Cascaded Approach for Correcting Ionospheric Frequency Modulation in HF Sky-Wave Radars

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Abstract Ionospheric frequency modulation causes spreading of the surface clutter in Doppler domain which greatly limits the detection performance of HF sky-wave radars. This paper proposes a cascaded approach to correct the ionospheric frequency modulation. This approach consists of two correction steps. At the first step, time-frequency distribution (spectrogram or pseudo Wigner-Ville distribution) of the time-varying signal is adopted and a peak-tracking scheme is designed to obtain a coarse ionosperic modulation estimation from the time-frequency distribution. At the second correction step, a parametric method based on piecewise polynomial phase model is exploited to eliminate the residual contamination. Simulation results show the effectiveness of this cascaded approach even for very serious cases where broadened Bragg lines are overlapped.

Key words frequency modulation; ionosphere; piecewise polynomial phase; sky-wave radar; time-frequency distribution

校正高频天波雷达电离层频率调制的级联方法

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【摘要】电离层频率调制导致地表面杂波的多谱勒展宽，极大地限制了高频天波雷达的目标探测性能。本文针对这种电离层频率调制，给出了一种级联的两步校正处理的方法。在第一步校正中，首先分析这种时变信号的时频分布，并设计了一种谱峰追踪方法从时频分布中获得粗糙的电离层频率调制估计。然后采用基于分段多项式相位模型的参数化方法作二次校正处理，消除残余调制污染。模拟结果表明，即使对Bragg峰发生混叠的重污染的情形，这种级联的校正方法都具有非常好的效果。

关 键 词 频率调制; 电离层; 分段多项式相位; 天波雷达; 时频分布

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Doppler processing is critical for target detection in HF sky-wave radar. However, the movement of ionosphere produces ionospheric frequency modulation which causes significant spreading of both the surface clutter and the echo of target in Doppler domain[1-3]. This greatly limits the target detection performance of HF sky-wave radars.

Some methods based on instantaneous frequency estimation have thus been proposed to correct the ionospheric frequency modulation[1-5]. In these methods, extraction of a modulated Bragg line or other reference signals from the broadened clutter is a critical stage. Sometimes, the ionospheric modulation is so rapid that the Bragg lines are overlapped with each other[6]. At this condition, those methods are not very efficient[3]. Correction methods exploiting the spatial correlation of the ionospheric contamination can avoid this problem[7]. But in general cases, the correlation is very low even between neighboring rang bins [8], and this limits the applications of the methods.

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In this paper, an approach of cascaded corrections is proposed to treat the violent ionospheric frequency modulation. It consists of two steps. At first step correction, time-frequency distribution (TFD) of the contaminated data is adopted in order to track the instantaneous locations of the Bragg peaks. Spectrogram (SPEC) and pseudo Wigner-Ville distribution (PWVD) are used and compared. Different from the approaches of Ref. [9] and Ref. [10] where complicated TFDs such as smoothed PWVD (SPWVD) are performed to detect target echo in sea clutter, a specific peak tracking scheme (SPTS) is proposed to extract a coarse frequency modulation from the TFD of the time-varying Bragg lines. After the first step correction, the spreading of the signal is compressed and thus the Bragg lines can be separated. Second step correction is exploited to eliminate the residual contamination and improves the quality of the restoration. At this stage, a parametric method based on piecewise polynomial phase model is utilized [4-5].

Compared with the method presented in Ref. [3], the cascaded method has the advantages in the following three aspects: (1) Ref. [3] needs to filter out a Bragg line. This is impractical for severe contamination cases. In this paper, the overlapping problem is avoided by using the first step in the cascade approach. (2) PWVD with center finite difference used in Ref. [3] may induce very large frequency estimation variance for the cases of high sea states[3]. (3) The second step correction based on the parametric model can greatly improve the performance of the method proposed in this paper.

Simulation results verify the effectiveness of this cascaded method even for very serious case where broadened Bragg lines are overlapped.

1 Cascaded Correction Approach

When violent ionospheric frequency modulation occurs, Bragg lines may be overlapped in Doppler domain. In this case, the TFD is an effective tool [10]. Concerning the low computational loads and feasibility of implementation, we used the SPEC and the PWVD rather than some other TFDs, such as SPWVD, et al, though they may have better performance. In our strategy, the overall performance can be improved by the second step correction but only with slight extra computations.

The SPEC and the PWVD are defined by:

$$S_x(t,f)=\left|\int_{-\infty}^{+\infty}x(u)h^*(u-t)e^{-\mathrm{j}2\pi fu}\mathrm{d}u\right|^2 \qquad (1)$$

$$\mathrm{PWD}_x(t,f)=\int_{-\infty}^{+\infty}x(t+\tau/2)x^*(t-\tau/2)h(\tau)\mathrm{e}^{-\mathrm{j}2\pi f\tau}\mathrm{d}\tau \qquad (2)$$

respectively. The t and f stand for time and frequency, $h(t)$ is a sliding window. The SPEC is a tradeoff between time and frequency resolution, while the resolution of the PWVD does not have this restraint but suffers from more cross-terms.

Here the instantaneous frequency estimation (IFE) is formed by locating the peak of the TFD at each time instance. For a discrete time signal, this procedure can be described as:

$$\hat{f}_i(n\varDelta)=\arg\max_f\left|\mathrm{TFD}_x(n\varDelta,f)\right|,\ n=0,1,\cdots,N-1 \qquad (3)$$

where TFD_x denotes the SPEC or PWVD which is a discrete version of Equ. (1) or Equ. (2). The $\varDelta$ is the sampling interval and N is the number of pulses in a coherent integration. Thus the ionospheric frequency modulation can be calculated by:

$$\hat{f}_{\mathrm{ion}}(n\varDelta)=\hat{f}_i(n\varDelta)-f_{\mathrm{B}} \qquad (4)$$

where f_{B} is the frequency of the first-order Bragg line[11]. From Equs. (3)～(4), we can track the variation of the Bragg peak and estimate the ionospheric Doppler shift at each time instance. However, the Bragg lines have time-varying amplitudes [11]. Thus the maximum peak of the TFD at different time instances may not stand for the same Bragg line, which causes great difficulty in direct peak tracking (DPT). But the dominant peak of the TFD at any time should be one of the first-order Bragg lines. This is reasonable because the two Bragg lines are irrelevant with each other, which guarantees that the Bragg lines are not weak simultaneously. Hence, a specific peak-tracking scheme (SPTS) for the extraction of the ionospheric modulation is therefore described as:

(1) Set $\hat{f}_{\mathrm{ion}}(0)=\hat{f}_i(0)$ when $n=0$.

(2) Loop for each n from 1 to $N-1$, do:

$$\hat{l}=\arg\min_l\left\{\left|\hat{f}_i(n\varDelta)+lf_{\mathrm{B}}-\hat{f}_{\mathrm{ion}}((n-1)\varDelta)\right|\right\}$$

where $l\in\{-2,-1,0,1,2\}$. And then let:

$$\hat{f}_{\mathrm{ion}}(n\varDelta)=\hat{f}_i(n\varDelta)+\hat{l}f_{\mathrm{B}}$$

(3) Finally form a correction function:

$$F_c(n)=\mathrm{e}^{-\mathrm{j}2\pi\sum_{k=0}^{n}\hat{f}_{\mathrm{ion}}(k\varDelta)}\qquad n=0,1,\cdots,N-1$$

The above scheme implies a fact that the variation of the ionospheric Doppler shift in one pulse repetition interval $\varDelta$ is much smaller than f_B, the frequency of the Bragg line. Multiplied by $F_c(n)$, the Bragg lines of the contaminated data $x(n)$ can be greatly sharpened but with a possible Doppler shift in its spectra. This shift can be easily corrected by symmetrizing the pair of Bragg lines.

Due to the effects of low resolution and cross terms in the TFDs, some residual contaminations are still retained after the first step correction. The goal of the second step correction is to estimate the residual contamination. Since the Bragg lines are separated enough after the first step, they can be easily filtered out. Thus some existing correction methods can be used. Here a piecewise parametric method based on polynomial phase model is adopted [4-5]. In this method, high order ambiguity function (HAF) analysis is used to estimate the polynomial phase coefficients. More details about the algorithms can be referred to Refs. [4-5].

2 Simulations and Results

Data set with distinct sea clutter components collected by an experimental HF surface wave radar (HFSWR) is used in the following simulations. The HFSWR operates at a frequency of 8 MHz and the Bragg returns would have Doppler frequencies at about $\pm$0.29 Hz[10]. The pulse repetition interval (PRI) is 0.65 s and the coherent processing interval is 167 s. The solid line in Fig. 1 is the Doppler power spectrum of typical sea clutter. A target with Doppler frequency of 0.15 Hz is artificially added in the data.

As described in Refs. [1-5], in order to demonstrate the effectiveness of the cascaded method described in Section 1, artificial contamination is added into the real HFSWR data. As an example, the raw data of the solid line in Fig.1 is perturbed by a strong sinusoidal frequency modulation with 0.25 Hz in amplitude and 20 s period[1], given as:

$$g(t) = \exp\{\mathrm{j}0.25\sin(0.1\pi t)\} \qquad (5)$$

Note that according to Refs.[1,2,6], the frequency modulation of Equ. (5) is regarded as a kind of severe ionospheric contamination. The dotted line in Fig. 1 is the spectrum of the contaminated signal. From the spectrum, the two first-order Braggs are broadened to be overlapped and the target signal can't be discriminated from this spectrum.

The SPEC and PWVD (both with Hanning window) of the contaminated data are shown in Fig. 2a and Fig.2b respectively. It is clear that the SPEC almost has not visible cross-terms, while the WVD has relative strong cross-terms.

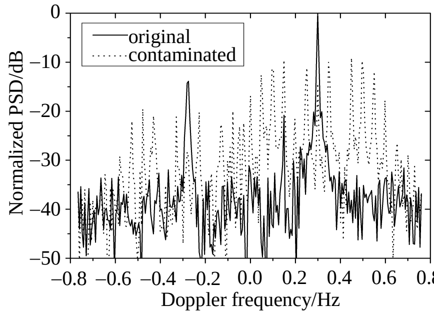
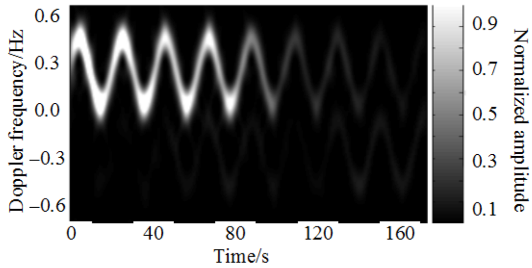
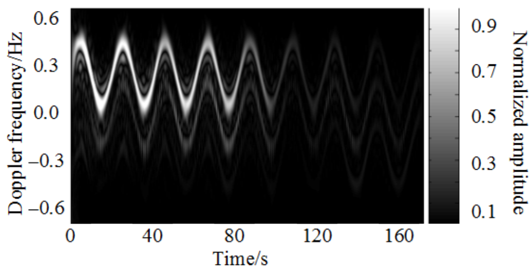


Fig.1　Power spectrum of raw data and contaminated data



a. SPEC



b. PWVD

Fig.2　The SPEC and PWVD of the contaminated data shown in Fig. 1

Fig.3 shows the estimation performance of the ionospheric modulation from the two TFDs of Fig. 2. Line-a and c are the estimation errors of the SPEC with the DPT and the proposed STPS respectively. Line-a,b,c,d denote the Doppler estimation error of SPEC, PWVD, SPEC with SPTS, PWVD with SPTS. Line-b and d are the estimation errors of the PWVD using the DPT and the STPS respectively. For line-a and b, from about 120 s to 156 s, the direct peak tracking encounters some problems, while the proposed STPS works well for the whole domain. Note that in our experiments, the PWVD does not have better performance over the SPEC since its cross terms countervail the merit of better resolution. Moreover, the PWVD performs worse when high-order sea clutter enhances or the two Bragg lines are comparable. Therefore, the SPEC is recommended because of its robustness and low computational complexity.

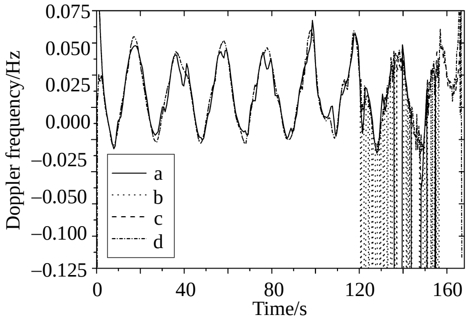
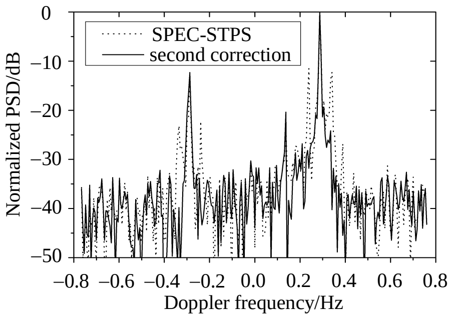
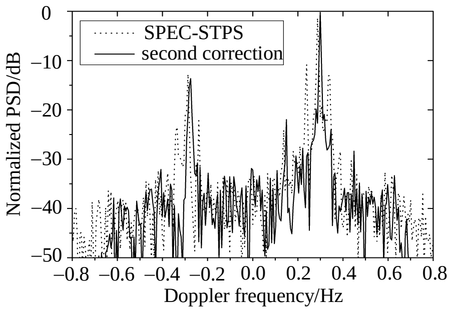


Fig.3 Estimation performance of instantaneous frequency modulation



a. Restored spectra after original correction using SPEC-STPS and after the second correction



b. Restored spectra using PWVD-STPS and after the second correction

Fig.4 Restored spectra using different methods

The dotted lines in Fig. 4a and Fig.4b are the corrected spectra after the first step correction using SPEC-STPS and PWVD-STPS, respectively. Visible strong peaks are appeared around the Bragg lines. Piecewise polynomial phase method[4-5] is used to do the second step correction, i.e., correcting the residual contamination. The solid lines in Fig. 4a and Fig.4b are the results after the second correction. Obviously this correction significantly improves the quality of the restoration. And compared the restored spectra (solid lines) in Fig. 4a and Fig.4b with the original spectra shown as the solid line in Fig.1, the cascaded correction strategy given in this paper restored the contaminated signal very well.

3 Conclusions

This paper proposes a new ionospheric contamination correction approach which consists of the coarse correction using time-frequency analysis and the fine correction based on the piecewise polynomial phase model. From the simulations, the cascaded correction approach provides an efficient way to de-contaminate the signals perturbed by frequency modulation even at the severe contamination condition where the Bragg lines are broadened to be overlapped.

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