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A two-dimensional phase coding for range ambiguity suppression

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ABSTRACT

Based on a two-dimensional phase coding, a novel range ambiguity suppression technique is proposed in this paper. By transmitting two-dimensional phase coded signals, the two-dimensional spectrum of the range ambiguous signals will be shifted along both range and azimuth directions compared with that of desired signals. Then, part of the two-dimensional spectrum of the range ambiguous signals will be located outside the two-dimensional spectral support, which is known in priori, of the desired signals. Considering the range frequency and Doppler oversamplings, a filter corresponding to the two-dimensional spectral support of the desired signals is applied, which suppresses the range ambiguity. Simulation results of both point targets and distributed targets validate the effectiveness of the proposed method.

1. Introduction

Range ambiguity may appear in a SAR image if echoes of different distances from different transmitted pulses are received simultaneously. The range ambiguous signals may overlap with the echoes of an image scene which are desired signals we need. The round-trip propagation time of the range ambiguous signals may differ from that of the desired signal by a multiple of the pulse repetition interval length. Since wide swath coverage and high resolution have contradicting requirements on the design of pulse repetition frequency (PRF) for spaceborne synthetic aperture radar (SAR) systems. When PRF is set higher to ensure higher azimuth resolution, the range ambiguities become more severe, which leads to significant deterioration of SAR imaging performance [1].

To deal with this problem, many techniques have been proposed: i) techniques at receiver by using additional signal processing methods; ii) techniques at both transmitter and receiver. For example, techniques to suppress range ambiguity are proposed by combining the signals received from different channels [2,3]. Reconstructing echo signals from multichannel information with a lower PRF to suppress range ambiguity is proposed [4], where high azimuth resolution is maintained. Moreover, the use of alternating up and down chirp modulation is presented to deal with the range ambiguous signals [5] by reducing its peak power, but the range ambiguous signal energy may not be reduced. OFDM techniques are also proposed for range ambiguity suppression and inter-range-cell interference (IRCI) cancellation [6–9]. Among the techniques for ambiguity suppression, azimuth phase coding (APC) [10] has recently received particular interest because of its low implementation complexity and providing degrees of freedom in the system design [11,12]. The desired signal and range ambiguous signals have the same azimuth bandwidth and the Doppler spectral support. For APC, the Doppler spectrum of the range ambiguous signals will be shifted from that of desired signals. Then, the spectrum of range ambiguous signals located between the azimuth band of desired signals and the PRF can be filtered. The amount of the ambiguous energy that can be removed depends on the Doppler oversampling rate. However, the Doppler oversampling rate is usually limited for wide swath coverage, which may seriously affect the suppression performance of APC. In this paper, a novel two-dimensional phase coding technique is proposed for range ambiguity suppression. Our newly proposed technique removes the range ambiguous signal energy not only in Doppler frequency domain but also in range frequency domain by both range and azimuth phase coding without the need of any extra hardware support. It allows for a simple signal processing and provides more degrees of freedom in choosing the PRF. Moreover, the method is effective against not only the ambiguous energy of point targets but also that of distributed targets.

The paper is organized as follows. In Section 2, spaceborne SAR signal model and range ambiguity are first introduced. Then, the

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principle of APC is briefly reviewed. Also, the concept and property of range phase coded waveforms are presented. In Section 3, a novel two-dimensional phase coding technique is proposed. In Section 4, the performance of ambiguity suppression is shown and simulation results of both point and distributed targets are presented.

2. APC and range phase coded waveforms

2.1. Signal model

Fig. 1 shows the spaceborne SAR imaging geometry, where the SAR platform moves along the X-axis with a constant velocity v. Here, α denotes as the azimuth angel. The dashed line shows the synthetic aperture length of the scatter. R_b denotes the closest range between the antenna phase center and the scatter in an image scene, k is the range ambiguity order, and $R_{amb}^{(k)}$ is the closest range between the antenna phase center and the scatter in the range ambiguous area of order k.

Due to long slant range and wide swath coverage of spaceborne SAR, echoes of different distances from different transmitted pulses arrive at a receiving antenna simultaneously, which leads to the aliasing in fast time domain. Fig. 1 illustrates the echoes of an image scene arrived at the receiving antenna simultaneously with the echoes of the range ambiguous area of the first order from the last pulse and the echoes of the range ambiguous area of the negative first order from the next pulse. The image scene is an area to be imaged. The desired signals are defined as the echoes of the image scene. Then, the desired signal that can be expressed as:

$$
\begin{aligned}
&s(t_k,t_m)\\
&\quad=\sigma w_r(t_k)w_a(t_m)\\
&\qquad\times\exp\left(-\frac{j4\pi f_c R(t_m;R_b)}{c}+j\pi\gamma\left(t_k-\frac{2R(t_m;R_b)}{c}\right)^2\right)
\end{aligned}
\tag{1}
$$

and the overlapped echo of scatter in the range ambiguous area of order k can be expressed as:

$$
\begin{aligned}
&s_a^{(k)}(t_k,t_m)\\
&\quad=\sigma w_r'(t_k)w_a'(t_m)\exp\left(-\frac{j4\pi f_c(R(t_m;R_{amb}^{(k)})-\frac{k\cdot c}{2\cdot PRF})}{c}\right.\\
&\qquad\left.+j\pi\gamma\left(t_k-\frac{2R(t_m;R_{amb}^{(k)})}{c}-\frac{k}{PRF}\right)^2\right)
\end{aligned}
\tag{2}
$$

$$
R_b=R_{amb}^{(k)}-\frac{k\cdot c}{2\cdot PRF}
\tag{3}
$$

Then, we transform Eqns. (1) and (2) into the range frequency domain:

$$
\begin{aligned}
S(f_r,t_m)&=\sigma W_r(f_r)w_a(t_m)\exp\left(\frac{-j\pi f_r^2}{\gamma}\right)\\
&\quad\times\exp\left(-j\frac{4\pi(f_r+f_c)}{c}R(t_m;R_b)\right)
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
&S_a^{(k)}(f_r,t_m)\\
&\quad=\sigma W_r'(f_r)w_a'(t_m)\exp\left(\frac{-j\pi f_r^2}{\gamma}\right)\\
&\qquad\times\exp\left(-j\frac{4\pi(f_r+f_c)}{c}\left(R(t_m;R_{amb}^{(k)})-\frac{k\cdot c}{2\cdot PRF}\right)\right)
\end{aligned}
\tag{5}
$$

where c is the speed of light, σ denotes the complex scattering coefficient, t_k is the fast time, t_m is the azimuth slow time, γ stands for the frequency modulation rate, f_c and f_r are the carrier frequency and the range frequency, respectively. $R(t_m;R_b)$ and $R(t_m;R_{amb}^{(k)})$ stand for the instantaneous range between the antenna phase center and the scatter in the imaging area and range ambiguous area of order k at t_m, respectively. $w_r(\cdot)$ and $w_r'(\cdot)$ are the range window functions in fast time domain. $W_r(\cdot)$ and $W_r'(\cdot)$ are the range window functions in range frequency domain and $w_a(\cdot)$ and $w_a'(\cdot)$ denote the azimuth window functions, respectively, of the desired signal and the range ambiguous signals. Moreover, the Doppler frequency linearly depends on the azimuth angle of the scatter. Since the scatter in the image scene and the range ambiguous areas experience the same azimuth angle history in their synthetic aperture lengths, the desired signal and the range ambiguous signals have the same azimuth bandwidth B_d and the same Doppler spectral support $[-B_d/2, B_d/2]$. On the other hand, the bandwidth of the original transmitted linear frequency modulated (LFM) signal is B_r, which is also the range bandwidth of both the desired signal and the range ambiguous signals. So the desired signal and range ambiguous signals also have the same range spectral support $[-B_r/2, B_r/2]$. As a result, the desired signal and the range ambiguous signals have the same two-dimensional spectral support $[-B_d/2, B_d/2]\times[-B_r/2, B_r/2]$.

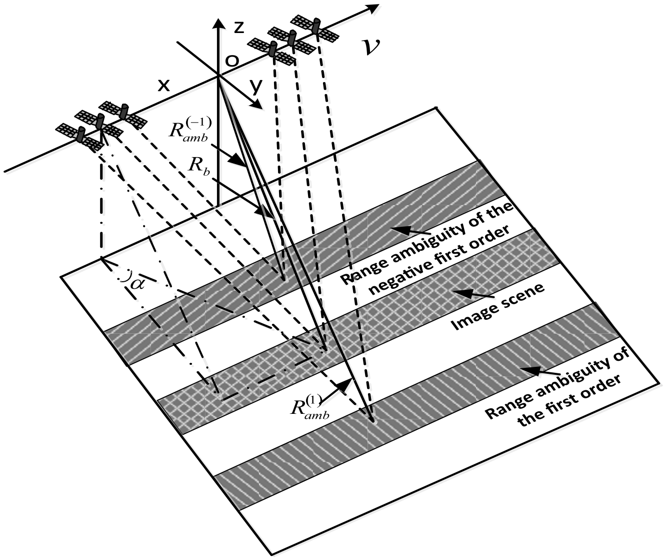

Fig. 1. Imaging geometry.

With the demand of higher resolution and wider swath, range ambiguity becomes more severe, which leads to significant deterioration of HRWS imaging performance in the conventional SAR system.

2.2. APC

APC is first to transmit signals with azimuth phase coding, which makes the range ambiguous signal spectrum shifted, and then to filter out the spectrum of the range ambiguous signals outside the azimuth band of a desired signal. The transmit signals with azimuth phase coding is:

$$
\begin{aligned}
s(t_k,t_m)&=w_r(t_k)\exp\left(j2\pi f_c t_k+j\pi\gamma t_k^2\right)\\
&\quad\times\exp\left(-\frac{j\pi}{M}(PRF\cdot t_m)^2\right)
\end{aligned}
\tag{6}
$$

where M (positive integer) is the APC shift factor and PRF stands for the pulse repetition frequency. The last term of Eqn. (6) is the azimuth phase coding term. It codes on phase at each slow time.