The Joint Inverse Filtering and Parametric Identification for Complex Radar Image

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Abstract

The paper suggests combining the inverse filtering and the parametric identification in the post-processing sequence of the complex radar image. The image can be modeled assuming the superposition of the identical partial responses from the effective target point-scatterers. Their positions correspond to the geometrical profile of target in the image coordinate plane. The proposed algorithm of radar image post-processing consists of the parametric and the non-parametric procedures which are used to improve the image resolution and to identify geometrical form of the target. The presented simulated results illustrate the main steps of radar image post-processing.

1. Introduction

The modern wideband radar systems perform target recognition and identification owing to their high range resolution [1]. High range resolution of a radar system makes it possible to get the information about the target's shape and geometrical dimensions, which may be used for the target identification. It is known that the response from a target on a short radar pulse may be described as a superposition of the responses from the point scatterers [2]. The information about the positional relationship of the most powerful scatterers of the target may be used for the determination of the target's shape and dimensions. The responses from the point scatterers may be considered as partial duplicated signals differ in delays and levels. However, the distance between scattering centers may be far lesser than the radar range resolution, which considerably complicates the target recognition directly from its radar range profile. The implementation of the complex radar image technology requires the coherent pulse radar mode. The main reason for the using of the complex imaging technology in wideband radar systems is the necessity of the image resolution improving. The paper considers coherent X-band radar emitting a wideband signal in the form of a sequence of short pulses without chirp modulation. In this case the overlapped over several resolution elements range profile of the target can be obtained due to the pulse duration.

2. Complex Radar Image Model

The backscattering of the radar target can be represented as the superposition of radar responses from point scatterers. Thus the processed radar image is a surface in the plane with x and y coordinates. This two dimensional (2-D) function can be described using the point spread function (PSF) written in following way

$$s(x, y) = s_X(x) \cdot s_Y(y) \tag{1}$$

where $s_X(x)$, $s_Y(y)$ are cross-sections of the point spread function in two orthogonal dimensions. Physically these functions can be determined by the range and cross-range profiles of the point scatterer radar response.

In order to illustrate the point spread functions of wideband radar systems which use different image processing principles, the corresponding cross-sections are shown in Fig. 1. The radar waveform parameters are pulse power, carrier frequency, pulse duration τ and pulse period T. The radar range resolution is approximately determined by $c\tau/2$. The Gaussian waveform is supposed for short pulse azimuth scanning (SPAS) radar system and rectangular waveform is assumed for the inverse synthetic aperture radar (ISAR). In first case the radar image is processed by coordinate system transform of radar data to reshape the true configuration of the target. The cross-range resolution is proportional to the range ρ and beam width φ_A product.

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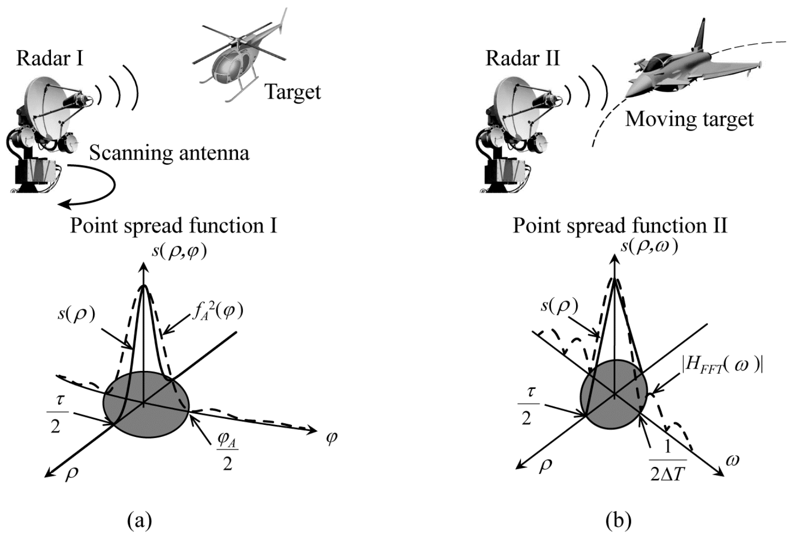

Fig. 1. The scheme (a) of the short pulse azimuth scanning (SPAS) radar system, the inverse synthetic aperture radar (ISAR) principle scheme (b) and corresponding point spread functions (PSF) are shown.

The ISAR image of moving target is processed using matched filtering of received signal and then the fast Fourier transform of data is performed for each range bin [3]. This type of radar system is characterized by the Doppler resolution which is inversely proportional to the observation time ΔT. The Doppler shift is proportional to the cross-range of the scattering center with a scaling factor related to the radar wavelength and the rotation rate of the target. Thus the inherent PSF of SPAS radar is determined by pulse envelope, for example, Gaussian and antenna pattern presented in Tab. 1. And PSF for ISAR having triangular cross-section along the range due to the matched filter response follows the shape of FFT frequency response in the orthogonal cross-section.

The complex radar image is a response of radar system which can be expressed as

$$z(x,y) = u(x,y) * s(x,y) + n(x,y) \tag{2}$$

where $u(x,y)$ is an unknown function of target radar portrait determined in limited region of radar image 2-D spectrum and characterized by the peaks of amplitude distribution within the target size in image plane that in the simplest case we could approximate by a super position of the responses from the set of the P effective point-scatterers:

$$u(x,y) = \sum_{p=1}^{P} a_p \cdot \exp(j\theta_p) \cdot \delta(x - x_p, y - y_p) \tag{3}$$

a_p, θ_p are amplitude and initial phase respectively of the signal reflected from the p-th scatterer having x_p, y_p coordinates in the image plane; $n(x,y)$ is an additive complex white Gaussian noise (AWGN).

Table 1. The examples of cross-sections of wideband radar system PSF's.

Radar System	**Cross-Section of PSF $s(x, y)$**	
	$s_X(x)$	**$s_Y(y)$**
SPAS	$s_G(\rho) = \exp\left[-\pi\left(\frac{2\rho}{c\tau}\right)^2\right],\ \rho = x$	$f_A^2(\varphi) = \left(\sum_{k=-1}^{1}\left(\frac{23}{54}\right)^k \cdot \mathrm{sinc}\left[\pi \cdot \left(\frac{\varphi}{\varphi_A} - k\right)\right]\right)^2,\ \varphi = y$
ISAR	$s_\Delta(\rho) = \left(1 - \frac{2\lvert\rho\rvert}{c\tau}\right) \cdot \mathrm{rect}\left(\frac{\rho}{c\tau}\right),\ \rho = x$	$H_{FFT}(\omega) = \sum_{k=-\infty}^{\infty} \mathrm{sinc}\left[\left(\omega - \frac{2\pi k}{T}\right) \cdot \frac{\Delta T}{2}\right],\ \omega = y$

3. Radar Image Post-Processing

According to the traditional approach radar image can be processed using inverse filter that allows to improve image resolution and to obtain the target radar portrait written as follows

$$w(x, y) = z(x, y) * g(x, y) \tag{4}$$

where g(x,y) corresponds to the inverse filter satisfying the criterion of minimizing of square error

$$\varepsilon = \int_{\Delta} \left| w(x, y) - u(x, y) \right|^2 dxdy \tag{5}$$

for the limited image region Δ where target is located. The synthesis of such filter is well-known and it is called a Wiener filter.

The next step of enhanced post-processing shown in Fig. 2 is a parameter estimation assuming the target as a set of the point-scatterers. Thus it is necessary to select model order P and estimate the vector of parameters $\mathbf{r}_p = [a_p, \theta_p, x_p, y_p]^T$ for each scatterer. This procedure implements the parametric identification of the inverse filter output image that utilizes the information criterion for model order selection [4] and 2-D Matrix Pencil method for parameter estimation [5]. The super-resolution achieves by the accuracy of estimation. One can see the effect observing the synthesized image using obtained parameters and expressed as

$$v(x, y) = \sum_{p=1}^{\hat{P}} \hat{a}_p \cdot \exp(j\hat{\theta}_p) \cdot f(x - \hat{x}_p, y - \hat{y}_p)\,, \tag{6}$$

where $f(x,y)$ is a narrowing PSF

$$f(x, y) = s(k_X \cdot x, k_Y \cdot y)\,,\ k_X > 1,\ k_Y > 1; \tag{7}$$

$\hat{P}$ is a selected model order and $\hat{a}_p, \hat{\theta}_p, \hat{x}_p, \hat{y}_p$ are estimated parameters of the pth scatterer.

3. Simulated Results

In the following example ISAR simulated data were borrowed from the open source [6] and used for radar image post-processing procedure. The complex radar image of aircraft MiG-25 can be processed using these data [7]. The data were simulated for more than 100 point scatterers.

Fig. 3 shows the contour maps of the simulated aircraft ISAR image (a) blurred and noised by complex value AWGN (signal to noise ratio, SNR = 15 dB), the performance of Wiener deconvolution (b) using the designed filter based on the known PSF and the decomposition (c) of scatterer responses as a result of the filter output parametric identification.

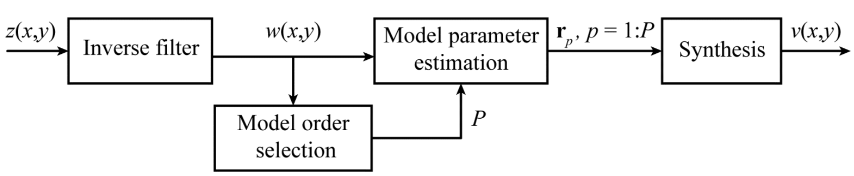

Fig. 2. Diagram of the radar image post-processing algorithm.

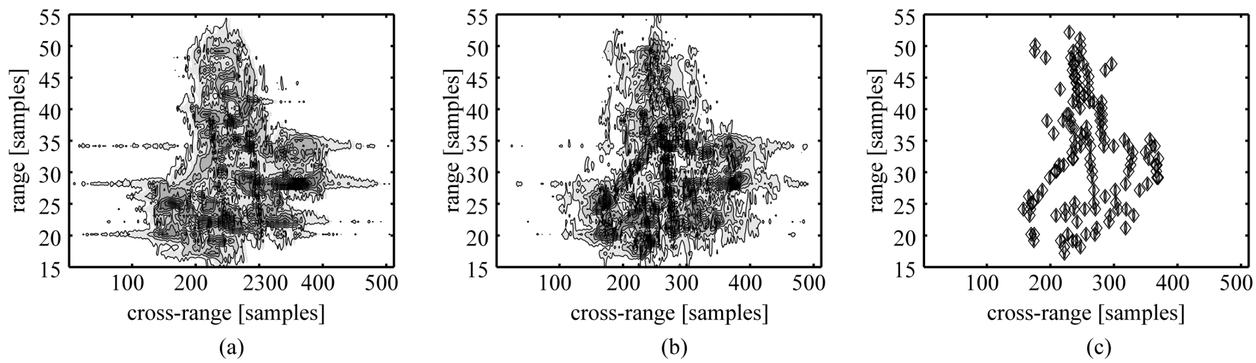

Fig. 3. The simulated aircraft ISAR image (a) with blurring and additive white Gaussian noise (SNR = 15 dB), the deconvolution (b) using the Wiener filter and the decomposition (c) of scatterer responses (marked with diamonds) synthesized using the estimated scatterer parameters for inverse filtering image.

The shown contour maps demonstrate the radar image deblurring, the improving of the image resolution and denoising achieved by the combined approach of image post-processing based on the parametric and non-parametric methods of image processing.

4. Conclusion

In this paper the joint inverse filtering and parametric identification for post-processing of the complex radar image is suggested. In order to achieve the improving of radar image resolution significantly by image processing it is need to know prior information about radar image PSF and model of the target radar portrait assuming the superposition of the identical partial responses from the target point-scatterers. This information is used for parametric and non-parametric procedures of radar image post-processing algorithm that is utilized to identify geometrical form of the target. The simulation example demonstrates improving the quality of radar image for the actual conditions.

5. References

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