Electromagnetic Feature Extraction of Complex Targets from Measured High Resolution SAR Imagery

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Abstract. Electromagnetic feature is the inherent characteristic of SAR imagery, which is of great importance for SAR image interpretation and target recognition. Scattering centre is the essential characteristic of radar target electromagnetic scattering in high frequency region and high resolution SAR image interpretation. Attributed scattering centre model is based on both physical optics theory and geometry theory of diffraction. Compared with classical Prony model, it is more accurate when it comes to modeling the electromagnetic scattering characteristic of high resolution SAR target. However, because of its high dimensionality and complex scattering mechanism of real targets, methods to extract the relevant electromagnetic feature become more complicated as well. On the basis of previous studies, the paper makes a deep study on the methods to extract the electromagnetic feature of complex targets from measured high resolution SAR imagery. It proposes a method of extracting attributed scattering centre feature of complex targets from measured high resolution (0.3-0.1m) SAR imagery. The method has been validated by the results of measured MSTAR (0.3m) and MiniSAR (0.1m) imagery.

Keywords: High resolution SAR imagery; Electromagnetic scattering; Attributed scattering centre model; Feature extraction

1. Introduction

Electromagnetic feature is the inherent characteristic of SAR imagery, which is of great importance for SAR image interpretation and target recognition. Scattering centre is the essential characteristic of radar target electromagnetic scattering in high frequency region and high resolution SAR image interpretation [1]. Therefore, establishing an exact and right scattering centre model is the foundation to interpret high resolution SAR imagery. At present, there are several scattering centre models commonly employed by people, including ideal point scattering centre model, Prony model [2], attributed scattering centre model [3-7] and so on. Attributed scattering centre model proposed by Moses is based on the solutions to both physical optics and the geometry theory of diffraction [4]. It is mainly used to describe backscatter characteristics of radar targets in the high-frequency area. This model shows that backscatter response relies on frequency and azimuth angle. Its parameter incorporates rich physics and geometric properties and can provide a more concise description of radar targets. In conclusion, attributed scattering centre model is much more accurate in modeling the scattering characteristics of high resolution SAR image targets than any other model.

Based on attributed scattering centre model, Electromagnetic feature extraction of complex targets from measured high resolution SAR imagery is actually a high dimensional parametric estimation problem. Many researches have conducted the study of the problem. In addition, an image domain way to extract features has been proposed in references [8-10]. Unfortunately, this approach is not convergent in many conditions [11]. Akyildiz el at [4] and Ji Kefeng el at [11] introduced a normalized attributed scattering model to improve the numerical properties of the algorithm. However, because the scattering mechanism of real targets is more

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complex and the model is not precise in modeling scattering mechanism of real targets, the approach is not so effective in the measured high resolution SAR imagery. As a result, it is necessary to improve the approach that extracts features of complex targets effectively from measured high resolution SAR imagery.

On the basis of previous studies, the paper makes a deep study on the methods to extract the electromagnetic feature of complex targets from measured high resolution SAR imagery. By analyzing the limitations of the existing methods, a feature extraction approach is finally put forward which is suitable for measured high resolution (0.3-0.1m) SAR imagery. In the end, we use the results of MSTAR (0.3m) and MiniSAR (0.1m) SAR image data to validate the effectiveness of our approach.

2. Attributed scattering centre model

In high frequency region, the backscatter response can be regarded as a sum of contributions of individual scattering centers. Considering that it is affected by frequency and azimuth angle, the formula is as follows:

$$\tilde{E}(f,\phi;\theta) = \sum_{k=1}^{n} \tilde{E}_k(f,\phi;\theta_k) \tag{1}$$

Where $\theta^T = [\theta_1^T, \cdots, \theta_n^T]$ and

$$\begin{aligned} \tilde{E}_k(f,\phi;\theta_k) = A_k \cdot &\left(j\frac{f}{f_c} \right)^{\alpha_k} \cdot \exp(-2\pi f \gamma_k \sin\phi) \\ &\cdot \mathrm{sinc}\left(\frac{2\pi f}{c} L_k \sin(\phi - \overline{\phi}_k) \right) \\ &\cdot \exp\left(\frac{-j4\pi f}{c}(x_k \cos\phi + y_k \sin\phi) \right) \end{aligned} \tag{2}$$

Here, f is frequency, ϕ is aspect angle, f_c is the centre frequency, c is the propagation velocity. Each term $\tilde{E}_k(f,\phi;\theta_k)$ is represents a single scattering centre response described by parameter vector $\theta_k = [x_k, y_k, \alpha_k, \gamma_k, \overline{\phi}_k, L_k, A_k]^T$, x_k and y_k are the downrange and cross range location, A_k is a complex-valued amplitude, α_k described its frequency dependence. The parameter γ_k, L_k and $\overline{\phi}_k$ define the angle dependence of the scattering. According to the difference of the three parameters, there are tow types of scattering centre: localized and distributed. For localized centers, $L_k = \overline{\phi}_k = 0$ and γ_k represents the angle dependence of the response. For distributed centers, $\gamma_k = 0$, L_k is the length of the scattering centre and $\overline{\phi}_k$ its orientation angle.

In order to improve the numerical properties of parameter estimation, we introduce a normalized attributed scattering centre model [4, 11]:

$$\begin{aligned} E_k(f_{xn}, f_{yn}) = A_k \cdot &\left(j\sqrt{(f_{xn}^2 + f_{yn}^2)} \right)^{\alpha_k} \cdot \exp(-f_2 \gamma_{p_k}) \\ &\cdot \exp\left(-j2\pi(\frac{f_{xn}}{\beta} x_{p_k} \eta_x + f_2 y_{p_k} \eta_y) \right) \\ &\cdot \mathrm{sinc}\left(\sin\left(\tan^{-1}\left(\frac{f_{yn}}{f_{xn}} \right) - \frac{\overline{\phi}_{p_k} \phi_m}{2} \right) \right. \\ &\left. \cdot \frac{\pi\sqrt{(f_{xn}^2 + f_{yn}^2)} L_p}{2\sin(\phi_m/2)} \right) \end{aligned} \tag{3}$$

The normalized model is a resolution-independent description of attributed scattering centre model. According to the normalized model, the parameter estimation of $\theta_k = [x_k, y_k, \alpha_k, \gamma_k, \overline{\phi}_k, L_k, A_k]^T$ is changed into the estimation of normalized parameter vector $\theta = [x_p, y_p, \alpha, \gamma_p, \overline{\phi}_p, L_p, A]^T$.

3. Methodology

3.1. The existing feature extraction approaches

Electromagnetic feature extraction using attributed centre model of complex target from measured high resolution SAR imagery is a high dimensionality parameter estimation problem. The problem can be states as follows: Given a SAR imagery, find the set of parameters and the number of scattering centers that best fit the

given imagery. Koets el at [8] and Yang Jin el at [9] proposed a image domain feature extraction of attributed scattering centre from SAR imagery, and validated its effective by simulation experiment. The essential theory of the approach is: In high resolution imagery domain, the response of scattering centre is isolated in a high energy region, and each region includes the responses of some scattering centers. So we can segment the whole image into a number of high energy region firstly, then utilize the approximate maximum likelihood estimator to process each high energy region in order to get parameter sets of each scattering centre in the high energy region, until all the high energy regions are processed. Specifically, the approach includes four steps: image segmentation, the selection of the model type, the estimate of initial value and the parameter optimization. However, this approach is not convergent in many conditions. Then Akyildiz el at [4] and Ji Ke-feng el at [11] improved the stability of the approach by introducing a normalized attributed scattering centre model.

3.2. Drawbacks of the existing approaches

Unfortunately, in the experiments of measured SAR imagery, we find this approach presented [9] is not suitable for measured SAR imagery. Through an in-depth study, we find the approach has three drawbacks.

(1) The mismatch of model phase. On the assumption that location of scattering canter is fixed, attributed scattering centre model the phase of real scattering mechanism of complex target as a linear form. The linear phase is given by equation (4):

$$\phi = -j2\pi(\frac{f_{xn}}{\beta}x_p\eta_x + f_2 y_p\eta_y) \tag{4}$$

However, location of real scattering centre depends on frequency and aspect [1], so the model phase mismatches real scattering mechanism of radar target. This mismatch mainly results in two sorts of effects: 1) the linear least squares estimation of parameter A is not as effective as it should be. 2) It is not appropriate to using complex data in the cost function of approximate likelihood estimation.

(2) The response of each scattering center of complex target is mixed with the others in measured imagery data, while that is isolated in simulated imagery data. The mixture brings tow problems: 1) There exist some differences between phase history of distributed scattering centre of real targets in the cross range and the $\sin c(\cdot)$ form predicted by attributed scattering centre model. From Fig 2, a is SLICY Test Target which is constituted by tow upright cylinders and a trihedral on the top of the base, tow dihedrals and a horizontal quarter cylinder in front of the base; b is MSTAR measured imagery data of SLICY Test Target; c is image domain feature of a distributed scattering center which is corresponded to the quarter cylinder; d is phase history of the quarter cylinder which is different from the feature of $\sin c(\cdot)$ function. Therefore, we can't utilize frequency feature data to initialize $L_p, \bar{\phi}_p$ as the method presented in [10]. 2) The selection of the model type based on simulation imagery can't apply to measured SAR image.
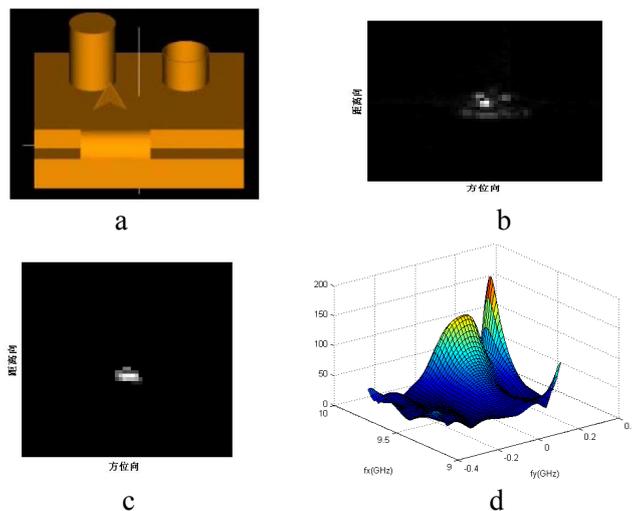

Fig.1. Feature of distribute scattering center in image domain and phase-history domain of measured data. a. SLICY Test Target, b. MSTAR measured imagery data, c. image region feature of quarter cylinder which is modeled as a distributed scattering center, d. phase history of quarter cylinder

3.3. The modified feature extraction approach

To meet the challenges in the feature extraction using attributed scattering centre model of complex targets from measured high resolution SAR imagery, the paper proposes a modified approach to extract features from measured simulated SAR imagery. The approach includes: 1) redesigning parameter A and the cost function of approximate maximum likelihood estimation; 2) presenting a method of selecting the model type based on image domain features, and initializing the parameters L_p and $\bar{\varphi}_p$ in the process.

3.3.1. Design of the parameter A and the cost function of approximate maximum likelihood estimation

To eliminate the influences brought about by the mismatch of the model, we use the data envelopment fitting method to design parameter A and cost function of approximate maximum likelihood estimation.

$$\hat{A} = \frac{\max\left(abs(d_R)\right)}{\max\left(abs(s_R)\right)} \tag{5}$$

Where, d_R and s_R are the original image data of scattering centre and the predicted image data when $A = 1$;

$$J(\theta_k) = \left[abs\left(d_{R^k}\right) - abs\left(e_{R^k}\right)\right]^T \left[abs\left(d_{R^k}\right) - abs\left(e_{R^k}\right)\right] \tag{6}$$

Where, d_{R^k} and e_{R^k} are the original image data of scattering centre and the predicted image data.

3.3.2. Selection of the model type

According to the image segment method presented in [12], we can seek a peak zone in which the amplitude of each pixel is higher than the highest peak $-3dB$. Assume that in this region the number of peak value pixels is N: when $N = 1$, we calculate the $-3dB$ width of the region. If the outcome is bigger than the threshold, we consider that this region corresponds to a distributed scattering centre, and initialize L_p as the width; otherwise, it corresponds to a localized scattering centre. When $N > 1$, we must take the relative downrange locations of these peak value pixels into consideration. In SAR imagery, the relative downrange locations of different peak values corresponding to the same distributed scattering centre are very close. Assume that (R_n, C_n) is the relative downrange and cross range location nth peak value pixel, if P_n ($n \neq 1$, P_1 represents the highest peak pixel) satisfies the formula (6), we think the region of the highest peak pixel corresponds to a distributed scattering centre and initialize L_p as $|C_n - C_1|$; otherwise, it corresponds to a localized scattering centre.

$$|R_n - R_1| < t,\ t < 1 \tag{7}$$

Considering that the value of $\bar{\phi}_p$ is always small, we choose zero as initial value of $\bar{\phi}_p$. The method utilizes the inherent differences between the distributed scattering centre and the localized scattering centre in image domain, so it can improve the accuracy and the reliability of the selection of the model type.

The methods of initialization of other parameters and other procedures of parameter estimation are shown in [8] and [9].

4. Experiments and Analyze

In order to test the validity of the modified approach, we present feature extraction experimental results on three data sets: 1) MSTAR (0.3m) measured SAR imagery data; 2) MiniSAR (0.1m) measured SAR imagery data. Here we just give some typical examples of the experiments.

4.1. Result of MSTAR measured imagery data

MSATR measured data [13] was collected by X band SAR in spotlight mode and HH polarization of Sandia National Laboratories in 1995. The imaging parameters of MSTAR measured data are as follows:

$f_c = 9.6GHz$, $B = 0.6GHz$, and the resolution is 0.3m.

Fig 2 shows the results of applying both the existing approach presented in [9] and the modified approach to MSTAR (0.3m) measured high resolution image data (chip number "HB05649.016"). This original image is shown in a. The real target of measured image is a T-72 tank. The data was collected such that the barrel of the tank was broadside to the radar. This corresponds to an azimuth of $80.77°$, where $0°$ is taken to be the front of the tank. From Fig 2 We can conclude that the result of the modified approach is better than that of the approach presented in [9]. Reconstructed image of the modified approach (d) which is composed by 24

estimated scattering centers reveals the major details of the original image, and the error image of the modified approach (e) can be regarded as a noise image. If we only consider the rectangular region at the centre of the image that contains the tank, we find that reconstructed image of the modified approach accounts for 87.1% of the energy of the target region. The tank barrel is modeled as a set of distributed scattering centers in the reconstructed image, which proves that the proposed method of selecting the model type is effective.
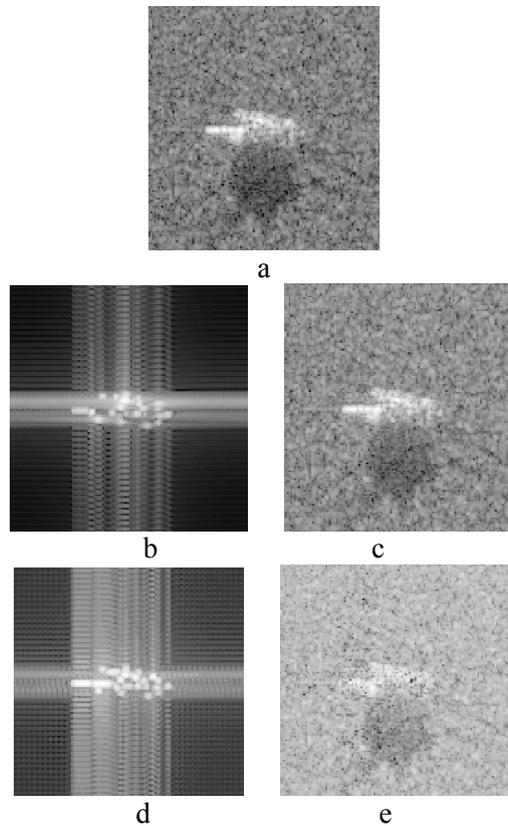

Fig.2. Result of MSTAR measured image data. a. MSTAR measured image data; b. Reconstructed image of the approach in [9]; c. Error image of the approach in [9]; d. Reconstructed image of the modified approach; e. Error image of the modified approach. Scale: magnitude in logarithm

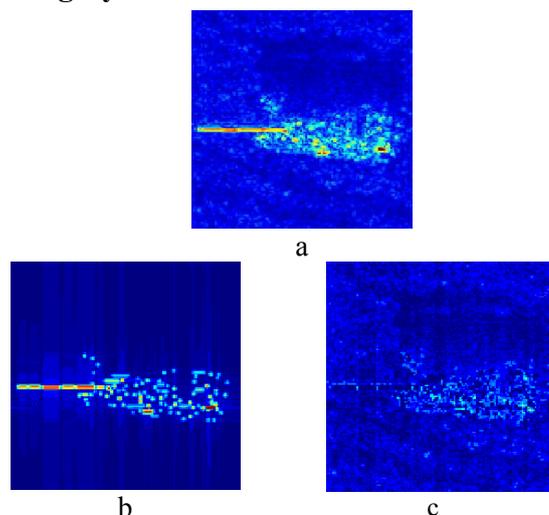## 4.2. Result of MiniSAR imagery data

Fig.3. Results of MiniSAR measured image data. a. MiniSAR measured image data; b. Reconstructed image with estimated scattering centers; c. Error image

In order to validate the applicability of the modified approach, we also applied our approach to MiniSAR (0.1m) measured data. MiniSAR measured data [14] was collected by mini-SAR of Sandia National

Laboratories in 2005. Fig 3 shows the result of applying the modified approach to MiniSAR (0.1m) measured high resolution imagery data. The original image (a) is a target chip of a MiniSAR measured imagery data. The real target is a tank with an unknown type. Compared with MSATR measured imagery data, MiniSAR measured imagery data contains more details of the target. From Fig 3 We can see that the modified approach is also effective on MiniSAR (0.1m) measured high resolution imagery data. Reconstructed image which is composed by 24 estimated scattering centers regenerate the barrel, the side and the tail information of the tank well, and reveals the major details of original imagery and accounts for 80% of the energy of the target region.

5. Conclusion

On the basis of previous studies, the paper makes a deep study on the methods to extract the electromagnetic feature of complex targets from measured high resolution SAR imagery, analyzes the limitations of the existing methods, and proposed an approach using attributed scattering centre model to extracting electromagnetic feature of complex target from measured high resolution SAR imagery. Experiment results illustrate that the proposed approach is effective on MSTAR (0.3m) and MiniSAR (0.1m) SAR imagery data.

Feature work will focus on SAR target recognition and classification that is based attributed scattering center feature, and validate the effective of our approach by the performance of the recognition and classification.

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