InISAR Imaging of Maneuvering Target Base on Motion Compensation and Image Coregistration

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Abstract. The imaging of maneuvering target is the main research content of Interferometric Inverse Synthetic Aperture Radar (InISAR). Since it is quite difficult to obtain the effective data of the moving target, both the residual translational compensation and least square method are proposed to realize the imaging of the target according to the principle of InISAR in this letter. First step, the echo model is established to perform motion compensation. Second step, perform image registration on the signal. Third step, the ISAR image is obtained via extracting the peak value, then perform the interference processing imaging. Finally, Simulation results show that this method can be used for image recognition.

1. Introduction

Generally speaking, compared with optical imaging, electromagnetic imaging has obvious advantages regardless of day, night, and weather conditions, the inverse synthetic aperture radar (ISAR) is the main two-dimensional (2-D) imaging equipment for acquiring moving targets. Due to the complexity of the moving target state, the stable imaging calculation of the target is also accompanied by challenges, so as to reduce the target recognition effect.

In order to enhance the high-resolution imaging of non-cooperative moving targets and the recognition probability [1-2], the research of three-dimensional (3-D) imaging is the key content in interferometric ISAR (InISAR) [3]. Reference [4] proposed the extension of the iterative optimization-based SA-ISAR imaging to the 3-D InISAR imaging, however, complex iterative algorithms are more challenging for real-time imaging. Reference [5] proposed three-dimension (3-D) reconstruction method for recovering the shape of a rigid target from the ISAR image sequence, then, Liu Y [6], et al. further study an improved combined processing approach of InISAR imaging. In fact, to our knowledge, the use of constructed echo signals will inevitably cause the difficulty of echo sequences extraction to some degrees, such as, translational & rotation error and phase blur.

In this letter, the method to improve the effect of InISAR imaging, which residual translational motion compensation for range profile and rotation vector estimation by least square method for image registration was proposed.

The structure of this letter is as follows: In Section II, the InISAR signal model of maneuvering target is discussed, as well as the approach of motion compensation and image coregistration are both
described. In Section III, we analyze the performance of the proposed approach based on simulation and real data. In Section IV, we draw our conclusion.

2. Inisar SIGNAL MODEL

2.1. InISAR System geometry model

As shown in Fig.1, the InISAR system consists of mutually perpendicular AB and AC antenna pairs, that antenna A is not only a transmitter but also receiver, while antenna B and antenna C are just as receivers. The radar coordinate system is defined as (U, V, W) frame. L represents the baseline length of antenna A and B, the midpoints D is between segment AB. We assume that there is a far-field target P described both in the initial coordinate (x, y, z) and relative motion coordinate (x′, y′, z′) of motion, where the origin O locates at the target’s center, O′ represents the center of non-initial origin coordinates.

![Fig. 1 Geometry for the InISAR](image)

2.2. Antenna Signal Model

Suppose the antenna A transmits the chirp signal is the following expression:

$$s(\hat{t}, t_m) = \text{rect}\left(\frac{\hat{t}}{T_p}\right) \exp\left(j2\pi\left(f_c t + \frac{k\hat{t}^2}{2}\right)\right)$$

Where $\text{rect}(\cdot)$ is the transmitted signal’s envelope, $f_c$ represents the central frequency of the transmitter, $k$ represents the frequency modulation rate, $T_p$ represents the pulse width, $T$ denotes the pulse repetition period, $\hat{t} = t - mT$ represents the fast time, $t_m = mT$ represents the slow time, $m = 0, 1, 2, \ldots, M - 1, M$ represents the total number of pulses.

Suppose target P’s backscattering coefficient is $\sigma_p$, the slant distance between P and A, B, C are $R_{AO}$, $R_{BO}$, $R_{CO}$ respectively. Then, the echo signal of antenna has the form of:

$$s_{x}(\hat{t}, t_m) = \sigma_p \text{rect}\left(\frac{\hat{t} - 2R_{AO}/c}{T_p}\right) \exp\left[j2\pi\left(f_c\left(t - \frac{2R_{AO}}{c}\right) + \frac{k}{2}\left(t - \frac{2R_{AO}}{c}\right)^2\right)\right]$$

Where $c$ represents the wave velocity, Suppose the reference distance is $R_{ref}$, dechirp on Equation (2) can be obtained as follows:
$$S_{\lambda}(\hat{t}, t_m) = \sigma_p \text{rect} \left( \frac{\hat{t} - 2R_{AO}}{T_p} \right) \cdot$$

$$\exp \left[ -j \frac{4\pi k}{c} \left( \frac{\hat{t} - 2R_{ref}}{c} \right) R_{\lambda AO} \right] \cdot$$

$$\exp \left[ -j \frac{4\pi k}{c} f_r R_{\lambda AO} \right] \cdot$$

$$\exp \left[ j \frac{4\pi k}{c} f_r R_{\lambda AO}^2 \right]$$

then, Fourier transform(FT) is taken in the distance direction to obtain the one-dimensional distance profiles expression:

$$S_{\lambda}(\hat{f}, t_m) = \sigma_p T_p \sin c \left[ T_p \left( \hat{f} + \frac{2k}{c} R_{\lambda AO} \right) \right] \cdot$$

$$\exp \left[ -j \frac{4\pi \hat{f}}{\lambda} R_{\lambda AO} \right] \cdot$$

$$\exp \left[ j \frac{4\pi k}{c} R_{\lambda AO}^2 \right]$$

where $\lambda$ represents the signal wavelength, $R_{\lambda AO} = R_{AO} - R_{ref}$, assuming that $R_{\lambda AO}$ is relatively fixed in imaging time $\hat{t}$ and varies linearly in time $t_m$, satisfies stop-go-stop pattern. The second exponential term in (4) represents echo doppler, which is use to the image of azimuth, but it will cause the migration through resolution cell (MTRC). The third exponential term denotes the residual video phase (RVP), and it will also debase the imaging performance. Thus, we should correct MTRC via keystone transform to the second exponential term, and remove the third exponential term. Then, one-dimensional range profiles with the form of:

$$S_{\lambda}(\hat{f}, t_m) = \sigma_p T_p \sin c \left[ T_p \left( \hat{f} + \frac{2k}{c} R_{\lambda AO} \right) \right] \cdot$$

$$\exp \left[ -j \frac{4\pi \hat{f}}{\lambda} R_{\lambda AO} \right] \cdot$$

$$\exp \left[ j \frac{4\pi k}{c} R_{\lambda AO}^2 \right]$$

Where $T_r$ represents Coherent accumulation time, $R_{\lambda AO}$ represents target initial time reference distance, $v$ represents radial velocity, A two-dimensional ISAR R-D image can be obtained by using the slow time Fourier transform. Thus, we can write as:

$$S_{\lambda}(\hat{f}, f_m) = \sigma_p T_p T_r \sin c \left[ T_p \left( \hat{f} + \frac{2k}{c} R_{\lambda AO} \right) \right] \cdot$$

$$\sin c \left[ T_r \left( f_m + \frac{2v}{\lambda} \right) \right] \cdot$$

$$\exp \left[ -j \frac{4\pi}{\lambda} R_{\lambda AO} \right]$$

Similarly, the image after R-D imaging processing of echo by receiving antenna B is as follows:
\[
S_B(\hat{f}, f_m) = \sigma_Jr_T \sin c \left[ T_e \left( \hat{f} + \frac{k}{c} (R_{A\text{LOS}} + R_{ABO}) \right) \right] \cdot 
\sin c \left[ T_e (f_m + \frac{R_{A\text{LOS}} + R_{ABO}}{\lambda}) \right] \cdot \exp \left( -j \frac{2\pi}{\lambda} (R_{A\text{LOS}} + R_{ABO}) \right) \cdot
\]

(7)

Then \( S_B(\hat{f}, f_m) \) multiply by the conjugate of the signal \( S_A(\hat{f}, f_m) \), the interference phase can be written as follows:

\[
\Delta \varphi_{AB} = \text{Angle} \{ S_A^*(\hat{f}, f_m) S_B(\hat{f}, f_m) \} \]

(8)

Where \( \text{Angle}(\bullet) \) means take the complex phase, simplify as:

\[
\Delta \varphi_{AB} = \frac{\pi f_c}{c} \cdot \frac{2L(x_0 + x_p) - L^2}{R_0} \]

(9)

\( x_0, x_p \) are the initial and radial coordinates of the target P respectively, \( R_0 \) represents the distance from baseline midpoint D to P. Similarly, the interference phase of antenna A and C is as follows:

\[
\Delta \varphi_{AC} = \frac{\pi f_c}{c} \cdot \frac{2L(x_0 + x_p) - L^2}{R_0} \]

(10)

Thus, the projection coordinates of target P in the direction of baseline AB and baseline AC can be obtained as follows:

\[
x = X_0 + x_p = \frac{cR_0 \Delta \varphi_{AB} + L}{2\pi f_c L} \]

(11)

\[
z = Z_0 + x_p = \frac{cR_0 \Delta \varphi_{AC} + L}{2\pi f_c L} \]

(12)

In the far-field condition, the radar line of sight can be approximately the Y-axis direction, which can be obtained through radar ranging and range-direction resolution. Combined with Equations (11) and (12), the spatial coordinates can be obtained, as well as range-direction parameters, sampling rate and other parameters, 3-D imaging can be realized.

2.3. Motion compensation and image coregistration

According to the aforementioned analysis, envelope alignment based on maximum correlation is the common method before signal recovery, at the mean time, the random distance error between the envelopes of the range profile should be remove. Furthermore, to achieve a high-quality image of the motion compensation and the signal recovery, residual translational motion compensation for range profile and total rotation vector estimation by least square method for image registration are both devised in this paper [8].

Since the positions and phases of the three antennas A, B and C are different in the range and azimuth directions, taking antenna A as the reference of the echo signal causes the residual envelope offset term and initial phase error in the echo signals of antenna B and C. According to Equation (6), antenna B receives echo signal and processes it to obtain R-D two-dimensional image. So that,

\[
R_{ABO} \approx R_{ABO0} \pm vt_m + \Omega_v \]  \]

(13)

Where \( \Omega_v \) presents the total rotational vector, At time \( t \), the residual translational component of the target's rotation center coordinate \( \chi' \) can be expressed as:
Similarly, the residual translational component of the target’s rotation center coordinate \( z’ \) can be expressed as:

\[
R^\prime_{\Delta CO} = (R^\prime_{CO} - R^\prime_{ref}) - (R^\prime_{AO} - R^\prime_{ref})
\]

\[
= R^\prime_{BO} - R^\prime_{AO}
\]

\[
= \frac{L(L - 2z')}{R^\prime_{BO} + R^\prime_{AO}} \approx \frac{L(L - 2z')}{2R^\prime_{AO}}
\]

(14)

Similarly, the residual translational component of the target’s rotation center coordinate \( z’ \) can be expressed as:

\[
R^\prime_{\Delta CO} = (R^\prime_{CO} - R^\prime_{ref}) - (R^\prime_{AO} - R^\prime_{ref})
\]

\[
= R^\prime_{CO} - R^\prime_{AO}
\]

\[
= \frac{L(L - 2z')}{{R^\prime_{BO} + R^\prime_{AO}}} \approx \frac{L(L - 2z')}{2R^\prime_{AO}}
\]

(15)

Combine with (14) and (15), we can get the new range information. In addition, the CLEAN technique can be used to the peak extraction to acquire a high resolution ISAR image from the defocused image. In this way, the estimation of the effective rotation vector can be calculated by the direction \( \phi = \angle OAO' \) and rotation speed \( \Omega_e \) of the total rotation vector in azimuth direction. Apparently, this is transformed into the calculation process of multiple regression estimation. Then the Doppler peak of antenna A appears at \( -\frac{2R_{AO}}{\lambda} \). According to the definition of Doppler frequency:

\[
f_a = -\frac{2d}{\lambda \Delta t} R_{AO}(t_m)
\]

we can derive its peak value:

\[
f_{dA} = -\frac{R_{AO}}{\pi} \left( \Omega_e \cos \phi \cdot d\phi_{ab} - \Omega_e \sin \phi \cdot d\phi_{ac} \right)
\]

(17)

Make \( a = \Omega_e \cos \phi, \ b = \Omega_e \sin \phi \), the \( k \) th scattering point of echo equation can be written as:

\[
Z_k = aX_k + bX_k
\]

(18)

where \( Z \equiv f_{dA}, \ X \equiv -\frac{2R_{AO}}{\pi} d\phi_{ab}, \ Y \equiv -\frac{2R_{AO}}{\pi} d\phi_{ac} \). In this case, structured the function \( \psi(a,b) \) as:

\[
\psi(a,b) = \sum_{i=1}^{K} [Z_i -(aX_i + bX_i)]^2
\]

(19)

Moreover, we using the LSM to solve the coefficients a and b, the estimation of \( \hat{a}, \ \hat{b} \) can be obtain, then the estimation of \( \Omega_e, \ \phi \) can be expressed respectively as:

\[
\hat{\Omega}_e = \sqrt{\hat{a}^2 + \hat{b}^2}
\]

(20)

\[
\hat{\phi} = \arctan \left( \frac{\hat{b}}{\hat{a}} \right)
\]

(21)

3. Simulation Results Analysis

Here, we show the simulation of 3-D shape target by using a computer tool, which is shown as Fig. 2.
During the simulation, we set the signal-to-noise ratio (SNR) is 10dB, the angle of effective rotation of the vector is $\phi=10^\circ$, the other parameters of the InISAR system are listed in Table 1.

| Parameter | Value     | Parameter | Value     |
|-----------|-----------|-----------|-----------|
| $L$       | 2m        | PRF       | 200Hz     |
| $f_c$     | 10GHz     | $R_0$     | 5km       |
| $B$       | 200MHz    | $\Omega$ | 0.03rad/s |
| $T_p$     | 10 $\mu$s | SNR       | 10dB      |

Fig. 3 shows the result of two-dimensional (2-D) images of dechirp targets before compensation. It can be seen that 2-dimensional imaging will cause false scattered point clusters due to the existence of the quadratic term related to azimuth time, which the image generated by range-doppler method is defocused in azimuth dimension, resulting in the decrease of imaging quality. Fig.4 shows the result of residual translational motion compensation. Apparently, the target scattering 2-D imaging becomes more concentrated after compensation.

In order to accurately estimate the azimuthal peak value, the effective rotation vector $\Omega_z$ is set as 0.03rad/s to 0.07rad/s. The imaging results are shown in Fig 5.
Fig. 4 Residual translational compensation

(a) \( \omega = 0.03\text{rad/s} \)  
(b) \( \omega = 0.05\text{rad/s} \)  
(c) \( \omega = 0.07\text{rad/s} \)

Fig. 5 Imaging results when the effective rotation vector direction rotation angular velocity is \( 0.03\text{rad/s}, 0.05\text{rad/s}, 0.07\text{rad/s} \)

(a) \( \omega = 0.03\text{rad/s} \)  
(b) \( \omega = 0.05\text{rad/s} \)  
(c) \( \omega = 0.07\text{rad/s} \)

Fig. 6 Imaging results when the effective rotation vector direction rotation angular velocity is \( 0.03\text{rad/s}, 0.05\text{rad/s}, 0.07\text{rad/s} \)

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