

Two New Approaches for Detecting a Maneuvering Air Target in Strong Sea-Clutter

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SUMMARY & CONCLUSIONS

Two new approaches for detecting a maneuvering air target in strong sea-clutter are proposed in this paper. One is based on the adaptive chirplet decomposition, and the other is inspired by the spectral subtraction. Experiments with real-world data samples show that both methods presented in this paper can effectively enhance the Doppler radar signals from maneuvering air targets though each has different strength and weakness.

1. INTRODUCTION

This paper is concerned with a method of detecting a maneuvering air target in the presence of strong sea-clutter. It is well understood that the sea-clutter is primarily due to Bragg scattering from the surface of the sea. When the target moves slowly with a velocity comparable to the ocean gravity waves, the first-order Bragg lines, generated by resonance with the incident high frequency wave, will dominate the Fourier spectrum [2]. Such dominant components can be roughly modeled by the summation of sinusoids. Based on such an assumption, Root [5] first proposed the Fourier transform based clutter rejection algorithm to enhance the radar signal. The success of this class of algorithms [9] largely hinges on the accuracy of Bragg frequency estimation. Traditionally, the frequency estimation (including amplitude, frequency, and phase) is directly obtained from frequency peaks in the discrete-time Fourier spectrum. Because of energy leakage and window effect, such estimation usually is biased, unless the resonance with the incident high frequency wave happens to be the frequency bin of the discrete-time Fourier spectrum. Moreover, the maneuvering air target may generate the time varying Doppler frequency, which will introduce more problems to precisely estimate the Bragg frequencies.

As an alternative, this paper proposes two new approaches. One is still based on the sinusoidal model assumption. Instead of using the discrete Fourier transform, we apply the sampling-grid free adaptive chirplet decomposition to the sea-clutter contaminated radar signals. The sinusoidal components with low central frequencies are extracted as the sea-clutter. After subtracting these extracted chirplets, we can obtain the enhanced target signal. In real conditions, the sea-clutter can not be exactly modeled by the summation of sinusoids because of the fluctuation of sea

waves. Both the amplitude and frequency of the sea-clutter may include some fluctuations, so that the Fourier spectrum of the sea-clutter has certain bandwidth around the Bragg lines. To better track such fluctuations, we proposed another approach, that is, a spectral subtraction based method. In this method, the Gabor transform is applied for the radar signals. The sea-clutter is modeled by two Gaussian peaks in the frequency domain and subtracted from the Gabor coefficients. The sea-clutter cancelled target signal is reconstructed from the subtracted Gabor coefficients.

The paper is organized as follows: firstly the principles of two new approaches are briefly introduced; then, the preliminary experimental results are given; finally, a short conclusion is made.

2. METHODS

In this section, we briefly introduce two new approaches for air target detection, that is, the chirplet-based and spectral subtraction-based methods.

2.1 Adaptive Chirplet Method

The sampling-grid free adaptive chirplet decomposition [10] is the extension of the so-called adaptive normalized Gaussian representation [7] and matching pursuit methods [4]. In both the adaptive normalized Gaussian representation and the matching pursuit methods, the number of the predetermined parameter vectors in the dictionary is finite, no matter how big the dictionary is. If the parameter vector of an elementary function does not belong to the dictionary, then one elementary component will be spread everywhere. This kind of mismatch not only degrades the estimation accuracy, but also reduces the speed of convergence.

Without invoking computational expensive, multivariable, numerical optimization methods, the technique introduced in [10] analytically refines the coarse estimation obtained by the method introduced in [7] or [4]. The resulting decomposition algorithm is not only fast, but also is free of sampling-grid. For the sake of presentation clarity, in this paper we call the method presented in [10] as the *sampling-grid free adaptive chirplet decomposition*.

For a given signal $s(t)$, the sampling-grid free adaptive chirplet method decomposes it as a superposition of a group of linear chirplet functions, i.e.,

$$s(t) = \sum_{k=1} A_k h_k(t) \quad (1)$$

where the linear chirplet function has a form:

$$h_k(t) = \sqrt{\frac{\alpha_k}{\pi}} \exp\left\{-\frac{\alpha_k}{2}(t-t_k)^2 + j\left(\omega_k + \frac{\beta_k}{2}(t-t_k)\right)(t-t_k)\right\} \\ \alpha_k, \beta_k, t_k, \omega_k \in \Re \quad (2)$$

When the chirp rate β_k is equal to zero and the parameter α_k approaches zero, the linear chirplet function $h_k(t)$ reduces to a sinusoid signal. If we assume that the chirplet associated with sea-clutter has a low frequency ω_k and a slow frequency change rate β_k , then we can obtain the sea-clutter by adding a group of chirplets which have a small ω_k and a small β_k . After removing the estimate of the sea-clutter from the source radar signal, we can get the enhanced target signals. Compared with the general highpass digital filtering, such subtraction does no harm to the residual target signal components.

In theory, the Bragg lines have the Doppler frequencies of

$$f_B = \pm \sqrt{\frac{g}{\pi\lambda}} \quad (3)$$

where g is the gravitational acceleration (9.8 m/s²), and λ is the radar wavelength. The chirplets with central frequencies in the range $(-1.75|f_B|, 1.75|f_B|)$ and low chirp rates are considered to be associated with the sea-clutter. Then the reconstruction of these chirplets is subtracted from the source Doppler radar signal.

2.2 Spectral Subtraction Method

The second method introduced in this paper is based on spectral subtraction. The concept of spectral subtraction was first introduced for speech processing [2], and was used to estimate the spectrum of the underlying signal by subtracting the noise spectrum from the raw sample's spectrum. Figure 1 depicts the basic operation of the spectral subtraction. It has been found that the spectral subtraction technique is especially effective when the background noise is nearly time-invariant. The sea-clutter in each dwell is often considered time-invariant. Even when there are some amplitude and frequency fluctuations in sea-clutter, the fluctuations are much slow compared with the Doppler radar signal from a maneuvering air target. So the spectral subtraction method can be applied to remove the sea-clutter.

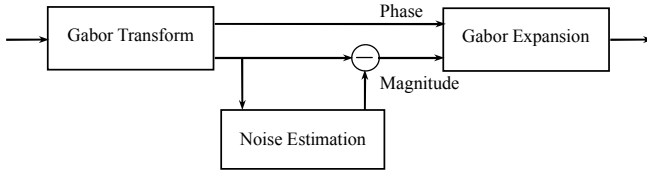


Figure 1 Block diagram of spectral subtraction

Assume that the sea-clutter creates two pseudo sinusoidal components, $e^{j\omega_+ t}$ and $e^{j\omega_- t}$. Then, the noise power spectrum is

roughly equal to $W(\omega-\omega_+) + W(\omega-\omega_-)$, where $W(\omega)$ represents the Fourier transform of the window function $w(t)$. Hence, the central issue of the spectral subtraction based approach is to estimate $W(\omega-\omega_+)$ and $W(\omega-\omega_-)$.

For the Gabor transform, the window $w(t)$ is usually a normalized Gaussian function. In this case, the power spectrum in the vicinity of sea-clutter can be approximated by two Gaussian functions, $G(\delta_+, \mu_+)$ and $G(\delta_-, \mu_-)$, respectively. The parameters (δ, μ) denote the standard deviation and mean. While (δ_+, μ_+) is concentrated in the positive frequency ω_+ , $G(\delta_-, \mu_-)$ is centered in the negative frequency ω_- .

The procedure of the sea-clutter cancellation using the spectral subtraction method can be summarized as follows:

- Compute the discrete Gabor transform $c_{m,n}$ [6]

$$c_{m,n} = \sum_k s(k)w(k-mT)e^{-j2\pi\Omega nk} \quad (4)$$

where the subscript m is a time index and the subscript n is a frequency index. $w(k)$ is a Gaussian window function.

- In order to reduce the effect of rapid changes, compute the median values of $|c_{m,n}|$ with respect to time index m , i.e.,

$$\sigma_n = \text{median}\{|c_{m,n}|\} \quad (5)$$

- Perform two Gaussian curve fittings, i.e.,

$$\min \|G_{n_+}(\delta_+, \mu_+) - \sigma_{n_+}\| \quad (6)$$

and

$$\min \|G_{n_-}(\delta_-, \mu_-) - \sigma_{n_-}\| \quad (7)$$

Then, the full band noise spectrum is approximately equal to:

$$e_n = G_{n_+}(\delta_+, \mu_+) + G_{n_-}(\delta_-, \mu_-) \quad (8)$$

- Subtract e_n from $|c_{m,n}|$ for all m and n to obtain “noise-free” Gabor coefficient magnitudes.

- Use “noise-free” Gabor coefficient magnitudes and unchanged Gabor coefficient phases to compute the discrete Gabor expansion. The resulting signal is the enhanced Doppler radar signal from maneuvering air targets.

3. EXPERIMENTS AND RESULTS

The experimental signals were collected by high frequency surface wave radar using a 10-element linear receiving antenna array [8]. The radar carrier frequency was 5.672 MHz and the pulse repetition frequency was 9.17762 Hz. Each trial corresponds to a block of 256 pulses. Hence, the coherent integration time of each signal is 27.89 seconds.

In this paper, we choose three sample signals: the first has a target signal with small frequency modulation; the second has a target frequency close to the sea-clutter; the third has a target frequency cross sea-clutter.

Since maneuvering air targets often generate time varying Doppler radar signals, the joint time-frequency representation of the target signal has been proven as a practical analysis tool [8]. Compared to the conventional power spectrum, the time-frequency plot not only provides the signal's global information, but also illustrates how the signal frequency content evolves over time. The short-time Fourier transform

(STFT) based spectrogram has been widely applied in radar signal processing because of its efficient implementation.

The source signals and the enhanced signals with the corresponding power spectra and spectrograms are shown in Figures 2~10 (The bottom plot shows the time waveform of the Doppler radar signal with real part in solid and imaginary part in dotted). To make fair comparisons, the spectrograms of source signals and enhanced signals use an identical intensity range.

All experiments and the resulting plots presented in this paper were accomplished by using LabVIEW 7.1 as well as Time Frequency Analysis Toolkit 7.5 with LabVIEW Advanced Signal Processing Toolkit 7.5 (National Instruments, TX).

3.1 Signal with small frequency modulation

Figure 2 shows a source signal with small target frequency modulation. The real and imaginary parts of the analyzed signal are dominated by the strong sea-clutter. The sea-clutter can be precisely approximated by two sinusoids. From the corresponding Fourier spectrum, we notice that there are two prominent Bragg lines around zero frequency and the target signal has about 30 db lower amplitude than that of the sea-clutter. The sea-clutter can be clearly observed in the corresponding spectrogram. It dominates two frequency bands around zero frequency. We can also find that the sea-clutter components are almost time-invariant.

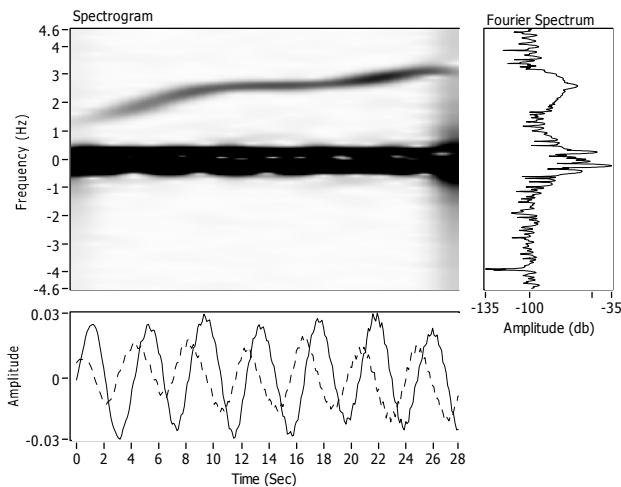


Figure 2 The source signal with small target frequency modulation. The sea-clutter with large amplitude is represented by two black bands around zero Hz in the spectrogram.

After applying the adaptive chirplet method, we can obtain the enhanced target signal as shown in Figure 3. Both the time waveform and the Fourier spectrum show that the sea-clutter with relatively low frequency has been effectively suppressed. The target signal with a relatively high frequency has been prominent. The intensity of the target signal in the spectrogram has been also comparable with that of the residual sea-clutter. One can further suppress sea-clutter by

removing more chirplets, but at the risk of altering the useful Doppler radar signal. The selection of the frequency threshold ω_k balances the sea-clutter suppression and the Doppler radar signal distortion.

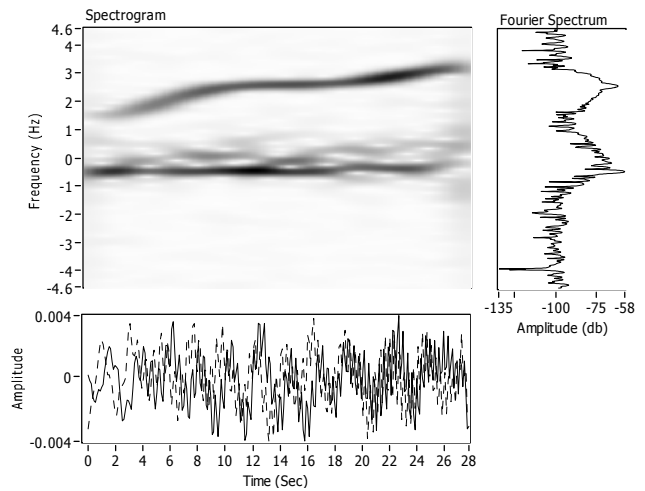


Figure 3 The target signal with a small frequency modulation enhanced by the adaptive chirplet method. The intensity of the sea-clutter in the spectrogram has reduced, and the residual sea-clutter is shown in gray around zero Hz. The intensity of the air target signal has been comparable with that of the residual sea-clutter.

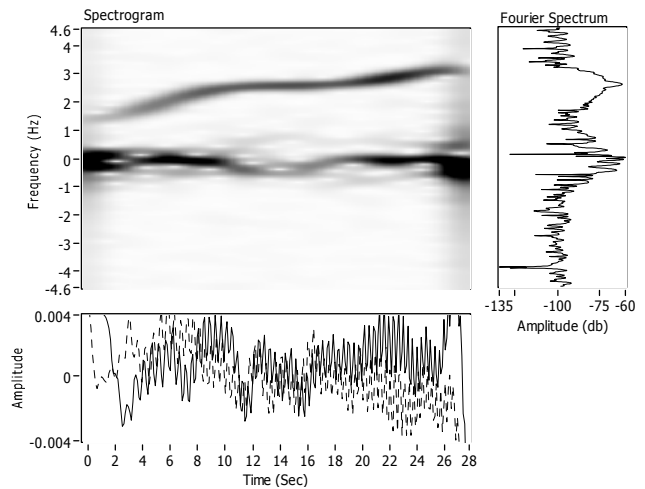


Figure 4 The target signal with small frequency modulation enhanced by the spectral subtraction method. The intensity of the sea-clutter has reduced. But there is more high-amplitude residual sea-clutter than that from the adaptive chirplet method.

After applying the spectral subtraction method, we can obtain the enhanced target signal as shown in Figure 4. It's similar to the result from the adaptive chirplet method.

In order to reconstruct the signal at borders, the periodic border extension has been applied to the Gabor transform. The extension introduces some discontinuity at the borders. After the nonlinear spectral subtraction is applied to the Gabor coefficients, the border signal can not be recovered and some

high-amplitude error can be easily observed at the reconstructed signal and the corresponding spectrogram.

3.2 Signal with frequency near sea-clutter

Figure 5 shows a signal with a low target frequency. Compared with the signal as shown in Figure 2, the sea-clutter in this signal has obvious amplitude variation, and can not be precisely approximated by two sinusoids. The time varying sea-clutter can be also seen from the spectrogram, especially at negative frequencies. The target signal at around 16 Sec has the Doppler frequency very close to the sea-clutter component.

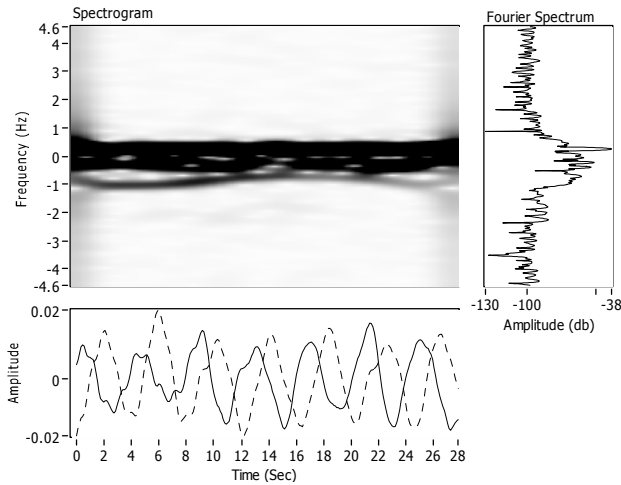


Figure 5 The source signal with a low target frequency. The target frequency is very close to that of the sea-clutter. The sea-clutter with negative frequencies is shown as a fluctuated black band in the spectrogram, so the sea-clutter at negative frequencies is time varying.

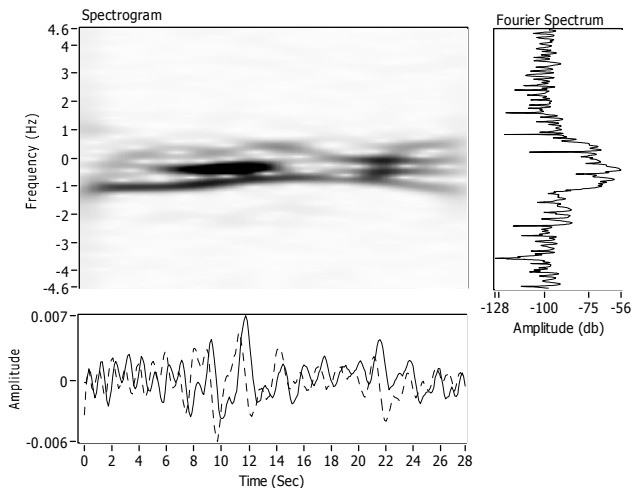


Figure 6 The low frequency target signal enhanced by the adaptive chirplet method. The sea-clutter at positive frequencies has been effectively removed, while there is some high-amplitude residual sea-clutter with negative frequencies.

After the adaptive chirplet method and the spectral subtraction method are applied to the source signal, the resulting enhanced signals are shown in Figures 6 and 7.

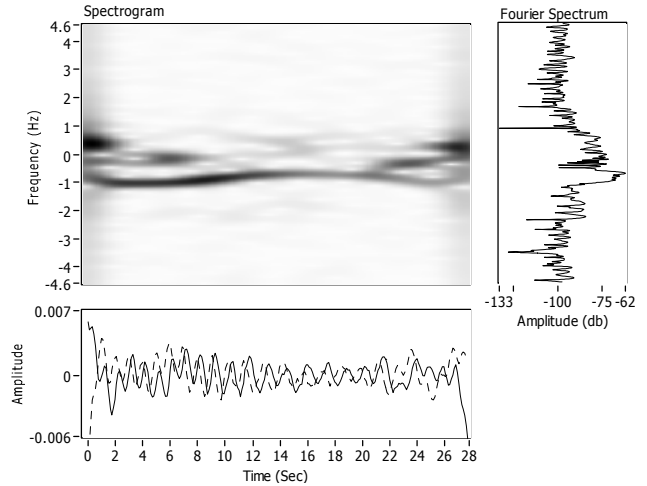


Figure 7 The low frequency target signal enhanced by the spectral subtraction method. The time varying sea-clutter at negative frequencies can be also effectively removed with the time-invariant sea-clutter at positive frequencies by the spectral subtraction method.

Notice that there is some heavy residual sea-clutter at around 11 Sec in Figure 6, while there is few residual sea-clutter in Figure 7. The results show that the adaptive chirplet method is less effective than the spectral subtraction method when the sea-clutter is also time varying.

3.3 Signal with a target cross sea-clutter

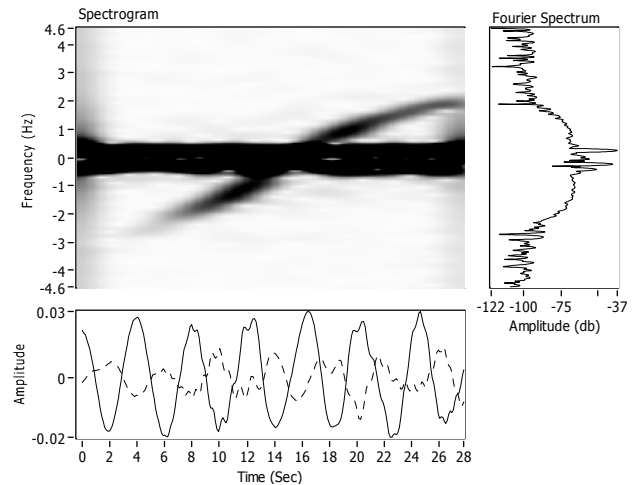


Figure 8 The source signal with a target cross clutter. The sea-clutter is time-invariant at positive frequencies, but time varying at negative frequencies.

Figure 8 shows another Doppler radar signal with a target cross sea-clutter. Although the real part of the Doppler signal is very close to a sinusoid, the imaginary part shows some complicated amplitude and frequency variations. After the

sea-clutter cancellation is applied to the source signal, the results from different methods are shown in Figures 9 and 10, respectively.

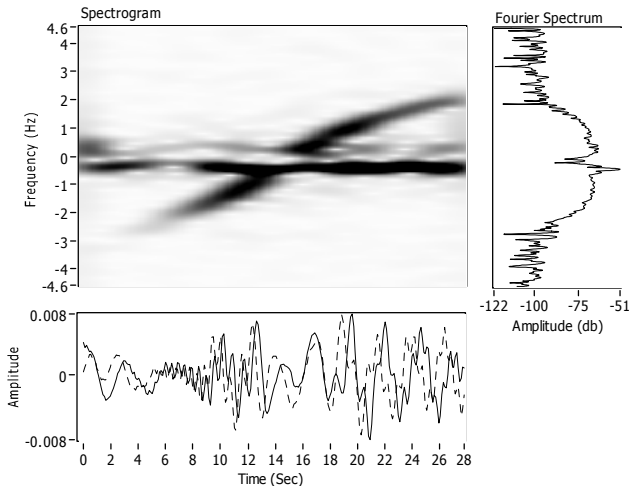


Figure 9 The signal with a target cross clutter enhanced by the adaptive chirplet method. The sea-clutter at positive frequencies has been effectively reduced, but there is some heavy residual sea-clutter at negative frequencies.

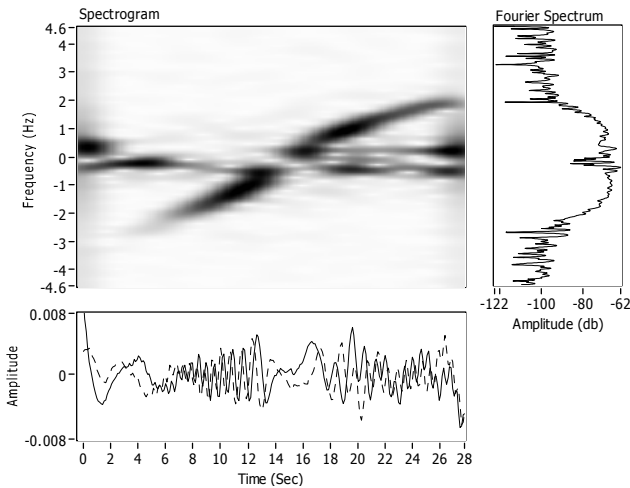


Figure 10 The signal with a target cross clutter enhanced by the spectral subtraction method. The sea-clutter at both positive and negative frequencies has been effectively removed. But compared with the result shown in Figure 9, the target signal at positive frequencies has been reduced.

Figure 9 shows the sea-clutter at positive frequencies has been effectively removed, and the target signal has almost not interfered. But there is heavy residual sea-clutter at negative frequencies.

Figure 10 shows that the sea-clutter has been effectively suppressed and few target signal components have been lost. The maneuvering air target with a target frequency cross sea-clutter can be easily detected in the enhanced spectrogram, but the amplitude of the target signal at low positive frequencies is obviously reduced.

3. CONCLUSION

Generally speaking, the sampling-grid free adaptive chirplet decomposition based algorithm does not alter the Doppler radar signal. It can be especially effective if the Bragg phenomenon is time-invariant. But when the amplitude and frequency fluctuations are not neglectable in the sea-clutter, the chirplet with Gaussian envelope and linear frequency modulation is not precise to describe such fluctuations. On the other hand, the spectral subtraction based method takes into account the fluctuations in the sea-clutter. Amplitude and frequency fluctuations can spread the bandwidth of Bragg lines. Two Gaussian functions with certain bandwidths are used to approximate the spectrum of the sea-clutter, so that the spectral subtraction is not sensitive to the time varying Bragg lines. Moreover, there is no threshold issue and thereby the process is completely automatic, but when the target frequency is close to the Bragg lines, the spectral subtraction also reduces the amplitude of the target signal. Thus, when the target frequency is very close to the time varying sea-clutter, both approaches should be applied with caution. Further research work should be carried out for this condition.

Recently, there is a tendency to apply quadratic time-frequency representations for the detection of Doppler radar signal in the presence of a strong sea-clutter [8]. The quadratic time-frequency representation of the sea-clutter-cancelled signal clearly shows the moving property of the air target. It may be much easier to detect the maneuvering air target in joint time-frequency representation of the enhanced target signal.

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BIOGRAPHIES

Yu Zhang was born in Zhejiang, China in 1978. He received the B.Sc. and Ph.D. degrees in electronic engineering from Fudan University, Shanghai, China in 1998 and 2003, respectively. He was a visiting student with Universidade de Tras-os-Montes e Alto Douro, Vila Real, Portugal from September to December 2002. Since July 2003, he has been a software engineer with DSP group, National Instruments. His research interests are in time-frequency analysis and wavelet analysis.

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