Enhanced target detection using fractional Fourier transform features with threshold-modified normalization

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Abstract

Feature extraction from the normalized transformation domain is a key technique in target detection. Traditional normalization approaches assume that matrix elements follow a normal distribution, but any deviations from this assumption can lead to significant systematic errors. This article presents a novel method that modifies the normalization process in the fractional Fourier transform (FRFT) domain by incorporating a threshold mechanism to counteract the effects of non-normal distributions. Three modified FRFT features are then extracted from this modified FRFT domain. Furthermore, we propose a target detection method that utilizes these three adjusted features. Experimental results based on measured data indicate that the modified FRFT features exhibit superior classification capabilities for sea clutter and targets compared to the original ones. Additionally, the experiments also demonstrate that under the same conditions, the proposed detection method outperforms traditional FRFT feature detector and the tri-feature based detector.

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Enhanced target detection using fractional Fourier transform features with threshold-modified normalization

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Feature extraction from the normalized transformation domain is a key technique in target detection. Traditional normalization approaches assume that matrix elements follow a normal distribution, but any deviations from this assumption can lead to significant systematic errors. This article presents a novel method that modifies the normalization process in the fractional Fourier transform (FRFT) domain by incorporating a threshold mechanism to counteract the effects of non-normal distributions. Three modified FRFT features are then extracted from this modified FRFT domain. Furthermore, we propose a target detection method that utilizes these three adjusted features. Experimental results based on measured data indicate that the modified FRFT features exhibit superior classification capabilities for sea clutter and targets compared to the original ones. Additionally, the experiments also demonstrate that under the same conditions, the proposed detection method outperforms traditional FRFT feature detector and the tri-feature based detector.

Introduction: Accurate detection of targets within sea clutter is essential for maritime civilian operations and defense, playing a pivotal role in subsequent target tracking and identification processes. Feature detection in radar-based maritime target detection is gaining increasing importance [1]. Numerous feature detection methods have been developed [2-13], exploiting the unique characteristics of maritime targets and sea clutter across various transformation domains to improve their separability. Despite ongoing proposals of new features, refining existing feature extraction techniques and enhancing the performance of current features remain key research areas.

A common strategy in feature extraction involves normalizing the transformation domain matrix of the cell under test (CUT) using reference cells (RCs) to suppress sea clutter [2][5][13]. However, this normalization often assumes a default normal distribution, which can reduce its effectiveness in real-world scenarios. To address this issue, this article introduces a novel approach that enhances the normalization process within the FRFT domain. Our method mitigates systematic errors caused by inaccurate standard deviation estimates during normalization by incorporating a threshold, thus correcting instabilities due to non-normal distributions. Using this modified approach, three FRFT features are extracted from the adjusted FRFT domain. Additionally, by applying a convex hull detection algorithm in the three-dimensional feature space, we establish a FRFT feature target detection method based on threshold-modified normalization processing. And the performance of the proposed method was tested using measured data.

Problem Description: The problem of radar target detection in sea clutter can be transformed into the following binary hypothesis testing problem, as shown in (1).

\[
H_0: \begin{cases} 
\mathbf{x}(n) = c(n), n = 1, 2, \ldots, N \\
\mathbf{x}_p(n) = c_p(n), p = 1, 2, \ldots, K 
\end{cases}
\]

\[
H_1: \begin{cases} 
\mathbf{x}(n) = s(n) + c(n), n = 1, 2, \ldots, N \\
\mathbf{x}_p(n) = c_p(n), p = 1, 2, \ldots, K 
\end{cases}
\]

where \( N \) represents the length of the received complex time series, \( K \) represents the number of RCs, \( \mathbf{x}(n) \) and \( \mathbf{x}_p(n) \) are the radar echo time series received at the CUT and RCs, \( c(n) \) and \( c_p(n) \) are the sea clutter time series received at the CUT and RCs, and \( s(n) \) is the unknown radar echo. The null hypothesis \( H_0 \) and the alternative hypothesis \( H_1 \) correspond to either the presence of only sea clutter or the presence of sea clutter and targets at the CUT, respectively.

The Features Extracted from the FRFT Domain: Three features are extracted from the unmodified FRFT domain, and their detailed exposition is as follows.

Peak of FRFT (PF) is defined as the maximum value of the FRFT full range spectrum of the CUT. The calculation is shown in (2), (3), and (4).

\[
PF(x) = \max \{ NFRFT(a,u|x) \} 
\]

\[
NFRFT(a,u|x) = \frac{1}{K-1} \sum_{k=1}^{K} FRFT(a,u|x_k) 
\]

\[
FVE(x) = \frac{1}{K} \sum_{k=1}^{K} FVE(x_k) - \frac{1}{K} \sum_{k=1}^{K} FRFT(a,u|x_k) 
\]

\[
FVE(x) = \frac{1}{K} \sum_{k=1}^{K} FVE(x_k) - \frac{1}{K} \sum_{k=1}^{K} FRFT(a,u|x_k) 
\]

where \( K_u(n,u) \) is the kernel function, \( \alpha \) is rotation angle, \( u \) is frequency component.

Relative FRFT vector entropy (RFVE) is defined as the ratio of information entropy between the CUT and the RCs at the optimal fractional transform parameter, which reflects the level of disorder in the signal waveforms. The calculation is shown in (5) and (6).

\[
RFVE(x_i|x) = \frac{FVE(x_i)}{\sum_{i=1}^{N} FVE(x_i)} 
\]

\[
RFVE(x_i|x) = \frac{FVE(x_i)}{\sum_{i=1}^{N} FVE(x_i)} 
\]

where \( NFRFT(a_{optimal},u|x) \) is the optimal proportion of \( NFRFT(a_{optimal},u|x) \) at the optimal rotation angle \( a_{optimal} \).

Maximum singular value of FRFT (MSF) is defined as the maximum singular value obtained by singular value decomposition (SVD) of the FRFT local spectrum of the CUT. The calculation is shown in (7).

\[
MSF(x) = \text{SVD}_{\text{max}} \{ NFRFT_{local}(a,u|x) \} 
\]

From Fig. 1, it can be seen that under this data condition, the distribution models of the three features are different, and there is a significant difference in their ability to distinguish between sea clutter and targets. Firstly, all types of features do not follow a normal distribution. The feature samples extracted from the sea clutter cell often have a large degree of clustering near the mean of the feature, which is intuitively reflected as a small variance. At the same time, their PDF has a long tail. The feature samples extracted from the target cell often have a large variance and a wide range of distribution throughout the entire range. Therefore, using a certain feature alone and using the constant false alarm (CFAR) concept at each distance cell for target detection is usually difficult to achieve ideal results. Because it deviates from the CFAR's specific background model and the target features exhibit a wide range of distribution. Secondly, this conclusion points...
out that the FRFT feature extraction method that directly default radar echo features to a normal distribution have theoretical shortcomings and the need for correction.

**Modified Normalization Operation and Features:** As mentioned in the feature extraction process, in order to suppress sea clutter, RCs are often used to normalize the features at the CUT, as shown in (8). And this process is referred to as normalization operations (NO).

\[
A_{NO,CUT}(A_{CUT}:A_i) = \frac{A_{CUT} - 1}{K - 1} \sum_{p=1}^{K} A_p - \frac{1}{K} \sum_{p=1}^{K} (A_p - \frac{1}{K} \sum_{p=1}^{K} A_p)^2
\]

where \(A_{CUT}\) and \(A_i\) respectively represent the transformation domain matrix at the CUT and the RCs.

NO is generally carried out on the transformation domain matrix of the CUT and its object should be the element which is a random variable whose amplitude distribution follows a normal distribution. Only in this case can the RCs be used to further suppress the features of the sea clutter cells. However, as mentioned earlier, the commonly used features of radar echoes from both target and sea targets do not follow a normal distribution, and the corresponding PDFs have long tails or long heads. If NO is directly carried out, it will also amplify the features of some sea clutter cells while suppressing other clutter cells. The main reason for the instability of this operation is that it needs to be divided by the standard deviation of the transformation domain matrix on each RC during the process. After this step, the originally weak sea clutter features may be amplified due to inaccurate estimation of the standard deviation.

To stabilize its effect, a modified NO using threshold control is proposed. The calculation is shown in (9), (10), and (11).

\[
A_{NO-modified,CUT}(A_{CUT}:A_i) = \frac{A_{CUT}}{1 - \frac{1}{K} \sum_{p=1}^{K} (A_p - \frac{1}{K} \sum_{p=1}^{K} A_p)^2}
\]

\[
A_{CUT}(x,y | A_{CUT}:A_i) = \begin{cases} 
A_{CUT}(x,y) - \frac{1}{K} \sum_{p=1}^{K} A_p(x,y), & A_{CUT}(x,y) - \frac{1}{K} \sum_{p=1}^{K} A_p(x,y) > g \\
0, & A_{CUT}(x,y) - \frac{1}{K} \sum_{p=1}^{K} A_p(x,y) \leq g
\end{cases}
\]

\[
g = V_{\text{sorted}}(P_{\text{threshold}}, \#(A_i) | A)
\]

where \(x\) and \(y\) represent the two-dimensional coordinates in the transformation domain matrix \(A\), \(g\) is the threshold. \(V_{\text{sorted}}(A_i)\) represents the sequence obtained by sorting the values of elements in \(A\) from high to low. \(P_{\text{threshold}}\) represents the threshold factor that determines the proportion of elements in \(A\) passing through the threshold. \(\#(A)\) represents the number of elements in \(A\).

After modified NO, the instability is reduced, which can effectively improve the signal-to-clutter ratio (SCR) of the feature domain. PF is a feature obtained by taking peak values, which means that there is already a threshold based on the maximum value in the matrix. Therefore, it has a good ability to distinguish between targets and sea clutter. Comparing Fig.1 and Fig.2, the RFVE and MSF features modified by this method have significantly enhanced their distinguish ability. The PF, RFVE, and MSF used in the following text are all modified features for this method.

**Experiments and Discussions:** The measured data used in this letter are from the Sea-Detecting Radar Data-Sharing Program (SDRDSP) [14-15] proposed by the Sea Target Detection Group of the Naval Aviation University of China. Four groups of measured sea clutter and target data are being selected from the dataset, corresponding to sea state 2-5, and the details of the data are being shown in Fig. 3. The targets are two light buoys situated at distances of 2.97 and 3.19 nautical miles from the radar.

In experiments, the time series of length 2^{17} is divided into 2964 vectors of length 256, using a window with a stride of 32. The observation time for each vector is 0.128 seconds. For each vector at the CUT, the modified PF, RFVE and MSF are computed.

Train the convex hull detector in the three-dimensional feature space using the features of sea clutter cells under a given false alarm rate. Based on the positional relationship between the detected feature samples and the trained convex hull detector in three-dimensional space, target detection is completed. Two detection methods are also tested for comparison: one utilizes three unmodified FRFT features, while the other is a tri-feature based detector employing RAA, RDPH, and RVE [4]. Fig. 4 shows the positional relationship between the convex hull decision region and two types of samples in the three-dimensional feature space under sea state 5. Fig. 5 shows the average detection performance of the detector based on three modified FRFT features under different sea states. Fig. 6 shows the average detection probabilities of three types of detectors at different false alarm probability, under sea state 5.
Comparing a and b in Fig.4, it can be seen that using modified normalization processing can effectively improve the classification performance of features. Additionally, when compared to features heavily dependent on SCR in Fig.4 c, FRFT domain features exhibit better detection performance for targets under high sea states.

From Fig. 5 it is evident that under a false alarm probability of $10^{-4}$, the proposed detection method based on normalization modified with threshold maintains a robust detection performance for maritime targets in moderate to low sea states. Even under high sea states, there is still a good detection probability when the false alarm rate is high.

By comparing the comprehensive detection probability statistics in Fig. 6, it is evident that the proposed detection method significantly enhances performance compared to the unmodified FRFT feature detector and tri-feature based detector. At the false alarm probability of $10^{-4}$, the detection probability improves by approximately 6% and 10%. And at the false alarm probability of $10^{-2}$, the detection probability increases by around 13% and 7%. In summary, under high sea states, the proposed detection method demonstrates more stable and superior performance compared to the other two algorithms.

**Conclusion:** In this study, a threshold-modified normalization-based FRFT feature target detection method is derived and designed, for the target detection problem under sea clutter background. Compared with the existing process of extracting features from normalized feature domains, this method can reduce the instability of the normalization process caused by non-normal distribution models. The detection performance and the practical application of the proposed detection method is tested using the measured sea clutter and target data. The results clearly demonstrate that, under various false alarm probability conditions, it has a better clutter suppression effect and superior detection performance compared to the traditional FRFT feature detector and tri-feature based detector.

**References**


