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An Improved Space Debris ISAR Imaging Algorithm

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Abstract: According to the Characteristics of space debris, single-range matching filtering (SRMF) can be used for space debris inverse synthetic aperture radar (ISAR) imaging. Combined SRMF and Coherent CLEAN algorithm can effectively solve high sidelobes problem brought by Fourier transform. However, when the SNR is low, the position error of scattering centers extracted by SRMF-CLEAN is big, and even some weak scatterings can't be extracted. This paper uses Sequence CLEAN instead of Coherent CLEAN to availably solve the above problems. The experiment results confirm the validness of the proposed algorithm.

Introduction

In the space, expect for the work state of the rail spacecraft there also exists a great number of meteorites, the abandoned rockets and the failure spacecraft. Because of the high speed of these objects, it will cause serious threat for the normal operation of the spacecraft. So, detection and identification of the space debris become an important task. For the space debris whose size is smaller than 1cm, we can protect it by setting an appropriate shield; for the space debris whose size is bigger than 10cm, we can use the universal radar network and optical sensor to track and detect it. The main targets that we observe are the size between 1cm and 10cm. However, the current bandwidth still can not meet its imaging requirements.

Because of space debris usually round its axis for high speed spin, it to echo Doppler modulation is different from the regular exercise target to echo Doppler modulation. In general, the conventional ISAR imaging methods for the high-speed spin based on the turntable model is failure. Based on the fact that space debris rotates around its axis spin, someone put forward single range matching filtering (SRMF) imaging algorithm [1]. SRMF algorithm is mainly through different structure under the rotation radius matched filter respectively, the horizontal echo data matched filter, and get the strength of scattering center estimation for different radius. Then, we can estimate the form and dimension. SRMF makes use of fast Fourier transform (FFT) to improve the imaging efficiency. Compared to SRDI, SRMF has the advantage of high resolution and less amount of calculation. However, Fourier transform has high sidelobes, it will affect accurate estimation of the target. SRMF-CLEAN[2], can effectively solve the high sidelobes brought by the FFT. When the SNR is high and the range between the scatters is large, the imaging effect using this method is ideal. However, when the distance from one scatter to another is small or the SNR is low, position error using the algorithm is larger, even some weak scattering centers can not be extracted.

Coherent CLEAN algorithm exists instability, so Bose etc[3-5]puts forward Sequence CLEAN. Sequence CLEAN algorithm searches highest m peaks, and forms a tree. Among, every father node contains m child nodes. The m nodes are the peaks after reducing the parent. Each node presents a real target. The node stores the location and the scattering intensity of the object. At last, search the tree, from the all Sequence of the tree of the most energy select the possible path. The experiment results verify that the Sequence CLEAN algorithm can effectively solve the above problems.

SRMF Imaging Algorithm

In general, ISAR imaging acquires the high resolution range profile image by sending broadband signal. Even if using the high power radar, it is difficult to observe the object that the size is between 1cm and 10cm from 100km to 1000km. We can use the fact that space debris usual rotate with certain angular velocity. At the same time, observing the same target at least a spin cycle and using the transverse echo information can get 2-D target image.

The following studies are often based on the two assumptions: one is that after motion compensation, space debris convert into turntable model; the other is that during the observation, the spinning speed is constant. The radar spinning model is shown as Figure1. R axis is radar line of sight, Z is the axis of spin, the angle between R and Z is α. P is one of the scatters, P' presents the projection point of P in the imaging projection plane. w is the spin angular velocity of the target.

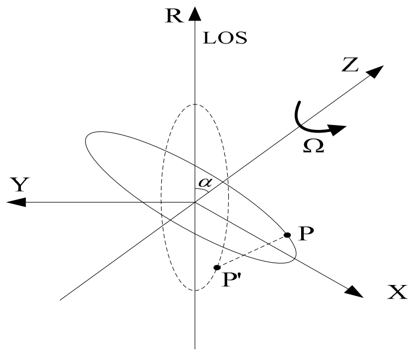


Fig. 1. High-speed spinning rotate coordinate system

Supposing P is one of the scatters on the target, and the echo of this scatter is shown as follows:

$$s(t_m) = \sigma \exp[j2\pi f_c(t - 2R(t_m))/c] \tag{1}$$

t_m is the horizontal sampling time, σ is the scattering strength of this scatter, f_c is the carrier frequency, and $R(t_m)$ is the range from the scatter P to the radar, c is the speed of light. Mixing the carrier frequency with (1) can get the baseband signal, shown as follows:

$$s(t_m) = \sigma \exp(-j4\pi f_c R(t_m)/c) = \sigma \exp(-j4\pi R(t_m)/\lambda) \tag{2}$$

λ is the radar signal wavelength. We can get the phase of the echo signal:

$$\varphi(t_m) = \frac{4\pi}{\lambda} R(t_m) \tag{3}$$

$$R(t_m) = R_0 + \rho \sin(wt_m + \theta) \sin\alpha \tag{4}$$

R_0 is the distance from the radar to the rotation center of the target, ρ is the rotation radius. If only the translation motion exists, the Doppler of each scatterer of the target will be identical and makes no contribution to the radar imaging. Thus translation motion should be compensated out. After compensating the motion component, it becomes turntable model. In this condition, we only consider the rotate component:

$$R(t_m) = \rho \sin(wt_m + \theta) \sin\alpha \tag{5}$$

If the observation time is short, we can suppose that the angle between the line of sight and the axis of spin is constant. $\rho \sin\alpha$ represents the ρ' in the image plane. The scattering point of Doppler frequency shift is shown as follows:

$$f_D = \frac{1}{2\pi} \times \frac{d\varphi}{dt_m} = \frac{2w\rho' \cos(wt_m + \theta)}{\lambda} \tag{6}$$

When the angle of spin is smaller, we can use the following assumption:

$$\begin{cases} \sin(wt_m)=wt_m \\ \cos(wt_m)=1 \end{cases} \tag{7}$$

If the above assumption establish, we can use the conventional RD imaging algorithm to image for the target. However, the main observation object is the high speed rotating space debris. The main character of this object is that the speed of spinning is very big. Even in the short period of observation, the angle is quite bigger. In this condition, the above assumption is not established. The conventional RD imaging algorithm is lapsed. However, the target spin angular velocity caused the Doppler frequency and the observation time is longer than the spin period. Echo signal produced extra frequency modulation, rotate the target echo signal generated in the sine phase modulation[6-7].

Under the high frequency condition, the metal target scattering field can be expressed as a few scattering intensity stronger point of superposition [8]. The echo signal model is shown:

$$s(t_m) = \sum_{k=1}^{K} \sigma_i \exp(-j4\pi\rho' \sin(wt_m + \theta) / \lambda) \tag{8}$$

Set up for different radius of the reference to match signal:

$$S_r^k(t_m) = \exp[-j4\pi r \sin(wt_m)] \tag{9}$$

Convolution the reference signal and echo signal can get the signal output of a radius. However, the operation is more complex. We can put the signal into a frequency domain.

After matching filter and ignoring the influence of clutter, the output becomes:

$$s(t) = F_f^{-1}[S(f)S_{ref}^*(f)] \tag{10}$$

Where $S(f)$ is that the signal do FFT, $S_{ref}(f)$ is the reference matched signal do FFT. The output of the signal is shown as follows:

$$s(t) = \sum_m A_m psf(t - \frac{\gamma_m}{w}) \tag{11}$$

Where, $psf(.)$ is the point spread function, it can used to ensure the resolution. Through choosing different spin radius and matching the reference signal, we can get the intensity of different radius and the 2-D image.

Sequence CLEAN Algorithm

SRMF algorithm image using the matching filter, can effectively improve the image efficiency and resolution. But it will produce high sidelobes inevitably during the matching filter. This will affect the estimation and identifying of target. So, by combining SRMF algorithm and the CLEAN can get the object image.

Coherent CLEAN usually supposes that all of the scatters in the scenarios are isolated, and the distance from one scatter to another is very large, the echo data is no interference. When the distance is small, using this method will reduce the position error larger. When the echo data is interfered with the noise, it will lead some scatters can not be found. At the same time, when the signal energy attains the noise level, it will stop, and each time it chooses the biggest value to carry on decreasing. So that will cause to calculate unsteady and terminate to decrease in advance.

However, even the biggest point is a spurious target, Sequence CLEAN can extract the accurate position. After eliminating a real target mainlobe and sidelobes, the energy will reduce. More peaks corresponding to real targets will expose. Each time, if the subtracted point is a real target, the final signal energy must be the smallest. This is the superior discretion standard for Sequence CLEAN.

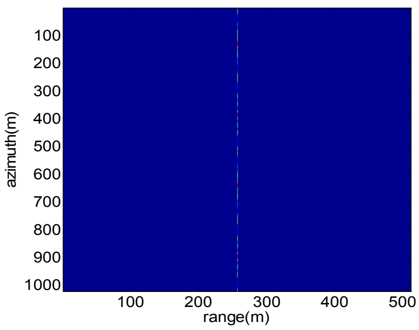
Sequence is a tree search algorithm which chooses the best possible Sequence of target subtraction so as to maximize target mass cancellation. For m=1, Sequence CLEAN is the Coherent CLEAN algorithm. In order to search the best possible Sequence of target subtraction, it is very important to valuate the signal energy in each fall generation cycle.

The algorithm steps are given as follows:

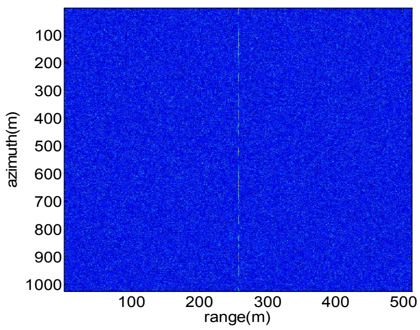
1) calculate the energy $T(k)$ about signal $S\_r_{(k)}: T(k)=\int_{-\infty}^{+\infty} S\_r_k(x)S\_r_k^{*}(x)dx$
2) using SRMF algorithm process each range unit data to obtain 2-D image;
3) find the biggest m peaks, and record the position and amplitude of the peaks;
4) make use of the peaks information structure PSF, and reduce it, $S_{k,i}=S\_r_{(k)}-BP_{(k,i)}$, then obtain the new signal $S_{k,i}$
5) calculate the new signal energy: $T_i(k+1)=\int_{-\infty}^{+\infty} S_{k,j}(x)S_{k,j}^{*}(x)dx$;
6) compared $T_i(k+1)$ with $T(k)$, if the former is bigger than the latter, we think it is a spurious target, and terminate it; else save the position and amplitude, then $k=k+1$, repeated steps 2)-5);
7) repeat the above-mentioned steps for the m peaks;
8) when all of the targets be found or the energy attain the noise level, it terminate;
9) form the clean image by convolving the mainlobe of the PSF with properly sized functions at the estimated target locations.

The Simulation Experiment and performance analysis

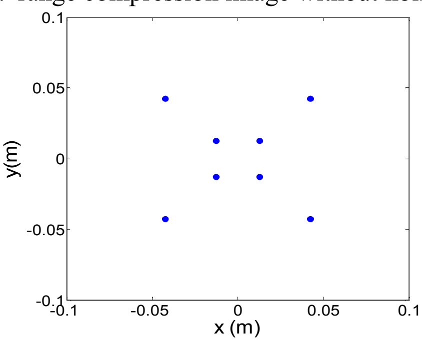
The position of simulation scatters are $(0.6r,0.25\pi)$, $(0.6r,0.75\pi)$, $(0.6r,1.25\pi)$, $(0.6r,1.75\pi)$, $(2r,0.25\pi)$, $(2r,0.75\pi)$, $(2r,1.25\pi)$, $(2r,1.75\pi)$, where $r=0.03$. The complex scattering coefficient are 1, 0.8, 0.6, 0.2, 1, 0.8, 0.6, 0.2, the model of the point is shown as Fig 2c. Range compression image without noise and with noise are shown as Fig 2a and Fig 2b.From the Fig 2d, because of SRMF has high sidelobes weakness, some scatterers that the complex can not be found. Combined SRMF with Coherent CLEAN can effectively solve this problem. However, when the SNR is low or the distance from one scatter to another is big, using this method can not solve the above problem basically. From Fig 2e, we can find that the position error is large, and some weak scatters can not be found. Using Sequence CLEAN instead of Coherent can effectively solve the above problems, the result is shown as Fig 2f. Because of Sequence CLEAN can judging the scatterers are real or not. From the Fig f, we find that all of the scatters can be found accurately. The experiment results explain that Sequence CLEAN can overcome the influence of spurious scatters and noise.



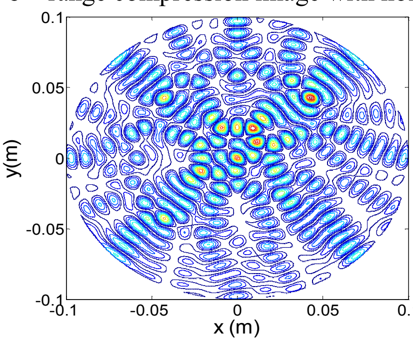
a range compression image without noise



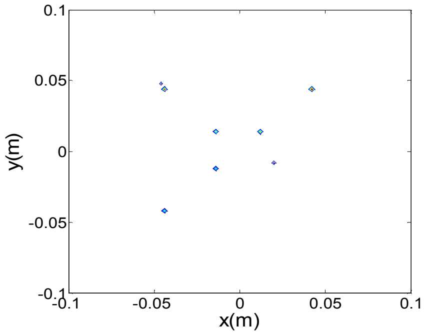
b range compression image with noise



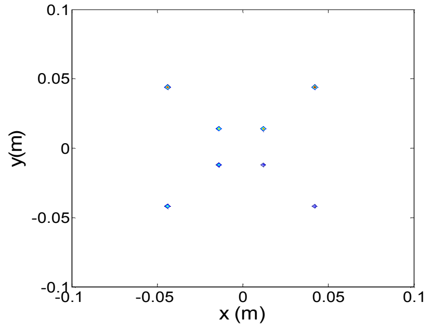
c The model of target



d SRMF image



e Coherent CLEAN image



f Sequence CLEAN image

Figure 2 The results of the experiment

Table1 The coordinate contrast of scattering point

NO	Original value ($\times10^{-2}$)	Coherent CLEAN($\times10^{-2}$)	European distance 1	Sequence CLEAN($\times10^{-2}$)	European distance 2
1	(4.24, 4.24)	(4.34, 4.29)	1.1180	(4.3, 4.25)	0.6083
2	(-4.24,4.24)	(-4.23, 4.33)	0.6083	(4.23, 4.27)	0.3606
3	(-4.24,-4.24)	(-4.33,- 4.23)	0.9055	(4.23, 4.18)	0.6083
4	(4.24,-4.24)	Not find	∞	(4.22,- 427)	0.0361
5	(1.27, 1.27)	(1, 1.05)	0.2955	(1.31, 1.23)	0.0566
6	(-1.27, 1.27)	(-1.12, 1)	0.3089	(-1.27, 1.27)	0
7	(-1.27,- 1.27)	(-0.94, -1.04)	0.4022	(-1.3,- 1.32)	0.2319
8	(1.27,- 1.27)	(0.72,- 2.02)	0.9031	(1.28,- 1.4)	0.1304

European distance 1 is the position error between the Coherent CLEAN and original, European distance 2 is the position error between the Sequence CLEAN and original. The larger the European distance, the larger the position error is. From the table1, we find that the position of the scatter centers acquired using Sequence algorithm is more accuracy than using the Coherent algorithm.

Summarize

Based on the fact that space debris spin around with its axis, setting up different matching filter for different rotation radius can get target scattering point estimated value of polar coordinates. The image obtained by this method has higher side-lobe. Joint the SRMF with Coherent CLEAN technology can eliminate the influence. But when SNR is small, by this method it can not get all of the scatters. Using Sequence CLEAN instead of Coherent CLEAN can be accurately rebuild all of the scattering points. Simulation results show that the approach is effectively and accuracy.

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