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RESEARCH ARTICLE

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Preprocessing of ionospheric echo Doppler spectra

Abstract The real-time information of the distant ionosphere can be acquired by using the Wuhan ionospheric oblique backscattering sounding system (WIOBSS), which adopts a discontinuous wave mechanism. After the characteristics of the ionospheric echo Doppler spectra were analyzed, the signal preprocessing was developed in this paper, which aimed at improving the Doppler spectra. The results indicate that the preprocessing not only makes the system acquire a higher ability of target detection but also suppresses the radio frequency interference by 6–7 dB.

Keywords oblique backscattering sounding, signal preprocessing, radio frequency interference

1 Introduction

High frequency (HF) oblique backscattering sounding system uses modulated pulses to detect the ionosphere [1]. The delay and Doppler of the echoes can be evaluated and used to estimate the state of the sea. After calculating the multi-path spread and Doppler spread of the real data, we can get the parameters of channels such as the coherence time and the coherence bandwidth. Consequently, we can get the optimal code length and suitable modulation parameters for both radio communication system and sky-wave radar.

The WIOBSS developed by our group adopts the advanced coding technique, software defined radio (SDR) technique, and VXI bus technique [2]. It has the advantage of low transmitting power, small size, and mobility, etc. It makes the real-time webbing in the war realizable. As the receiver sensitivity reaches −105 dBm, evident vertical incident echoes from the ionosphere above can be obtained with a transmitting power as low as 9 W. The echoes with group delay beyond 1 000 km can be received by WIOBSS in the oblique backscattering sound [3].

Wuhan ionospheric oblique backscattering sounding system (WIOBSS) has radio frequency interference (RFI) like all the common HF receivers. Because WIOBSS is an intra-pulse system, the spectra of its echoes have some characters different from the traditional sky-wave radar. Currently, many radar systems have special preprocessing techniques. Jindalee [4] in Australia sounded the ocean state by ionospheric backscatter. Before estimating the ocean parameters, they modified the echo spectra with phase grad [5]. The HF ground-wave radar in the radio propagation laboratory in Wuhan University preprocessed the echoes in the way of software calibrating the channel amplitude responses in every range cell and supplied efficient samples to get the parameters of the sea with MUSIC algorithm [6].

As WIOBSS differs from the traditional radar, its echo spectra are special. In this paper, the real echo spectra were analyzed and a new preprocessing method was brought forward. The coordinates of the ground wave were reconfirmed, the dead zones were eliminated, and the RFI was weakened for the real data. As a result, the signals in the dead zones were compensated effectively, and the RFI was lowered by 6–7 dB.

2 Signal analyses

2.1 Principle and realization

The waveform of WIOBSS is phase coded pulses. It is represented as $s(t) = u(t)\mathrm{e}^{\mathrm{j}2\pi f_0 t}$, where $u(t) = |u(t)|\mathrm{e}^{\mathrm{j}\phi(t)}$ is the complex envelope, and f_0 is the carrier frequency.

Assume that the transmitting power is low enough and the ionospheric system can be regarded as a linear time-variant system. The autocorrelation function of the codes modulating the pulses is Dirac shape. If the autocorrelation function acts on the ionospheric system as impulse function, the function of the ionospheric system could be acquired through impulse response $h(t, t_p)$, called bi-temporal response function, where t is the time variant of the system, t_p is the group delay. The time-range function [7–8] of the ionospheric channel at any given time is attainable in the real detection. The signal holds

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the ionospheric information after being reflected by the ionosphere, and then scattered back by the ground in the same way. The echoes processed by digital down converter (DDC) are given by the convolution integral

$$\tilde{r}(t) = \int_R h(t,\tau)u(t-\tau)\mathrm{d}\tau \tag{1}$$

If the complex envelope $u(t)$ delays for t_p and the length of correlation is T_0, the cross-correlation function for the delayed signal and the echoes at t_c can be expressed as

$$\begin{aligned} C_{\tilde{r}u}(t_c,t_p) &= \frac{1}{T_0}\int_{t_c-T_0}^{t_c} \tilde{r}(t)u(t-t_p)F_2\mathrm{d}t \\ &= \frac{1}{T_0}\int_{t_c-T_0}^{t_c}\int_R h(t,\tau)u(t-\tau)u(t-t_p)\mathrm{d}\tau\mathrm{d}t \end{aligned} \tag{2}$$

The timing of transmitting-receiving for WIOBSS is shown in Fig. 1. It represents the condition of transmitting through pulse duration and receiving for twice the time. 1 or 0 is the code of m sequences. The timing was output by DSP (digital signal processing) and FPGA (field programmable gate array). The signal processing flow is shown in Fig. 2. In WIOBSS, the carrier-free waveform was synthesized in AD9857 and the carrier phase was modulated by a kind of pseudo-random code-m sequence. The character of alternating transmitting and receiving periods made it possible that only one antenna is used by the whole system.

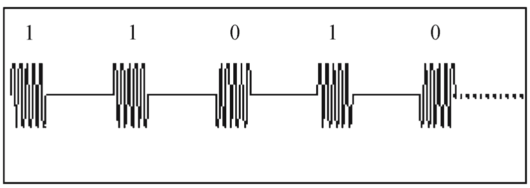

Fig. 1 The timing of transmitting-receiving for WIOBSS

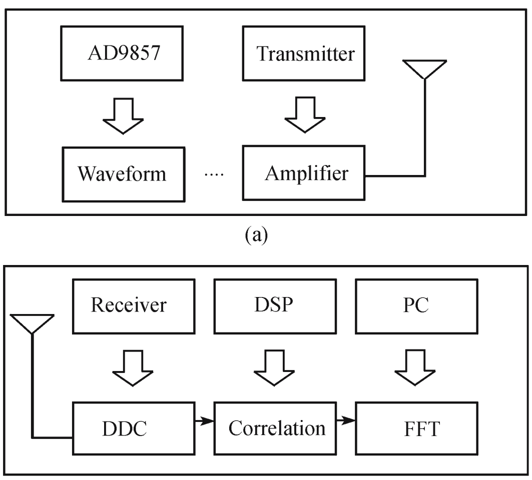

Fig. 2 The signal processing flow
(a) The transmitting part; (b) the receiving part

The range resolution of WIOBSS reaches 6.25 km. Assuming that the pulse duration is 41.66 μs, the code length is 511, the code width is one pulse, the interval is 10 pulses and sounding times is 256, then we can obtain that the Doppler resolution is 0.018 3 Hz. The echoes with 843.75 km group path at 16:47 on June 22, 2004 are shown in Fig. 3. According to Fig. 3, the echo was scattered by ground and its Doppler shift was about 0.37 Hz. Generally, the echo reflected by F_2 layer has the Doppler shift about 0.1–0.42 Hz, and by calm F layer about 0.1 Hz [9]. The Doppler shift in this detection at 800–1 000 km was about 0.3 Hz. It was concluded that the ionosphere was not calm during the detection.

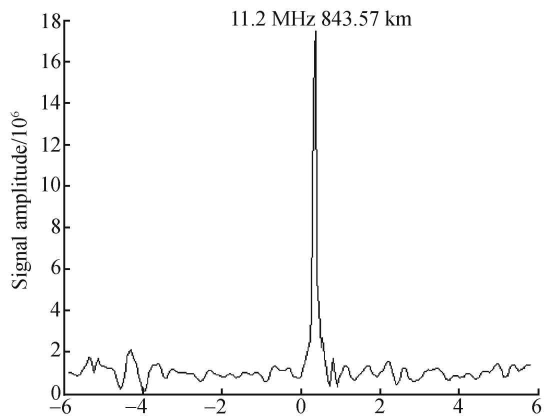

Fig. 3 The Doppler shift of the echo

2.2 The character of echo spectra

The sounding procedure was: first, sounding at 3–30 MHz by swept frequency; second, adjusting the gain mode and band width of the receiver; lastly, sounding the frequencies with strong echoes in swept frequency mode, or sounding at a fixed frequency. A 3-D figure for typical Doppler spectra of WIOBSS is shown in Fig. 4. From the figure, the characteristics of the echo spectra could be concluded here.

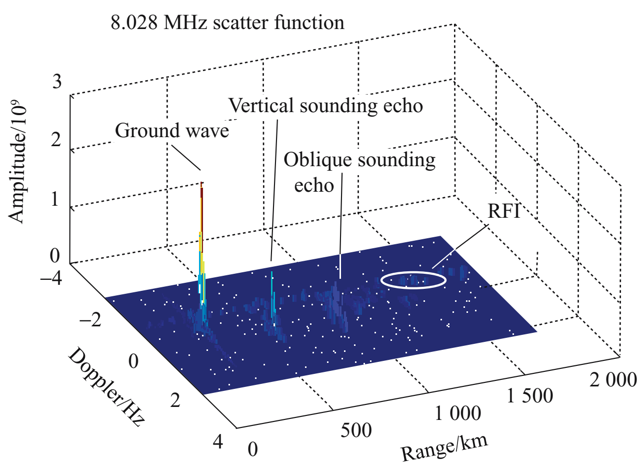

Fig. 4 Doppler spectra before processing

1) The ground wave is not in the first gate. In the experiment, the transmitting antenna was separated from the receiving antenna by about 50 m, which was far less than the range gate (6.25 km). The peak of the ground echoes or the local echoes of WIOBSS should be in the first range gate theoretically. Actually, the time cost in receiving and processing was nearly several milliseconds. In range, the delay was about 30–40 range gates. This delay varied with receiver parameters, sounding times, and sounding frequency.

2) The dead zones: while transmitting, WIOBSS is also receiving. The signal at the front of the receiver should be suppressed by the switch to protect the receiver. The suppressing extent was given by the switch controlling procedure. Analysis showed that the amplitude of the suppressed signal was lower than the background noise. The consequence was that dead zones appeared, in other words, no signal could be recognized apart from the noise in these range gates, which debased the quality of the figures and increased the difficulty in estimating the phenomena.

3) WIOBSS operates on the frequencies 3–30 MHz, while most of the radio equipment work on the same frequency band. That leads to serious RFI, which distributes nearly on the whole band, and endangers the system [10]. The most notable feature of RFI is spreading widely on the range direction in the range-Doppler figure [3,10–11].

3 Preprocessing the echo spectra

In WIOBSS, the carrier-free signal had been divided into I/Q paths. Then the divided signals were sent to the DSP. In the DSP, the correlation operation between these signals and the shifted local codes was fulfilled. The result of this operation was sent to a PC. There, the result was used to get the echo spectra by fast Fourier transform (FFT) and the echo spectra were preprocessed. The preprocessing flow is shown in Fig. 5.

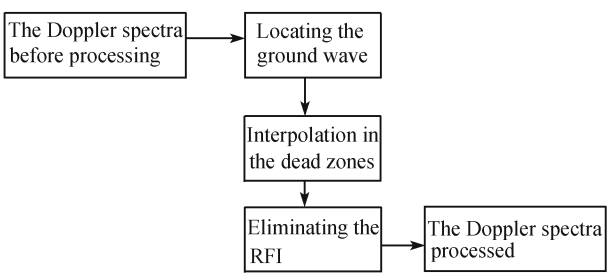

Fig. 5 The preprocessing flow

3.1 Locating the ground wave and coordinating the data

The delay incurred by the hardware operation was random, so the zero point in range was not fixed in each experiment. The delay for processing also caused that the ground wave did not always locate at the same zone point on the reference frame in the detections. However, the ground wave located at the zero point in range in the ionospheric sounding. Thus, before FFT along the time axis in each of the detection, we had to coordinate the data. Because the amplitude of the ground wave was large and always distributed at the front 60 range gates, we considered that the location of the strongest signal in the front 60 range gates was the zero point in range. The data behind the ground wave were coordinated along the range axis in turn. While showing in the figures, the amplitude of the ground wave should be reduced, or the color for signals would approach the color for the noise.

3.2 Interpolation in the dead zones

The dead zones brought great difficulty in estimating the phenomena. Sometimes, they even led to misjudgments. The echoes in adjacent gates were correlated; therefore, interpolation at the dead zones could restore the real spectra. Spline interpolation is estimating the signal amplitude in the dead zones with spline function, and regarding the signal amplitudes in the zones near the dead zones as the references. Average interpolation is regarding the average of the signal amplitudes in the zones near the dead zones as the value interpolated. Burg interpolation is estimating the parameters for autoregressive (AR) model [12] with the data before the dead zones $x_0, x_1, \ldots, x_{N-1}$, and using the result to estimate the value in the dead zone x_N.

3.3 Eliminating the radio frequency interference

There are many methods for wiping off the RFI, such as the adaptive filtering, advanced average range spectra method [10], time-frequency analysis [11], and so on.

The form of RFI is that the interference spreads in nearly all the range gates on a single frequency. Therefore, in the corresponding Doppler cell, the power is extremely large. The method of processing in the range domain is shown here. If we perform FFT on the data along the range axis, a peak higher than the background noise will appear, locating at the place of RFI. Then we perform FFT with the result of the correlation to transform it to frequency domain

$$x(m,k)=\sum_{n=0}^{N-1}x(m,n)\mathrm{e}^{-\mathrm{j}(2\pi/N)nk},\quad k=0,\ 1,\ldots,\ M-1 \tag{3}$$

Perform FFT on the expression in Eq. (3) along the range axis

$$x(p,k)=\sum_{m=0}^{M-1}x(m,k)\mathrm{e}^{-\mathrm{j}(2\pi/M)mk},\quad p=0,\ 1,\ldots,\ N-1 \tag{4}$$

where M is the number of the range gates, N is the sounding times. The whole course is equivalent to 2-D FFT. Then, we find out the peak, which corresponds to the energy of the RFI, along the Doppler axis. Lastly, attenuate the peak and perform inverse fast Fourier transform (IFFT) on the data in the range domain to the time domain. Actually, if the echoes are strong, the amplitudes in all the range gates after 2-D FFT will be rather large. The choice of threshold will be difficult, and may lead to misjudgments.

Here is another method for the threshold processing based on statistical signals. Radio frequency interference distributes within the whole range domain and the amplitudes are higher than the background noise. If choosing the maximum of the background noise as the threshold δ, and assuming that the signal amplitude for each Doppler frequency is $A(i, j)$, then

$$n(i,j)=\begin{cases}1, & A(i,j)>\delta \\ 0, & A(i,j)\leqslant\delta\end{cases} \tag{5}$$

Get this parameter in Eq. (5) for p sampled signals

$$\text{num}\,(i)=\sum_{j=1}^{p} n(i,j) \tag{6}$$

Judge the existence of the RFI

$$\begin{cases}\text{num}\,(i)>\beta, & \text{interference} \\ \text{num}\,(i)\leqslant\beta, & \text{others}\end{cases} \tag{7}$$

If RFI exists, attenuate the $A(i,j)$. The principle and algorithm in this method are relatively simpler than the other methods.

Both δ and β are confirmed by the values of experience. The number of the range gates in which the echoes distribute is fewer than that where the RFI distributes. Several detection results reveal that if the values of δ and β are chosen properly, RFI can be eliminated accurately without any influence on the echoes.

4 Results and analysis

The data processed below are the same to those in Fig. 4. They were recorded on November 6, 2004. The parameters in this detection were as follows: the operating frequency was 10.871 MHz; the code length was 511; the code-width was twice the pulse width; the interval was a tenth of the pulse width and the sounding times was 256. The transmitting antenna was a log periodic antenna and the receiving antenna was a dipole antenna. Preprocessing the data in the first 300 range gates, the Doppler figure is shown in Fig. 6.

Compared with Fig. 4, the quality of Fig. 6 is far better. The ground wave was located at exactly zero and its amplitude was attenuated nearly to the value of the background noise. The echoes were highlighted, which was rather important to improve the sounding performance. The data were coordinated for calculating the Doppler, which would improve the reliability of the result.

The RFI was basically eliminated in Fig. 6. The greatest attenuation reached 6–7 dB. However, if the RFI had the same Doppler as echoes, we would not be able to distinguish them

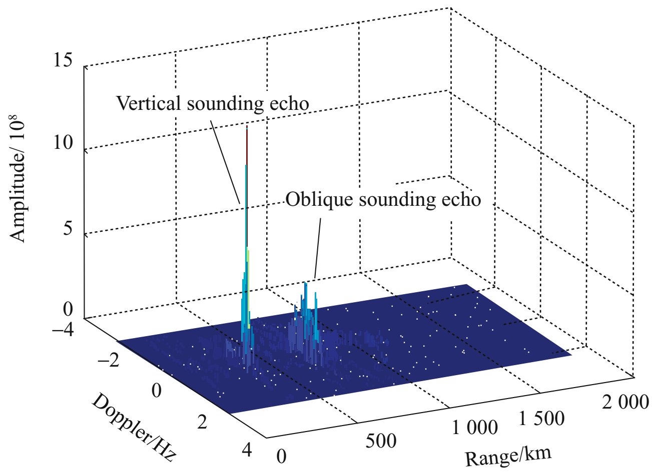

Fig. 6 Doppler spectra processed

from each other and the echoes would also be eliminated. If not, they would be distinguished accurately. Therefore, to some extent, this method may improve SNR and lose some information.

Because the beam angle is wide, the multi-path spread of the echoes is large. The number of the range gates in which the echoes distributed reached dozens. It looks like there are several echo regions in Fig. 4. The problem of dead zones can be solved properly through interpolation. After interpolating, the echo regions join together. The extension reaches over 500 km, which corresponds to ionospheric echoes. The real echoes recur and misjudgments are avoided.

If we transmit all the pulses once and then receive all the echoes, there will be no spacing dead zones. However, the dead zone would centralize on the range nearby.

5 Conclusion

The purpose of preprocessing is to improve the sounding performance, including increasing SNR, eliminating the clutter, and to restore the ionospheric information. In this paper, several preprocessing methods are applied to get better Doppler spectra. Some problems may appear and misjudgments may occur without preprocessing. For instance, it is difficult to extract the parameters of the ionosphere and carry out high resolution spectral estimation. Thus, it means a lot to preprocess the real data. In future work, it is necessary to pay more attention on the algorithm in the follow-up data processing and parameter accuracy in echo estimation.

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