Auto-extraction of space debris features based on autofocus search and inverse Radon transform

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Abstract. A method for automatic and accurate feature extraction of space debris is proposed. The echo model of space debris in orbit is formulated first. Then an autofocus search method is presented to obtain the Doppler signature of space debris based on the predicted orbit. The inverse Radon transform (IRT) is used to automatically extract features of space debris. The extraction of spin periods is considered as an example to illustrate the effectiveness of the proposed method. Quantitative simulation results prove that estimated parameter is sufficient in accuracy.

1. Introduction

As it is mentioned in JFCC SPACE satellite situation report in 2015 [1], about 22% of space targets are spacecrafts (includes satellites, space station and so on), and about 78% of space targets are space junk (includes space debris and abandoned spacecrafts). These numbers imply that it is absolutely essential to do the research on space debris identification [2]. Various kinds of space debris features are required to realize the identification of space debris [3, 4], such as shape, spin period, and so on.

At present, for the narrow-band radar, the researches on the feature extraction of space targets are mostly based on Radar Cross-Section (RCS) [5-9]. The resolution of small-sized space targets, especially space debris, is restricted by the range resolution [9]; thus, it is generally unsatisfactory to extract the feature of space debris only from the amplitude of echoes in this situation. In fact, for the narrow-band coherent radar, more features of radar targets can be extracted from the phase of echoes [10-14].

The method proposed in [13] extracts the spin period of space targets in orbit from the phase of radar echoes successfully in an user-assisted fashion. In addition, when the predicted orbit is not sufficient in accuracy, the effectiveness of this method is below expectations. Therefore, we propose an autofocus search method to compensate orbit errors and then utilize the inverse Radon transform (IRT) to automatically extract the spin period of space debris.

The rest of this paper is organized as follows: Section 2 gives the signal model. Section 3 introduces the autofocus search method and discusses the auto-extraction of space debris spin period based on the IRT. The simulation results are shown in Section 4. The conclusions are presented in Section 5.

2. Signal model

The single pulse radar transmits linear frequency modulated (LFM) signals to space, and we assume that the signal model of the transmitted signal is

$$s_t(t_m,t_n) = rect(\frac{t_m}{T_p})e^{j2\pi(f_0 t_m+\frac{1}{2}Kt_m^2)}e^{j2\pi f_{RF}t_n}, \tag{1}$$

$$rect(\frac{t_m}{T_p}) = \begin{cases} 1 & -\frac{T_p}{2} < t_m < \frac{T_p}{2} \\ 0 & \text{otherwise} \end{cases}, \quad (2)$$

where $K = B / T_p$ is the slope of LFM, t_m is the fast time, t_n is the slow time, B is the bandwidth of LFM signal, T_p is the pulse width of LFM signal, f_0 is the initial frequency of LFM signal, and f_{RF} is the center frequency of the transmitted signal.

The received signal is

$$s_r(t_m, t_n) = \delta r[t_m - \tau(t_m)] e^{j2\pi f_{RF}[t_n - \tau(t_n)]}, \quad (3)$$

$$r(t) = rect(\frac{t}{T_p}) e^{j2\pi(f_0 t + \frac{1}{2}Kt^2)}, \quad (4)$$

where δ is the complex scatter coefficient of space target, $\tau(t) = (2R_0 - 2vt - at^2)/c$ is the delay of radar echoes, R_0 is the radial range, v and a are the radial velocity and radial acceleration respectively, and c is the speed of light.

After removing the carrier from the received signal, the baseband signal can be written as

$$s_r'(t_m, t_n) = \delta r[t_m - \tau(t_m)] e^{-j2\pi f_{RF}\tau(t_n)}. \quad (5)$$

The substitution of these relations in (5) yields,

$$s_r'(t_m, t_n) = \delta rect \frac{t_m - \tau(t_m)}{T_p} e^{-j2\pi f_{RF}\tau(t_n)} \cdot e^{j2\pi[f_0(t_m - \tau(t_m)) + \frac{1}{2}K(t_m - \tau(t_m))^2]}. \quad (6)$$

Then the signal is processed by a matched filter, and the matched filter output is

$$s_{rc}(t_m, t_n) = \delta T_p sinc[\pi K T_p (t_m - \tau(t_m))] e^{-j2\pi f_{RF}\tau(t_n)}. \quad (7)$$

The envelope shape of $s_{rc}(t_m, t_n)$ is a *sinc* function, and the peak position is decided by $\tau(t_m)$ which is related to the radial range. The exponential function in (7) contains the phase information which is modulated by the motion of space target. Because of the radial velocity and radial acceleration of space target, the signal energy spread on several range bins and different Doppler units. It is necessary to compensate the velocity error and acceleration error before the coherent integration.

3. Auto-extraction method

3.1 Autofocus search

Based on the predicted orbit of space debris, we use an autofocus search method to estimate the velocity error and acceleration error. Then subtly align the envelope and compensate the phase error of the echoes before the coherent integration. While eliminating the effect of translational component of space debris, the residual rotational component of space debris could be used to extract the characteristic. The detail of the proposed method is discussed as follows.

a. Generate sampling gates by the predicted orbit of space debris. Then collect echoes by the sampling gates and convert the frequency of the echoes down to baseband.

b. Choose appropriate search values of search parameters based on the predicted orbit of space debris.

Based on the predicted range of space debris $R_p(j)(j = 1, 2, \ldots, N)$, generate the range search values $\hat{R}_{i,j}$ for each baseband echo which can be written as

$$\hat{R}_{i,j} = R_p(j) + \hat{v}_i (j-1) prt + \frac{1}{2} \hat{a}_i ((j-1) prt)^2, \quad (8)$$

where $\hat{v}_i$ $(i = 1, 2, \ldots, M)$ is the search value of radial velocity, and $\hat{a}_i$ is the search value of radial acceleration, prt is the pulse repetition time, i represents the i-th search value, j represents the

j -th baseband echo, M is the total number of search values, and N is the total number of the echoes to be coherent integrated.

An appropriate value of N could be calculated as

$$N = \left\lceil \left(\frac{R_t}{R_{\max}} \right)^4 \frac{\sigma}{\sigma_t} \right\rceil, \tag{9}$$

where R_t is the radial range of space debris, σ_t is the RCS of the space debris, $R_{\max}$ is the maximum radar detection distance when the RCS of space debris is σ, and $\lceil \cdot \rceil$ represents the rounding operation.

The search values of the velocity and acceleration could be expressed by the initial values and the search steps.

$$\begin{cases} \hat{v}_i = \hat{v}_0 + \Delta v(i-1) \\ \hat{a}_i = \hat{a}_0 + \Delta a(i-1) \end{cases}, \tag{10}$$

where $\hat{v}_0$ and $\hat{a}_0$ are the initial values of velocity and acceleration; Δv and Δa are the search steps of these two search parameters which are decided by the migration of envelopes and the spread of Doppler.

We assume that the migration of the envelope is less than the range sampling cell L_r, and the spread of Doppler is less than the Doppler cell L_d. Then the two search steps could be calculated as

$$\begin{cases} \Delta v \le \dfrac{cL_r}{2F_s Nprt} \\ \Delta a \le \dfrac{\lambda L_d}{2(Nprt)^2} \end{cases}, \tag{11}$$

where F_s is the sampling frequency of the received signal, and λ is the wavelength of the transmitted signal.

c. Align the envelope in a straight line by the range search parameter.

The generation of the sampling gates in step a is a pre-alignment of the envelope. Assume that τ_0 is the start time of received signal which is decided by the distance between radar and space debris, and τ_0' is the start time of sampling gate. Because of the digital sampling, τ_0' is quantified by the sampling clock. Therefore, there is an error $\Delta\tau_0$ between τ_0' and τ_0. The delay error $\Delta\tau_0$ must settle for $|\Delta\tau_0| \le 1/F_s$, and the accurate value of the delay error can be calculated as

$$\Delta\tau_0 = \frac{2\left(\hat{R}_{i,j} - \left\lceil \dfrac{\hat{R}_{i,j} \cdot 2F_s}{c} \right\rceil \dfrac{c}{2F_s} \right)}{c}. \tag{12}$$

According to the time shift property of discrete Fourier transform (DFT), if $x[n] \leftrightarrow X(e^{j\Omega})$ (a couple of Fourier transform pairs), then $x[n-m] \leftrightarrow X(e^{j\Omega})e^{-j\Omega m}$. In the digital sampling system, the delay error $\Delta\tau_0$ can not be expressed in time domain but can be transformed to a phase error $e^{-j\Omega\Delta\tau_0}$ in frequency domain. To subtly align the envelope, the frequency spectrum of the baseband signal is multiplied by the envelope alignment factorial $\mathrm{Envelop}_{\mathrm{com}}(i, j)$, which is

$$\mathrm{Envelop}_{\mathrm{com}}(i, j) = e^{j2\pi F_s \Delta\tau_0}. \tag{13}$$

After that the signal is processed by a matched filter in frequency domain. Then the frequency domain signal is transformed into the time domain signal.

d. Compensate the phase error. Multiply the above signal by the phase compensation factorial $\mathrm{Phase}_{\mathrm{com}}(i, j)$ in the time domain, which is related to the range search parameter as

$$\text{Phase}_{\text{com}}(i,j) = e^{j2\pi f_{RF}\frac{2\hat{R}_{i,j}}{c}} = e^{j4\pi\frac{\hat{R}_{i,j}}{\lambda}}. \tag{14}$$

e. After the envelope alignment and phase compensation, utilize fast Fourier transform (FFT) in Doppler dimension, and then record the peak value in Range-Doppler dimension.

f. Change another search value, and repeat steps c to e.

g. Find the maximum value in the recorded peak values, and record the data in Doppler dimension which are corresponding to the maximum value. The Doppler data of different time frames are ranked in order of time and then a time-frequency graph is obtained which contains the Doppler signatures of space debris.

3.2 Feature extraction

The Doppler of the three-axis stabilized target focuses on a single spectrum line, and it means that the phase center is stable. However, the Doppler of the roll or spin target is like a mountain or has many separate spectrum lines which is caused by the movement of multiple scattering centers [13].

When space debris spin, the scattering center of space debris will cause a sinusoid in the time-frequency plane [15]. Many papers introduce the characteristic extraction of radar target based on the IRT [15, 16]. In this paper, the IRT is used to estimate the spin period of space debris automatically.

According to the IRT principle, a sinusoid in the time-frequency plane can be transformed into a point in the IRT plane. To integrate all energy along a sinusoid into one point, an appropriate value of the rotate angle $\hat{\theta}$ is required [15]. For the highest energy concentration, the optimal value of $\hat{\theta}$ should be $\hat{\theta} = 2\pi T / T_{\omega}$, where T is the observation time, and T_{ω} denotes the spin period.

With different search values of the rotate angle, we obtain different peak values in the IRT domain. The maximum peak value corresponds to the optimal rotate angle $\hat{\theta}$. Then the value of spin period can be calculated. Note that the components with zero Doppler in the time-frequency plane will disturb the estimation of optimal rotate angle; thus, it should be eliminated by high pass filter before the IRT operation.

4. Simulation

The feasibility and effectiveness of the proposed method are validated by numerical simulations. Assume that there are three strong scattering centers (p_1, p_2, p_3) on space debris with different scattering coefficients $(1, 0.8, 0.6)$, and the local coordinates of them are $[0,0,0]$, $[-0.5,-0.5,-0.8]$, $[1,0.8,0.4]$ respectively. We also assume that the spin period of space debris is 20.49s. The radar system parameters are shown in Table. 1.

Table 1 The radar system parameters

Parameters name	Parameters value
Carrier frequency	3[GHz]
Pulse repetition frequency	300[Hz]
Bandwidth of transmit LFM signal	5[MHz]
Number of integrated pulses	256
Total observation time	50[s]

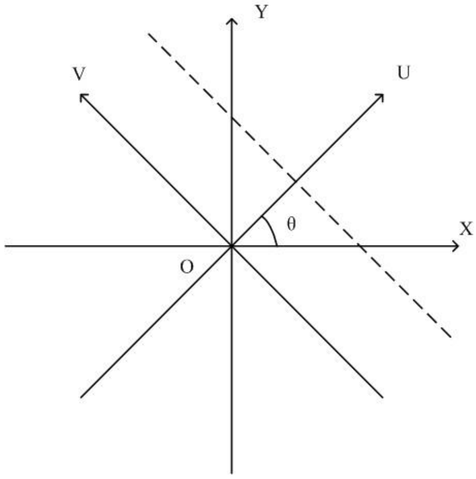

Fig.1 The time-frequency graph of the simulation data

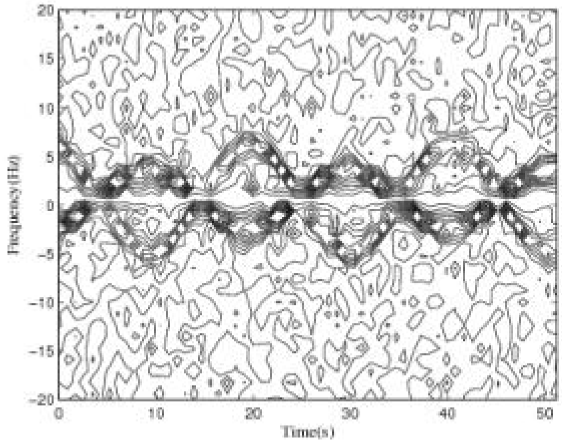

Fig.2 The time-frequency graph without zero Doppler components

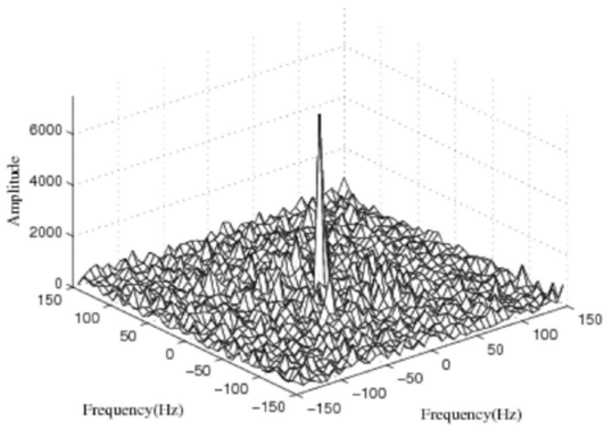

Fig.3 Peak values in the IRT domain with different search values of spin period

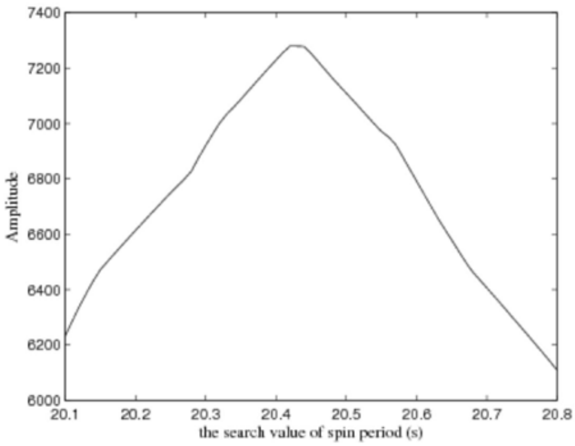

Fig.4 Inverse Radon transform with highest energy concentration (the search value of spin period is 20.42 s)

According to the execution steps of the proposed method discussed in section 3, we obtain the primary results, as shown in Fig. 2. The movement of strongest scattering center p_1 causes the straight line in the time-frequency plane, and that of the scattering centers p_2, p_3 cause two different sinusoids. The different peak values in the IRT domain with different search values of spin period are shown in Fig. 3. The IRT plane with the highest energy concentration is figured in Fig. 3.

According to Fig. 4, the estimated spin period is 20.42s, and the relative error is 0.342%. The simulation proves that the proposed method is appropriate to extract the spin period of space debris and the estimated parameter is sufficient in accuracy. This experiment also reveals that the present method is effective to integrate the energy of sinusoids in the time-frequency plane even when there is a stable scattering center.

In addition, based on the estimated spin period and the coordinates of the peak in Fig. 4, it is possible to estimate the shape of space debris [15].

5. Conclusion

In this paper, an automatic method for features extraction of space debris based on the autofocus search algorithm and the inverse Radon transform is presented. The simulation results prove that the proposed method is feasible to extract the feature of space debris in orbit from the phase of radar echoes. The presented auto-extraction method can be generalized to extract the shape of space debris with a fast spin rate, which is our future work.

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