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Improved TQWT for marine moving target detection

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Abstract: Under the conditions of strong sea clutter and complex moving targets, it is extremely difficult to detect moving targets in the maritime surface. This paper proposes a new algorithm named improved tunable Q-factor wavelet transform (TQWT) for moving target detection. Firstly, this paper establishes a moving target model and sparsely compensates the Doppler migration of the moving target in the fractional Fourier transform (FRFT) domain. Then, TQWT is adopted to decompose the signal based on the discrimination between the sea clutter and the target's oscillation characteristics, using the basis pursuit denoising (BPDN) algorithm to get the wavelet coefficients. Furthermore, an energy selection method based on the optimal distribution of sub-bands energy is proposed to sparse the coefficients and reconstruct the target. Finally, experiments on the Council for Scientific and Industrial Research (CSIR) dataset indicate the performance of the proposed method and provide the basis for subsequent target detection.

Keywords: marine moving target detection, improved tunable Q-factor wavelet transform (TQWT), fractional Fourier transform (FRFT), basis pursuit denoising (BPDN).

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1. Introduction

In the military and civilian fields, it is essential to effectively detect low-observable marine moving targets [1]. It is generally believed that the sea clutter consists of wind waves, gravity waves, surface capillary waves, etc, and the physical mechanism is complicated [2]. Owing to weak resolution, long distance, and strong clutter scattering of the radar, the target resolution bin’s signal-to-clutter ratio (SCR) is low and the target is easily obscured by sea clutter, which greatly degrades the detection performance [3]. In modern radar systems, the movement of the target is complex and diverse, and the Doppler frequency of the target is approximately proportional to velocity. A moving target with constant acceleration or variable acceleration produces a secondary phase modulation, resulting in a broad spectrum [4].

Classical clutter suppression methods such as moving target indication (MTI) and moving target detection (MTD) [5] suppress the clutter by the difference of sea clutter and the target in the time or frequency domain, but the complex scattering and motion characteristics of the sea clutter cause the weak energy of the target in the time domain, and the target spectrum and the clutter spectrum aliasing in the frequency domain, so classical methods are inefficient. The fractional Fourier transform (FRFT) [6,7] is proposed to detect marine moving targets; however, in low SCR environments the fractal-characteristic is ineffective for robust marine detection. Since the traditional Fourier transform-based coherent accumulation is only a matched filter with a linear phase signal, the tunable Q-factor wavelet transform (TQWT) [8,9] can achieve the separation of the constant moving target and the sea clutter. And it is adopted to process targets with a constant speed, whose spectrum is narrow. The broad spectrum of the moving target by constant acceleration or variable acceleration affects oscillation characteristic (Q value), resulting in unsatisfactory results with TQWT processing, suppressing the sea clutter and also suppressing the target. Using the micro-Doppler information of the target, a new method for marine micromotion target detection is presented based on Radon-linear canonical ambiguity function (RLCAF) via the micromotion characteristic [10]. However, under high sea states, the signal model is not applicable and the accumulation time needs to be long.

Considering the strong sea clutter and complicated motions of the target, it is necessary to find new approaches to suppress sea clutter and detect moving targets with constant acceleration or variable acceleration. The linear frequency modulation (LFM) signal is used as a first-order approximation model for moving targets with constant acceleration or complex moving conditions within a short time [11]. And FRFT is used to process the LFM signals in high
SCR environments; with the decline of SCR, the peak of the moving target in the FRFT domain is obscured by the peak value of the sea clutter, which may cause the false alarm. TQWT achieves the separation of the target and the sea clutter by different oscillation characteristics between the moving target and the sea clutter [12]. We propose a marine target detection algorithm based on the improved TQWT, which can suppress the sea clutter and improve the SCR, and facilitate the subsequent target detection.

The remaining of this paper is organized as follows. In Section 2, the model of the moving target is established, and the compensation of Doppler migration of the moving target in the FRFT domain is analyzed. In Section 3, we illustrate the improved TQWT detection algorithm to suppress the sea clutter and the improve SCR, and the energy selection method based on the optimal distribution of sub-bands energy to sparse the wavelet coefficients is presented, which is followed by experimental results with the Council for Scientific and Industrial Research (CSIR) dataset in Section 4. Finally, Section 5 presents some concluding observations.

2. FRFT of moving targets

Assuming that the velocity of the moving target is denoted as \( v = v_0 + at \), where \( v_0 \) is the initial speed, and \( a \) is the acceleration, then the distance of the target at the radar line of sight has the following form:

\[
R(t) = \int v dt = v_0 t + \frac{1}{2} at^2.
\]

The radar signal echoes can be formulated [13–15] as

\[
s(t) = A(t) \exp \left( \frac{4 \pi}{\lambda} R(t) \right),
\]

so the moving target with acceleration modelled as LFM signals in the sea clutter can be expressed [13] as

\[
x(t) = s(t) + c(t) = A(t) \exp \left( j 2 \pi f_d t + j 2 \pi \mu t^2 \right) + c(t) = A(t) \exp \left( \frac{4 \pi v_0}{\lambda} t + j \frac{2 \pi a}{\lambda} t^2 \right) + c(t)
\]

where \( A(t) \) is the signal amplitude, and the spectrum of the target is broad; \( f_d \) is the Doppler frequency corresponding to the velocity \( v_0 \) of the target, \( f_d = 2v_0/\lambda \); \( \mu \) means the signal’s chirp rate which is related to the acceleration \( a \), \( \mu = 2a/\lambda \); \( \lambda \) is the radar transmitting signal’s wavelength; and the sea clutter is denoted as \( c(t) \).

In actual situations, there are micromotion marine targets. The speed of the target with constant acceleration or variable acceleration is denoted as \( v = v_0 + at + \frac{1}{2} g a t^2 \), where \( g_a \) is the variable acceleration, then \( R(t) = \int v dt = v_0 t + \frac{1}{2} at^2 + \frac{1}{6} g_a t^3 \), so the signal target can be modelled as a quadratic frequency modulated (QFM) signal:

\[
s(t) = A(t) \exp \left( j \frac{4 \pi v_0}{\lambda} t + j \frac{2 \pi a}{\lambda} t^2 + j \frac{2 \pi g_a}{3 \lambda} t^3 \right).
\]

It is well known that the moving target with constant acceleration or variable acceleration may be considered as LFM signals within a short time. And we would like to deal with this kind of target in this paper.

The FRFT [6] uses a single variable to represent time-frequency information, and has no cross-term interference. It is the generalization of the ordinary Fourier transform with an order parameter \( p \). And FRFT degenerates into the Fourier transform when the order \( p = 1 \). The FRFT decomposes the signal into a linear combination of the orthogonal chirp basis function, suitable for processing time-varying non-stationary signals, especially for LFM signals. According to the theory that the chirp signal is the basis function of the FRFT, the received radar signal is transformed to the FRFT domain to concentrate the energy of the moving target with acceleration in the narrow band which makes the target separate from the sea clutter interference. The FRFT of LFM signal \( x(t) \) [6,16] is

\[
F_{\alpha}[x(t)] = A(t) A_\alpha e^{\frac{j 4 \pi v_0}{\lambda} t + j \frac{2 \pi a}{\lambda} t^2 + j \frac{2 \pi g_a}{3 \lambda} t^3}.
\]

When the rotation angle \( \alpha \) matches the acceleration \( a \), i.e., \( \alpha_0 = \tan^{-1} \left( -\frac{\lambda}{4 \pi a} \right) \), the amplitude is given by

\[
|F_{\alpha}[x(t)]| = \left| A(t) A_\alpha \delta \left( \frac{4 \pi v_0}{\lambda} - u \csc \alpha_0 \right) \right| + |F_{\alpha_0}[c(t)]|.
\]

The FRFT compensates the acceleration of the moving target and accumulates the target energy, so it can be equivalent to a constant acceleration target. The sea clutter may be seen as a monochromatic signal to some extent, so its energy cannot be accumulated in the FRFT domain. Therefore, the radar echo signal can be subject to the FRFT to achieve the separation of the moving target and the sea clutter. The LFM signal is matched and accumulated well in the FRFT domain as shown in Fig. 1. If the moving target with variable acceleration, that is, the micromotion target, may be considered as an LFM signal in a short period of time, we can use the segmented sliding window FRFT to process the micromotion target. However, the FRFT is ineffective in the case of a low SCR, so we should use the TQWT to obtain the sea clutter and the target’s different oscillation characteristics to suppress the sea clutter and improve the SCR.
Fig. 1 shows the distribution of the FRFT domain spectra of the sea clutter and simulation moving target echoes in CSIR Fynmeet radar. The data packet TFC15_001 is used as a real sea clutter and the centre frequency is 9 GHz. The minimum detectable distance is 2 999.7 m, and the maximum range is 4 439.7 m with a range resolution of 15 m. And the staring antenna mode is VV polarization in the direction of 166.02°, and the elevation angle ranges from –1.182° to 1.192°. The sea clutter state is around four Douglas scales[2], which corresponds to 2 to 3 meters high. A full description of the dataset was given in [17].

Fig. 1(a) displays the spectrum of the sea clutter without the real target in the FRFT domain. The energy of the sea clutter in the FRFT domain is mainly distributed around the transform order \( p = 1 \), i.e., in the frequency domain. Consequently, the sea clutter consists of multiple single-frequency signals. Actually, the acceleration of the sea clutter is small and only lasts for a short time. And it is reflected in the frequency domain by broadening or frequency shift of the Doppler spectrum peak. Fig. 1(b) shows the FRFT spectrum of the simulated moving target in the sea clutter, and the initial velocity \( v_0 = 2 \) m/s, acceleration \( a = 5 \) m/s\(^2\), SCR = 3 dB, and the moving target’s energy is mainly concentrated on the transformed order \( p = 1.086 \). When the rotation angle matches the chirp rate, the spectrum of the moving target becomes a narrow band and the acceleration of the moving target is compensated.

Fig. 1(c) and Fig. 1(d) illustrate the sea clutter and the moving target energy distribution in the FRFT domain. We can see that sea clutter energy is scattered in the FRFT domain, there is no obvious energy aggregation point, and the simulated moving target is approximated as the LFM signal, forming a distinct peak at the matching rotate angle. However, it is difficult to separate a moving target from the sea clutter very clearly at a low SCR. Consequently, suppressing the sea clutter before detecting the target is essential.

According to (5), when the rotation angle of the FRFT domain matches the acceleration of the simulated moving target, the compensation of the moving target can be achieved. The energy of the simulated target in the frequency domain is distributed in the wide spectrum, and it is maximized in the FRFT domain by rotating the time axis, so the spectrum becomes narrower as an impulse function. When performing the FRFT in practice, grading iterative calculation [14] can be used to reduce the computational complexity. Due to the influence of background noise and clutter, there will be errors in the compensation of the moving target. Therefore, some methods are needed to improve the compensation accuracy, such as the step-by-step rough search and pseudo Newton search method [18], the FRFT extreme value hybrid optimization algorithm [19].
the golden section optimized peak search method [20] and so on.

3. Improved TQWT detection algorithm

3.1 Principle of TQWT

The TQWT [8] is a wavelet transform that can preset quality factor $Q$ to analyze discrete-time signals with perfect reconstruction performance in recent years. Wavelet transform has localized characteristics in both time and frequency domains, the multi-scale analysis of the signal can be used to separate the target from the sea clutter. The suppression of the sea clutter is achieved based on different oscillation characteristics. The target signal is rigid, and its frequency spectrum is narrow due to the fixed radial velocity, so the oscillation characteristics are strong and the quality factor $Q$ is high. The sea clutter, due to complex scattering characteristics and sea surface motion caused by spectral broadening, has weak oscillation characteristics and the quality factor $Q$ is low. Fig. 2 shows those characteristics. There is a maneuvering small rigid inflatable boat (RIB) in range bin 20 of TFC15_011 in high sea states (four Douglas scales). Due to the broad spectrum of the moving target with constant acceleration or variable acceleration, the TQWT cannot reconstruct the target and suppress the sea clutter better. The proposed approach uses the FRFT to compensate Doppler migration of moving targets’ constant acceleration or variable acceleration, then suppress the sea clutter and reconstruct the moving target through TQWT.

![Fig. 2 Time-frequency analysis (TFC15_011, gate 20)](image)

The TQWT can preset the $Q$ value corresponding to the target’s oscillation characteristic, compute the high-pass wavelet sub-band and low-pass wavelet sub-band, and realize the decomposition and reconstruction of the radar echo signals. TQWT is characterized by three parameters: the quality factor $Q$, the oversampling rate $r$ and the decomposition level $J$, which are related to the scaling parameters of the low pass filter $\alpha$ and the high pass filter $\beta$ [8,9,21].

The quality factor $Q$ reflects the signal’s oscillation and is defined as the ratio of the center frequency $f_0$ of the signal to its bandwidth $B$. And the relationship with scaling parameter $\beta$ is as follows:

$$Q = \frac{f_0}{B} = \frac{2 - \beta}{\beta}. \tag{7}$$

Wavelet redundancy is decided by the oversampling rate $r$, which means there are $r \cdot N$ coefficients if the signal $x$ has $N$ samples. And the relationship with $\alpha$ and $\beta$ is as follows:

$$r = \frac{\beta}{1 - \alpha}. \tag{8}$$

When the parameters $Q$ and $r$ are selected, the scaling parameters of the multi-resolution filter banks can be obtained from (7) and (8):

$$\begin{cases} 
\beta = \frac{2}{Q + 1}, \\
\alpha = 1 - \frac{\beta}{r} = 1 - \frac{2}{(Q + 1)r}. 
\end{cases} \tag{9}$$

Multi-level wavelet decomposition is implemented by repeatedly applying the filter bank to its low-pass channel. And wavelet coefficients are composed of high-pass sub-bands. Due to the bandwidth limitation of the high-pass filter, the maximum number of decomposition levels is given by

$$J_{\text{max}} = \left\lfloor \frac{\log \left( \frac{\beta N}{8} \right)}{\log \left( \frac{1}{\alpha} \right)} \right\rfloor \left\lfloor \frac{\log \left( \frac{N}{4(Q + 1)} \right)}{\log \left( \frac{(Q + 1)r}{(Q + 1)r - 2} \right)} \right\rfloor \tag{10}$$

where $\lfloor * \rfloor$ indicates rounding down.

3.2 Choice of $Q$ factor

It is well known that the sea clutter’s spectrum centre is near zero, and the spectrum is broadened from approximately $f_1$ to $f_2$ because of the scattering and motion of the sea clutter. In view of [2], the average speeds of the sea clutter spectrum, $V_{VV}$ with VV polarization and $V_{HH}$ with HH polarization, in the upwind direction and the low pitch angle, are assumed to [2] be

$$\begin{cases} 
V_{VV} = 0.25 + 0.18U, \\
V_{HH} = 0.25 + 0.25U. 
\end{cases} \tag{11}$$

where $U$ means the wind velocity. The half-power bandwidth $\Delta$ varies, but can be roughly expressed as

$$\Delta = 0.24U. \tag{12}$$

The Doppler frequency of the sea clutter is calculated by the following formula:

$$f_d = \frac{2v}{\lambda_0} \tag{13}$$
where $\lambda_0$ is the radar transmitted signal wavelength.

In CSIR data packet TFC15.001, the staring antenna mode is VV polarization in the direction of 166.02°, and the elevation angle ranges from $-1.182°$ to $1.192°$. Thus Doppler frequency $f_0$ and spectrum width $\Delta B$ of the sea clutter can be expressed as

$$f_0 = \frac{2V_{VV}}{\lambda_0} = \frac{0.5 + 0.36U}{\lambda_0}, \quad (14)$$

$$\Delta B = \frac{2\Delta}{\lambda_0} = \frac{0.48U}{\lambda_0}. \quad (15)$$

Then the Doppler shifts $f_1$ and $f_2$ are as follows:

$$\begin{cases} f_1 = f_0 - \frac{\Delta B}{2} = \frac{0.5 + 0.12U}{\lambda_0} \\ f_2 = f_0 + \frac{\Delta B}{2} = \frac{0.5 + 0.6U}{\lambda_0}. \end{cases} \quad (16)$$

When the target’s spectrum is drowned in the clutter spectrum, in other words, the target’s Doppler frequency ranges from $f_1$ to $f_2$, the corresponding radial velocity can be expressed as

$$\begin{cases} v_1 = 0.25 + 0.06U \\ v_2 = 0.25 + 0.3U \end{cases}. \quad (17)$$

It has been proved that higher $Q$ values cannot obtain better performance but increase computational complexity on the contrary because of too many decomposed sub-bands [21]. Suppose that $Q = 1$ is suitable for stationary targets to get good performance results. Then the minimum Doppler frequency $f_1$ is normalized to $Q = 1$ and other frequencies are scaled up according to the rule. Thus the calculation formula for the normalized $Q$ factor is

$$Q = \frac{Q_v}{Q_1} = \frac{f_v}{f_1} = \frac{v}{v_1} = \frac{v}{0.25 + 0.06U}, \quad (18)$$

and $v$ is the target’s speed between $v_1$ and $v_2$.

The experimental data is TFC15.001. The wind velocity $U$ is around 8.109 2 m/s. The corresponding wave height is 2 m to 3 m, a fourth-level sea state [2]. In other words, when we assume that the target velocity ranges from 0.736 5 m/s to 2.682 7 m/s, the $Q$ factor range is [1, 3.642 5] respectively. Suppose the velocity of the simulated target ranges from 1 m/s to 3 m/s, and the $Q$ factor values range within [2, 4]. Fig. 3 illustrates the performances of the reconstructed target using different $Q$ factors, and the evaluation standard of the reconstruction performance is the output SCR.

![Fig. 3 Output SCR changing with different velocities](image-url)
In Fig. 4(b), the reconstructed results of different $Q$ factors are shown, implying that $Q = 4$ is the best for the reconstruction.

### 3.3 Algorithm analysis

For the detection of moving targets with constant acceleration or variable acceleration in the sea clutter, the moving target generates a nonlinear phase due to the influence of acceleration, which approximates LFM signals and appears as the broadening spectrum. Because of the strong backscattering of the sea surface and the motion of the sea clutter, the clutter spectrum is broad, which is approximated as the multi-component monochromatic signal [6]. In low SCR environments, the moving target falls into the sea clutter spectrum easily. To solve the problem, we propose the improved TQWT algorithm to separate the moving target from the sea clutter. Firstly, the FRFT is used to achieve the targets’ acceleration compensation, which provides the basis for the reconstruction of the subsequent TQWT process. The energy of the moving target is cumulated as an impulse signal, while the sea clutter spectrum is broad. Based on the discrepancy between the moving target and sea clutter oscillation characteristics, select appropriate $Q$ factors to decompose the signal after FRFT processing, and use the basis pursuit denoising (BPDN) algorithm to get the sparse representation of the moving target, finally select wavelet coefficients used for target reconstruction by the energy selection method.

The model of the moving target in the sea clutter can be established as follows:

$$x = s + c$$  (19)

where $s$ represents the moving target signal, which can approximate the LFM signal, and the sea clutter is marked as $c$, which can be modelled as the monochromatic signal.

The block diagram of the marine target detection algorithm on the basis of FRFT and TQWT is indicated in Fig. 5, and the following is the detailed process.

**Step 1** The FRFT processing is performed on the radar echo signal. According to the calculation method given in Section 2, the target signal energy in the FRFT domain is accumulated, the acceleration is compensated; and it becomes an impulse signal, and then it is transformed into the time domain by inverse FFT, which facilitates subsequent processing.

**Step 2** For the transformed signal, use (7)–(10) to select the appropriate TQWT parameters, quality factor $Q$, oversampling rate $r$ and decomposition level $J$, and extract the different oscillation components.

**Step 3** Optimize wavelet coefficients through the BPDN algorithm [22]. Due to the influence of the strong sea clutter and TQWT oversampling, multiple sets of wavelet coefficient solutions will be obtained. Formally, this can be translated to an optimization problem:

$$\arg\min_w \|x - TQWT^{-1}(w)\|_2^2 + \lambda \|\theta \odot w\|_1$$

and $TQWT^{-1}$ denotes the inverse transform of the TQWT, and the role of $\lambda$ is to allocate the proportion of the two terms. $\theta$ is used to balance various TQWT norms on behalf of regularization parameters and $\odot$ denotes element-wise multiplication. Afonso put forward the split augmented Lagrangian shrinkage algorithm (SALSA) [23] to solve the optimization problem. According to [24], the SALSA parameter $\mu$ is chosen to be 0.5 which affects the convergence speed, and the choice of $\mu$ can be selected by “trial and error”: generally, it may be roughly proportional to the signal energy, and the number of optimization
iterations is set to 50 in the paper. These parameters are selected empirically through multiple experiments.

**Step 4** The energy selection method extracts the energy levels including the target, and the target is reconstructed using the inverse transform of the TQWT to complete the separation of the moving target and the sea clutter.

### 3.4 Energy selection method

Based on the optimal distribution of sub-band energy, we define the selection standard for reconstructing wavelet coefficients named energy selection algorithm. The signal energy is expressed as the sum of squares of wavelet coefficients. The parameters $\alpha$ and $\beta$ are calculated by (9), with a certain quality factor $Q$ and oversampling rate $r$, and the transformed frequency of each layer of decomposition might be calculated from [11].

The sub-band with the largest energy is taken as the main unit of the target. When the target Doppler frequency $f_d$ is equal to the $j$th level center frequency $f_c$ of the wavelet transform which can be obtained from [11], the value of level $j$ can be determined, that is, when the target submerges in the $j$th level, and the energy of the $j$th level is higher than other levels.

$$f_c = \alpha^j \cdot \frac{2 - \beta}{2\alpha} \cdot f_s = f_d$$  \hspace{1cm} (20)

Then

$$j = \log_\alpha \left( \frac{f_d}{f_s} \cdot \frac{4}{2 - \beta} \right) + 1$$  \hspace{1cm} (21)

where $f_s$ is the sample frequency of the input signal.

Assuming that the level calculated by (21) is $J_0$, the target Doppler frequency submerges in the $J_0$th level. Each layer includes target and clutter components, and the target dominates in some certain energy levels, for example, $m$ levels; because of the target spectrum is distributed within a certain bandwidth, there are target components in the neighboring levels as well, but the energy layer far away from level $J_0$ mainly contains the clutter. We retain the target component levels whose energy divided by the energy of level $J_0$ is greater than or equal to the threshold $T$, and discard the other levels; so the wavelet coefficients of $J_0 \pm m$ levels are used to reconstruct the signal, and can be expressed [25] as

$$\frac{E_i}{E_{J_0}} = \frac{w_i^* w_i}{w_{J_0}^* w_{J_0}} \geq T$$  \hspace{1cm} (22)

where the superscript $*$ means conjugate transpose, $i$ represents the adjacent level of $J$ for reconstruction purpose, $E_i$ represents the energy of the $i$th level, and $W_i$ represents the wavelet coefficients. A large number of experiments prove that the target may be well reconstructed with threshold $T = 0.1$, which makes target energy more focused and reduces the sea clutter interference.

The reconstructed signal energy proportion changes with threshold $T$ displayed in Fig. 6. From Fig. 6, the reconstructed signal energy proportion is higher than 95% when $T = 0.1$; as the threshold $T$ increases, the proportion decreases, and the reconstructed signal loss increases; as the threshold $T$ decreases, the proportion exceeds 100%, which includes sea clutter, and the sea clutter interference increases in the reconstructed signal; so $T = 0.1$ is the best choice.

The wavelet sub-band energy distribution maps before and after processing by the TQWT energy selection method are revealed in Fig. 7. Fig. 7(a) shows that the target Doppler frequency calculated by (21) falls in the 39th sub-band and the target is located at the 39th sub-band and adjacent sub-bands, and the sea clutter is dominant in other sub-bands. Fig. 7(b) shows the selected energy distribution, and these sub-bands are extracted to reconstruct the target.
4. Experiments

4.1 CSIR data set introduction

In July 2006, the CSIR in Pretoria, South Africa, conducted experiment trials at the Overberg TestRange near Arniston. A significant library of both sea clutter data and radar reflectivity data from various small maritime vessels were recorded [26]. The radar’s operating frequency is from 6.5 GHz to 17.5 GHz transmitting pulsed continuous waveforms, with a pulse-to-pulse frequency agility bandwidth of 500 MHz. The data analyzed are named TFC15_018, and there is an RIB in the 18th range bin, and its speed is changed during the observation time. Table 1 shows the radar parameters.

| Parameter          | Value          |
|--------------------|----------------|
| Data               | TFC15_018      |
| Transmit frequency | 9 GHz          |
| Radar height/m     | 67             |
| Antenna            | Stare          |
| Antenna elevation  | −1.192°        |
| Initial range/m    | 3 000.6        |
| Range bin          | 96             |
| Range resolution/m | 15             |
| Wind speed (m/s)   | 8.557 9        |
| Sample period/ns   | 100            |
| Pulse width/μs     | 0.1            |
| Polar VV           |                |
| Duration/s         | 31.079 8       |
| Pulse number       | 155 400        |
| PRI/μs             | 200            |
| Wave height/m      | 3.108 7        |
| Target RIB         |                |

Table 1 2006 CSIR Fynmeet radar parameters

4.2 Experimental results

In order to display the processing result more clearly and synchronously reduce the computational complexity, the processing results of the data from 26 s to 28 s are as follows. And the moving target can be modelled as LFM signals. The spectrum of the original echo is revealed in Fig. 8.

From Fig. 8, we can see that the red circle marks the broad spectrum of the target, which is aliased with the sea clutter spectrum, and the target’s and clutter’s amplitudes are similar. The traditional constant false alarm rate (CFAR) detection cannot get the desired result. The signal is subject to marine target detection processing based on FRFT and TQWT: FRFT is used to achieve the compensation of the target’s acceleration; the sparse representation of the signal is performed through the TQWT, and the decomposed wavelet coefficients are optimized by the BPDN algorithm. The reconstructed wavelet coefficients are selected according to the energy selection method in Section 3.3, and the spectra of the reconstructed target and the residual sea clutter are revealed in Fig. 9.

![Fig. 8 Spectrum of the original echo](image)

![Fig. 9 Spectra of the reconstructed target and the residual clutter](image)

Fig. 9(a) shows the spectrum of the reconstructed target. The surrounding clutter is significantly attenuated. The signal in the negative frequency axis is mirrored with the target. The amplitude is 35 dB lower than the target and can be easily removed in the subsequent target detection. Fig. 9(b) shows the residual clutter spectrum. Compared with the original clutter spectrum, only the target and mirrored frequency components are separated into the target spectrum. After the reconstruction of the target, the amplitude has a certain loss, but most of the clutter is in the remaining clutter component, so that the SCR is improved.
Fig. 10 shows the time-frequency analysis results on the basis of the improved TQWT sea clutter suppression algorithm. Fig. 10(a) shows the time-frequency domain of the initial echo signal. The frequency of the target changes with time, which can be seen from the figure. Fig. 10(b) depicts the time-frequency analysis result of the signal after FRFT processing. Compared with Fig. 10(a), the frequency of the target becomes a constant, and the target energy is accumulated, which proves that the FRFT has good energy aggregation for the LFM signal.

![Detection results of the proposal method (TFC15_018)](image)

Fig. 10(c) and Fig. 10(d) show the time-frequency analysis results of target and residual clutter after TQWT suppressing sea clutter, which can be seen as a decomposition of Fig. 10(b), separating the target from the sea clutter and achieving sea clutter suppression.

Otherwise, the acceleration of the target for a long time is variable and cannot be directly accumulated by the FRFT, that is, the Doppler migration of the moving target with variable acceleration which is modelled as the quantised frequency modulated (QFM) signal just as (4) in Section 2, cannot be compensated through FRFT processing. However, it is approximately seen as an LFM signal in a short period of time, and the segmented sliding window FRFT can be used to achieve the effective accumulation of the moving target. Considering the changed acceleration of the target and TQWT processing optimal observation time, the segmented sliding window FRFT is used to process the original signal, the time interval of the window is 2 s, and the overlap time of intervals is 0.5 s. Then, after the segmented sliding window FRFT, the moving target with variable acceleration can be modelled as a constant moving target, and the target can be separated from the sea clutter by using the TQWT to process the signals in the FRFT domain.

The experimental results of the proposed method are illustrated in Fig. 11. Fig. 11(a) shows the time-frequency analysis result of the original 18th range bin radar echo during the observable time. We can see that the Doppler frequency of the moving target is changed. And the Doppler spectrum of the reconstructed target in Fig. 11(b) plotted by short-time Fourier transform shows that TQWT processing cannot reconstruct the target with constant or variable acceleration completely, and the target cannot detect in some time (for example, 23 – 26 s). From Fig. 11(c), after improved TQWT processing, the moving target with constant acceleration or variable acceleration is perfectly
reconstructed compared to Fig. 11(b), and the sea clutter is separated into other component as shown in Fig. 11(d), which provides a basis for subsequent target detection.

Finally, Fig. 12 illustrates the effect of SCR of the input signal on the sea clutter suppression and marine target detection. To compare the performance between the proposed method and TQWT processing, the simulated micromotion moving target \( (v_0 = 2 \, \text{m/s}, a = 5 \, \text{m/s}^2, g_s = 3 \, \text{m/s}^3) \) is used to achieve the simulation. The simulated target is added to the TFC15001 10th range bins, which consists of pure sea clutter merely, and the single-pulse input SCR (SCRin) ranges from –20 dB to 0 dB.

The simulated moving target in the real sea clutter is carried out in Fig. 12 after the proposed method and TQWT processing. From Fig. 12, it can be seen that in low SCR environments, the proposed algorithm output SCR (SCRout) is improved by 5 dB to 20 dB compared to the TQWT processing, and the output SCR of the improved TQWT is adequate for CFAR detection. It also validates the effectiveness of the improved TQWT processing for
sea clutter suppression and marine moving target detection in low SCR environments. Because of the complex motion of the moving target, the TQWT processing cannot get higher SCR gain. However, the improved TQWT uses the FRFT to compensate the Doppler migration of the moving target with constant acceleration or variable acceleration, separates the sea clutter and the moving target through TQWT by different oscillation characteristics and gets higher SCR gain for target detection.

We can draw the conclusion that the marine target detection algorithm based on the improved TQWT can separate the target with constant acceleration or variable acceleration from the sea clutter from the experimental results. The reconstructed target is a monochromatic signal ultimately and cannot provide motion information. The experiments on the CSIR dataset verify the effectiveness of the proposed method and provide guidance for practical engineering applications.

5. Conclusions

In this paper, to deal with the disadvantages of the existing clutter suppression and moving target detection methods, with the merits of the FRFT and TQWT, the acceleration of the moving target in the echo signal is compensated, the TQWT is used to separate different oscillation components, and the marine target detection method on the basis of the improved TQWT is proposed. First, properties of moving targets are analyzed and LFM or QFM signals are approximated, and the energy concentration characteristic, that is, Doppler migration compensation of the LFM signal by FRFT is studied. Then, using the difference between the concentrated target and sea clutter oscillation characteristics, select the wavelet basis function corresponding to the Q value which is matched with the target oscillation characteristic, and separate the target from the sea clutter as well as improve the output SCR. Finally, the experiments with the CSIR data verify the performance of the proposed method.

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