WIDE SWATH FMCW SAR DATA PROCESSING IN SQUINT MODE

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Abstract  This paper concentrates on the data processing of Frequency Modulation Continuous Wave (FMCW), Synthetic Aperture Radar (SAR) in the case of wide swath and squint mode. In the mode, the Doppler centroid dramatically varies along slant range compared to conventional pulsed-SAR. This poses a challenge for system design and signal processing since a very large azimuth bandwidth would be introduced. In the paper, we accommodate the Doppler centroid variations with range by an improved spectral-length extension method, where a bulk range shift and updated Doppler centroid variations are introduced to greatly reduce the azimuth aliasing with respective to the existing methods. Moreover, an image formation approach that integrates wave number domain algorithm is presented to focus the raw data of FMCW SAR in the case of wide swath and squint mode. Point target simulation experiment demonstrates the advantages of the presented method.

Key words    Frequency Modulation Continuous Wave (FMCW); Synthetic Aperture Radar (SAR); Doppler centroid; Wave number domain algorithm

CLC index    TN958

DOI  10.1007/s11767-014-3132-8

I. Introduction

The combination of Frequency Modulation Continuous Wave (FMCW) and Synthetic Aperture Radar (SAR) provides a low-cost, small size, and high image quality solution for remote sensing. Therefore, FMCW SAR has made a great progress in recent years, many demonstration systems and focusing algorithms have been developed[1–3].

However, with double antennas configured in FMCW SAR, a good isolation between transmitter and receiver is required, which limits the transmitted power of FMCW SAR[4]. As a result, the range of FMCW SAR is usually much shorter than that of pulsed-SAR. To obtain a wide swath at a low altitude, a wide beam width in elevation is usually employed in FMCW SAR.

Comparing with the broadside mode, high-squint mode can provide the information about the surface structure through the measurement of backscattered azimuth angle dependence and also increases the flexibility with which a desired area on a surface is imaged within a single pass of the platform[5,6]. Hence, the squint mode is widely deployed in pulsed-SAR and FMCW SAR.

Nevertheless, two challenges are caused by the signal processing in the wide swath and squint mode. One is the spatial variant range-azimuth coupling phase and the other relates to the Doppler centroid variations with range. While plenty of efforts are paid on the first issue[7,8], the latter calls very little attentions in the literatures. In fact, the Doppler centroid variations with range may exceed Pulse Repeat Frequency (PRF) and consequently severe azimuth aliasing would occur.

C. Prati and N. Cadalli considered Doppler centroid variations with range in wave number algorithm, where one-dimensional interpolation was employed to get a high sampling wave number in azimuth before azimuth Fast Fourier Transform (FFT)[9,10]. Nevertheless, the interpolation in the time domain leads to a huge computation load, especially in the case of high squint. A. Moreira and Y. H. Huang discussed the accommodation ap-
proach of Doppler centroid variations with range in the frequency domain for airborne SAR\cite{11}. However, only the case of pulsed-SAR was discussed and the solution was introduced very briefly. In fact, the Doppler centroid varies much faster along range in FMCW SAR due to the lower altitude of platform, leading to much larger looking angle variations than airborne pulsed-SAR\cite{12}. Moreover, the PRF is usually lower because the limited storages of FMCW SAR. As a result, severe azimuth aliasing would exist in FMCW SAR image. Hence, a more efficient and accurate accommodation method is urgently desired. In addition, the dechirp-on-receive operation and the continuous transmitted pulse make the received signal of FMCW SAR different from that of pulsed-SAR. Consequently, the method proposed in Ref. [9] cannot be directly applied in the case of FMCW SAR. It is significant to study the matter seriously in the development of FMCW SAR.

In this paper, we present a modified azimuth spectral-length extension method to well suit for the case of FMCW SAR, where the imaging geometry in squint mode is investigated in detail and a bulk range shift is introduced. The method is verified by simulation experiment. Results show its advantages over its predecessors.

The paper is arranged as follows. The imaging geometry and the Doppler centroid variations with range in squint mode are illustrated in Section II. In Section III, we propose a modified spectrum-extension method to better accommodate the Doppler variations in FMCW SAR. Section IV describes the procedure of signal processing, where wave number domain algorithm is integrated to deal with the spatial variant range-azimuth coupling in squint mode. In the following section, we perform a simulation experiment to evaluate the proposed method. Section VI concludes the whole paper.

II. Doppler Centroid Variations in Squint Mode

In the section, we focus on the imaging geometry of FMCW SAR in wide swath and squint mode, such as the case of automobile FMCW SAR and Unmanned Aerial Vehicle (UAV) FMCW SAR. The large Doppler centroid variations with range are derived. First of all, we give the imaging geometry of FMCW SAR in wide swath and squint mode in Fig. 1.

As demonstrated in Fig. 1, we define the antenna looking angle at middle range as $\theta_{\text{side}}$ and the corresponding squint angle is denoted as $\theta_{\text{sq}}$. The squint angle along range is labeled as $\theta_{\text{sq}}$. $r_0$ stands for the nearest range between point target and the Antenna Phase Center (APC) of radar. $H$ is the height of platform and $Y_c$ denotes the azimuth displacement of point target from Zero Doppler Plane (ZDP), which can be determined by

$$Y_c = \frac{H \tan \theta_{\text{sq}}}{\cos \theta_{\text{side}}} \quad (1)$$

According to the geometry in Fig. 1, we calculate the radial projection unit of the azimuth velocity as follows.

$$\sin \theta_{\text{sq}} = \frac{Y_c}{\sqrt{r_0^2 + Y_c^2}} \quad (2)$$

Combining Eqs. (1) and (2), the Doppler centroid variations with range can be formulated as

$$f_{\text{dc}}(r_0) = \frac{2v}{\lambda} \frac{1}{\sqrt{1 + \left(\frac{r_0 \cos \theta_{\text{sq}}}{H \tan \theta_{\text{side}}}\right)^2}} \quad (3)$$

where $v$ is the velocity of APC and $\lambda$ denotes the wavelength of radar. It can be observed from Eq. (3) that Doppler centroid variations with range are nonlinear with the ratio of $H/r_0$ for given $\theta_{\text{side}}$ and $\theta_{\text{sq}}$, namely, the cosine of the looking angle.

With large variations of looking angle employed in FMCW SAR, the Doppler centroid variations