A Novel 3-D Imaging Technique for Interferometric Circular SAR System

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Abstract

This paper introduces an interferometric circular synthetic aperture radar (CSAR) system for three dimensional (3-D) imaging of targets. A new interferometric CSAR method is presented by using the phase difference between a pair of two dimensional (2-D) CSAR images which are reconstructed from data obtained at two distinct circular apertures. Compared with the conventional interferometric SAR along a straight path, this imaging mode can be used not only to detect the hidden target in the scene, but also to improve the resolution of SAR system. To demonstrate the imaging capabilities of this approach, an indoor experiment is conducted within microwave chamber at X-band frequencies (8–12 GHz).

1. Introduction

Circular synthetic aperture radar (CSAR), which operates along a circular path, has raised an increasing interest in the SAR community [1-4]. Compared with conventional SAR using a straight path, three main merits have been exploited for such geometry. First, obtaining data from a circular orbit can be helpful in improving the resolution of SAR system. Second, observing from different directions can detect hidden target when its orientation is unknown. Third, the circular SAR system can be used to reconstruct the 3-D profile of the target. For a highly directive target, it has no resolving ability in the direction normal to the data collection plane. This is the main restriction to CSAR tomography, particularly in airborne applications, where the look angle diversity is usually large.

CSAR imaging system was firstly be used in two dimensional high resolution imaging. One method for CSAR imaging is to divide the 360 degree circular path into small arc segments, and then to utilize the reconstruction algorithm for the linear SAR system with slant correction [5]. Another algorithm which was based on the Fourier analysis for CSAR was presented in [6]. However, it only acquired the two dimensional circular SAR image, which is not accurate when the targets are distributed in three dimensional space.

CSAR can be used for 3-Dimaging, which is known as elevation and circular synthetic aperture radar (E-CSAR) system [7-8]. The sensitivity of the algorithm in the altitude domain depends on the target's support region in the frequency domain. The height resolution for this system is limited by the volume occupation in the spatial frequency domain. Another way to obtain the height resolution is by adding multi-pass in height direction [9]. However, it must be measured at uniform elevation angle intervals, which is hardly satisfied in the real environment.

In this paper, an imaging algorithm for three dimensional target reconstruction with interferometric CSAR observations is proposed. It uses the phase information of two CSAR images which are formed from the data collected at two complete circular apertures. The advantage of this method is that it can obtain high resolution image with height information. This method is verified by the experimental result obtained within the microwave chamber.

2. System Model

The geometry of interferometric circular SAR is illustrated in Figure 1. The targets with reflection coefficient $\psi(x, y, z)$ are placed on the turntable which can rotate around the plane $u-v$ with its origin at O, as shown in Figure 1(a). The distance between the transmit antenna and origin is R_0, and the position of transmit antenna (Tx) in the coordinate $O-uvz$ is $(0, -R_0, 0)$. The position of receive antennas ($Rx1$ and $Rx2$) in the coordinate are

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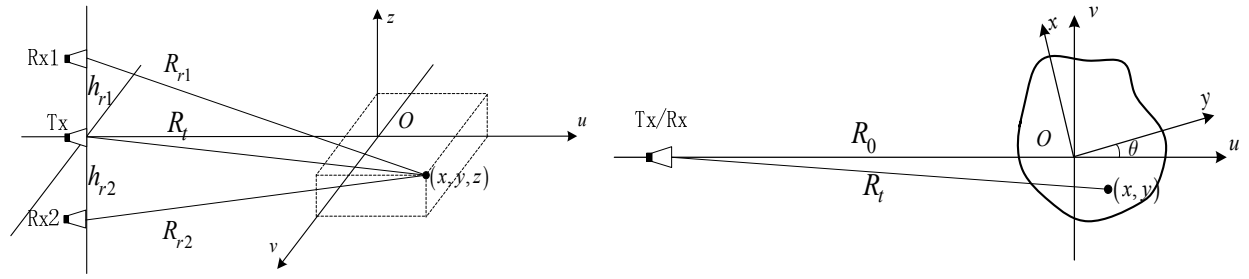
$(0,-R_0,h_{r1})$ and $(0,-R_0,h_{r2})$. The distance between the transmit antenna and target is R_t, and the distance between the receive antennas and target are R_{r1} and R_{r2} respectively. Figure 1(b) gives the top view of the system. The rotated angle θ stands for the instantaneous position of the turntable. The coordinate $O-uv$ is related to radar, and the coordinate $O-xy$ is related to target.



(a)Side view (b) Top view

Fig. 1 Geometry of the system

3. Imaging Algorithm

Assuming the transmit antenna and receive antennas are located in the far-field region of the objects, thus the amplitude attenuation of the scattering field is negligible compared to the phase contribution. The scattering electric field of targets can be expressed as

$$E_{si}(f,\theta)=C_0\iiint_{D^3}\psi(x,y,z)\exp\left[-j\frac{2\pi}{\lambda}(R_t+R_{ri})\right]dxdydz \tag{1}$$

Where C_0 is constant; D is the region of the targets. The wavelength of the signal is λ, and the subscript $i=1,2$ refer to two receive antennas. The distance R_t and R_{ri} are expressed as

$$R_t(x,y,z)=\sqrt{u^2+(v+R_0)^2+z^2} \tag{2}$$

$$R_{ri}(x,y,z)=\sqrt{u^2+(v+R_0)^2+(z-h_{ri})^2} \tag{3}$$

Where $R_t(x,y,z)$ is the distance between the transmit antenna and the target, and $R_{ri}(x,y,z)$ the distance between the receive antennas and the target.

The reconstructed image can be obtained by

$$I_i(x,y)=\iint E_{si}(f,\theta)\exp\left\{j\frac{2\pi}{\lambda}\left[R_t(x,y,z)+R_{ri}(x,y,z)\right]\right\}dfd\theta \tag{4}$$

The above equation is based on back projection algorithm, and the computational load is quite heavy. There are many fast reconstruct methods which are based on Fourier spectrum analysis [10-11]. The resolution of SAR image is also discussed in the reference [10-11].

Assuming that there is only one target at position (x,y) with height z, then the phase difference between the two circular SAR images $I_1(x,y)$ and $I_2(x,y)$ is

$$\Delta\phi(x,y)=\frac{2\pi}{\lambda}\left[R_{r1}(x,y,z)-R_{r2}(x,y,z)\right] \tag{5}$$

The difference between distance $R_{r1}(x,y,z)$ and $R_{r2}(x,y,z)$ can be expressed as

$$R_{r1}(x,y,z)-R_{r2}(x,y,z)\approx 2z(x,y)\frac{h_{r1}-h_{r2}}{R_0} \tag{6}$$

In the practical situation, the height of receive antennas always satisfy $h_{r2}=-h_{r1}=h$. Take equation (6) into account, equation (5) turns to

$$\Delta\phi(x,y)=\frac{4\pi hz(x,y)}{\lambda R_0} \tag{7}$$

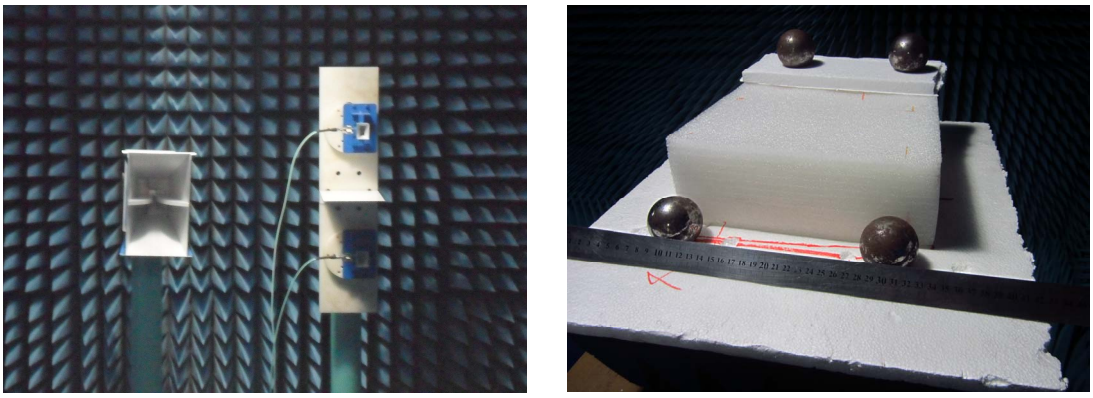
The height information of target is then given by

$$z(x,y)=\frac{\lambda R_0\Delta\phi(x,y)}{4\pi h} \tag{8}$$

The height of target is related to the phase difference, whereas the phase varies with period 2π . Phase unwrapping technique should be used to obtain the absolute unambiguous height.

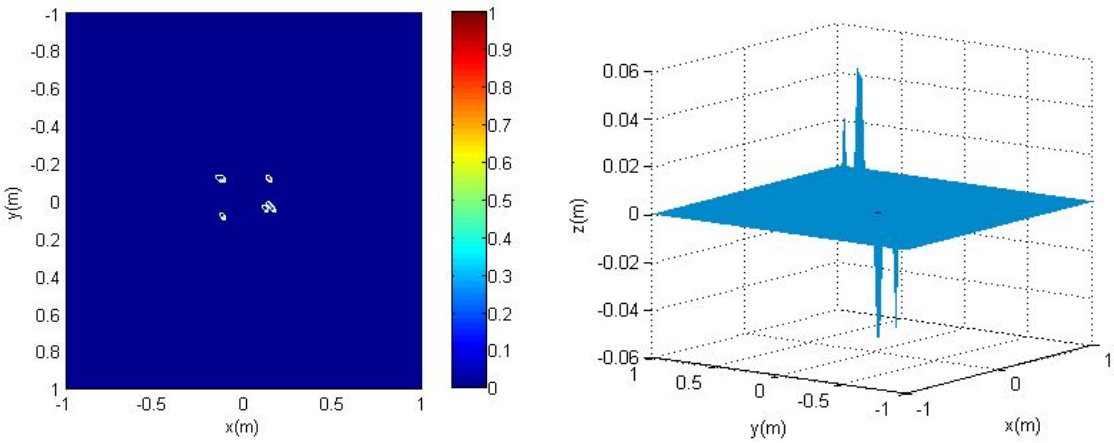
4. EXPERIMRNTAL RESULTS

The experiment was conducted in microwave chamber with dimension $7m\times4m\times3m$. The step frequency signal is generated by an Agilent Vector Network Analyzer (VNA). The received signal is also captured by VNA but with different ports. The transmitting and receiving antennas are standard horn antennas working at 8-12GHz. To collect scattering data from the targets, one transmit antenna and two receive antennas are placed on the supporter, as shown in Figure 2(a). Isolation materials are placed between transmit antenna and receive antennas to avoid mutual coupling. Target is laid on a low scattering reflection supporter made of foam, as shown in figure 2(b). Four metallic spheres with radius 2.5cm are placed on the foam. The height difference between the spheres is about 10cm. The distance between the center of supporter and the antenna is about 4m.



(a) Antenna setup (b) Targets model

Fig. 2 Experimental system



(a) Two dimensional CSAR image (b) Three dimensional CSAR image

Fig.3 Experimental results

The measurement data is obtained by the rotation of the turntable. The frequency sample is 401 and the angular sample is 1201. The total rotated angle is 360 degree. The imaging result of proposed method is given in Figure 3. Figure 3(a) shows the top view image of the targets and Figure 3(b) shows the side view of the targets with the height information. The result in Figure 3(b) shows that the height difference between the spheres is about 10cm, which is consistent well with targets model.

5. Conclusion

This paper proposed a novel method to reconstruct the three dimension image of targets from the scattering data. It exploits the phase difference of two dimensional circular SAR image to reconstruct the height information. The experiment is performed and the result shows the accuracy of the proposed method. At this stage, it can be tentatively foreseen that the presented interferometric circular SAR system can be equipped on the airplane platform.

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