A New Synthetical Method of Feature Enhancement and Detection for SAR Image Targets

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***Abstract*—Target detection is important content in Synthetic Aperture Radar (SAR) image applications. There is a common target detection method, which is called the Constant False Alarm Ratio (CFAR) detector. But it must satisfy the condition under strong contrast ratio between target area and background clutter area. In fact, it is very difficult for SAR images to satisfy the condition. In order to enhance the contrast ratio and to improve the detection effect, according to the characteristics of SAR images, this paper proposed a new synthetical algorithm based on the curvelet transform and CFAR detector, called the CT-CFAR algorithm. The real SAR image data was used to test the new algorithm, and the experimental results show that the CT-CFAR algorithm can effectively improve the contrast ratio of a SAR image. Comparing with the CFAR detector, it not only can effectively detect the target, but also can obtain higher detection ratio and lower false alarm ratio.**

***Index Terms*—synthetic aperture radar, target detection, curvelet transform, feature enhancement, constant false alarm rate**

I. INTRODUCTION

Synthetic aperture radar is an active microwave imaging radar, with the capability of long-distance imaging under all-weather and all-time, and with some penetration ability to vegetation and soil, so SAR is widely used in many fields. Especially under the bad weather environment conditions, the traditional optical and infrared imaging sensors cannot obtain data, but SAR can. This is rather obvious advantage for SAR sensor. Target detection is one of the important contents for SAR imaging remote sensing [1]. There are many theories and methods about how to fast, accurately and effectively detect target information from SAR images [2]-[5], and the most common SAR target detection method is the CFAR detection algorithm [6], [7]. Through setting the false alarm probability in advance and according to the SAR image background clutter statistical model, the detection threshold can be confirmed. When the grey values of all pixels are compared with the threshold value, the target detection is finished with the CFAR detector. The CFAR method is an adaptive detection algorithm via holding constant of the false alarm, but the condition is that there has obvious contrast between the target and background regions. SAR imaging mechanism is very complicated, and it is affected by many factors, such as radar imaging system parameters, material, surface structure and roughness. Sometimes the environmental factors also bring large affection, for instance, the SAR image under calm sea environment is completely different with the one under huge wave. In the practical applications, it is very difficult for SAR images to satisfy the conditions of CFAR detection. So SAR images must be processed before using CFAR detector. The curvelet transform is a multi-scale geometry analysis theory and has many advantages, for example, good multi-directional and good directional anisotropic, so it is widely used in image processing, such as smoothing noise, edge extraction, image fusion, feature enhancement [8]-[12]. Starck et al used the curvelet transform to enhance in image, and proposed an image enhancement algorithm based on curvelet transform [10]. The method adopted the piecewise nonlinear enhancement and get the intention of enhancing edge and detail information after an image is decomposed by curvelet transform. Because the method is only suitable for the low noise image, the processing effect is very poor like SAR image including a lot of noise. Then, Bai et al proposed an improved algorithm via increasing the coefficient of curvelet transform to enhance the image edge features [11]. The literature [12] performed the image transform operations with the curvelet theory, then it processed the low-frequency parts and the high-frequency parts with different methods, respectively, reaching the aim of enhancing edge information. These methods almost process all decomposed scale coefficients after the image is transformed by curvelet theory. In the actual application, it is not necessary to process all decomposed coefficients, as not only wastes the memory cost but and spends the running time. Therefore, this paper proposed a selective combination method to enhance the target region, according to the features of SAR imaging and the principle of CFAR detector. Firstly the SAR image is decomposed with curvelet transform theory; secondly the selected multi-scale decomposition coefficients are used to perform the enhancement operations, note instead of all

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decomposition coefficients; finally, it makes the inverse curvelet transformation and target detection. So it saves the running time and improves the computational efficiency.

II. Curvelet Transform Theory

Wavelet transform makes up the deficiency of Fourier transform and it can capture the point singular signal, so it is quickly got the wide applications and popularizations since it is proposed by Morlet in 1984 [13]. However, the advantage of wavelet transform cannot be extended to two-dimensional or higher dimensional function space, so it cannot effectively deal with the linear or planar singularity signal of high dimensional function. Similarly, in order to remedy the defects of wavelet transform, Candès and Donoho proposed the fire-new multi-scale geometric analysis theory in 2004, namely the second generation curvelet transform theory [14].

The curvelet transform employs the inner product of basic function and signal function to achieve sparse representation of signal. For the function $f \in L^2(R^2)$, the definition of the curvelet transform is given by

$$c(j,l,k) = \left\langle f, \varphi_{j,l,k} \right\rangle = \int_{R^2} f(x)\varphi_{j,l,k}(x)dx \tag{1}$$

here $\varphi_{j,l,k}$ denotes the curvelet function, j, l, k denote the scale, direction and position, respectively. And the definition of the curvelet transform in frequency domain is given by

$$\begin{aligned} c(j,l,k) &= \frac{1}{(2\pi)^2}\int \hat{f}(\omega)\hat{\varphi}_{j,l,k}(\omega)d\omega \\ &= \frac{1}{(2\pi)^2}\int \hat{f}(\omega)U_j(R_{\theta_l}\omega)\exp[i < x_k^{(j,l)}, \omega >]d\omega \end{aligned} \tag{2}$$

here U_j is a window function in frequency, and it is expressed by φ. The definition of the window function is given as follows.

$$U_j(r,\theta) = 2^{-j\frac{3}{4}}W(2^{-j}r)V\left(\frac{2^{\lfloor j/2 \rfloor}}{2\pi}\theta\right) \tag{3}$$

In equation, $\lfloor j/2 \rfloor$ denotes the integer part of $j/2$. The window function U_j is a "wedge" window under polar coordinates, a wedge-shaped area limited by the support interval of $W(r)$ and $V(t)$. $W(r)$ and $V(t)$ are a pair of window function. Besides, $W(r)$ is a radial window function, and $r \in (1/2, 2)$; $V(t)$ is an angle window function, and $t \in [-1,1]$. Both window functions $W(r)$ and $V(t)$ satisfy the following conditions.

$$\sum_{j=-\infty}^{\infty} W^2(2^j r) = 1; \qquad r \in (3/4,\ 3/2) \tag{4}$$

$$\sum_{t=-\infty}^{\infty} V^2(t-l) = 1; \qquad t \in (-1/2,\ 1/2) \tag{5}$$

In (2), R_{θ_l} denotes the rotation matrix that uses θ_l as radian, $\theta_l = 2\pi \times 2^{-\lfloor j/2 \rfloor} \times l$.

$$R_{\theta_l} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{6}$$

Set the input signal is $f[t_1, t_2]$ in Cartesian coordinates, and $0 \le t_1 \le t_2 < n$, the discrete form definition of curvelet transform can be given by

$$c^D(j,l,k) = \sum_{0 \le t_1, t_2 < n} f(t_1,t_2)\ \varphi_{j,l,k}^D(t_1,t_2) \tag{7}$$

here $\varphi_{j,l,k}^D$ denotes a discrete curvelet function, and superscript D denotes the digital form.

III. Description of CT-CFAR Algorithm

A. Theory of CFAR Detector

At present, CFAR detection theory is still an important means for radar target detection, and is also a common method for SAR image target detection. The whole course of CFAR detector mainly includes the following three steps. The first step is to set the appropriate false alarm probability. The second step is to obtain the detection threshold using the clutter statistical distribution model. The third step is to perform the compare operations between the grey value of each pixel and the threshold value. However, the concrete algorithms have some differences. For instance, setting the target region and background clutter region, estimating background clutter statistical model and removing false alarms, all will bring some affection.

In SAR image target detection algorithms based on CFAR, the key step is to confirm the detection threshold T. Not only is the SAR imaging principle complex, but also are SAR image background clutter distribution types various. Different background will produce different types of statistical distribution. Namely, there is a rather close relationship between the threshold T and the background clutter distribution model. Suppose that the probability density function of the background region and target region in the SAR image are described with $p_B(x)$ and $p_T(x)$, respectively [6], and the definitions of false alarm rate P_f and detection rate P_d are given by Equation (8) and Equation (9).

$$P_f = \int_T^{\infty} p_B(x)dx \tag{8}$$

$$P_d = \int_T^{\infty} p_T(x)dx \tag{9}$$

here the threshold T will be solved by Equation (10).

$$1 - P_f = \int_0^T p_B(x)dx \tag{10}$$

In Equation (10), P_f is the false alarm probability, different P_f will produce different threshold T. The distribution types of SAR image background clutter often include the lognormal distribution, Rayleigh distribution, Weibull distribution, K distribution, Gamma distribution, and Pearson distribution. Furthermore, the Rayleigh distribution is a special case of the Weibull distribution. According to the different distribution types, some typical

CFAR detector can be obtained, for example, the two parameters CFAR detector based on Gauss distribution [15], the CFAR detector based on Weibull distribution [16] and the maximum likelihood estimation CFAR detector based on K distribution [16], [17]. The basal CFAR detectors may be divided into four categories, such as the Cell-Average CFAR (CA-CFAR) detector, the smallest of CFAR (SO-CFAR) detector, the order statistics CFAR (OS-CFAR) detector and the greatest of CFAR (GO-CFAR) detector. Other algorithms are the development, combination and variation from the four basal algorithms.

Before the basal CFAR detectors are used, they need satisfy a condition, i.e. there is the strong contrast in a SAR image. In practical cases, many SAR images cannot satisfy the condition, but they are very important for target detection. For example, there are many weak scattering targets, camouflaged targets and hidden targets in the SAR image, but there are not the strong contrast conditions for CFAR detector. In order to achieve the condition, some new ideas and methods are introduced for enhancing the contrast of target region and background region, such as the principle of coherence [18], the automatic indexing method [19] and the extended fractal feature [20]. These detectors usually perform some processing operations to the SAR image. The purpose is to enhance the contrast of the SAR image and improve the signal-to-noise ratio (SNR). And then the next steps are as same as the basic CFAR detector. The CT-CFAR detector proposed in this paper belongs to the improved type, and the following parts will detailedly describe the implementation process.

B. *Theory of CT-CFAR Algorithm*

On the basis of in-depth study on the curvelet transform theory and CFAR detection principle, after combining with the characteristics and practical applications of SAR images, the CT-CFAR algorithm for SAR target detection is proposed in this paper and the flow chart is shown in Fig. 1. First, the algorithm employs the curvelet transform to perform the multi-scale decomposition of the input SAR image, and then extracts all decomposed scale coefficients, selects some coefficients to be enhanced, which are the main information of target regions. At the same time, the original SAR image performs the filtering processing, which is to get the information of background regions. Finally, the target region image (feature image) and the background clutter image (background image) perform incoherent processing, obtaining the enhanced SAR image, and then uses the CFAR detector to detect the target region in the enhanced SAR image. The concrete steps of the CT-CFAR algorithm are as follows.

(1) Input the original SAR image.

(2) Perform filtering processing to the original SAR image. Speckle noise is the main noise in the SAR image. So there are many methods introduced for smoothing the noise. The CT-CFAR algorithm uses the mean filtering method to remove the speckle noise. Because the method does not consider protecting edge and detail information and only smoothes the speckle noise as much as possible. The aim is to get the background image.

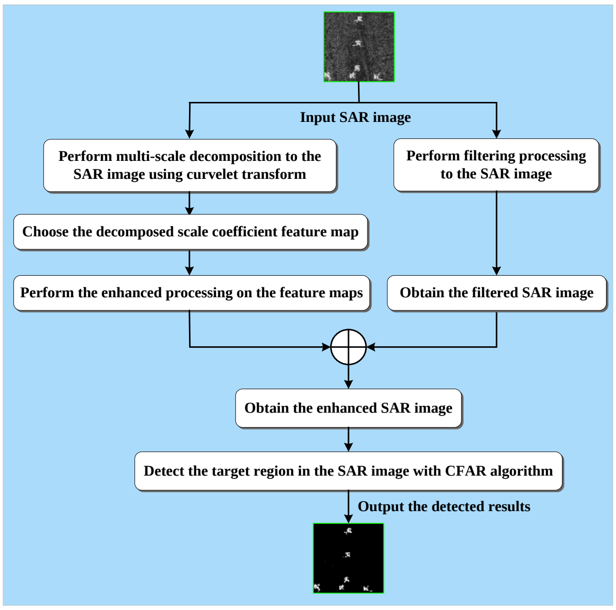

Figure 1. Flow chart of CT-CFAR algorithm

(3) Perform the multi-scale curvelet decomposition of the original SAR image. The key technique of the curvelet transform is how to determine the number of decomposition level scale.

Like the wavelet transform, the decomposition scale of curvelet transform is not too big, but not too small. Experiments show that if the decomposition scale is five or six, it is more suitable, so the number of decomposition scale is 5 in the CT-CFAR algorithm. The first scale is a fine scale, and it mainly contains the details information; the fifth scale is a rough scale, mainly containing the background or trend information. From the second to fourth scale, they are called detail scales, including eight, sixteen and sixteen directions in every decomposition scale, respectively. The curvelet decomposition has the characteristics of multi-scale and multi direction, and is very suitable for SAR image processing, because the SAR imaging has strong directional sensitivity.

(4) Obtain the multi-scale decomposition coefficient of the SAR image and select the feature coefficients. After the SAR image is decomposed by the curvelet transform, all coefficients in each decomposed level scale can be extracted and then they perform the enhanced processing. Selecting coefficient is not blind to select all coefficients, but on purpose to select some or all of the feature coefficients.

(5) Perform coefficient enhancement processing. The selected coefficient feature map performs the enhancement processing operations. Aim is to highlight the target features in SAR images, and to expand the difference between the grey level of the target area and the background area, so that some information, which cannot be detected in the original SAR image, becomes very easy to be detected. Namely, the feature information of target region is much stronger, and the clutter information of background region is much weaker.

(6) Obtain the enhanced SAR image. The enhanced feature coefficient maps and the filtered SAR image

perform the incoherent sum operation. The results are the enhanced SAR image whose gray contrast is expanded.

(7) Detect the target region with CFAR detector. Through setting constant false alarm rate and using CFAR detector, the target regions can be effectively detected from the enhanced SAR image, i.e. the segmentation of the target region from the background clutter.

IV. Experimental Results and Analysis

The practical SAR images are used to test the CT-CFAR algorithm via a series of comparative experiments, and the experimental results are shown in Fig. 2, Fig. 3 and Fig. 4. The first set of experimental data came from the Moving and Stationary Target Acquisition and Recognition (MSTAR) database of airborne SAR image, and they are shown in Fig. 2(a) and Fig. 2(A). The target region in the SAR image is the tank targets and the background clutter is scrubland. The image resolution is 0.3m, and the size of the image is 128 ×128 pixels. The characteristic of the two SAR images is relatively low Signal-to-Clutter Ratio (SCR), i.e. the contrast degree between the target region and background clutter region is not obvious. Fig. 2(b) and Fig. 2(B) are the corresponding enhanced images of Fig. 2(a) and Fig. 2(A), respectively. Namely, they are processed by the CT-CFAR algorithm, achieving the purpose of improving the SCR of the two SAR images. Using the multi-scale curvelet transform theory decomposes the two images, and all decomposed coefficients at every scale are obtained. Some coefficient feature maps are selected and processed in detail information. Next the inverse curvelet transform is performed. After the original SAR images are filtered by the mean filter, it combines with the enhanced image and the processed results are shown in Fig. 2(b) and Fig. 2(B). The detected results of Fig. 2(a) and Fig. 2(A) are shown in Fig. 2(c) and Fig. 2(C), respectively; Fig. 2(d) and Fig. 2(D) are the detected results of Fig. 2(b) and Fig. 2(B), respectively. In the detection process, the detection conditions are same, i.e. assumes that the background clutter distribution model, the false alarm rate and the detection algorithm are same. Here, the false alarm rate P_f used in this experiment is 1E-8. But the experimental results have great difference, which are shown in Fig. 2(c) -(d) and Fig. 2(C)-(D). It can be seen in Fig. 2 that the original CFAR algorithm cannot effectively detect the target region, but the CT-CFAR algorithm can effectively detect the target region and more abundant information can be obtained.

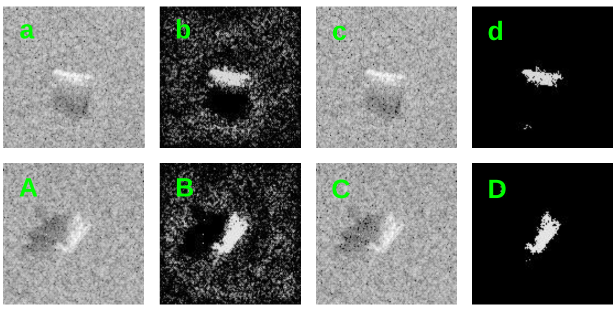

Figure 2. Experimental results of low SCR SAR images

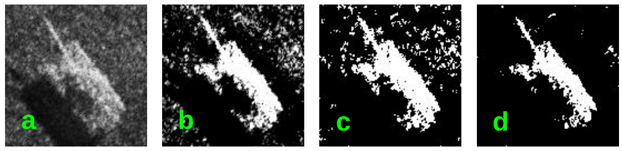

Figure 3. Experimental results of high SCR SAR images

The second set of experimental results is shown in Fig. 3. Where Fig. 3(a) is the original SAR image data, which were the open data from airborne SAR database at Sandia National laboratories, USA. The target is also tank in Fig. 3, the size is 128×128 pixels, spatial resolution is 0.1m and the background clutter is jungle. The enhanced result of Fig. 3(a) is Fig. 3(b) obtained by the CT-CFAR algorithm. Fig. 3(c) and Fig. 3(d) are the detection results of Fig. 3(a) and Fig. 3(b) with the CFAR detector and the CT-CFAR algorithm, respectively. Comparing with the first set of experiments, the SAR image shown in Fig. 3(a) has the higher SCR than Fig. 2(a) and Fig. 2(A). Therefore, the CFAR detector can also detect the target effectively, but compared with the CT-CFAR algorithm, under the same conditions, it will produce a larger false alarm. In this sets experiment, the false alarm rate P_f is 1E-13. This experiment shows, for high SCR SAR images, the target region can be detected effectively by the two methods, but the CT-CFAR algorithm is more accurate.

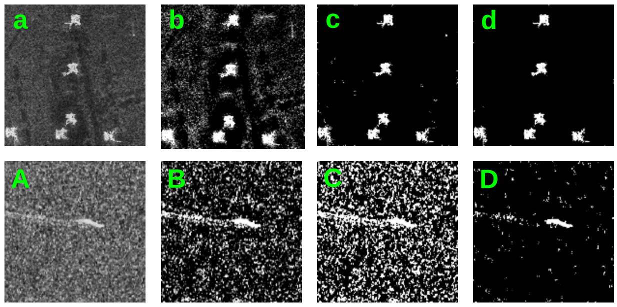

Figure 4. Compared experimental results of high and low SCR SAR images

The third set of the experimental results further shows that the CT-CFAR algorithm is the feasible and effective method for target detection. The experimental original SAR image data is shown in Fig. 4(a) and Fig. 4(A), respectively. The SAR image shown in Fig. 4(a) came from the open airborne SAR database at Sandia National Laboratories, the size is 256×256 pixels, the resolution is 1m, the target region are some military vehicles and tanks, and background clutter is bush. The SAR image data in Fig. 4(A) was from ESA's ERS-2 satellite, the image size is 256×256 pixels, with 30m spatial resolution, the image background is sea clutter, namely the ocean area, target region is a larger ship. The feature of the two image is that Fig. 4(a) belongs to the high SCR image while Fig. 4(A) is the low SNR image. Fig. 4(b) and Fig. 4 (B) are the enhancement SAR images obtained by the CT-CFAR algorithm, and they are corresponding to the Fig. 4(a) and Fig. 4(A), respectively. Fig. 4(c) and Fig. 4(C) are the detected results of the original SAR image using the CFAR detector; Fig. 4(d) and Fig. 4(D) are the detection results got by using the CT-CFAR algorithm. In this set of experiments, the false alarm P_f is 1E-18. For the high SCR SAR images, both CFAR detector and CT-CFAR algorithm can detect the target regions, as shown in Fig. 4(c) and Fig. 4(d), but under the same conditions, the false alarm of the CT-CFAR algorithm is less than the CFAR detector. For the low SNR SAR images, the CFAR algorithm cannot effectively detect the target regions, such as shown in Fig. 4(C), but the CT-CFAR algorithm can effectively detect the target, which is shown in Fig. 4(D).

V. Conclusion

Target detection is always an important application field for SAR image processing and interpretation, but the complex SAR imaging mechanism brings some difficulties and large challenge for the interpretation and application. According to the characteristics of SAR image and the principle of curvelet transform, in order to overcome the deficiency when the CFAR detector is directly used to detect targets in low SCR images, a new CT-CFAR target detection algorithm was proposed in this paper. Different experimental results show that the proposed method can effectively detect the SAR image target, especially in low SCR SAR image, while the CFAR detector is not.

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