A method of multi-channel SAR moving target detection and imaging based on complex CNN

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Abstract: Aiming at the problem of the detecting difficulty and imaging the moving target submerged in clutter, a multi-channel Synthetic Aperture Radar (SAR) moving target detection and imaging method based on complex Convolutional Neural Network (CNN) is proposed. First, using Range Doppler algorithm (RDA) to image SAR data to obtain images with clutter, noise and defocused moving targets. Then, the SAR image is used as the input of complex CNN. A SAR image with the clutter and noise eliminated, and the moving target in focus is obtained after processing by neural network. The simulation experiment results show this method is effectiveness.

1. Introduction
Ground moving target indication (GMTI) and ground moving target indication imaging (GMTIm) are important applications of SAR. As for multi-channel SAR systems, classic algorithms for moving target detection include displaced phase center offset antenna technology (DPCA)\textsuperscript{[1]}, along-track interference technology (ATI\textsuperscript{[2]}), space-time adaptive processing technology (STAP)\textsuperscript{[3]} and other algorithms. However, the SAR imaging algorithm is originally designed for stationary targets. Moving target imaging will be offset and defocused due to its motion. The azimuth velocity causes the azimuth shift and azimuth defocus. In addition, the imaging of moving targets is also affected by clutter and noise, which pose challenges for SAR imaging.

In decades, deep learning has made outstanding achievements in some fields, including SAR recognition\textsuperscript{[4]} and SAR target detection\textsuperscript{[5]}. Except for classification and detection problems, CNN applied in the SAR field also solves many regression problems, for example, literature \textsuperscript{[6]} proposed a SAR-GMTI method based on complex CNN. Literatures \textsuperscript{[7]} and \textsuperscript{[8]} used CNN for SAR imaging. Moreover, literature \textsuperscript{[9]} also studied the estimation method of moving target range velocity and slant distance based on CNN. Currently, most of the CNNs used in the SAR field are classification and detection problems. The regression problems in SAR field based on complex CNN are still a novel and interesting direction.

This paper proposes a moving target detection and focuses imaging algorithm based on complex CNN. First, the complex image of the moving target after RDA imaging and the corresponding ideal scattering point is used as the training data pair. After the network training is completed, the verification complex image is input into the network to obtain moving target with clear clutter and well focus. The structure of this paper: Section 2 introduces the multi-channel moving target signal model. Section 3 describes the way to generate training data pairs, and contents of complex CNN via the signal model in detail. Section 4 conducts experimental simulation and analysis on the proposed algorithm. Section 5
draws conclusions and looks forward to future research directions.

2. Multi-channel moving target signal model

The geometric relationship between the airborne multi-channel radar system and the point target in the SAR imaging slant-range plane is shown in Figure 1. The airborne radar works in the front and side view mode, and the \( y - axis \) is regarded as the distance direction. When the azimuth slow time of \( \eta = \eta_c \), the moving target point P is located at the center of the beam where the radar emits pulses. At this time, the coordinates \((x_0, y_0)\) of the point target P are located in \((0, R_0)\), and the azimuth velocity and radial velocity are \( v_x \) and \( v_y \), respectively. The radar flies with a constant speed along the \( x - axis \) at a speed \( V_a \), and the \( x - axis \) is regarded as the azimuth direction. The working mode of the multi-channel SAR is single-transmit and dual-receive mode, channel 1 is used to transmit and receive signals, and channel 2 is used to receive signals.

![Figure 1 Multi-channel SAR slant-range plane geometric relationship diagram](image)

The instantaneous slant distance between the moving point target and the \( m^{th} \) receiving antenna is Equation (1), which is carried out by second-order Taylor expansion:

\[
R_m(\eta) = \sqrt{\left[ (R_0 + v_y \eta)^2 + (v_a \eta - v_x \eta + m \eta_d)^2 \right]} \approx R_0 + v_y \eta + \left( \frac{v_a \eta - v_x \eta + m \eta_d}{2R_0} \right)^2 \tag{1}
\]

In Equation (1), \( \eta \) represents the azimuth slow time. For a single-transmit and dual-receiver SAR system, the signal expression after range compression received by receiving antenna of \( m^{th} \) is:

\[
s_{mrc}(\tau, \eta) = Ap_r \left( \tau - \frac{R_0(\eta) + R_m(\eta)}{c} \right) \omega_\alpha(\eta - \eta_c) \exp \left( -j2\pi \frac{R_0(\eta) + R_m(\eta)}{\lambda} \right) \tag{2}
\]

In Equation (2), \( A \) represents the constant related to the target backscattering coefficient, \( \tau \) is the fast range time, \( \omega_\alpha(\cdot) \) represents the azimuth envelope, \( \eta_c \) represents the time when the beam center crosses, and \( R_0(\eta) \) represents the instantaneous tilt between the transmitting antenna and moving target. \( p_r(\cdot) \) represents the range of impulse response amplitude, as a sinc function.

After performing range migration correction and azimuth compression processing on the signal after distance compression in sequence, the Doppler frequency, Doppler center frequency of the moving target and the image domain signal expression of the moving target in the \( m \)-th channel is obtained, respectively, which expressed as follows\[^{[10]}\):

\[
k'_a = \frac{2(V_a - v_x)^2}{\lambda R_0} \tag{3}
\]

\[
f_{mv} = -\frac{2 v_y}{\lambda}
\]

\[
s_{mim}(\tau, \eta) = Ap_r \left( \tau - \frac{2R_0}{c} \right) p_a(\eta - \eta_c + \eta_m) \exp \left( -j \frac{\pi(\eta_m^2)}{2\lambda R_0} \right) \exp(-j2\pi f_{mv} t_d) \tag{4}
\]

In equation (4), \( p_a(\cdot) \) represents the amplitude of the azimuth impulse response, and \( t_d = d/(2(V_a - v_x)) \) is the time domain sampling interval, \( \eta_m = R_0 v_y/(V_a - v_x)^2 + m \eta_d/2(V_a - v_x) \).
3. Complex convolutional neural network for moving target detection and imaging

This section discusses the method of using complex CNN to detect and image moving targets, where deep imaging learns the mapping from defocused SAR images to moving target images. The steps of the proposed method are as follows: Firstly, defocus moving target plus clutter and noise background image blocks are generated as input. With the help of training data, the network is trained by minimizing the loss function to obtain the optimal weights. When the training finished, the network is used as an imaging processor to achieve the task of eliminating clutter and SAR moving target imaging in focus. The data set generation and network architecture will be described in detail.

3.1. Training data set generation

Training imaging requires defocusing moving target image and corresponding static target image data pair. The moving target signal model is used for simulation owing to the lack of SAR moving target imaging data set. For SAR-GMTI system, the parameters involved the speed and slant distance of each mission are different. According to Equation (3), the carrier speed and slant distance play an important role in moving target refocusing. Thus, in order to make the network suitable for all tasks, the speed and slant distance of the SAR-GMTI system are randomly selected with uniform distribution. In addition, multiple moving targets are randomly distributed in a given imaging area. The target motion parameters and reflection coefficients are randomly generated with uniform distribution. The main task of this network is to extract moving targets from clutter and focus imaging. If the radial velocity of the moving target is considered, the moving target will shift in the azimuth direction, which is not conducive to focusing and imaging, so the radial velocity is set to zero in this paper. The clutter used in the paper obeys the Rayleigh distribution, and the noise adds Gaussian white noise.

Since the input of the network is the imaging of complex image matrix after the moving target, whereas if the size of the complex image matrix is too large, it will take a lot of time to train the network. Moreover, many clutter regions excluding the moving target will not help the training of the network. Therefore, the data generated by the simulation should be as small as possible. Considering that the moving target is defocused in the azimuth direction, the azimuth sampling point of the image block should be set to be larger than the distance sampling point. And the phase is very important for the detection and imaging of moving target owing the moving target is a complex matrix after imaging, so the SAR complex image matrix is input into the complex CNN with the size $1 \times W \times H$. As for output, SAR images generally display amplitude information, so the output of the network is taken as an absolute value.

3.2. Complex convolutional neural network structure

Figure 2 shows the network structure used in this paper, where Complex Conv, Complex ReLU, and Complex BN represent complex convolutional layers, complex activation functions, and complex batch normalization functions, respectively. In this figure, $3 \times 3 \times 64$, s=1 means that the parameters of the complex convolutional layer are that the size of the convolution kernel is 3, 64 feature maps, and the step size is 1. The detailed information of this network is given below.

![Figure 2 Complex network framework](image-url)
1) Residual Blocks: The network includes 5 residual blocks, and each ResBlock contains two Complex Conv layers, with a convolution kernel and 64 feature maps, followed by Complex BN layer and Complex ReLU activation function. In addition, it also includes two jump connections. As shown in figure, ResBlocks can alleviate the degradation problem and facilitate the training of deeper networks, while the BN layer can solve the problem of gradient disappearance or gradient explosion. Therefore, these two structures are selected in this work.

2) Loss function: On account of importance of the amplitude and phase in the SAR image, similar to speech signal, the Euclidean distance loss function is commonly used in tasks of speech enhancement. And the common loss function based on CNN regression tasks also involves the Euclidean distance loss function. Thus, the function used is defined as follows:

\[ L(I, O) = \frac{1}{W \times H} \sum_{w=1}^{W} \sum_{h=1}^{H} \| g_{\phi}(I_{w,h}) - O_{w,h} \|_2^2 \] (5)

In Equation (5), \( I \) represents the input of the network, \( g_{\phi}(I) \) represents the output through the network, and \( O \) represents the well-focused complex matrix of the stationary target corresponding to the defocused moving target. The network weights are updated through the optimization algorithm. After the optimal weights are obtained, the network determines the functional relationship between input and output, and then eliminates clutter and focuses imaging.

3) Network output: The image output size via network should be the same as the input image size, so the last layer uses a convolution kernel size of 3, 1 feature map and complex Conv layer with the step size of 1 to obtain a prediction image of \( 1 \times W \times H \).

4. Experimental verification

In this section, we use simulated point target data plus clutter and noise to verify the effectiveness of the method in this paper. The analog point target signal uses Equation (4). The dual-channel airborne radar works in the X-band, with carrier frequency \( f_c = 5.3 \text{GHz} \), pulse repetition frequency \( PRF = 200 \), antenna spacing \( d = 0.5 \text{m} \), and azimuth and range sampling points are 200 and 120, respectively. Carrier speed \( V_a \sim U(150,250 \text{ m/s}) \) and slant distance \( R_0 \sim U(15,20 \text{ km}) \), network input complex matrix size is \( (W,H) = (200,120) \), the number of moving targets \( N \sim U(1,10) \), moving target reflection coefficient \( \sigma \sim U(0.8,1.2) \) and moving target azimuth speed \( v_x \sim U(1,15 \text{ m/s}) \), range speed setting is 0. Adding the Rayleigh clutter with \( SCR = 10 \text{dB} \) and Gaussian white noise with \( SNR = 18 \text{dB} \), the network is trained on GTX1660Super GPU, the total of 20,000 training images and 20,000 test images are used, the optimizer choose Adam, the batch size is 4, the learning rate is 0.001, and a total of 10 Epochs are trained. In addition, the training time is about 10h.

Figure 3 Experimental results of sports goals (A1) SAR Data (B1)Ideal scattering point (C1)DPCA detection results (D1)Complex CNN experimental results in this article
Figure 3 shows the verification result, and the Figure 4 shows the azimuth slice result of the Mark point in Figure 3. Among them, (A1) represents the RDA imaging result of the verification data, (B1) is the imaging result of the ideal scattering point model, and (B2) is the azimuth slice of the scattering point. (C1) shows the moving target signal obtained after DPCA detection, which displayed that the clutter has been eliminated, and only the moving target signal remains. (C2) shows the azimuth slice of the moving target, and the azimuth velocity causes the moving target to defocus in the azimuth direction. (D1) represents the imaging result obtained after the verification data by neural network. It shows that not only the clutter is eliminated, but the focusing effect of moving target is also perfect. As shown in (D2) and (B2), the results show that the azimuth slice is relatively near, and the correlation coefficient between the experimental results and the ideal scattering point is 0.9631, which shows that our network is effective in eliminating clutter and focusing on moving targets.

5. Conclusion
This paper proposes a multi-channel SAR moving target detection and imaging method based on complex CNN. First, this paper uses RDA to perform imaging processing on the echo signal of moving target with clutter and noise, and then input the imaging result into the trained complex CNN for clutter elimination and moving target focusing imaging, and finally get a SAR image with excellent focusing effect. This paper uses simulated point targets and clutter to verify the algorithm, which proves that the algorithm can detect the moving targets and complete the refocusing imaging of moving targets.

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Figure 4 Azimuth slice of (B2) Ideal scattering points (C2) DPCA (D2) Complex CNN
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