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A Clutter suppression method based on Doppler-Crossed STAP

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Abstract: When using space-time adaptive processing (STAP) for wind farm clutter suppression in certain radar system of high frequency, the complete Doppler is usually used for estimating the clutter covariance matrix (CCM). We notice that the wind farm clutter is symmetrical in Doppler domain. Based on this symmetrical characteristic, a clutter suppression method based on Doppler-Crossed STAP is proposed. We use positive Doppler domain data for negative Doppler domain clutter covariance matrix (CCM) estimation and negative Doppler domain data for positive CCM estimation simultaneously. The results based on typical wind farm clutter data show that, the method based on Doppler-Crossed STAP can get 6dB bigger output signal to clutter plus noise rate than existing methods. Which means the method can suppress the windmill clutter and maximize the output signal at the same time.

1. Introduction

A certain high-frequency radar system relies on ionosphere reflection of electromagnetic waves to achieve over-the-horizon wide-area detection. The system faces challenges such as low working frequency, complex electromagnetic environment, and diverse types of clutter. Additionally, the limited resolution in terms of range, azimuth, and Doppler makes it difficult to effectively suppress clutter, especially wind farm clutter and moving target clutter in a ground background, using single-dimensional processing method in space, time, or frequency.

Space-time adaptive processing method (STAP) is an important method for clutter suppression and is widely applied in radar, sonar, seismic detection, and communication fields[1-4]. In these applications, STAP is necessary due to the coupling of interference or clutter with target signals in the space-time domain.

STAP requires accurate estimation of the clutter covariance matrix (CCM) of the clutter under test (CUT)[5-8]. In current engineering applications of STAP, the clutter covariance matrix is typically estimated using all Doppler data as samples. However, this approach can lead to a decrease in the signal-to-clutter-plus-noise ratio (SCNR) and poses a risk of missed detections.

For this issue, the analysis begins by analysing wind farm clutter. The analysis reveals that clutter exhibits symmetric characteristics in the Doppler domain. After analysis, it is found that clutter exhibits symmetric characteristics in the Doppler domain. Taking advantage of this characteristic, a cross-domain STAP approach is adopted. Specifically, clutter data from the positive Doppler region is used as samples to calculate adaptive weights, which are then applied to suppress clutter in the negative Doppler domain. Conversely, samples from the negative Doppler domain are used to suppress clutter in the positive Doppler domain. By analysing typical clutter data, the method based on Doppler-Crossed STAP not only effectively suppresses clutter but also improves target loss by more than 6 dB, thereby enhancing the visibility of weak targets.

2. Doppler-Crossed STAP

2.1 Clutter Analysis

Wind farm clutter is generated by the rotating components of wind turbines, typically manifesting as equally spaced Doppler modulation. The echo in the Doppler domain is represented as:

$$S_N(f) = \sum_{m=-N_1}^{N_1} c_m \delta(f + m f_T) \quad (1)$$

In equation (1), c_m represents the spectral lines amplitude, N_1 is the number of one-sided spectral lines, and f_T is the modulation period.

$$f_T = PNf_r \quad (2)$$

In Equation (2), N represents the number of blades of the rotating components, f_r is the rotor speed, and P is defined as follows: $P = 1$ for an even number of blades, and $P = 2$ for an odd number of blades.

For the analysis of the modulation characteristics of rotating components of wind turbines, three typical types of wind turbine structures, rotational speeds, and theoretical modulation periods are summarized in Table 1:

Table 1: Modulation Spectrum Parameters of Typical Wind Turbine Components.

Wind turbine type	Number of blades	Blade length(m)	Rotational speed(r/min)	Theoretical Modulation period(Hz)
1	3	61	20	2
2	3	70	20	2
3	3	82	17	1.7

The modulation period of wind farm clutter is approximately 2 Hz. Due to the low resolution of a certain high-frequency radar system, wind farm clutter with varying rotational speed overlap, resulting in an unclear modulation spectrum. The typical Distance-Doppler spectrum of wind farm clutter, as shown in Figure 1, exhibits a distinct symmetric characteristic.

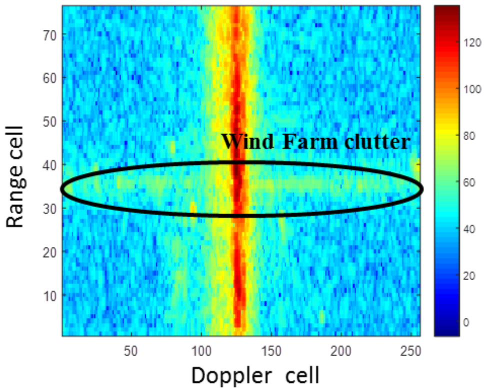


Figure 1: Distance-Doppler spectrum of wind farm clutter

2.2 Problem Description

Assume the radar receive antenna is a linear array with N elements, where the element spacing is d. The number of pulse in a coherent processing interval (CPI) is K. The data for l-th distance cell is represented as x_l, $x_l \in C^{1\times NK}$.

$$x_l = a_l s_{w_s,w_t} + c_l + n_l \tag{3}$$

In equation (3), c_l represents clutter, n_l represents noise, s_{w_s,w_t} represents Space-Time steering vector of the target, a_l represents the amplitude of the target.

$$s_{w_s,w_t} = s_{w_t} \otimes s_{w_s} \tag{4}$$

In equation (4), s_{w_t} represents time steering vector, $s_{w_t} = \left[1 \;\; e^{j2\pi w_t} \;\cdots\; e^{j(K-1)2\pi w_t}\right]$,where w_t represents normalized Doppler frequency; s_{w_s} represents the spatial steering vector, $s_{w_s} = \left[1 \;\; e^{j2\pi w_s} \;\cdots\; e^{j(K-1)2\pi w_s}\right]$ where w_s represents the spatial frequency and $\otimes$denotes the Kronecker product.

In the l_0-th range cell, We maximize the energy of the filtered signal to achieve the greatest clutter suppression[9-10], with the constraint that the target signal propagates through the filter undistorted:

$$\begin{cases} \max\limits_{s} \left|w^H s\right|^2 \big/ w^H \hat{R} w \\ \quad s.t. \|w\|^2 = 1 \end{cases} \tag{5}$$

The corresponding optimal weight vector is:

$$w_{l_0} = \frac{R_{l_0}^{-1} s_{w_s,w_t}}{s^H_{w_s,w_t} R_{l_0}^{-1} s_{w_s,w_t}} \tag{6}$$

In equation (6), s_{w_s,w_t} represents the steering vector of the frequency channel under test and the steering vector is known. R_{l_0} represents the clutter covariance matrix of the cell under test which is unknown. Currently, STAP estimate R_{l_0} using other reference cells outside the CUT, and the estimated value of R_{l_0} is denoted as $\hat{R}_{l_0}$.

$$\hat{R}_{l_0} = \frac{1}{L}\sum_{l\in\Omega} x_l x_l^H \tag{7}$$

In equation (7), Ω represents the selected training sample space and x_l represents the data of the l-th training sample. The output SCNR for this range cell is:

$$SCNR = \frac{\left|w_{l_0}^H s_{w_s,w_t}\right|^2}{\left|w_{l_0}^H \hat{R}_{l_0} w_{l_0}\right|} \tag{8}$$

2.3 Algorithm Description of Doppler-Crossed STAP

In current engineering applications, the use of the full Doppler domain as estimation samples for the clutter covariance matrix leads to missed detection of weak small targets. To address this issue, this approach exploits the symmetry of wind farm clutter and employs a clutter covariance matrix estimation method based on Doppler-Crossed STAP.

The data x_l of the l-th range ring is split into positive Doppler data x_{l+}, $x_{l+} \in C^{1\times NK/2}$ and negative Doppler data x_{l-}, $x_{l-} \in C^{1\times NK/2}$.

$$x_{l+} = a_{l+} s_{w_{s+},w_{t+}} + c_{l+} + n_{l+} \tag{9}$$

In equation (9), c_{l+}, n_{l+} represents the clutter and the noise of positive Doppler data. $s_{w_{s+},w_{t+}}$ represents the Space-Time steering vector of the positive Doppler target, a_{l+} represents the amplitude of the target.

$$s_{w_{s+},w_{t+}} = s_{w_{t+}} \otimes s_{w_{s+}} \tag{10}$$

In equation (10), $s_{w_{t+}}$ represents time steering vector of positive Doppler data, $s_{w_{t+}} = \left[1 \;\; \mathrm{e}^{\mathrm{j}2\pi w_{t+}} \;\; \mathrm{L} \;\; \mathrm{e}^{\mathrm{j}\,(K/2-1)2\pi w_{t+}}\right]$; s_{w_s} represents the spatial steering vector of positive Doppler data, $s_{w_s} = \left[1 \;\; \mathrm{e}^{\mathrm{j}2\pi w_s} \;\; \mathrm{L} \;\; \mathrm{e}^{\mathrm{j}\,(K/2-1)2\pi w_s}\right]$, $\otimes$ represents the Kronecker product.

Let the l_0-th range cell be CUT, then the STAP weight vector in the positive Doppler domain for this CUT can be calculated using samples from the negative Doppler domain data:

$$w_{l_{0+}} = \frac{R_{l_{0+}}^{-1} s_{w_{s+},w_{t+}}}{s^H_{w_{s+},w_{t+}} R_{l_{0+}}^{-1} s_{w_{s+},w_{t+}}} \tag{11}$$

In Equation (11), $s_{w_{s+},w_{t+}}$ is the steering vector in the positive Doppler domain for the detected frequency channel, and the steering vector is known. $R_{l_{0+}}$ represents the clutter covariance matrix of the cell under test which is unknown. The Doppler-Crossed STAP method estimates the $R_{l_{0+}}$ using negative Doppler domain samples from other reference cells outside the CUT. The estimation of $R_{l_{0+}}$ is $\hat{R}_{l_{0+}}$:

$$\hat{R}_{l_{0+}} = \frac{1}{L}\sum_{l\in\Omega} x_{l-} x_{l-}{}^{H} \tag{12}$$

In equation (12), Ω represents the selected training sample space and x_{l-} represents the negative Doppler domain data of the l-th training sample. The output SCNR for this range cell is:

$$SCNR = \frac{\left| w_{l_{0+}}^{H} s_{w_s, w_t} \right|^2}{\left| w_{l_{0+}}^{H} \hat{R}_{l_{0+}} w_{l_{0+}} \right|} \tag{13}$$

2.4 The Processing Flow of Doppler-Crossed STAP

When using STAP for wind farm clutter suppression, due to the large detection area of a certain high-frequency radar system, a wide-transmit and narrow-receive simultaneous multi-beam configuration is typically employed. Conventional STAP methods process element-level or sub-array-level data and handle data from only one beam at a time, which is unable to meet the requirements of simultaneous multi-beam processing. By employing beam-level STAP with dimensionality reduction, the requirements of simultaneous multi-beam processing can be met while reducing the algorithm's computational load.

The main processing flow includes:

(a) First, obtaining the simultaneous multi-beam range-Doppler data formed after DBF (Digital Beam forming);

(b) Performing zero-Doppler ground clutter filtering on the range-Doppler data of each beam to eliminate the influence of ground clutter;

(c) Calculating the average energy along the Doppler dimension for each range cell to obtain the clutter's range dimension energy distribution;

(d) Detecting clutter based on the range dimension energy distribution to identify the beams and range cells where clutter is present;

(e) Performing Doppler-Crossed STAP processing on the clutter, including sample selection, covariance estimation, and weight calculation. During the STAP processing, by cross-processing the positive and negative Doppler regions, the loss of targets in the clutter area can be effectively reduced;

(f) Not performing any processing on non-clutter areas to ensure that targets in non-clutter areas are not lost, ultimately obtaining the spectrum after clutter suppression.

The flowchart of clutter suppression method based on Doppler-crossed STAP is shown in Figure 2:

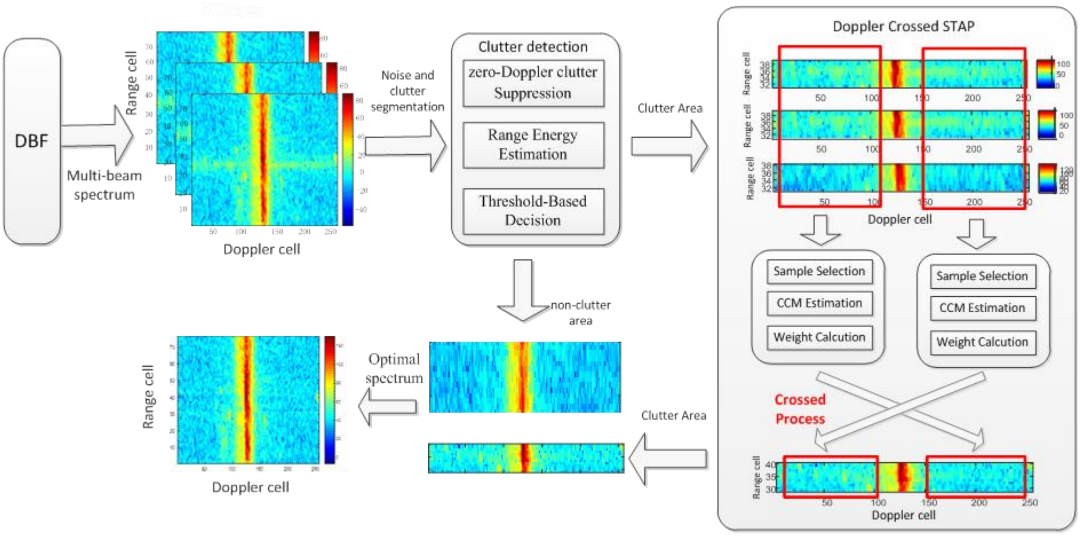
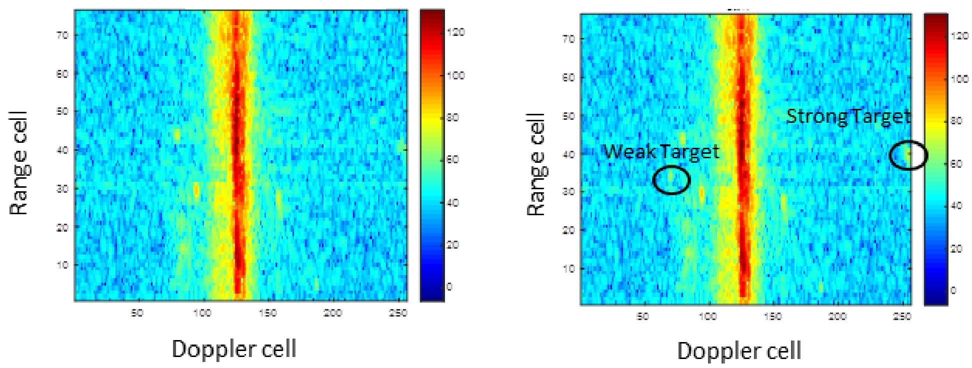


Figure 2: Flowchart of clutter suppression method based on Doppler-crossed STAP

2.5 Contrast and Analysis

Utilizing data from a high-frequency radar system for analysis, strong strip-shaped wind farm clutter is observed in the echo. As shown in Figure 1, clutter spreading occurs at the 36th range cell, affecting target detection in nearby areas and causing a large number of false targets.

Two methods were employed to suppress wind farm clutter: full Doppler domain processing and crossed-Doppler domain processing. The results obtained are shown in Figure3:



(a) Process with full Doppler domain data (b) Process with crossed Doppler domain data

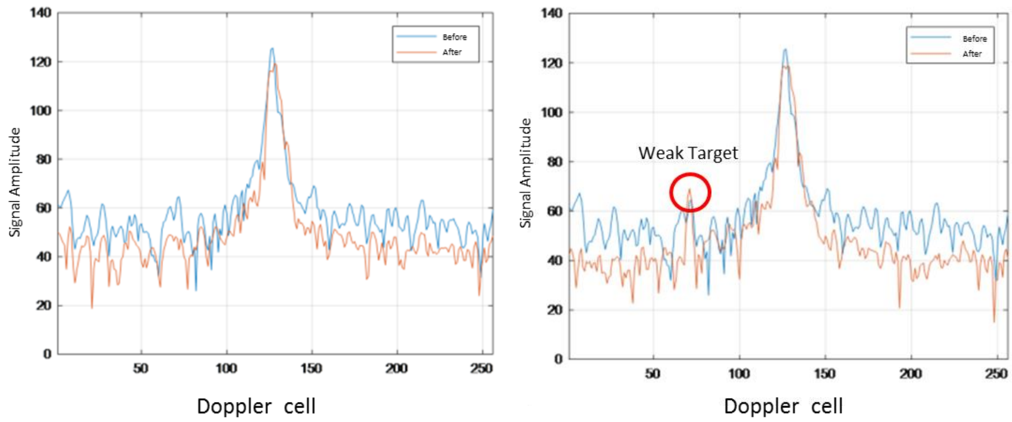
Figure 3: Results of clutter suppression processing based on Doppler-crossed STAP

Full Doppler Processing: Select all Doppler data from the range cells where clutter is present as samples, and complete the processing of all Doppler cells.

Doppler-Crossed Processing: To suppress clutter while minimizing target loss, perform Doppler cross-domain processing on the clutter area. Specifically, select positive Doppler cell data as samples to estimate covariance and calculate weights of negative Doppler regions, then suppress clutter in the negative regions. Next, select negative Doppler cell data as samples to estimate covariance and calculate weights of positive Doppler regions, then suppress clutter in the positive Doppler regions.

Which we can see in figure 3 is the weak target and the strong target are detected in Doppler-Crossed STAP method while are not in traditional STAP.

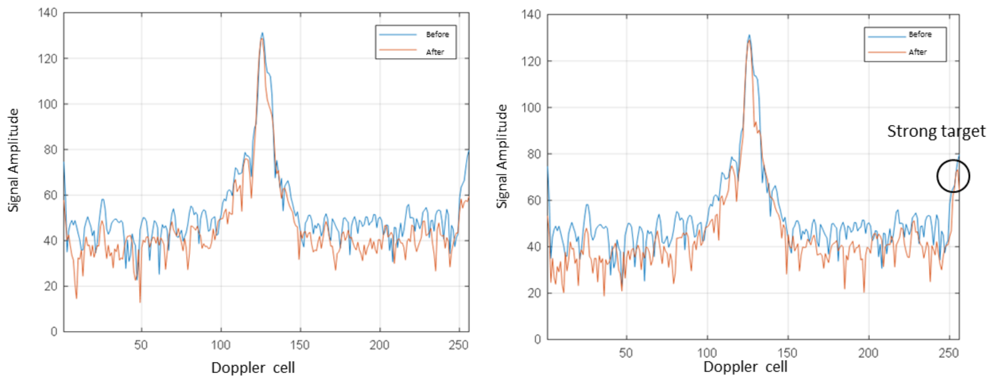
The clutter suppression results for the weak target is shown in Figure 4:



(a) Process with full Doppler domain data (b) Process with crossed Doppler domain data

Figure 4: Clutter suppression results for the weak targets

The clutter suppression results for the strong target is shown in Figure 5:



(a) Process with full Doppler domain data (b) Process with crossed Doppler domain data

Figure 5: Clutter suppression results for the strong target

The results indicate that both methods exhibit comparable performance in clutter suppression, with a CNR suppression ratio of approximately 10 dB. However, the full Doppler data method suffers from energy loss. By employing the Doppler-Crossed STAP, targets in the negative Doppler region become more prominent, while the SCNR of targets in the positive Doppler region is significantly improved. The SCNR of targets shows an improvement of about 6 dB.

3. Conclusions

This paper proposes a clutter suppression method based on Doppler-Crossed STAP. The method utilizes the symmetric characteristics of wind farm clutter in a high-frequency radar system. By cross-estimating the covariance matrix using both positive and negative Doppler data, the method achieves clutter suppression while reducing target loss. The processing results demonstrate that the proposed algorithm improves the SCNR by approximately 6 dB compared to traditional full Doppler processing methods, effectively enhancing the performance of STAP.

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