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Doppler estimating and compensating method based on phase*

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Abstract: According to the Doppler sensitive of the phase coded pulse compression signal, a Doppler estimating and compensating method based on phase is put forward to restrain the Doppler sidelobes, raise the signal-to-noise ratio and improve measuring resolution. The compensation method is used to decompose the echo to amplitude and phase, and then compose the new compensated echo by the amplitude and the nonlinear component of the phase. Furthermore the linear component of the phase can be used to estimate the Doppler frequency shift. The computer simulation and the real data processing show that the method has accurately estimated the Doppler frequency shift, successfully restrained the energy leakage on spectrum, greatly increased the echo signal-to-noise ratio and improved the detection performance of the radio system in both time domain and frequency domain.

Keywords: ionosphere, Doppler estimation, Doppler compensation, phase.

1. Introduction

The radar adopting pulse compensation technology owns both the large covering range of the wide pulse radar and the high range resolution of the narrow pulse radar[1]. There are two kinds of the pulse compression technology. One is the linear frequency modulation (LFM) and the other is the binary phase code (BPC). The LFM waveform is applied more widely. However with the arrival of the software defined radio theory[2], the phase coded system, which can be easily built as the digital radar with small size and low power, is valued more and more. In the Ionospheric detection domain, many Ionosondes such as the Digisonde produced by the University of Massachusetts Lowell's Center for Atmospheric Research (UMLCAR)[3], the Dynasonde evolved at National Oceanic and Atmospheric Administration (NOAA)[4], the Canadian Advanced Digital Ionosonde (CADI)[5], the European Doppler and Multipath Sounding Network (DAMSON)[6] and so on, all use the binary phase coded signal for detection.

However the binary phase coded signal is Doppler sensitive. When there is no Doppler frequency shift on the echo, the pulse compressor outputs a perfect auto-correlation function. While the variation in echo phase happens, the Doppler frequency shift is attached to the echo and induces the mismatch of the pulse compressor. The mismatch is mainly reflected in the following: the mainlobe output by the pulse compressor is decreased and spread, the level of the sidelobes is increased, the signal-to-noise ratio (SNR) falls greatly and the sounding resolution in both time and frequency domain is deteriorated. Therefore it is necessary to compensate the Doppler frequencies on the echoes to reduce the Doppler sensitivity of the binary phase coded waveform and improve the detection performance of the radio system[7–9].

The compensating method based on phase is simple, practicable and reliable, which can measure the Doppler frequency shift (DFS) to calculate the target velocity while improving the Doppler mismatch. So the method is valuable for the moving target detection radar to measure and compensate the Doppler at the same time. The rationale of the Doppler compensation based on phase is introduced in Section 2 first, and then the simulated echoes with different Doppler

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frequencies are applied to test the performance of the method in Section 3. Secondly, the Doppler compensating method is used to process the real data of the Wuhan Ionospheric oblique backscattering sounding system (WIOBSS), and the processing results is analyzed in Section 4. The conclusion is found in Section 5 finally.

2. Principle of Doppler compensation based on phase

In the traditional system using the binary phase code, the Doppler compensation is realized by compensating the local oscillator. This method adds the DFS f_d to the local oscillator frequency f_0, and then converts the local oscillator frequency to $f_0 + f_d$ to solve the Doppler mismatch. However while the Doppler frequency f_d is unknown or can not be accurately estimated, this Doppler compensating method becomes impracticable. Due to the multipath and multimode in the ionospheric backscattering detection, the received echoes is the superposition of the ground echoes, vertical incident echoes and backscattered echoes. Therefore there are many unpredictable Doppler components attached on the superposed echoes and it is impossible to compensate the Doppler components by the local oscillator channels before pulse compression. So only after the pulse compressor divides the echoes by delay, the Doppler compensation for the ionospheric backscattering echoes is practicable. The Dpooler compensation scheme is shown in Fig. 1.

While the binary pseudorandom code with length n is used as the modulating signal, the discrete amplitude sequence of the N-th sampling of the zero intermediate frequency (IF) is

$$A(t) = [a(t), a(t+T_p), \ldots, a(t+(n-1)T_p)] \tag{1}$$

where T_p is the pulse repeated cycle. The complex signal in the inphase and quadrature (I/Q) channels of the zero IF can be expressed as

$$\begin{aligned} X_{IQ} = {} & [a(t)\mathrm{e}^{\mathrm{j}\omega t}, a(t+T_p)\mathrm{e}^{\mathrm{j}\omega(t+T_p)}, \ldots, \\ & a(t+(n-1)T_p)\mathrm{e}^{\mathrm{j}\omega(t+(n-1)T_p)}] \end{aligned} \tag{2}$$

where ω is the angular frequency. The correlation accumulation T_{IQ} of the local code $X = (x_1, x_2, \ldots, x_n)$ and the complex signal X_{IQ} in the pulse compressor is

$$\begin{aligned} T_{\mathrm{IQ}} = {} & \sum_{i=0}^{n-1} x_i \cdot a(t+iT_p) \cdot \mathrm{e}^{\mathrm{j}\omega(t+iT_p)} = \\ & \mathrm{e}^{\mathrm{j}\omega t} \cdot \sum_{i=0}^{n-1} x_i \cdot a(t+iT_p) \cdot \mathrm{e}^{\mathrm{j}\omega T_p i} \end{aligned} \tag{3}$$

Equation (3) shows that Doppler angular frequency ω has modulated the echo. When the Doppler value is zero, we get the perfect correlation $\sum_{i=0}^{n-1} x_i \cdot a(t+iT_p)$. When the Doppler is a nonzero value, the factor $\mathrm{e}^{\mathrm{j}\omega T_p i}$ acts as the weighted coefficients in the correlation accumulation to reduce the mainlobe and elevate the sidelobe level. The factor $\mathrm{e}^{\mathrm{j}\omega t}$ modulates the correlation accumulated results again, decreases the mainlobe to sidelobe ratio (MSR) and induces the Doppler shift. The Doppler compensating method is used to partly eliminate the modulating effect of the angular frequency ω on the echo to restrain the energy leakage on the spectrum caused by the discrete Fourier transform (DFT), so the SNR is increased and the detection resolutions in both time and frequency domain are improved.

The relationship of the phase φ, angular frequency ω and DFS f_d is shown as

$$\varphi = \omega t = 2\pi f_d t + \tilde{\varphi}(t) \tag{4}$$

The phase is the product of ω and time t. It can be divided into the linear component $2\pi f_d t$ including the DFS information and the nonlinear component $\tilde{\varphi}(t)$ including the Doppler frequency spread information[10–11]. The Doppler compensating method based on phase uses the echo amplitude and the nonlinear component of the phase to compose the compensated echo with zero DFS.

The Doppler compensation shown in Fig. 1 is implemented after the pulse compressor has recognized the echoes with range gate. First, the echo amplitude a and original phase φ varying between $\pm\pi$ are extracted and then the original phases are strung to a continuous series. The strung phase undulatingly runs upward or downward with the positive or negative Doppler value. The slope of the phase determines the Doppler shift, and the Doppler spread can be calculated by the fluctuation on phase. The oblique line, gotten by the least square fit to the strung phase, is the linear component of the phase. The nonlinear component is obtained by subtracting the linear component from the strung phase[12]. Finally the echo amplitude a and the nonlinear component $\tilde{\varphi}(t)$ of the strung phase are used to compose the compensated echo T'_{IQ}. T'_{IQ} can be converted to frequency domain to get the compensated echo spectrum with zero DFS by FFT.

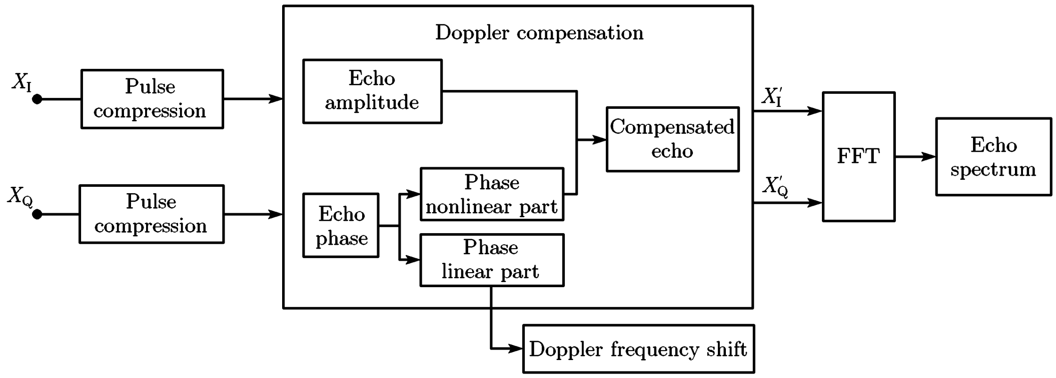


Fig. 1 The Doppler compensation scheme

$$T'_{\mathrm{IQ}} = \mathrm{e}^{\mathrm{j}\tilde{\varphi}(t)} \cdot \sum_{i=0}^{n-1} x_i \cdot a(t + iT_p) \cdot \mathrm{e}^{\mathrm{j}\omega T_p i} \qquad (5)$$

Equation (5) shows that the Doppler compensating method based on phase effectively amends the second modulation by $\mathrm{e}^{\mathrm{j}\omega t}$ in the pulse compressing process. Compared with the original echo, the echo peak in the spectrum has been shifted to zero Doppler axes and the energy leakage on spectrum has been well controlled. Therefore the echo SNR will be improved and the Doppler spread caused by the detection target can be measured accurately.

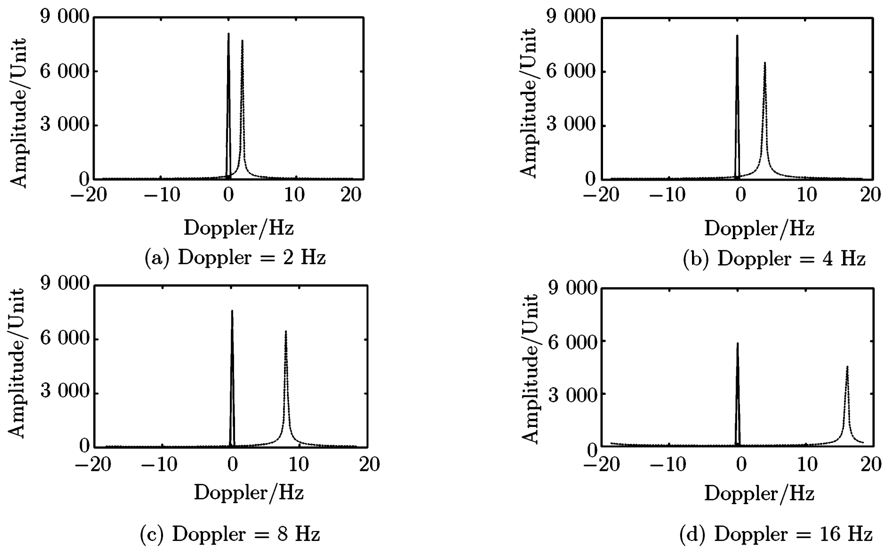
Furthermore the DFS f_d can be calculated by the slope of the phase nonlinear component $2\pi f_d t$. Therefore while the Doppler shift is compensated to improve the performance of the radio system, the average line-of-sight velocity of the target is also obtained.

3. Simulating results

The almost-perfect sequence with length 64 is used for the computer simulation[13]. The peak power of the transmitted pulses is defined as one unit, the pulse repetition frequency is 2.4 kHz, the duration ratio is 10%, and the modulated pulse train is transmitted 128 times continuously. Thus the above operation parameters are determined that the Doppler unambiguous range is [−18.75 Hz, +18.75 Hz] and the Doppler resolution of FFT is 0.293 Hz.

The spectrums of the simulated echoes with 2 Hz, 4 Hz, 8 Hz, 16 Hz DFS are shown as dashed peak in Fig. 2 respectively. Due to the zero-Doppler-axis symmetry feature of the Doppler spectrum, the positive Doppler values are considered in the simulation. As shown in Fig. 2, with the increase of the DFS, the echo amplitude is falling, the noise level is increased, and the echo spectrum spreads more and more. Because of the 0.293 Hz spectrum resolution of FFT, the measured DFSs are 2.051 Hz, 4.102 Hz, 7.91 Hz and 16.11 Hz respectively.

The Doppler resolution of the phase method is proportional to the sampling accuracy, so very high Doppler resolution can be gained with 16 bit sampling accuracy. The echo phase method can take the place of FFT to estimate the DFS for Doppler compensation. The DFSs of the simulating echoes are accurately estimated by the slope of echo phase, so the peaks of the compensated echo spectrum shown as solid line in Fig. 2 are all shifted to zero Doppler axes. After the Doppler compensation base on phase has successfully restrained the energy leakage on spectrum, the echo amplitude is increased, the spectrum spread is narrowed and the noise level is fallen. Therefore the echo SNR is increased and the measuring accuracy for the Doppler shift and spread is improved greatly.



(a) Doppler = 2 Hz (b) Doppler = 4 Hz (c) Doppler = 8 Hz (d) Doppler = 16 Hz

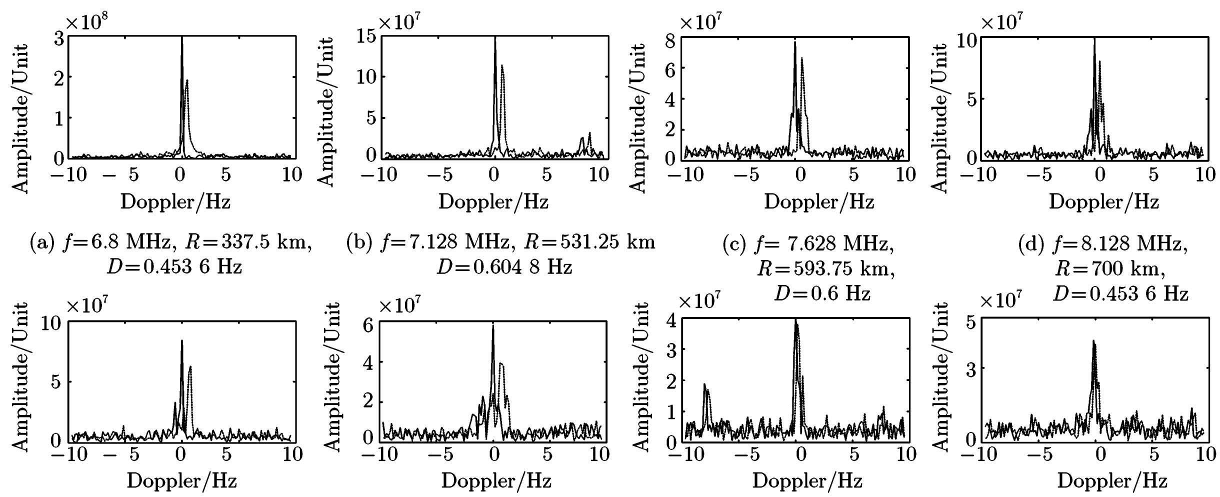
Fig. 2 The computer simulating results

4. Processing and analyzing the real data

The real data are recorded by the WIOBSS, which is developed by the Ionosphere Laboratory of Wuhan University[12,14]. Because of the wide beam of the log-periodic antenna, the high-frequency (HF) over-the-horizon radar will receive the ground echo, vertical and oblique incident ionospheric echoes simultaneity. In order to avoid the range sidelobes of the ground echoes with high power to affect mainlobes of the vertical incident echoes and submerge the weak oblique incident ionospheric echoes, the almost-perfect sequence with 124 bit period is used for detection without range sidelobes. The applied pulse wide is 83 μs, the duration ratio of the pulse train is 20%, the pulse train is transmitted 128 times continuously to record 128 sets of echo data, and the transmitting peak power is set on 200 W. The signal in IF is sampled by the A/D converter and then sent in the pulse compressor to get the bi-temporal ionospheric response (BTIR)[15]. The BTIR is transformed to the frequency domain to acquire the channel scattering function (CSF) by FFT[16]. Therefore the pulse compressing gain is $10 \times \log 124 = 20.9$ dB the Doppler integrating gain is $10 \times \log 128 = 21$ dB, the Doppler unambiguous range of the CSF is [−9.68 Hz,+9.68 Hz] and the Doppler resolution is 0.151 2 Hz.

The real echo spectrums and the compensated spectrums of eight different operating frequencies are shown as dashed and solid lines respectively in Fig. 3. The echoes are selected from the echo front edge in the CSF. The operating frequency f, the group range R and the DFS D measured by phase are marked on every subplot. The DFS of each echo is accurately estimated by the phase, so the peaks of the compensated echoes are all shifted to the zero Doppler axes. The echoes shown in Figs. 3(a) and 3(b) are vertical incident echoes recorded with the 6.8 MHz and 7.128 MHz operating frequencies. Their SNR is very high and the spectrum spread is very narrow. After Doppler compensation, the echo amplitude is increased greatly, the spread become narrower and the noise level is reduced obviously. The echo in Fig. 3(c) spreads slightly. There are small peaks located beside the main echo in Figs. 3(d) and 3(e). The echo falls and spreads greatly as well as the noise level rises in Fig. 3(f). The Doppler compensating method increases the SNR and restrains the energy leakage of the four echoes obviously. The backscattered ionospheric echo from 912.5

km with 10.228 MHz operating frequency is shown in Fig. 3(g). The echo peak is located at 0.151 2 Hz Doppler frequency and the small peak located on the left of it (at −7.712 Hz) is the radio frequency interference (RFI). The RFI is a stable jamming on frequency and appears on all the range gates. It will effect the correct estimation and effective compensation of the DFS. Compared with the amplitude of the backscattered echo, the RFI amplitude in Fig. 3(g) is not so large to effect the echo phase, therefore the DFS is estimated and compensated effectively, but the SNR is not improved obviously. In ionospheric detection, the echo front edge goes further and further and amplitude becomes smaller and smaller with the increase of the operating frequency. When the operating frequency increases to 11.228 MHz, the echo front edge appears at 1 018.75 km as shown in Fig. 3(h), and the echo peak becomes much smaller. Due to the zero DFS of the real echo, the Doppler compensation can only increase a little SNR.



(a) f=6.8 MHz, R=337.5 km, D=0.453 6 Hz
(b) f=7.128 MHz, R=531.25 km D=0.604 8 Hz
(c) f= 7.628 MHz, R=593.75 km, D=0.6 Hz
(d) f=8.128 MHz, R=700 km, D=0.453 6 Hz
(e) f=8.728 MHz, R=712.5 km, D=0.756 Hz
(f) f=9.418 MHz, R=781.25 km, D=0.9 Hz
(g) f=10.228 MHz, R=912.5 km, D=0.151 2 Hz
(h) f=11.228 MHz, R=1 018.75 km, D=0 Hz

Fig. 3 The real and the compensated echoes

5. Conclusion

The Doppler estimation and compensation method in this paper are based on the echo phase measurement. The echo phase is divided into the linear component and the nonlinear component. The linear component is used to estimate the DFS. The phase nonlinear component and the echo amplitude compose the compensated echo. The simulating results show that this method can increase the SNR and improve the measuring accuracy in both time domain and frequency domain. The real data processing performance of the Doppler compensating method is also satisfied. However, the RFI is unfavorable for the Doppler estimation and compensation based on phase, therefore it is necessary to remove it before compensation.

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