THE ALGORITHM FOR ISAR IMAGING OF FAST MOVING TARGET USING RADAR WITH BINARY PHASE-CODED WAVEFORMS

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Abstract

The algorithm of ISAR imaging of space objects ($R_0 > 100$ km, $V \sim 500 \div 7000$ km/s) using the radar with binary phase-coded signals is presented in the paper. The algorithm is based on simultaneous determination of the speed and acceleration of several target points. The image brightness and tracks of the points are using to determine of their speeds and accelerations. The results of numerical modeling of three-point object are shown. The values of signal-to-noise ratio (SNR) when algorithm shows good results are found. For this value of SNR the algorithm doesn't depend from noise.

Keywords: radar with binary phase-coded signal, ISAR imaging

One of the main problems of the ISAR imaging is a good motion compensation for investigated object. The motion of real targets can be represented by translational and rotational motion. For various existing motion compensation algorithms, the range alignment is accomplished by tracking the time history of a reference point (such as the peak or the centroid) in the range compressed data and fitting it to a polynomial [1-5]. All of these methods consider the Doppler frequency shift for the target as a whole, and apply the same correction vector to all the scattering points in the image. However, as was shown in [6] for fast moving targets or when the dwell time is long, the phase error is different for all the target points. The method which was proposed in [6] is based on the projection procedure onto the system of the exponential functions. Unfortunately this method depends on the initial approaching. Apparently, it is caused by the choice of the function system for projection.

In this paper the algorithm of determination of the speed and acceleration (the phase error) of different target points using their image brightness and tracks in the range compressed data is proposed. Using the algorithm for the space object ISAR imaging is considered.

1. Statement of the Problem

The distance between the moving target and radar is R_0 ($R_0 > 100$ km). The radar radiates the series of N impulse with period T_2. Each impulse is binary phase-coded. The duration of the impulse is equal to T_1. To obtain the phase-coded impulse the maximal-length sequences (M-sequence) [7] is used. The M-sequence length is equal to M . So radiated signal can be wrote as:

$$s_n^t(t) = \begin{cases} \sum_{m=0}^{M-1} b_m Q((t - nT_2 - m\tau)/\tau)\exp(j2\pi f_0 t), \\ nT_2 < t < nT_2 + T,\ n = 0,1,2,\dots,N-1; \\ 0, \qquad \text{other } t. \end{cases} \quad (1)$$

Here $\{b_m\}_{m=0}^{M-1}$ is the M-sequence, $b_m = \pm 1$, M is the binary unit number in the impulse, $\tau = T_1 / M$ is the duration of the binary unit, $Q(u) = \begin{cases} 1, & 0 < u < 1 \\ 0, & u \notin (0,1) \end{cases}$ is the unit rectangular impulse, f_0 is the carrier frequency.

In the paper two model of target motion are considered. First of them suppose that the target centroid is moving away radar and has the speed V and acceleration A . In the second model suppose that the target is revolving on the near-earth orbit which has the radius R_0 . The radar is placed on the orbital plane and the target has the first space speed. The both models assume the rotation of the target with angle speed Ω . The problem geometry is shown on the Fig. 1.

Let us assume that the target is the solid satellite with the fixed rotation axis and the rotational angle of the target during impulse is small. In such case the target model can be considered as a two-dimensional (plane) system of the scattering points (Fig. 1). The distance between radar and target is far bigger than the cross target dimension. So the distance between radar and point of the target can be written as:

$$r_i(t) = r_0(t) + a_i F(\varphi_i(t)) . \quad (2)$$

For the first model of the target motion

$$r_0(t) = R_0 + Vt + At^2/2 \text{ and}$$

$$F(\varphi_i(t)) = \sin(\varphi_i + \Omega t) .$$

For the target on the near-earth orbit

$$r_0(t)=\sqrt{R_e^2+(R_e+R_0)^2-2R_e(R_e+R_0)\cos\psi(t)},$$

$$F(\varphi_i(t))=(R_e+R_0)\sin\varphi_i(t)-R_e\sin(\varphi_i(t)-\psi(t)),$$

where $\varphi_i(t)=\Omega t+\varphi_i$, $\psi(t)=\omega t+\psi_0$, $R_e=6378$ km is the Earth radius. The parameters a_i and φ_i are shown on the Fig. 1.

The reflected signal from the target is recorded by receiver at the time interval $[T_0+nT_2, T_0+T_g+nT_2]$, $n=0,1,...,N-1$. Here $T_0=2R_0/c$ is the time delay. The duration of the time interval T_g is determined so that the reflected impulse from the target completely belongs to it.

$$T_g=\Delta R/c+T_1.$$

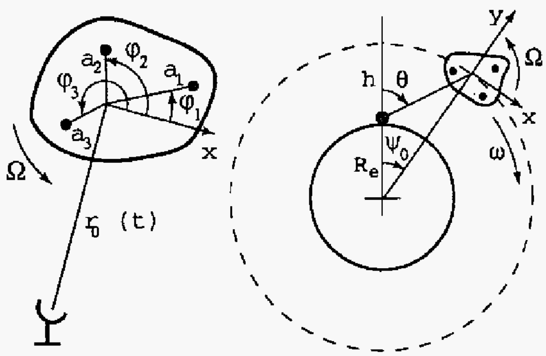

Fig. 1. The two-dimensional model of the target. Two model of the target motion.

There ΔR defines the expected value of the radar-to-target distance ($[R_0, R_0+\Delta R]$). The reference signal of comparison is formed from the radiated signal

$$s^c(t)=\exp[j2\pi f_0(t-T_0)],$$

here the intermediate frequency is equal to zero.

The received signal is treated with phase discriminator, then it is digitized and the result is written. Thus, the n-th impulse corresponds with signal:

$$s_n^s(t)=\sum_i g_i\sum_{m=0}^{M-1}b_m Q(t_i/\tau)e^{-j4\pi f_0(r_i(t)-R_0)/c}+\text{noice}. \quad (3)$$

Here $t_i=t-nT_2-2r_i(t)/c-m\tau$, g_i is the reflectivity of the i-th point of the target. The value "noice" in (3) describes the noises of different type and nature, which are caused by fluctuations in radar systems and faze distortions when signal propagation.

2. The Signal Processing

To take the range compressed data we used the procedure of matched filtering for digitized signal (3). The digitized signal is series from the N sequences $\{s_n^s(m)\}_{m=0}^{M_g-1}$. Each sequence corresponds to the impulse with number n, ($n=0,1,\ldots,N-1$) and its length is equal to $M_g=T_g/\tau$. The elements of these sequences is value of function $s_n^s(t)$ at the time $t_m=T_0+nT_2+\tau/2+m\tau$. Response of the matched filter can be found as the correlation function of the M-sequence and $s_n^s(t)$:

$$s_n(k)=\sum_{m=0}^{M-1}s_n^s(k+m)b_m,\quad k=0,1,\ldots,M_g-1. \quad (4)$$

It's known [8], that $s_n(t)$ is modulated by the Doppler frequency $f_D=2f_0r'(t)/c$. If the Doppler frequency is known a priori and constant then the Doppler frequency shift can be compensated without decreasing of the SNR and the target image quality. Otherwise it is needed in the procedure of the target motion compensation to obtain a high quality imaging. Let us assume that the Doppler frequency shift doesn't provide changing the duration of the binary unit and decorrelation of the radiated and received signals.

To compensate the target motion in this paper the algorithm of the simultaneous determination of the speed and acceleration of several target points is developed.

In each sequence (4) we determine the range cell with the most strong peak and make up the vector $\{s_n(k_n^1)\}_{n=0}^{N-1}$, where k_n^1 is the number of the determined range cell in the n-th impulse. In first impulse the additional peak points is selected. The number of the additional points can be different and depends on the problem statement (for example, target size). For the additional points the vectors $\{s_n(k_n^i)\}_{n=0}^{N-1}$ where k_n^i is the range cell number with the i-th additional points in the n-th impulse are make up too. Determination of the k_n^i ($n=1, 2, ..., N-1$) becomes easier by the following condition:

$$\Delta k_0^i-1\le\left|k_n^i-k_n^1\right|\le\Delta k_0^i+1,$$

where $\Delta k_0^i=\left|k_0^i-k_0^1\right|$, and the item "$\pm1$" takes into account the range walk effect. The range walk effect is connected with the discontinuity of the digitized signal.

The acceleration and speed of the i-th target point can be determined as joint resolution of two problem. First problem is the determination of the values of the speed (V_i) and the acceleration (A_i) of the i-th target point, which optimally describe the range point motion during the impulse series. The criterion of the optimum can be formulated as the minimum of following function:

$$f_i(V_i,A_i)=\sum_{n=1}^{N-1}\left(\Delta r_i(n)-V_inT_2-A_i(nT_2)^2/2\right)^2, \quad (5)$$

where $\Delta r_i(n)=(k_n^i-k_0^i)T_1c/M$ is the range shift of the i-th point during nT_2. This function has only one minimum for the fixed A_i. It allows to determine the value V_i when A_i is known.

The second problem is the determination of the acceleration A_i which provides most brightness image of the i-th target point. Solution of this problem is needed to make the point image which takes into account the defined speed and acceleration. The processing signal to obtain image consist of three stages. On the first stage the digitized signal $s_n^s(t)$ (3) is corrected taking into account the acceleration A_i and speed V_i (i.e. solution of the problem (5)):

$$\tilde{s}_n^s(t) = s_n^s(t)\exp\left(j4\pi f_0\left[V_i t + A_i t^2/2\right]/c\right). \quad (6)$$

Then, on the second stage, using of the formula (4) we found the vector $\left\{\tilde{s}_n(k_n^i)\right\}_{n=0}^{N-1}$:

$$\tilde{s}_n(k_n^i) = \sum_{m=0}^{M-1} \tilde{s}_n^s(k_n^i + m)b_m . \quad (7)$$

Third stage is the making of the i-th target point image. It is obtained by using the discrete Fourier transform of the vector $\left\{\tilde{s}_n(k_n^i)\right\}_{n=0}^{N-1}$. We used a fast Fourier transform (FFT) algorithm:

$$\tilde{X}_i(m) = \sum_{n=0}^{M-1} \tilde{s}_n(k_n^i)\exp\left(j2\pi nm/N\right). \quad (8)$$

The point brightness is defined by the value of maximum of the vector $X_{\max}^i(V_i(A_i), A_i) = \max\left\{\tilde{X}_i(m)\right\}_{m=0}^{N-1}$ which depends from the determined value of the speed and acceleration. Thus second problem is the maximization of the function $X_{\max}^i(A_i) \to \max$. As the numerical experiments shown this function has only one maximum. So to solve this problem the standard searching algorithm of the one-variable function extremum can be used.

Thus the problem of the determination of speed and acceleration of i-th target point can be formulated as:

$$\begin{cases} \sum_{n=1}^{N-1}\left(\Delta r_i(n) - V_i nT_2 - A_i\left(nT_2\right)^2/2\right)^2 \to \min, \\ X_{\max}^i(V_i, A_i) \to \max. \end{cases} \quad (9)$$

The solution of this problem is robust and doesn't depend on the initial approximation value of the speed and acceleration. The main requirement of the algorithm is possibility to determine the vector $\left\{k_n^1\right\}_{n=0}^{N-1}$. When the SNR in the compressed data (7) is bigger than 10 dB the target point can be easy identified and the requirement of the algorithm is satisfied. Such SNR can be attained by increasing of the M-sequence length, i.e. the impulse duration T_1. In this case the SNR is increased proportional to M. However, the impulse duration can not exceed $T_1 < 2R_0/c$. If the SNR doesn't exceed 10 dB in the compressed data, then the more complex methods of definition of the vector $\left\{k_n^1\right\}_{n=0}^{N-1}$ are needed to use (for example, the maximum-correlation method [9]). This problem can be solved by using systems of two radars. One of them defines the distance between target and radar. And other used for the target imaging. For example, the radar which are describes in [10] concerns to such systems.

Determined exactly motion equation for target points (i.e. values V_i and A_i) allows to obtain the final good target image. To do it the target is divided on the zone of the target points influence and for each zone the digitized signal is corrected accordingly to (6) taking into account the values V_i and A_i for dominant point. The signal compressing (7) and its FFT (8) allow obtaining the focused image of i-th zone. To take the final target image the differences between speeds of the different dominant target points must be taken into account. These differences provide the shift of the i-th zone on the value $m_i = 2f_0T_2(V_i - V_0)/(Nc)$ relatively first zone.

3. The Radar Signal Modeling. The Target Imaging

For example of numerical realization of the proposed algorithm we considered imaging of the plain three-point target. It is assumed, that the target image will have a resolution no worse than $\Delta_s = c\tau/2 = 0.5$ m. Thus, the duration of the binary unit is equal to

$$\tau = 2\Delta_s/c = (1/3)\cdot 10^{-8}\,\text{s},$$

i.e. the frequency band of the signal is equal to

$$\beta = c/(2\Delta_s) = 300\,\text{MHz}.$$

The impulse duration is equal to $T_1 = M\tau$ s. It is considered the series of $N = 128$ impulse with repetition period is equal to $T_2 = 0.5\cdot 10^{-3}$ s. The carrier frequency is $f_0 = 13.75$ GHz and corresponding wavelength is 2.18 sm. The bit duration of the radiated impulse corresponds to $\tau f_0 = 45.83$ period of the carrier frequency.

According to main radiolocation equation the SNR on the output of the receiver is defined by formula

$$SNR = 12.6\cdot\frac{P_t G^2\lambda^2\sigma}{R_0^4 B(NF_0)L}. \quad (10)$$

Where P_t is the power of the radiated impulse (watt), $G = \pi^2 D_a^2/(2\lambda^2)$ is the antenna gain factor, λ is the wavelength (sm), σ is the effective scattering square of the target (m^2), R_0 is the distant between radar and target (km), B is the receiver bandwidth (Hz), NF_0 is the noise coefficient of the receiver and L is the total coefficient of the looses of the system.

The noise influence is modeled by addition the random value which has the normal distribution with dispersion equal to $(SNR)^{-1}$ to each time reading

$$s^s(t) := s^s(t) + \frac{1}{\sqrt{2\cdot SNR}}\text{randn}(t).$$

The different stages of signal processing are shown in Fig. 2. The target is moving on the near-earth orbit with radius $R_0 = 300$ км ($\theta = 10°$) and its geometry is determined by the parameters (see at Fig. 1): $a_1 = 2$ m, $\varphi_1 = -\pi/4$, $a_2 = 2$ m, $\varphi_2 = 3\pi/4$, $a_3 = 10$ m, $\varphi_3 = \pi/4$. The angle speed of the target rotation is equal to $\Omega = 1$ rad/s. The final target image (Fig. 2 d) where the found value of the speed and acceleration for each point are taking into account is the focused and corresponds to its geometry. Preliminary signal processing with fixed speed and acceleration isn't focused (Fig. 2 c) because the accelerations of the target points have different values.

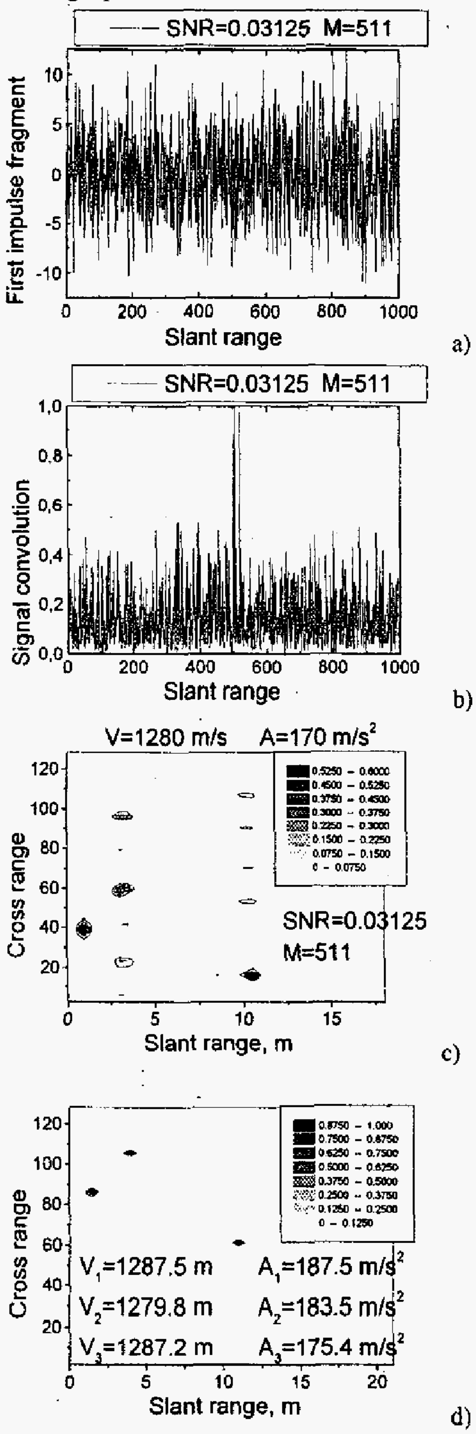

Fig. 2. Different stages of the signal processing: a) signal with noise at output of the phase discriminator; b) fragment of the compressed first impulse; c) the target image taking into account approximation parameters of target motion; d) final target image.

The noise dispersion values (SNR^{-1}) which provides the SNR in the compressed data equal to 10 dB for different M-sequence length is shown in the table 1 (column 2). The noise dispersion values when in final target image SNR is equal or bigger than 10 dB are shown in the column 3 of the Tabl. 1.

Table 1.

M	Value of noise dispersion (SNR^{-1})	
	Column 2	Column 3
255	$6.38 \cdot 10^{-2}$	$8.89 \cdot 10^{-3}$
511	$2.47 \cdot 10^{-2}$	$3.47 \cdot 10^{-3}$
1023	$7.81 \cdot 10^{-3}$	$2.22 \cdot 10^{-3}$
2047	$5.0 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$
4095	$2.2 \cdot 10^{-3}$	$4.59 \cdot 10^{-4}$

4. Conclusions

As the numerical experiment shown the accelerations of the target points have different values even for slow target rotation. Therefore to obtain the focused target image ones need to account the speed and acceleration of several target points. The proposed algorithm allows obtaining the focused image of the space objects ($R_0 > 100$ km, $V \sim 500 \div 7000$ km/s). The algorithm almost doesn't depend on the noise value if the noise dispersion in the received signal doesn't exceed the values which are shown in Tabl. 1. If the noise dispersion value in the received signal is bigger than the value shown in the column 3 of the Tabl. 1 then the target image can not be obtained. The improvement way of the proposed algorithm is the determination of the angle speed of the target rotation by the determined speed and acceleration of some target points.

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