Compensation for System Distortion Using Low Signal-to-noise-ratio Echo from Spherical Satellite

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Abstract— Compensation for amplitude and phase distortion in inverse synthetic aperture radar (ISAR) system is important for the system performance. People cannot help but take an active radar calibrator on a tower as an external test target to measure the distortion and carry out the compensation though it includes extraneous components and induces additional distortion. So a new method for distortion compensation is presented, which is based on the low signal-to-noise-ratio (SNR) echo from a spherical satellite. The technique of pulse compression based on matched filtering is used and then the target region is extracted and inverse matched filtering is applied to achieve the high SNR echo. Thus the amplitude and phase error coefficients can be calculated, which results in excellent compensation for the system distortion. Experimental results based on real radar data show the effectiveness of the proposed method. Comparison results with other scheme are also presented to prove the superiority of our approach.

1. INTRODUCTION

Inverse synthetic aperture radar (ISAR) has a rapid development all over the world, owing to its high resolution and the ability to extract target information such as structure, motion state, and other target identifying characteristics in all-weather and night and day circumstances [1]. In order to achieve the high-range resolution, ISAR system operates over large bandwidths, which brings in the issue of distortion. The non-ideal components comprising the system are not able to keep linear amplitude and phase characteristics across the bandwidth [2]. The generated waveform may undergo distortion in the transmitter, antenna, propagation medium [3, 4], and the receiver and so on. Thus the actual transmitted and received signal deviates from the ideal signal, which results in the bad performance of the signal-to-noise-ratio (SNR) and major lobe and side lobe.

There are two types of techniques to measure the amplitude and phase distortions in the system: closed loop and the employment of an external test target [2]. The former including pre-distortion technique [5–7] excludes antenna and propagation medium, leading to limited results. The latter uses the complete system and is better. The type of the test target may be a corner reflector, a metallic ball towed by a balloon, an active radar calibrator (ARC) on a tower, or a spherical satellite. However, the reflector suffers from high level of clutter. The metallic ball is difficult to carry out daily in practice. The current approach is to use the ARC. But the ARC includes optic transceivers, fibre-optic delay line, and amplifiers, inducing additional distortion [2]. Although it is best to take the spherical satellite as the test target, it is unpractical because the SNR is too low.

In this paper, we analyse the reason why the low SNR signal received from the satellite fails to compensate for the distortion. Then we utilize pulse compression technique based on matched filtering (MF) to find the target region and then take inverse MF on the region to get high SNR signal. Thus we can achieve the distortion coefficients and compensate for the system distortion. Experiments based on real radar data show that the results are better than that by the ARC.

2. THEORY STUDY AND PROPOSED METHOD

2.1. Theory of Compensation for System Distortion

Compensation for distortion in a system using stretch processing in pulse compression is complicated [8, 9]. But it is much simpler in a system using matched-filter correlation processing in pulse compression, because the system can be treated as a series of linear wideband sub-systems such as a transmitter, an antenna, a receiver and so on.

Let $F_{\text{ideal}}(f)$ represent the spectrum of the ideal transmitted signal $f_{\text{ideal}}(t)$. Denote $F_{\text{actual}}(f)$ as the spectrum of the actual received signal $f_{\text{actual}}(t)$ from the test point target. As for the linear system, the transmission characteristic can be obtained as follows:

$$H(f) = \frac{F_{\text{actual}}(f)}{F_{\text{ideal}}(f)} \tag{1}$$

A physical system will exhibit nonlinear frequency responses that can be described by a Fourier series expansion as follows [10]:

$$H(f) = \left[a_0 + \sum_{n=1}^{\infty} a_n \cos(2\pi c_n f)\right] \cdot \exp\left[-j2\pi b_0 f - j\sum_{m=1}^{\infty} b_m \sin(2\pi d_m f)\right] \tag{2}$$

which represents the system distortion. Thus (1) also represents the amplitude and phase error coefficients of the signal across its frequency band. And with the distortion coefficients we can compensate the radar returns as follows [2]:

$$F_{\text{comp}}(f) = \frac{F_{\text{target}}(f)}{H(f)} = F_{\text{target}}(f) \cdot \frac{F_{\text{ideal}}(f)}{F_{\text{actual}}(f)} \tag{3}$$

where $F_{\text{comp}}(f)$ is the compensated spectrum and $F_{\text{target}}(f)$ is the distorted spectrum of the real target. Thus, the compensated signal $f_{\text{comp}}(t)$ can be obtained by the inverse Fourier transform of $F_{\text{comp}}(f)$.

Specially, if the real target is just the test point target, then (3) would become:

$$F_{\text{comp}}(f) = F_{\text{ideal}}(f) \tag{4}$$

Hence, the compensated spectrum of the test point target is the ideal spectrum of the signal that is aimed to be transmitted. Thus, after the compensation we can obtain the undistorted signal.

2.2. Method for Compensation in Low SNR Condition

From the scheme described above, we can see that the key issue is the validity of the distortion coefficients in (1). However, the above scheme does not take into account noise. In practice, the signal from the target includes noise. Hence, (1) should be rewritten as:

$$H(f) = \frac{F_{\text{actual}}(f) - F_{\text{noise}}(f)}{F_{\text{ideal}}(f)} \tag{5}$$

where $F_{\text{noise}}(f)$ is the noise spectrum.

In high SNR condition, $F_{\text{noise}}(f)$ is much smaller than $F_{\text{atual}}(f)$, so it can be passed over and the coefficients calculated by (1) are effective. Whereas, in low SNR condition, $F_{\text{noise}}(f)$ is as much as $F_{\text{atual}}(f)$, so it must be taken into account and the coefficients calculated by (1) are ineffective.

According to (2), the phase characteristic of the real system is probably linear though it somewhat departs from the ideal linear. However, the phase characteristic calculated by (1) is far from linear in low SNR condition. Fig. 1 shows the situation. Fig. 1(a) shows the phase characteristic calculated by (1) based on the signal received from the ARC in high SNR condition while Fig. 1(b) from the spherical satellite in low SNR condition. We can see that the former is approximately linear while the latter is completely nonlinear. Hence the latter cannot exactly represent the characteristic of the system and is ineffective.

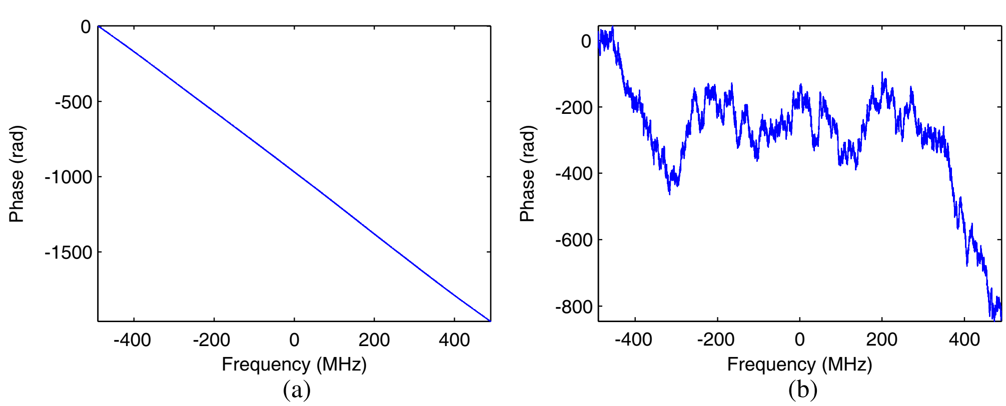


Figure 1: Phase characteristic calculated by (1) based on the echo from: (a) ARC in high SNR condition, and (b) satellite in low SNR condition.

Our method is to improve the SNR. It is well known that the signal power can be increased BT (B is the bandwidth and T is the pulse width) times by using pulse compression technique for the linear frequency modulation waveform. The quantity BT is referred to as the time-bandwidth product. As the ISAR system utilizes frequency modulation, the time-bandwidth product can be much greater than unity. Hence, the target region can be quickly found after pulse compression and then the SNR can be increased by inverse dealing. The concrete steps are as follows:

Step 1. Take the spherical satellite as the test target and get the received discrete-time signal $f_{\text{actual}}(t_n)$, which is low SNR.
Step 2. Take MF on $f_{\text{actual}}(t_n)$ and get the high-resolution range profile (HRRP) $f_{\text{actualM}}(t_n)$.
Step 3. Find and extract the target region $f'_{\text{actualM}}(t_n)$.
Step 4. Take inverse MF on $f'_{\text{actualM}}(t_n)$ and get $f'_{\text{actual}}(t_n)$, which is high SNR.
Step 5. Calculate the distortion coefficients: obtain the spectrum $F'_{\text{actual}}(f_n)$ of $f'_{\text{actual}}(t_n)$; construct the ideal transmitted signal $f_{\text{ideal}}(t_n)$ and get its spectrum $F_{\text{ideal}}(f_n)$; the ratio of the two spectra produces the transmission characteristic $H(f_n) = A(f_n)\cdot\exp[jP(f_n)]$, where $A(f_n)$ is the amplitude-frequency response and $P(f_n)$ is the phase-frequency response.
Step 6. Implement the least squares curve fitting on $P(f_n)$ to get the linear phase-frequency response $P'(f_n)$. Let $\Delta P(f_n) = P(f_n) - P'(f_n)$, which represents the departure between the actual phase response of the system and the ideal linear one. The coefficients used for compensation can then also be $\Delta H(f_n) = A(f_n)\cdot\exp[j\Delta P(f_n)]$.
Step 7. Take the Fourier transform on the received signal $f_{\text{target}}(t_n)$ from the real target to get $F_{\text{target}}(f_n)$ and divide it by the coefficients $H(f_n)$ or $\Delta H(f_n)$ to obtain the compensated spectrum $F_{\text{comp}}(f_n)$. After the inverse Fourier transform the compensated signal $f_{\text{comp}}(t_n)$ is achieved.

Steps 1 to 5 are enough for obtaining the distortion coefficients. Step 6 is for calculating the departure between the actual and ideal phase responses. A flowchart for better understanding of the proposed method is given in Fig. 2. After the compensation, we can carry out MF, motion compensation, and the range-Doppler method to get a clear image of the target.

The phase characteristic based on the above signal received from the spherical satellite in low SNR condition after processing is shown in Fig. 3, which is approximately linear now. Thus, the effective distortion coefficients can also be achieved in low SNR condition with the proposed method.

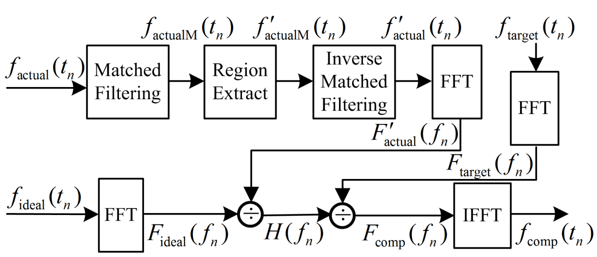


Figure 2: Flowchart of the proposed method.

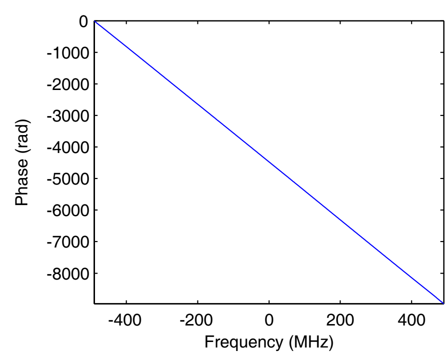


Figure 3: Phase characteristic based on the echo from satellite in low SNR condition after processing.

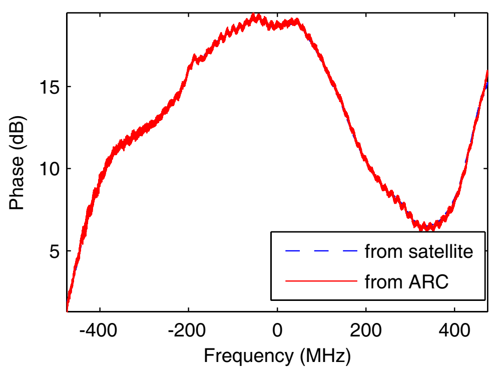
3. EXPERIMENT

The experiments are carried out on the basis of some ISAR system under field conditions in China. We take an ARC and a spherical satellite as the external test targets one at a time on the same day. And a non-point target is also observed.

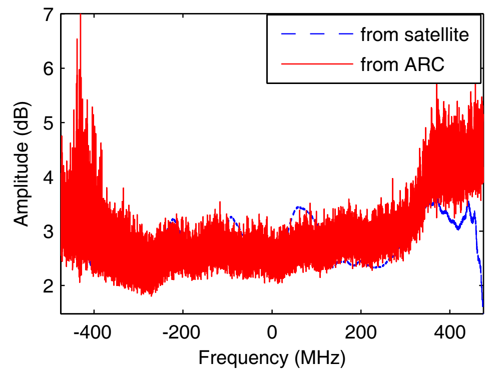
In order to demonstrate the effectiveness of the distortion coefficients calculated by the proposed method, we calculate the phase errors $\Delta P(f_n)$ based on the received signals from both the ARC and the satellite as shown in Fig. 4(a). The comparison of amplitude responses $A(f_n)$ is shown in Fig. 4(b). We can see the phase errors $\Delta P(f_n)$ are almost the same and the amplitude responses

$A(f_n)$ are similar. Thus the distortion coefficients extracted from the satellite echo are probably equivalent to those extracted from the ARC echo. As a result, the distortion coefficients calculated by the presented method are effective and can be used to compensate for the system distortion.

In order to see the compensation effect, we use the above two distortion coefficients to compensate some other echo from the spherical satellite and then apply MF to get the HRRP. The results are shown in Fig. 5. Due to the system distortion, the HRRP does not seem like a point target, and the SNR, the range resolution, and the time side lobe performance are significantly degraded before compensation. And the compensation is the solution. Furthermore, compensation by the spherical satellite is better than that by the ARC. This is because the ARC includes extraneous components, which induce additional distortion.



(a)



(b)

Figure 4: Comparisons of distortion coefficients extracted from satellite echo and ARC echo: (a) phase errors $\Delta P(f_n)$, and (b) amplitude responses $A(f_n)$.

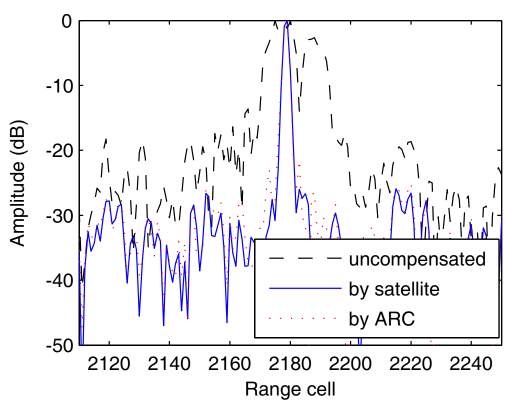
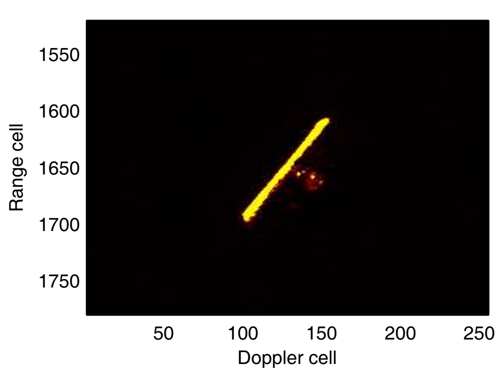
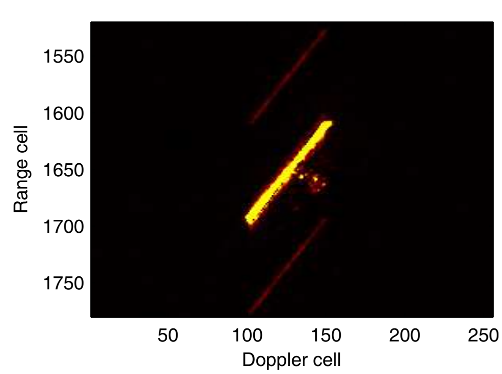


Figure 5: Comparison of the compensation results.



(a)



(b)

Figure 6: ISAR imaging results of non-point target after compensation: (a) by satellite, and (b) by ARC.

Compensation for the non-point target is presented to prove the effectiveness and the superiority of our method in Fig. 6, where ISAR imaging results are shown. Fig. 6(a) is the result after compensation by the satellite while Fig. 6(b) by the ARC. Comparing the two figures, we can see that the former has a clearer image of the target than the latter. And the latter has two virtual images symmetrically beside the target image, owing to the additional distortion of the ARC.

4. CONCLUSION

In the absence of any method for compensating for the system distortion, the system performance will be badly degraded. Theoretically speaking, the spherical satellite is the best external test target. But in practice, the SNR is too low. In this paper, we solve the problem based on MF and inverse MF techniques. Experiments using real radar data have verified the effectiveness and the superiority of our method. Yet, it should be mentioned that this study only focuses on the system distortion compensation, and thus compensation for target motion errors needs to be further studied for better imaging results.

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