Doppler Aliasing free Micro-motion Parameter Estimation with Terahertz Radar

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***Abstract*—Micro-Doppler, induced by micro-motion of targets, is an important characteristic for target recognition once extracted via parameter estimation. However, micro-Doppler is usually too significant to result in aliasing in the terahertz band. According to this problem, a Doppler aliasing free micro-motion parameter estimation algorithm based on the modulo generalized Hough transform is proposed. Its basic idea is to search and match the parameters of aliasing micro-Doppler curves in the time-frequency image.**

I. INTRODUCTION

Terahertz (THz) waves usually refer to electromagnetic waves with frequencies between 0.1-10 THz, which is a transitional band from electronics to photonics. Terahertz waves, due to their short wavelength, are more sensitive to Doppler than microwaves and hence more suited for micro-Doppler imaging.

Despite the advantages mentioned above, terahertz micro-motion parameter estimation faces a significant hurdle, i.e., the Doppler aliasing induced by the inadequate pulse repetition frequency (PRF). Terahertz radar usually utilizes frequency modulated continuous wave (FMCW) signals due to low peak power requirement. In order to ensure the linearity of FMCW signal, the equivalent PRF can't be too large, and therefore the limited PRF sets an upper limit to the maximal observable unaliased Doppler. Specifically, the Doppler frequency can be unambiguously observed only when it lies in the interval between –PRF/2 and PRF/2, and it will be aliased or folded up when Doppler values are outside the interval. In addition, micro-Doppler in the terahertz band tends towards being aliased as the carrier frequency is much higher than that in the microwave band.

Herein we propose an algorithm for estimating micro-motion parameters based on the modulo Generalized Hough transform (GHT). The main idea is derived from the GHT in image processing field, which searches sinusoidal curves or other types of curves hidden in the time-frequency distribution image. However, the GHT can't be used in the aliasing situation directly, so we improve this transformation and match the time-frequency curves of targets with equally aliased reference curves that are obtained by modulo. We then map the curve parameters to a parameter space, and finally estimate the parameters by extracting positions of peaks in parameter space.

II. MICRO-DOPPLER CHARACTERISTICS OF A PRECESSION CONE

For convenience, we only consider the micro-motion of the target rather than translation. The intended target in this paper is a precessional rotational symmetric cone, which is a simplified model of the ballistic missile target during the midcourse. Its position diagram observed by radar is shown in Fig. 1.

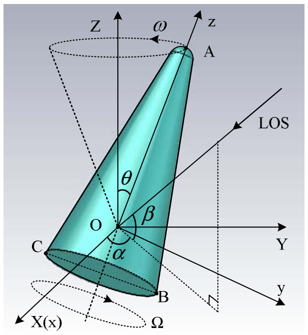

Fig.1, Diagram of a precessional cone in CST

A reference frame O-XYZ that takes the mess center of target as the origin is established. Considering the cone precessing around O-Z axis, the spin angular velocity is Ω , the angular velocity and angle of precession are ω and θ, the azimuth and pitch angles of the light of sight(LOS) are α and β , the initial distance between radar and target is R_0 .According to the theoretical calculation and the experimental measurement, every scatterer corresponds to a discontinuity in the Stratton-Chu integral, as the discontinuity of the curvature or surface from the point of geometry. Because the cone is rotational symmetric, spin makes no different to the echo modulation. Thus, the radial distance $r(t)$ between radar and any point P located at (x, y, z) on the target may be written as:

$$\begin{aligned} r(t) &= R_0 + \sin\beta\left(y\sin\theta + z\cos\theta\right) \\ &\quad + \left(x\cos\alpha + y\sin\alpha\cos\theta - z\sin\alpha\sin\theta\right)\cos\beta\cdot\cos\omega t \\ &\quad + \left(x\sin\alpha - y\cos\alpha\cos\theta + z\cos\alpha\sin\theta\right)\cos\beta\cdot\sin\omega t \\ &= R_0 + \sin\beta\left(y\sin\theta + z\cos\theta\right) + A\cos\left(\omega t + \varphi\right) \end{aligned}$$

In this equation, A is amplitude-modulated coefficient, φ is the initial phase. Assuming the locations of scatterers are fixed on the target, which is called the ideal scattering center model, then the micro-Doppler $f_d(t)$ of scatterers with the carrier frequency f_0 is:

$$\begin{aligned} f_d(t) &= -\frac{2f_0}{c}\frac{dr(t)}{dt} = \frac{2f_0}{c}A\omega\sin(\omega t + \varphi) \\ &= A_\omega\sin(\omega t + \varphi_\omega) \end{aligned}$$

where A_ω is the maximal micro-Doppler frequency, and φ_ω is its initial phase. The micro-Doppler of any scatterer on the cone is sinusoidally modulated with a period ω. Therefore the extraction of precession parameters is equivalent to the estimation of periods, amplitudes and initial phases of the sinusoidal curves in the time-frequency images. In general, amplitudes and initial phases usually reflect the relative positions of scattering centers, which can be used for space reconstruction and imaging of micro-motion targets.

It is obvious that micro-Doppler f_d is in proportion to the carrier frequency f_0 through equations above. The higher the f_0, the more evident is the micro-Doppler effect. Therefore, micro-Doppler value in terahertz band is far larger than that in microwave band under identical conditions, which substantially exceeds the up limit of PRF/2, hence aliasing is present. When micro-Doppler is aliased, the observed Doppler is no longer the correct value, but is aliased to the range of –PRF/2 to PRF/2. Estimation of the real Doppler value for SAR or ISAR becomes necessary as we cannot obtain perfect SAR/ISAR images without the real Doppler value. At the same time, traditional parameter estimation methods such as the Fourier transform and the Inverse Radon transform are not applicable for the aliasing situation because the micro-Doppler aliasing changes the signal properties and destroys the completeness of time-frequency curves.

III. ALIASING FREE PARAMETER ESTIMATION BASED ON MODULO GHT

It is well known that GHT is an effective way to detect curves in digital image processing when the curve expressions are known. The basic idea of GHT is to map the curves in measurement space to peaks in the parameter space. Curves which share the parameters correspond to the same peak in parameter space. We can then extract the parameters by identifying the positions of peaks in parameter space. Returning to the problem in this paper, the primary objective is to map the aliased sinusoidal curves in the time-frequency image to peaks in parameter space. GHT can't be directly applied to the Doppler aliasing situation as no analytical expression exists necessitating an improvement in this case.

To sum up, the parameter estimation approach will be carried out in six steps:

a).Obtain time-frequency distribution image TF of micro-motion targets by an appropriate time-frequency analysis (such as STFT).

b).Estimate precession angular velocity ω by autocorrelation method in order to reduce the parameter space. We assume that $\omega = 2\pi\ rad/s$ in this paper.

c).Establish the parameter space $K = (A_k, \varphi_k)$ and identify an appropriate search scope and step length based on both effectiveness and estimated precision. In this paper, we set the upper limit of the micro-Doppler frequency F reasonably according to the experimental conditions. The integration time $T = 1s$, micro-Doppler step length $\Delta f = 1Hz$, phase step length $\Delta\varphi = 1^\circ$.

d).Identify the coordinates of reference pixels in TF, especially in the micro-Doppler aliasing situation., The reference pixel coordinates for one targets with precession are $(t, \mathrm{mod}(A_k \sin(\omega t + \varphi_k) + PRF/2, PRF))$, where $\mathrm{mod}(\cdot)$ is modulo operation which is different from GHT.

e).Search and match the parameters, and average the values of reference pixels in each group in order to reduce detrimental effects of noise.

6).Extract positions of peaks in the parameter space. Their abscissa represents the initial phase and vertical ordinate of the maximum micro-Doppler value.

IV. RESULTS

We design a group of simulation experiments to validate our algorithm above. The carrier frequency is 340GHz, the signal-to-noise ratio (SNR) is 3dB, the left and right figures are time-frequency distribution images and parameter space images respectively. Some simulation results are shown in Fig. 1 and Fig. 2. In order to analyze the relationship between the estimation precision and SNR, we plot the errors of the scatterer P3 when SNR varies from -20 dB to 3 dB at 340 GHz, in Fig. 3.

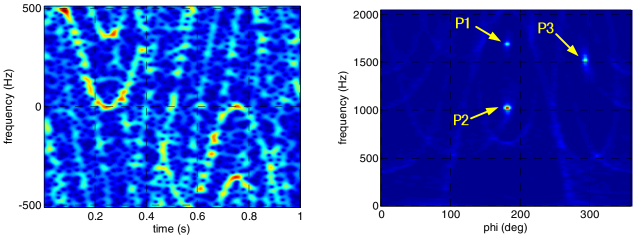

Fig.1, Results of experiment No. 1 (scatterers: P1, P2, P3)

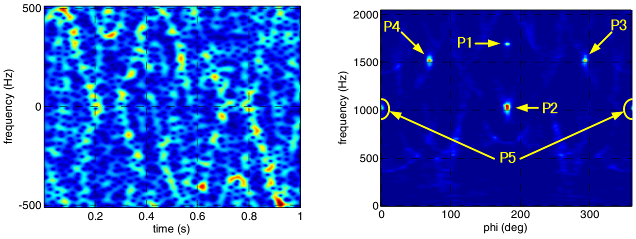

Fig.2, Results of experiment No. 2 (scatterers: P1, P2, P3,P4,P5)

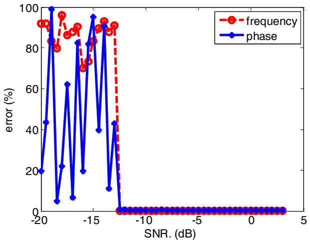

Fig.3, Errors at different SNR

V. SUMMARY

We have proposed a modulo GHT algorithm in this paper, and applied it to the estimation of micro-motion parameters in micro-Doppler aliasing situation. Its essence is to search the matching parameters of micro-Doppler in time-frequency distribution image, and it is especially suited for the micro-Doppler aliasing situation in terahertz band.Results of simulation experiments demonstrate the high precision of estimation and good anti-noise performance.

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