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HF Echo Arrival Angle Calculation and Error Reduction Method

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Abstract: To calculate the azimuth angle and elevation angle of the HF echo arrival angle, based on the calculation of one-dimensional single baseline measurement, this paper proposes a method to calculate the arrival angle of HF echo using two-dimensional equal length single baseline measurement. Methods, and for the characteristics of HF propagation, the measurement error caused by Doppler frequency shift and phase error was analyzed, and the two main error reduction methods were proposed

1. Introduction

The calculation of the HF echo arrival angle is an important part of the sky wave over-the-horizon radar. The accuracy of the arrival angle measurement directly affects the detection accuracy of the sky wave over-the-horizon radar. At present, the measurement and calculation of HF echoes are mainly time-differential measurement methods and interferometry methods. However, due to the fast propagation of HF waves, time-difference measurements often require the receiver to have extremely high clock sensitivity. To reduce the cost and improve the economy, the use of interferometry to measure the angle of arrival of HF echo has obvious advantages. However, the measurement of the angle of arrival of the HF echo using the interferometry method will produce a certain measurement error.

2. Interferometry to measure the arrival angle of HF echo

If the receiving antenna array is in the same horizontal plane, since the antenna array spacing is very small relative to the distance between the antenna and the measured target, the target echo can be approximated as a plane wave in the receiving antenna array. Therefore, the azimuth and elevation of the echo can be obtained according to the wave interference principle. The specific discussion is as follows:

As shown in Fig.1, A and B are in the same horizontal plane, and the distance between two points is d, and let d<λ/2, according to the principle of wave interference:

$$\Delta\phi = \frac{2\pi\Delta r}{\lambda} = \frac{2\pi}{\lambda} d \sin\theta \tag{1}$$

In the formula, $\Delta\Phi$ is the phase difference between two points, Δr is the wave path difference between echoes to two antenna elements, λ is the wavelength of the echo, and θ is the echo azimuth angle. This is a one-dimensional single-base echo direction finding algorithm. This method can only measure the position of the echo and cannot measure the elevation angle of the echo.

Therefore, to measure azimuth and elevation at the same time, a two-dimensional equal length single baseline method is used for measurement. As shown in Fig. 2, a rectangular coordinate system is composed of XYZ. Within the XOY plane, three points O, A, and B are selected and an antenna is set up at these three points to form a three-receiving antenna from O, A, and B. The unit consists of an antenna array with the OA perpendicular to the OB and the phase meter located at point O in this array as an echo receiving system. OA = OB = d, θ is the echo azimuth, φ is the echo elevation angle.

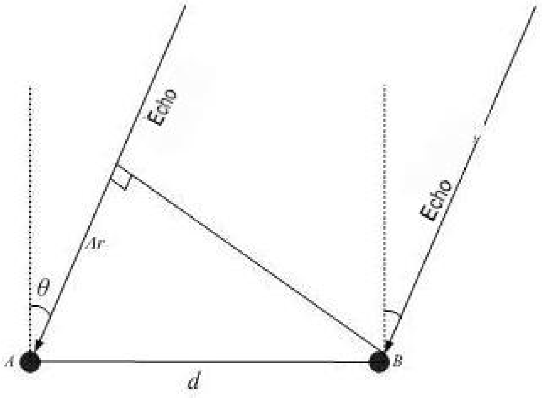

Figure 1 One-dimensional single baseline direction finding principle

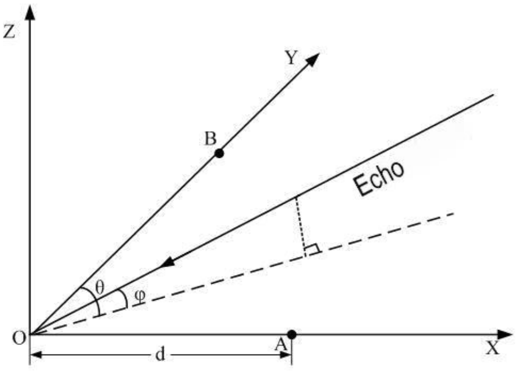

Figure 2 Two-dimensional isometric single baseline directional schematic

The principle of interference by waves is:

$$\Delta\phi_{OA} = \frac{2\pi d \sin\theta}{\lambda}\cos\varphi \tag{2}$$

$$\Delta\phi_{OB} = \frac{2\pi d \cos\theta}{\lambda}\cos\varphi \tag{3}$$

In equations (2) and (3), $\Delta\phi_{OA}$ is the phase difference between point O and point A, $\Delta\phi_{OB}$ is the phase difference between point O and point B, d is the length of the OA and OB baselines, λ is the echo wavelength, θ is the echo azimuth, φ is the echo elevation angle.

From equations (2) and (3), the azimuth and elevation of the echo can be obtained as:

$$\theta = \arctan(\frac{\Delta\phi_{OA}}{\Delta\phi_{OB}}) \tag{4}$$

$$\varphi = \arccos(\frac{\lambda}{2\pi d}\sqrt{\Delta\phi_{OA}{}^2 + \Delta\phi_{OB}{}^2}) \tag{5}$$

It must be noted that in the above calculation process, multiple values do not occur until the baseline length $d < \lambda/2$ is satisfied. If $d > \lambda/2$ there are multiple values of phase, multiple values of direction finding occur. Therefore, $d < \lambda/2$, the longer the baseline length, The higher the direction accuracy.

Therefore, the two-dimensional equal length single baseline direction finding method must meet two conditions when it is used:

(1) Two baselines are vertical;

(2) Single baselines are equal in length and $d < \lambda/2$.

From the above algorithm for measuring the echo arrival angle, the echo arrival angle is mainly related to the echo wavelength, the echo phase difference, and the position of the antenna setup.

3. Sources of Error Analysis and Reduction Methods

3.1 Doppler frequency shift induced elevation angle error

From equation (4), we can see that when using this algorithm to measure the angle of arrival of the echo, the azimuth angle of the echo θ is only related to the value of $\Delta\phi_{OA}$ and $\Delta\phi_{OB}$, independent of the wavelength of the echo λ. Equation (5) shows that the elevation angle is not only related to the sum but also to the wavelength of the echo. Therefore, the error of echo frequency Doppler shift only affects the accuracy of elevation angle measurement. However, in the short-wave single-station positioning, the elevation angle is an important parameter to determine the distance between the target and the launch circle. Therefore, the accuracy guarantee will directly affect the positioning accuracy of the skywave over-the-horizon radar.

Let the elevation angle error caused by the HF echo Doppler frequency shift $d\varphi$.

$$d\varphi = \frac{\frac{\sqrt{\Delta\phi_{OA}^2 + \Delta\phi_{OB}^2}}{2\pi d}}{-\sqrt{1-(\frac{\lambda}{2\pi d}\sqrt{\Delta\phi_{OA}^2 + \Delta\phi_{OB}^2})^2}} d\lambda \tag{6}$$

In the above equation, $d\lambda$ is the wavelength change caused by the Doppler frequency shift of the received echo.

From formula (6), we can see that in the case of a certain echo wave length and a certain phase difference, the elevation angle error caused by the Doppler shift is proportional to the change in wavelength, and the $d\varphi$ is related to the $\frac{\frac{\sqrt{\Delta\phi_{OA}^2 + \Delta\phi_{OB}^2}}{2\pi d}}{-\sqrt{1-(\frac{\lambda}{2\pi d}\sqrt{\Delta\phi_{OA}^2 + \Delta\phi_{OB}^2})^2}}$, with this coefficient change. The positive relationship with $d\varphi$ and $d\lambda$ also changes, the slope of the linear line changes.

Due to the small values of echo Doppler shift caused by ionosphere and ground scattering, it is generally lower than 1 Hz. Now assume that the detection frequency is 13.2MHz, and the frequency error caused by the Doppler frequency shift of the echo is 1Hz. The resulting result is $d\lambda = 1.72\times 10^{-6} m$. Therefore, the elevation angle errors due to Doppler shifts in the echoes are negligible.

3.2 Azimuth and elevation errors caused by phase error

From the above we can see that the echo arrival angle measurement is derived from the following two formulas

$$\theta = \arctan(\frac{\Delta\phi_{OA}}{\Delta\phi_{OB}}) \tag{7}$$

$$\varphi = \arccos(\frac{\lambda}{2\pi d}\sqrt{\Delta\phi_{OA}{}^2 + \Delta\phi_{OB}{}^2}) \tag{8}$$

From the above equation, the calculation error of the azimuth angle has nothing to do with the wavelength of the echo, but has a direct relationship with the value of the phase difference, and the elevation angle is related to the wavelength of the echo, the length of the baseline, and the phase difference, so the phase error is caused the main source of azimuth and elevation error. Fully differentiated equations (2), (3), mathematically derived, the expression of the azimuth and elevation angle errors caused by phase error is:

$$d\theta = \frac{\lambda}{2\pi d\cos\varphi}[\cos\theta d(\Delta\phi_{OA}) - \sin\theta d(\Delta\phi_{OB})] \tag{9}$$

$$d\varphi = -\frac{\lambda}{2\pi d\sin\varphi}[\cos\theta d(\Delta\phi_{OB}) + \sin\theta d(\Delta\phi_{OA})] \tag{10}$$

In the formula, $d\theta$ is the measured azimuth error, $d\varphi$ is the elevation error, $d(\Delta\phi_{OB})$ is the error of the phase difference between the receiver OB, and $d(\Delta\phi_{OA})$ is the error of the phase difference between the receiver OA. $d(\Delta\phi_{OB}) = d(\Delta\phi_{OA}) = d\Delta\phi$

Then equations (9) and (10) can be changed to

$$d\theta = \frac{\lambda}{2\pi d\cos\varphi}(\cos\theta - \sin\theta)d(\Delta\phi) \tag{11}$$

$$d\varphi = -\frac{\lambda}{2\pi d\sin\varphi}[\sin\theta + \cos\theta]d(\Delta\phi) \tag{12}$$

Determine the RMS value and get the error

$$\sqrt{\overline{(d\theta)^2}} = \frac{\lambda}{2\pi d\cos\varphi}\sqrt{\overline{(d\Delta\phi)^2}} \tag{13}$$

$$\sqrt{\overline{(d\varphi)^2}} = -\frac{\lambda}{2\pi d\sin\varphi}\sqrt{\overline{(d\Delta\phi)^2}} \tag{14}$$

3.3 Error Analysis and Reduction Methods

By formula (14) we can see:

(1) The measurement errors of the azimuth and elevation angles of the short-wave echo are proportional to the error of the phase $d(\Delta\phi)$ difference measured by the two receivers and inversely proportional to the ratio of the length of the baseline d and the wavelength λ of the HF d/λ, and thus it can be concluded that the detection frequency is determined. Increasing the length of the baseline d can reduce the error in the angle of arrival measurement. As shown in Fig. 3, the relation diagram of the hypothetical echo frequency of 8 MHz is shown and $\delta = \lambda / d$. From Fig. 3, the larger the baseline length is $d < \lambda/2$, the smaller the measurement error value is.

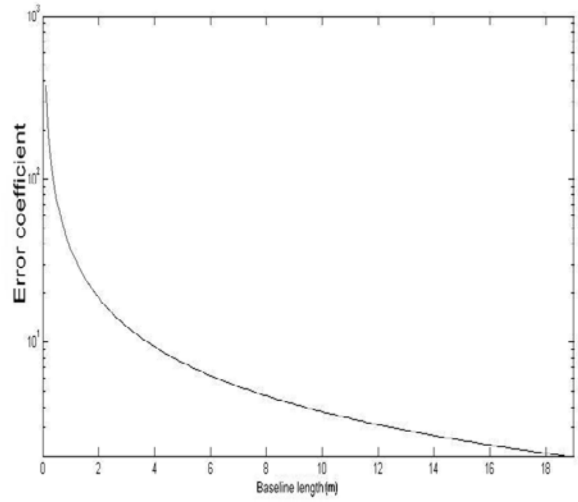

Figure 3 Relationship etween measurement error coefficient and baseline length

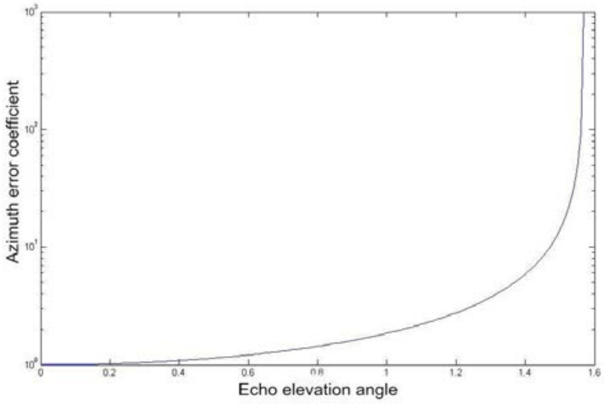

Figure 4 Relationship between azimuth error and elevation angle

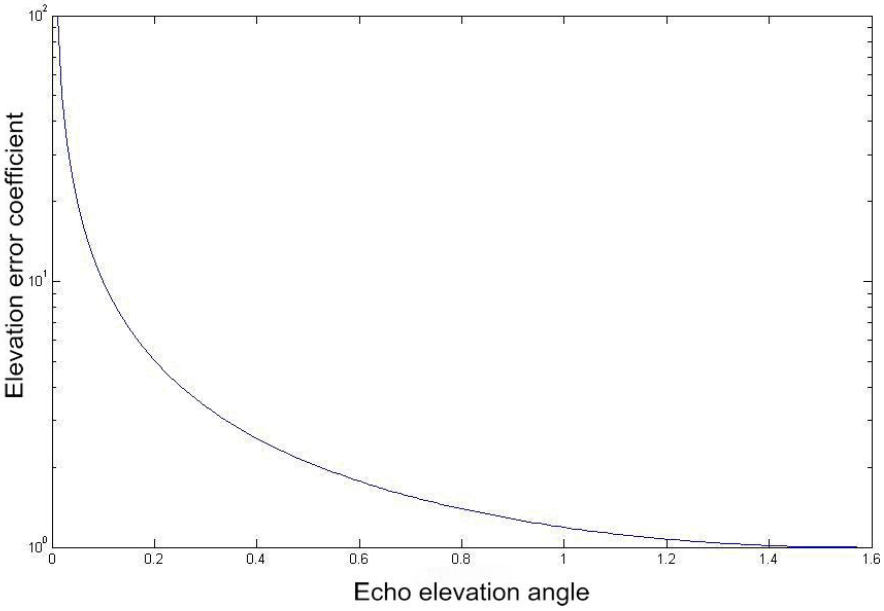

Figure 5 Relationship between elevation angle error and elevation angle

(2) The measurement accuracy of echo azimuth and echo elevation using this two-dimensional equal-length single baseline measurement is related to echo azimuth and elevation angle. In the horizontal plane $\varphi = 90^0$, the elevation angle φ accuracy is the lowest, and the azimuth angle θ has the highest accuracy. When, $\varphi = 0^0$,the elevation angle φ has the highest accuracy, and the azimuth angle θ has the lowest precision. When, $\varphi = 45^0$, the elevation angle φ and azimuth angle θ have the same direction-finding accuracy. The magnitude of the echo arrival angle is also related to the azimuth and elevation angle of the echo. The reasonable installation of the antenna array element can reduce the measurement error, as shown in Figure 4 and Figure 5;

(3) When the baseline length, the azimuth of the echo arrival angle may have multiple values.

The error generated in the above two cases is an unavoidable source of error in measuring the angle of arrival of the echo. Others are the measurement error caused by the accuracy of the equipment itself and the installation and installation of the antenna. Since the quantitative calculation cannot be performed, this will not be discussed here.

4. Conclusion

It is an effective method to measure the angle of arrival of HF echoes using a two-dimensional equal-length single baseline, and the sources of error mainly come from the time-varying characteristics of the ionosphere, the error of the phase difference measured by the receiver, and the precision of the equipment itself and the antenna erection. Installation and so on. Due to the time-varying characteristics of the ionosphere, the Doppler shift error is very small, and the measurement error caused by the accuracy of the equipment itself and the installation and installation of the antenna cannot be quantified. Therefore, the source of the two sources of error is mainly analyzed above, and the measurement error caused by the phase error has been discussed. Several measures have been proposed to reduce this error. This is to increase the angle of arrival of HF echoes. The measurement accuracy has a very practical significance.

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