

MTRC correction algorithm for Bistatic ISAR in presence of constant Bistatic angle

Ning Han

Mechanical Technology Research Institute
Mechanical Engineering College
Shi Jiazhuang, China
haning1103@163.com

GeFang Wang

Mechanical Technology Research Institute
Mechanical Engineering College
Shi Jiazhuang, China

YanMei Lv

Mechanical Technology Research
Institute
Mechanical Engineering College
Shi Jiazhuang, China

MingFei Xia

Mechanical Technology Research
Institute
Mechanical Engineering College
Shi Jiazhuang, China

Dong Zhang

Mechanical Technology Research
Institute
Mechanical Engineering College
Shi Jiazhuang, China

Abstract—With the preliminary hypothesis of constant bistatic angle, matching filter pulse compression with non-coherent bistatic ISAR imaging mechanism is adopted and the reason of space target migration through resolution cell (MTRC) while bistatic inverse synthetic aperture radar (ISAR) imaging is researched. Then the correction algorithm based on Keystone transformation is put forward with the monostatic MTRC correction method as reference analysis thread. The validity of this algorithm is verified through space target ideal scatters simulation experiment.

Keywords—bistatic inverse synthetic aperture radar; moving through cell resolution; constant bistatic angle; direct sampling in medium frequency

I. INTRODUCTION

Over these years, with the rapid development of four-strong-threaten, modern war puts more and more strict demand on the property of modern radar, so the monostatic radar faces more challenge and threat^[1]. With the advantage in safety and anti-destroy, bistatic radar earns more and more attention^[2]. Because bistatic inverse synthetic aperture radar (ISAR) imaging is not restricted by the moving format, bistatic ISAR imaging becomes an important research orientation with its inborn advantage of four-anti property^[3-6].

As the same problem in monostatic ISAR, MTRC also exists in bistatic ISAR. In order to solve this problem, the MTRC correction method in bistatic ISAR is researched^[2]. But the method in [2] can only be used in bistatic turret model. As for the space target with more common character, the turret model can not be used any longer and the correction method becomes invalid.

The echo model of is constructed when target moving track and bistatic baseline is not in the same plane^[7]. Based on the echo model, with the preliminary hypothesis of constant bistatic angle during imaging, the reason why MTRC exists is

researched. Then the MTRC correction algorithm is put forward with the monostatic MTRC correction method as reference analysis thread. Finally, the algorithm is validated via simulation.

II. ECHO MODEL WITH CONSTANT BISTATIC ANGLE

The imaging geometry of moving target in bistatic ISAR is showed in Fig.1.

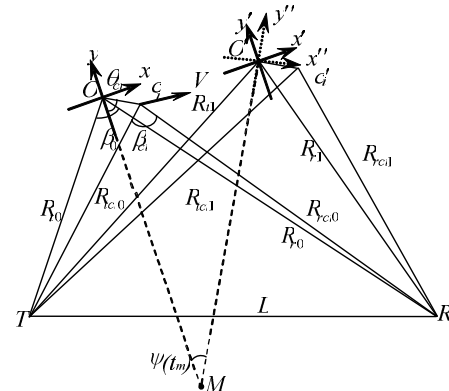


Figure 1. Imaging geometry of bistatic ISAR

In Fig.1, T is transmitting station; R is receiving station; axis y is the bisector of target bistatic angle at the beginning of observation; β_0 is target bistatic angle, β_{ci} is the bistatic angle of scatter c_i in target, and approximately $\beta_0 \approx \beta_{ci}$; O is the phase center; θ_{ci} is the angle of scatter c_i position vector and axis y minus direction; V is target moving velocity, M is the equivalent monostatic radar position at the beginning of observation; $\psi(t_m)$ is rotational angle of bisector during bistatic imaging.

According to the model in Fig.1, [7] concludes that, whether the track of moving target and bistatic baseline belongs to the same plane or not, the changing distance of scatters can be expressed in (1) during the imaging process.

$$\begin{aligned} R_{ci}(t_m) &= R_{ref}(t_m) + R_{rot}(t_m) \\ &= R_{ref}(t_m) - 2r_i \cos[\theta_{ci} + \psi(t_m)] \cos\left[\frac{\beta(t_m)}{2}\right] \end{aligned} \quad (1)$$

In (1), $t_m = mT$ ($m = 0, 1, 2, L$) is slow-time; $R_{ref}(t_m)$ is the distance between phase center and transmitting-receiving bistatic stations which is the translational moving item; $R_{rot}(t_m)$ is the rotational distance item; r_i is the distance between scatter c_i and phase center O ; $\beta(t_m)$ is imaging bistatic angle.

From (1), it shows that, during bistatic ISAR imaging, the changing distance of scatter can also be divided into translational item $R_{ref}(t_m)$ and rotational item $R_{rot}(t_m)$. The only difference is that there is another half bistatic angle cosine in rotational item, which can only affect the concrete data of scatter rotational Doppler but can not change the essence that scatters are differentiated by different Doppler data. So, the principle of bistatic ISAR imaging is similar to monostatic ISAR imaging. The 2D image reconstruction can be accomplished by range compression, translational compensation, cross-range compression and so on^[8].

If some radar transmits LFM signal with the repetition circle T and the bistatic radars are assumed to be ideal synchronized, the baseband echo of scatter c_i after medium-frequency direct sampling then desampling can be expressed as follows.

$$s_{ci}(\hat{t}, t_m) = \sigma_{ci} a_{ci}(\hat{t} - \frac{R_{ci}(t_m)}{c}, t_m) \times \exp\left[-j2\pi f_0 \frac{R_{ci}(t_m)}{c}\right] \quad (2)$$

In (2), σ_{ci} is the non-back scatter intensity of scatter c_i in the i th rangebin; a_{ci} is echocomplex envelope; \hat{t} is fast-time; t_m is slow-time; f_0 is radar carrier frequency.

III. ANALYSIS OF BISTATIC MTRC GENERATION CAUSE

For the bistatic radar system with fixed transmitting-receiving stations, during observation time, the bistatic angle of target can be approximated to be a constant without alteration. Based on this hypothesis, this paper analyzes the cause of bistatic MTRC and research according correction algorithm. For the convenience of narration in the latter of this paper, double passing distance of space target scatter c_i should be changed to be as follows by (3)

$$R_{ci}(t_m) = R_n(t_m) + R_{ri}(t_m) \quad (3)$$

In (3), $R_n(t_m)$ is the translational distance item and the effect of this item is assumed to be totally compensated by

range alignment and initial phase correction; $R_{ri}(t_m)$ is rotational distance item; With the hypothesis that the bistatic angle is constant during imaging, $R_{ri}(t_m)$ can be expressed by (4) as follows.

$$R_{ri}(t_m) \approx -2r_i \cos[\theta_{ci} + \psi(t_m)] \cos[\beta_0/2] \quad (4)$$

Derivate (4), we can get the rotational velocity as (5)

$$v_{ri}(t_m) = 2r_i \sin[\theta_{ci} + \psi(t_m)] \cos(\beta_0/2) \psi'(t_m) \quad (5)$$

With (5), rotational distance $R_{ri}(t_m)$ can be approximated as (6)

$$R_{ri}(t_m) = R_{ri0} + v_{ri}(t_m)t_m \quad (6)$$

In (6), R_{ri0} is the initial rotational distance.

If the rotational angle $\psi(t_m)$ of bisector can be approximated as (7)

$$\psi(t_m) = \psi_0 + \omega t_m \quad (7)$$

In (7), ψ_0 is the initial rotational angle; ω is the rotational velocity of bisector. During the imaging process, the equation $\omega = \omega_0$ is thought to be founded. Now, substitute (7) into (5) and simplify it

$$\begin{aligned} v_{ri}(t_m) &= 2x_i \cos(\psi_0 + \omega_0 t_m) \cos(\beta_0/2) \omega_0 - \\ &2y_i \sin(\psi_0 + \omega_0 t_m) \cos(\beta_0/2) \omega_0 \end{aligned} \quad (8)$$

For the above equation, in the time of $t_m = 0$, spread t_m via TAYLOR principle, and assume $\psi_0 = 0$, high-order item is neglected, we can get the follow equation

$$\begin{aligned} v_{ri}(t_m) &= 2x_i \cos(\beta_0/2) \omega_0 - 2y_i \cos(\beta_0/2) \omega_0^2 t_m \\ &= v_{ri0} + a_{ri0} t_m / 2 \end{aligned} \quad (9)$$

In (9), $v_{ri0} = 2x_i \cos(\beta_0/2) \omega_0$, $a_{ri0} = 4y_i \cos(\beta_0/2) \omega_0^2$.

Substitute (9) into (6)

$$R_{ri}(t_m) = R_{ri0} + v_{ri0} t_m + a_{ri0} t_m^2 / 2 \quad (10)$$

In general, the 3rd item in (10) is relatively smaller and can be neglected. Now, the rotational distance item of scatter c_i during constant bistatic angle can be simplified to be as (11)

$$R_{ri}(t_m) = R_{ri0} + 2x_i \cos(\beta_0/2) \omega_0 t_m \quad (11)$$

When the imaging bistatic angel is fixed to be β_0 , the range and cross-range resolution of bistatic ISAR can be respectively expressed as (12)、(13)^[3]

$$\rho_r = \frac{c}{2B \cos(\beta_0/2)} \quad (12)$$

$$\rho_a = \frac{\lambda}{2\Delta\theta \cos(\beta_0/2)} \quad (13)$$

In the above equations, ρ_r is range resolution; ρ_a is cross-range resolution; c is the light speed in vacuum; B is signal bandwidth; λ is the transmitting signal wave; $\Delta\theta$ is rotational angle of bisector during imaging process.

In ISAR imaging, to get the higher cross-range resolution, rotational angel $\Delta\theta$ with some extent is needed. During the imaging process, if range migration $R_{ri}(t_m)$ of some scatter overpass range resolution ρ_r , then the scatter would generate MTRC. By analyzing (11) and $v_{ri0} = 2x_i \cos(\beta_0/2)\omega_0$, we can know that, in bistatic ISAR imaging, the rotational movement of bisector will generate the MTRC of scatter. And the larger the cross dimension of scatter is, the MTRC is more severe. Take $\lambda = 2\text{cm}$, $B = 900\text{MHz}$, $x_1 = 5\text{m}$, $x_2 = 4\text{m}$, $\omega_0 = 0.1\text{rad/s}$ as the example. Assume the bistatic angle is a constant as 40° , then the range resolution ρ_r is 0.1774m , and if we expect the cross-range resolution to be 0.15m , the rotational angel has to be at least 4.0623° . Now, the range migration of scatter x_1 and scatter x_2 is respectively 0.6662m , 0.533m , which migrate 3.76 and 3 rangbins respectively. So, the range dimension of target image defocuses and the MTRC correction is needed to generate the clear image.

During the above analysis process, the 3rd item of (10) is neglected. The neglected item is related to range dimension. So to be strictly researched, the MTRC extent of scatter is not only related to the cross-range dimension but also related to the range dimension. But the square of imaging time is usually very small, so the neglecting of this item is totally acceptable.

IV. MTRC CORRECTION ALGORITHM

As the effect of $R_{ri}(t_m)$ has been totally removed, we can change (2) from time zone to frequency zone and get (14) as follows

$$S_r(f, t_m) = A(f) \sigma_a \exp\left[-j2\pi(f + f_0) \frac{R_{ri}(t_m)}{c}\right] \quad (14)$$

In (14), $A(f)$ is the fourier transformation of $a_{ci}(\hat{t} - \frac{R_{ri}(t_m)}{c}, t_m)$. Multiply (14) with $A^*(f)$ to accomplish matching filter, we get (15) as follows

$$S_r'(f, t_m) = |A(f)|^2 \sigma_a \exp\left[-j2\pi(f + f_0) \frac{R_{ri}(t_m)}{c}\right] \quad (15)$$

Substitute (11) into the last equation

$$S_r'(f, t_m) = |A(f)|^2 \sigma_a \exp\left[-j2\pi(f + f_0) \frac{R_{ri}(t_m)}{c}\right] \times \exp\left[\frac{-j2\pi}{c}(f + f_0)v_{ri0}t_m\right] \quad (16)$$

In (16), $\sigma_a = \sigma_{ci} \exp(-j2\pi R_{ri0}f_0/c)$. In (16), the 1st index item of spectrum is the position of target in time zero. The 2nd index item can be treated as different frequency with according different Doppler frequency shifts, which equals the MTRC of scatter.

In monostatic ISAR imaging, Keystone transformation is usually used to solve the MTRC problem. As the analysis thread to be refereed, this paper puts MTRC to be used in bistatic ISAR to correct MTRC. So, the virtual slow-time τ_m is defined and it satisfies (17)

$$(f + f_0)t_m = f_0\tau_m \quad (17)$$

Substitute (17) into (16), we can get the spectrum after Keystone transformation

$$S_r'(f, \tau_m) = |A(f)|^2 \sigma_a \exp\left[-j2\pi f \frac{R_{ri0}}{c}\right] \times \exp\left[\frac{-j2\pi}{c}f_0v_{ri0}\tau_m\right] \quad (18)$$

From (18), we can conclude that, after Keystone transformation, the 2nd index item in echofast-time spectrum has nothing to do with frequency and the linear movement of echo envelope has been removed. Now, anti-transform (18) to be time-zone and we can get the echo after MTRC corrected.

In fact, Keystone transformation is the scale transformation of slow-time axis t_m . The transformation extent is related with fast-time \hat{t} . The initial data in (2) is aligned with rectangular shape, in $\hat{t} - t_m$ plane. After Keystone transformation, the data is changed to be in $\hat{t} - \tau_m$ plane and the shape is changed to be trapezium shape. To compress the data in azimuth dimension, the according algorithm is researched to change the data to be rectangular. To solve this problem, the scale-variant transformation, which can accomplish Keystone transformation, is studied. This method changes the data in $\hat{t} - t_m$ plane to data in frequency zone which is in accordance with virtual slow-time τ_m . Then, the data in frequency zone is inverse fourier transformed to $\hat{t} - \tau_m$ plane and the data is rectangularly aligned now. At the same time we get the rectangular-shape data, the interpolation operation is avoided, which efficiently improves algorithm counting efficiency. With the above described advantages, this paper adopts the method to finish the Keystone transformation of data. In general, the MTRC correction method for bistatic ISAR of space target could be divided into such steps:

Step1: For the complex baseband echo, the match-filter pulse compression process is firstly executed to get the initial data without MTRC correction;

Step2: The translational compensation is carried out to remove the effect of translational item $R_{ri}(t_m)$;

Step3: The scale-variant fourier transformation and inverse fourier transformation is accomplished to finish the

Keystone transformation of echo data and get the data after MTRC correction;

Step4: Azimuth compression of data after correction is finished to get 2D image of the target.

The above analysis and study is only aimed at sole scatter MTRC correction method. In practical imaging process, target is composed of many scatters and the real echo could be treated as linear composition of the echo of every scatter. So, the algorithm researched in this paper could easily extend to the real target imaging process.

V. SIMULATION EXPERIMENT

This paper makes research on space target imaging. So, the simulation experiment is also aimed at space target bistatic ISAR imaging. The simulation scene and scatter model is showed in Fig.1 and Fig.2 respectively.

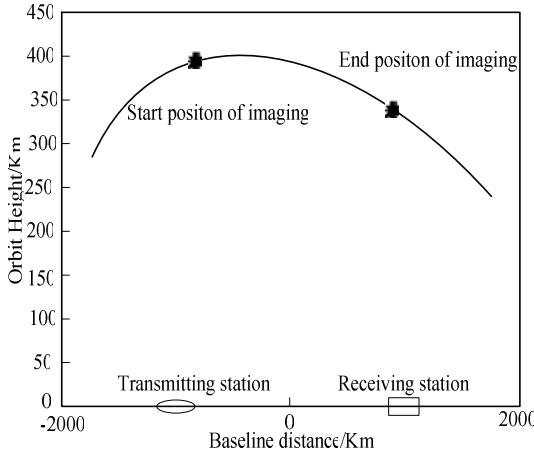


Figure 1. simulation scene

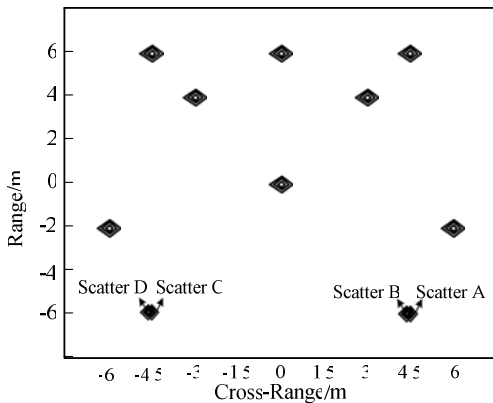


Figure 2. Scatter model

In Fig.1, circle stands for the transmitting station and rectangle stands for receiving station. The height of target circle is about 300Km, and the double passing distance is 4Km/s. Target circle is generated by STK software, and the circle parameters is set to guarantee the bistatic angle keeps constant during imaging process. In simulation, target is substituted by scatter model. As in Fig.2, the RCS of target is set to be 6m². Because the scatters energy in wideband

imaging is separated, so the equivalent RCS of every scatter is 0.5m². With the imaging resolution cell taken into consideration, the RCS level is normal in space target imaging. The signal-to-noise ratio of this imaging circle could be easily counted.

TABLE 1 PARAMETERS OF BISTATIC RADAR IN SIMULATION

parameter	index	parameter	Index
Carrier frequency	8GHz	Pulse width	30μs
Signal bandwidth	900MHz	Sampling frequency	1.5GHz
Pulse repetition frequency	150Hz	Baseline length	2000Km

Fig.1 shows the radar parameters of bistatic radar in simulation. During imaging simulation, the rotational velocity ω_0 of bisector is assumed to be 0.1rad/s and the bistatic angle is 120°. Now, according to (12), the image resolution is 0.33m. The cross-distance between A、B and C、D is 0.15m respectively. To differentiate the four scatters in cross-distance, the needed imaging rotational angle is 0.25rad counted by (13) according to the parameters in table 1. Within these imaging conditions, scatter A moves 1.125m during imaging process and migrates about 3.4 range cells because the rotation of bisector. So the MTRC correction is needed to get clear 2D image. Fig.3 and Fig.4 demonstrate the bistatic 2D images before and after MTRC.

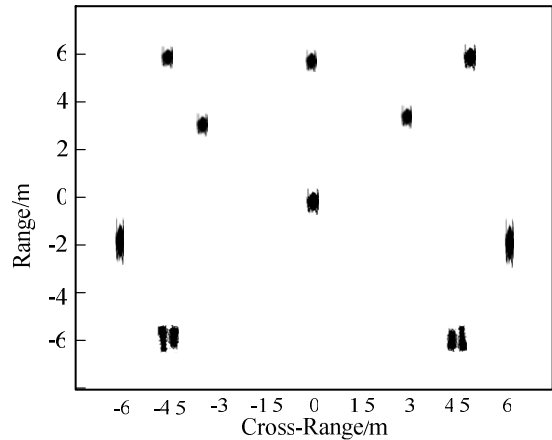


Figure 3. 2D image before MTRC correction

As in Fig.3, because the rang resolution is 0.33m, the 2D image can totally differentiate the 5 scatters which are in different range cells. And because the rotational angle during imaging process is 0.25rad, scatters A、B and scatters C、D could be differentiated in Doppler dimension. Fig.3 still shows that target scatters moves through some range resolution cells that is MTRC happened. And the larger the cross-range of scatter is, the MTRC is more severe, which is in accordance with the previous theoretical analysis.

Now, the 2D image is corrected via the algorithm researched in section 3 and we get the image after correction in Fig.4

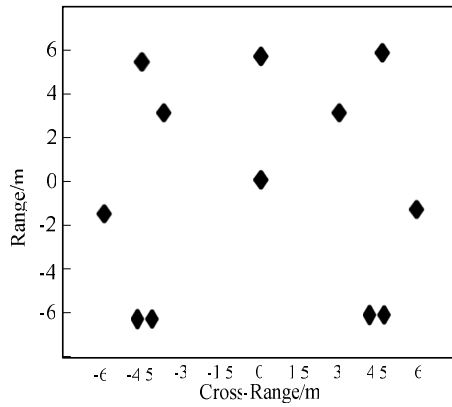


Figure 4. 2D image after MTRC correction

As shown in Fig.4, MTRC of scatters has been totally corrected and we get the clear image, which verifies the algorithm.

VI. CONCLUSION

With the assumption that the bistatic angle keeps constant during imaging process, the character of complex bistatic ISAR baseband echo is researched and the conclusion that the rotation of bisector during imaging process could lead to the MTRC is got. Keystone transformation is adopted to remove the MTRC in target range profile. Finally, space target model with ideal scatters is adopted in simulation experiment. The

experiment results show that Keystone transformation could effectively remove MTRC in bistatic ISAR.

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