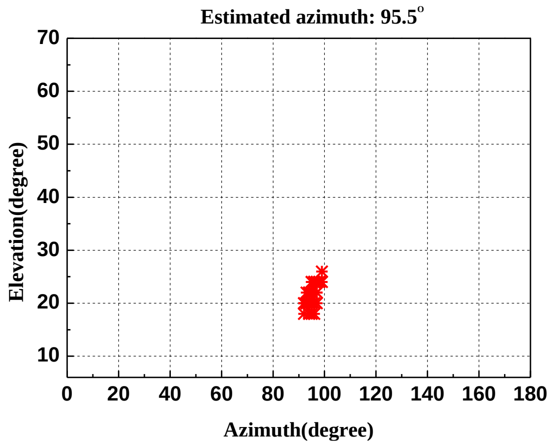
(a) Pol-MUSIC at 18:00 Beijing time



(b) MUSIC at 18:00 Beijing time



(c) Pol-MUSIC at 19:45 Beijing time



(d) MUSIC at 19:45 Beijing time

Fig. 14. DF result using LPDA-UCA at 6030KHz in 24 July, 2017: (a) DF with Pol-MUSIC method at 18:00, (b) DF with MUSIC method at 18:00, (c) DF with Pol-MUSIC method at 19:45, and (d) DF with MUSIC method at 19:45

IV. CONCLUSION

In conclusion, a circular array composed of log-periodic dipole antennas is studied in this paper. The UCA-LPDA has higher gain and polarization-sensitivity though it employs to only one sensor at each point of the spatial sampling. For the UCA-LPDA, a new Pol-MISCI method for unknown polarizations is derived. The proposed method does not need to search the polarization state of incoming wave. Using the polarization of the antennas, UCA-LPDA has a higher angular resolution for the DOA estimating than isotropic antennas. Simulations and actual signals DF experiments demonstrate the effectiveness and accuracy of using UCA-LPDA with Pol-MUSIC method. Because of the high gain, the UCA-LPDA can be used to estimate DOA for weak unknown polarized signals in the practical application.

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