IONOSPHERIC CLUTTER SUPPRESSION IN HF SURFACE WAVE RADAR

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Abstract—The ionospheric clutter has been proved to be one of the dominant clutters degrading the performance of the HF surface-wave radar (HFSWR) severely, so suppressing the ionospheric clutter is a vital part of radar signal processing sequence. In this paper, the spatial characteristics of the ionospheric clutter in a planar array are analyzed, then a new orthogonal projection method with eigenvalue decomposition (EVD) is proposed. The real data results are given to confirm that the proposed method is efficient in ionospheric clutter suppression and can enhance the capability of target detection dramatically.

1. INTRODUCTION

The HF surface-wave radar (HFSWR) is an effective and relatively low-cost means of providing over-the-horizon surveillance of surface vessels. It is achieved by the propagation of the HF vertically polarized electromagnetic wave along the ocean surface. So it is possible to detect targets up to few hundred kilometers. However, not all the energy emitted by the HFSWR propagates along the surface. Some energy is directed upward, then will be reflected from the ionosphere and returned to the radar under certain conditions [1]. As far as the HFSWR is concerned, the Doppler spectrum of the echo through the ionosphere is widened and shifted, and these unwanted echoes are generally called the ionospheric clutter. It has been proved that the ionospheric clutter is one of the dominant clutters degrading the performance of the HFSWR severely [2].

The ionosphere is the ionized part of the upper atmosphere and lies between about 80 km and 1000 km of altitude. It is a kind of color

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scattering, multi-mode and anisotropic propagation medium which distorts the HF wave complicatedly. The relevant processes of the HF electromagnetic waves interacting with the ionosphere are described in [3]. The HF radar signal propagates through the ionosphere primarily in three ways. The first is via near-vertical reflection of the radar signal from the ionosphere and back to the radar. The second is the result of reflections at angles less than vertical, causing it to travel outwards, whereupon it reflects from the ocean or land and returns along the same path or via a surface wave path. The third is the result of back-scattering phenomena related to the irregularities and the fluctuations of the ionosphere [2].

In order to mitigate the ionospheric clutter it is desirable that the receiving antenna systems provide a deep, broad null against signals arriving at near-vertical incidence [4]. Basing on the principle, a number of signal processing techniques have been developed to mitigate the ionospheric clutter. Leong [5] presented an adaptive system using horizontal antennas for the suppression of sky-wave interference in HFSWR. Four auxiliary horizontal dipoles, configured as two separate crosses, needed to be added to the HFSWR system that normally uses vertically polarized antennas. Exploiting the difference in polarization characteristics, the sky-wave interference component received by the vertically polarized antennas (main antennas) can be estimated from the received signal of the auxiliary horizontal antennas. By subtracting this estimate the interference was suppressed. Unfortunately this method will make the radar system more complicated, moreover the auxiliary horizontal antennas can pick up the unexpected radar signal in practice due to the imperfectness of the horizontal antennas. It means that the sky-wave interference is suppressed, and the radar signals are also weakened. Based on Leong’s work, Gao [6] and Wan [7] made some improvements. They proposed the scheme without implementing any auxiliary facilities, just using vertical antennas based on subarrays to suppress the ionospheric clutter. However, the receiving array in their method was a linear array which could not provide a desired null in the near-vertical direction appropriately.

In this paper, a new method with eigenvalue decomposition (EVD) on a planar array to suppress the ionospheric clutter is proposed. The reason to choose the planar array to be the receiving array is that the planar array yields better performance, it can recognize signals from different azimuths as well as different elevations. Thus the planar array is very appropriate for dealing with the issue of the ionospheric clutter suppression. In the following, the spatial characteristics of the ionospheric clutter in planar array are analyzed, which provide a theoretical basis for ionospheric clutter suppression. Then the
Orthogonal projection method with EVD is presented. The high efficiency of the proposed method is well tested by the real data.

2. ANALYSIS OF IONOSPHERIC CLUTTER IN SPATIAL DOMAIN

Consider a planar array with \( M \) sensors on \( xoy \) plane (\( xoy \) is the Cartesian co-ordinates). Take the first sensor at the origin of coordinate system as the reference sensor, \( (x_m, y_m) \) denote the \( m \)th (\( m = 1, 2, \ldots, M \)) sensor’s coordinates, and all the sensors are fully calibrated. Let \( X(n) = [x_1(n), \ldots, x_m(n), \ldots, x_M(n)]^T (n = 1, 2, \ldots, N) \) be the complex \( M \times N \) antenna array snapshot matrix received at a particular range bin which has been polluted by the ionospheric clutter, with \( M \) to be the number of the sensors, \( N \) to be the number of snapshot, and the superscript \( T \) denotes the transpose. Assuming \( X(n) \) contains \( K (K < M) \) wanted signals, the ionospheric clutter \( S_{io}(n) \) and an additive Gauss white noise \( N(n) \). Let \( (\theta_k, \varphi_k) \) denotes the azimuth and elevation of the \( k \)th \( (k = 1, 2, \ldots, K) \) wanted signal, then \( X(n) \) can be written as

\[
X(n) = \sum_{k=1}^{K} a(\theta_k, \varphi_k) S_k(n) + S_{io}(n) + N(n) \tag{1}
\]

where the \( S_k(n) \) is the \( k \)th wanted signal received by the first sensor (referenced unit), and the \( M \)-dimensional column vector \( a(\theta_k, \varphi_k) \) is the steering or direction vector corresponding to the direction \( (\theta_k, \varphi_k) \). For the planar array, it can be given by

\[
a(\theta_k, \varphi_k) = \frac{1}{\sqrt{M}}[\phi_1(\theta_k, \varphi_k), \ldots, \phi_m(\theta_k, \varphi_k), \ldots, \phi_M(\theta_k, \varphi_k)]^T \tag{2}
\]

where \( \phi_m(\theta_k, \varphi_k) = \exp \{ -j2\pi [x_m \cos \theta_k \cos \varphi_k + y_m \sin \theta_k \cos \varphi_k] / \lambda \} \) and \( \lambda \) is the wavelength. Let \( a^*(\theta_k, \varphi_k) \) be the weight vector of the received signal \( X(n) \) just as the digital beam-forming (DBF) method, with the superscript * being the complex conjugate operator. Then the signals from the direction \( (\theta_k, \varphi_k) \) are in-phase. It implies that the signals from the direction \( (\theta_k, \varphi_k) \) are strengthened and those from other directions are weakened. The weighted result can be expressed as:

\[
XW(n) = [xw_1(n), \ldots, xw_m(n), \ldots, xw_M(n)]^T (n = 1, 2, \ldots, N),
\]

where \( xw_m(n) \) is the element-by-element product of the \( m \)th element of the weight vector \( a^*(\theta_k, \varphi_k) \) (i.e., \( a^*(\theta_k, \varphi_k) [m] \)) and the snapshot vector received from the corresponding \( m \)th sensor \( x_m(n) \), that is

\[
xw_m(n) = a^*(\theta_k, \varphi_k) [m] \cdot x_m(n) (m = 1, \ldots, M) \tag{3}
\]
the correlation matrix of the weighted signal can be estimated as
\[
R = \frac{1}{M} \sum_{m=1}^{M} x_{wm} x_{wm}^H \tag{4}
\]
where the superscript \( H \) is the conjugate transpose operator, and \( R \) contains the most power of the signals from the direction \((\theta_k, \varphi_k)\). Thus we can estimate the correlation matrix of signals from other directions by changing the weight vector of the received signal.

For HFSWR in practice, the echo signals of interest, such as the target echoes are usually from the horizon, so \( \varphi_t = 0 \) (\( \varphi_t \) denotes the elevation of the target signal). But the ionospheric clutter is quite different. It is usually from the near-vertical direction, so \( \varphi_{io} = 90 \) (\( \varphi_{io} \) denotes the elevation of the ionospheric clutter). Then the steering vector of the ionospheric clutter \( a_{io} \) can be determined by substituting \( \varphi_k = \varphi_{io} = 90 \) into (1). If we let \( a_{io}^* \) be the weight vector of the received signal, the ionospheric clutter is strengthened and the other signals are weakened, then according to (3) (4), the estimation of correlation matrix of the ionospheric clutter \( R_{io} \) can be obtained.

3. ORTHOGONAL PROJECTION PROCESSING

The above analysis has provided a theoretical basis for the ionospheric clutter suppression. The correlation matrix of the ionospheric clutter \( R_{io} \) is a Hermitian matrix, so it can be eigen decomposed as
\[
R_{io} = \sum_{i=1}^{N} \lambda_i v_i v_i^H \tag{5}
\]
where \( \lambda_i (i = 1, 2, \ldots, N) \) are the eigenvalues in descending order and \( v_i (i = 1, 2, \ldots, N) \) are the corresponding eigenvectors. According to (4), the rank of \( R_{io} \) is \( M \), then \( \lambda_i = 0 \) for \( i > M \). As mentioned earlier, \( R_{io} \) contains a majority of the ionospheric clutter but few signals of interest. It can be regarded that the first \( L \) larger eigenvalues of \( R_{io} \) will be the ionospheric clutter eigenvalues and be equal to the ionospheric clutter power, since at the corresponding range bins, the ionospheric clutter dominates and is independent of the signals of interest and the noise. The dimension \( L \) of the ionospheric clutter subspace is estimated by comparing the logarithms of the eigenvalues \( \lambda_i (i = 1, 2, \ldots, N) \) to some preset threshold. According to matrix theory [8], the matrix \( V = [v_1, \ldots, v_L] \) forms an ionospheric clutter subspace. If the received snapshot vector \( x_m (n) (m = 1, 2, \ldots, M) \) is projected onto the orthogonal subspace of \( V \), then the ionospheric
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Clutter will be suppressed but the signals of interest will be preserved. The orthogonal projection matrix is

\[ P = I - VV^H \]  

The resultant signals after suppression are given by

\[ x_{m,\text{result}} = Px_m = x_m - VV^H x_m \]  

4. RADAR SIGNAL PROCESSING RESULTS

The proposed method for ionospheric clutter suppression was applied to the real data which were collected during the vessel detection experiment on January 10th, 2008, in Hainan Province. The radar in the experiment worked at 5 MHz with a chirp band of 30 kHz (i.e., the range resolution is 5 km), the receiving facility consisted of 16-element vertically polarized antennas which configured in a 4 × 4 planar array. The distances between adjacent sensors in horizontal and longitudinal direction were 20 m and 15 m respectively.

Figure 1(a) displays a typical Range-Doppler profile (form the first sensor) with the strong ionospheric clutter which is a large Doppler and a large distance targets mask and covers the majority of the profile. It is generally believed that the E and F layer clutter has the most effects on HFSWR [7], and the ionospheric clutter usually appears beyond 100 km just as the figure shows. Consequently, we implement the proposed suppression method only on the data at the range further than 10 km and give the result in Fig. 1(b). From the figure, we can see that the strong ionospheric clutter from E and F layer is effectively suppressed.

**Figure 1.** (a) Range-Doppler Profile with the ionospheric clutter. (b) Range-Doppler Profile after ionospheric clutter suppression.
suppressed. Fig. 2 is the detailed suppression result at the range of 140 km (i.e., the 28th range bin), where the dashed line represents the original Doppler spectrum and the solid one represents the Doppler spectrum after suppression. In this figure, a large extent protuberance in Doppler was removed. The power of the ionospheric clutter has been reduced by up to 23 dB, while there are quite little losses brought to the sea wave Bragg backscatter peaks at the Doppler frequency about ±0.23 Hz.

In the experiment, the cooperative vessel target could be well tracked until the target echo was masked by the ionospheric clutter, which is illustrated in Fig. 3. Fig. 3(a) plots the Doppler spectrum collected at 12:30 at the range of 100 km where the cooperative target appeared. Since it has not yet been affected by the ionospheric clutter, the cooperative target peak was very clear at the Doppler frequency −0.12 Hz and could be easily resolved. But 15 minutes later (i.e., 12:45) the cooperative target was about 105 km away from the radar and started stepping into the region of the ionospheric clutter as Fig. 3(b) is showing, and the suppression result is given in Fig. 3(c). By comparing the two figures (Figs. 3(b) and (c)), it can be easily observed as follows: In Fig. 3(b), although the ionospheric clutter is slight, the cooperative target echo is still submerged and cannot be detected, which is described with a dashed rectangle. Then after suppression (in Fig. 3(c)), the power of the ionospheric clutter is reduced but the cooperative target echo with Doppler frequency (−0.12 Hz) clearly stands out. Thus it can be retrieved at its original location. It is evident that the probability of detection has been increased dramatically by suppressing the ionospheric clutter with the proposed method.

![Figure 2. The Doppler spectrum at 140 km, the dashed line is the spectrum before suppression and the solid one is that after suppression.](image-url)
5. CONCLUSION

The spatial characteristics of the ionospheric clutter in the planar array is presented, which is the theoretic basis for the proposed orthogonal projection method. The method can effectively suppress the ionospheric clutter whereas hardly bringing any losses to the target echoes. Thus it can greatly enhance the target detection capability of the HFSW radars when there is the strong ionospheric clutter. All the experimental results above have confirmed the high efficiency of the proposed method.

Figure 3. (a) the Doppler spectrum at 12:30 at the range of 100 km (b) the original Doppler spectrum at 12:45 at the range of 105 km (c) the Doppler spectrum at 12:45 at 105 km after suppression.
REFERENCES


