

DISTORTION IN THE ISAR (INVERSE SYNTHETIC APERTURE RADAR) IMAGES FROM MOVING TARGETS

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ABSTRACT

A physics-based numerical model has been developed to model the formation of severe distortion that is observed in ISAR images from moving targets. When a target possesses a small time-varying perturbed motion, a modulation effect is introduced in the phase of the radar return from the target. As a result, a broad smearing appears in the cross-range of the ISAR image. An experiment is devised to demonstrate that significant distortion can occur in the ISAR image when a small perturbing motion is imposed on a target. The measured data are also used to validate the simulated results from the model. Excellent agreement is obtained between the simulated and measured ISAR images. The numerical and experimental studies described in this paper provide a better understanding of the distortion mechanism in ISAR imaging of moving targets.

INTRODUCTION

Inverse Synthetic Aperture Radar (ISAR) imaging provides a 2-dimensional radar image of a target. A 2-dimensional picture can potentially offer crucial distinctive information about the features of the target that can lead to more accurate target identification in Non-Cooperative Target Recognition application. However, ISAR image is generated from the target's rotational motion. This motion can be quite complex, such as the motion of a fast, maneuvering jet aircraft. As a result, severe distortion can occur in the ISAR image of the target [1]. An illustration is shown in Figure 1. Two ISAR images of an in-flight aircraft were taken in a consecutive sequence in time. The image on the left is well focused; the image on the right is severely blurred. It has been recognized that a time-varying Doppler shift due to perturbed motion in the rotation of the target is responsible for the image blurring [2].

Analyses of the target's rotational motion appearing in the literature describe the time-varying Doppler in terms of quadratic phase distortion and range-Doppler coupled migration [3, 4, 5]. Assumptions of range-Doppler coupling migration and quadratic distortion do not provide an adequate description of the severe distortion that are observed in some of the ISAR images of moving targets, in particular, from in-flight aircraft. A numerical model based on a time-varying rotational rate of the target

is developed to model the formation of distortion that is often observed in ISAR images of maneuvering targets. The distortion is attributed to a phase modulation effect in the returned radar echo from the target.

DESCRIPTION OF THE ISAR DISTORTION PROCESS

The phase of the radar return signal from a scatterer on a moving target is given by ,

$$\varphi = \frac{4\pi f}{c} (R - vt - X(t)) \quad (1)$$

where f is the transmitting radar frequency, R is the initial distance of the scatterer on the target from the radar at the on-set of the ISAR imaging scan, v is the radial velocity of the target and $X(t)$ is the displacement due to the rotation of the target along the radar's line of sight. Consider a scatterer on a 2-dimensional target with a pair of coordinates (x_0, y_0) with respect to the centre's rotation initially at time t_0 . The displacement along the radar's line of sight $X(t) = x(t) - x_0$ due to a rotation of the target is given by

$$X(t) = \left(x_0 \cos(\omega(t)t) - y_0 \sin(\omega(t)t) \right) - x_0 \quad (2)$$

Note that in order to describe a small fluctuation in the rotational motion, the rotational rate is written as a function of time, i.e., $\omega(t)$. That is to say, the temporal variation in the angular rotational rate is important for describing the ISAR distortion properly. A fluctuating motion can be superimposed on a constant rotation to generate distortion in the ISAR image; i.e.,

$$\omega(t) = \omega_c + \omega_r \sin(2\pi \Omega t) \quad (3)$$

where ω_r is the rotational amplitude, which is a function of Ω ; i.e., $\omega_r(\Omega)$ and its value increases with an increasing Ω . A simple sinusoidal motion is chosen here for the ease of numerical analysis and experimental validation. However, a realistic random fluctuating motion can be accurately described using a Fourier series, containing many sinusoidal terms [6].

The High Range Resolution (HRR) profile of a scatterer on a target can be expressed as [7],

$$H_l = \frac{A}{N} \frac{\sin\left(\frac{N\alpha}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)} \exp[j(\xi + \gamma R)] \exp[-j\gamma X(t)] \quad (4)$$

where

$$\xi = \frac{(N-1)}{N} \pi l, \quad \gamma = \frac{4\pi}{c} f_c,$$

$$\alpha = \frac{2\pi}{N} \left[\frac{2}{c} (R - X(t)) \beta + l \right],$$

A is the signal response of the scatterer, β is the bandwidth of the radar waveform, f_c is the band-centre frequency of the radar waveform and l is the range-bin index, $l = 0, \dots, N-1$. The first phase factor in equation (4), $\exp(j(\xi + \gamma R))$ determines the location of the scatterer's peak within the HRR range window. The second phase factor, $\exp(-j\gamma X(t))$ contains the rotational motion of the target. By substituting the expressions in Equations (2) and (3) into $X(t)$ in Equation (4), the phase factor, $\exp(-j\gamma X(t))$ can be rewritten as

$$\psi(t) = \exp(-j\gamma X(t)) = \zeta(t) \mu(t) \quad (5)$$

The first factor $\zeta(t) = \gamma y_0 \omega_r t$ corresponds to a uniform rotation of the target, forming an undistorted ISAR image in the absence of any fluctuating motion. The second factor $\mu(t)$ describes the phase modulation effect due to a small fluctuating motion of the target, introducing distortion to the ISAR image. To see the modulation effect more clearly, $\mu(t)$ is given by [7],

$$\begin{aligned} \mu(t) &= \exp\left(j\gamma y_0 \omega_r \int \sin(2\pi\Omega t) dt \right) \\ &= \exp(-j k \sin(\eta)) \\ &= \cos(k \sin(\eta)) - j \sin(k \sin(\eta)) \\ &= (J_0(k) + 2J_2(k) \cos(2\eta) + 2J_4(k) \cos(4\eta) + \dots) \\ &\quad - j (2J_1(k) \sin(\eta) + 2J_3(k) \sin(3\eta) \\ &\quad + 2J_5(k) \sin(5\eta) + \dots) \end{aligned} \quad (6)$$

where

$$k = \gamma y_0, \quad \eta = \sin^{-1} \left[-\omega_r \int \sin(2\pi\Omega t) dt \right]$$

and the J_s are the Bessel functions. It can be seen from Equation (6) that the time-varying motion consists of many higher order side-bands components as given by the Bessel functions. These higher order components have been shown to be responsible for the distortion appeared in High Range Resolution radar images [6].

To generate an ISAR image, a sequence of M consecutive HRR profiles is used. Each HRR profile has N range bins. Assuming the HRR profiles are range aligned and phase aligned among one another, a Fourier transform is performed at each down-range bin of the M HRR profiles to generate the cross-range bins. A matrix of M by N elements of cross-range and down-range bins are then used to construct the ISAR image; i.e., the intensity distribution of an ISAR image is given by [7],

$$I_{m,l} = \sum_{k=0}^{M-1} |H_{l,k}| \zeta_k \mu_k \exp\left[j \frac{2\pi}{M} m k \right] \quad (7)$$

where the subscript m is the cross-range index, $m = 0, \dots, M-1$. M is the number of HRR profiles used and l is the down-range bin index, $l = 0, \dots, N-1$.

EXPERIMENTAL VERIFICATION OF THE DISTORTION IN ISAR IMAGES

To verify the distorting effect in ISAR images, a delta-wing shaped target (Target Motion Simulator) was designed and built. Six trihedral reflectors were mounted on the apparatus as scattering sites on the target. A picture of the Target Motion Simulator experimental apparatus is shown in Figure 2. The delta-wing target measured 5 m on each of its three sides. The trihedral reflector has a length of 0.5 m on each of the sides, giving a radar cross section of 25dB. The fluctuating motion of the delta-wing target was provided by a programmable motor drive. The target was placed approximately 2 km from the radar. Data were collected from a radar system that employed a continuous FM-modulated waveform at X-band with a 300 MHz bandwidth, centred at 10.1 GHz. The ISAR image of the target has a down-range resolution, $\Delta r_d = 0.5$ m and a cross-range resolution, $\Delta r_c = 0.6$ m. When the target is rotating at a constant rate, its ISAR image is undistorted. Figure 3 shows an undistorted ISAR image of the target from the measured data; the target is rotating at 1.4 degrees/s. The six trihedral reflectors can be seen clearly. A small sinusoidal motion with an end-to-end amplitude of about 1 degree and an oscillating frequency of 1 Hz is then superimposed on top ISAR image as a result of the time-varying fluctuating of the constant rotation. Figure 4a shows a distorted motion. The corresponding ISAR image computed by the numerical model is shown in Figure 4b. The model predicts significant distortion in the ISAR image and the amount of distortion predicted compares quite well with the measured data.

CONCLUSION

We have demonstrated experimentally that the ISAR images of a target can suffer severe distortion when the target possesses a small time-varying perturbed motion during the image integration period. The large distortion is attributed to the modulation effect in the phase of the return signal of the target due to a fluctuating motion. This results in blurring in the cross-range direction of the ISAR image. A numerical model of the distortion process has been developed and has been shown to predict accurately the amount and the characteristics of the distortion in the ISAR images. The numerical predictions have been validated by experimental data. The model allows us to gain a better understanding of the distortion process in ISAR imaging. The new insights that have been obtained enable us to develop an efficient procedure for refocusing ISAR images for target recognition [8].

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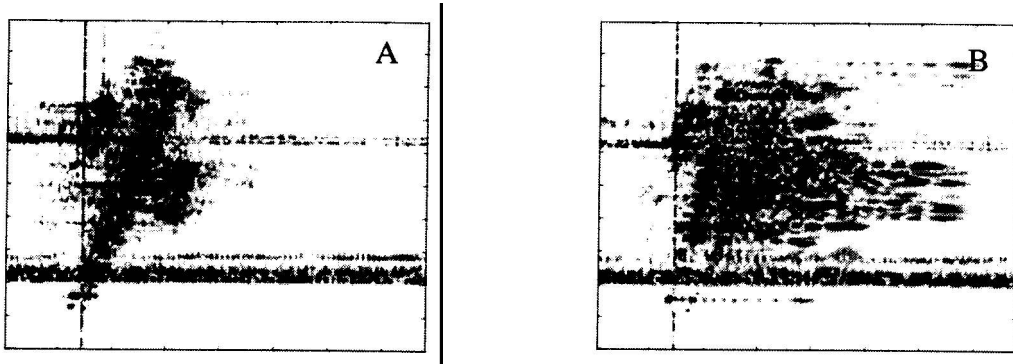


Figure 1 Experimentally measured ISAR images of an in-flight aircraft. a) well focused ISAR image; b) distorted ISAR image. Reference [1] Sparr et al.



Figure 2 The Target Motion Simulator experimental apparatus.

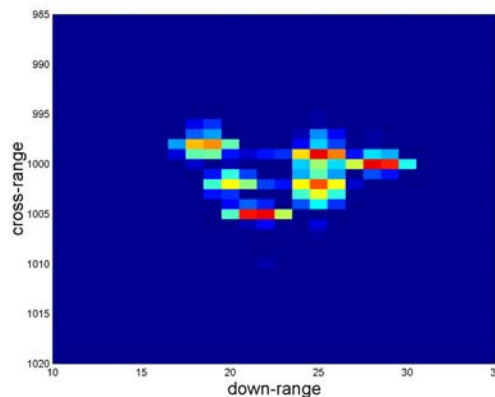


Figure 3 An undistorted ISAR image of the Target Motion Simulator (experimental image).

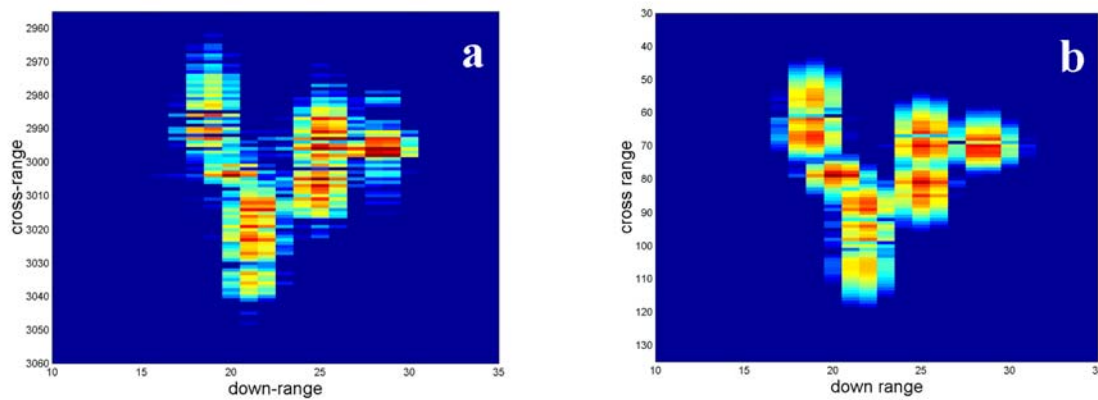


Figure 4 Distorted ISAR images of the Target Motion Simulator due to a small fluctuating motion introduced to the target. a) experimental, b) simulated.