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Clutter suppression and moving target imaging approach for multichannel hypersonic vehicle borne radar

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ABSTRACT

In this paper, a clutter suppression and ground moving target imaging algorithm is proposed for the hypersonic vehicle (HSV) borne multichannel synthetic aperture radar (SAR) system. Different from the traditional horizontal flight radar platforms, the HSV-borne radar platform is with a complex movement, and typically has a skipping trajectory. Therefore, the clutter suppression and imaging operations are difficult to implement. To deal with this problem, a descending stage signal model of multichannel SAR system is presented and studied for the HSV-borne radar. Then, the clutter and moving target echoes are transformed into the azimuth frequency domain. Considering that there exists a phase difference between clutter and the moving target, the clutter suppression approach is implemented with a series of spatial domain filters. After that, the moving target is focused based on the keystone transform. In addition, the performance analyses and related issues of the proposed method are presented. Finally, some simulation experiments are taken to validate the effectiveness of the proposed method.

1. Introduction

Traditional synthetic aperture radar (SAR) system works on air-borne [1,2] and space-borne [3,4] platforms, but there are some disadvantages on them: Air-borne radars fly with a relative low altitude and speed, and thus the detection area is small; Space-borne radars have a high flying altitude, where more transmitted power is needed to detect targets, and the platforms have a fixed orbit, which are more easily aimed at and struck. Hypersonic vehicle (HSV) [5,6], which has the advantages of high speed and high maneuverability, is difficult to be detected and struck. Moreover, HSV flies in near space commonly, which needs much less energy for ground target detection than space-borne radar, and it is an ideal platform to complete fast remote battlefield detection, fire control and high precision strike missions [6]. As a result, HSV platform radar is with a high research value, and the study of ground target detection in HSV-borne SAR system is quite significant. Currently, the ground stationary targets imaging algorithms for SAR system with near space vehicles have been presented and analyzed [7–12], but the ground moving target indication (GMTI) methods for HSV-borne radar have not been tackled yet.

At present, there exist lots of difficulties for GMTI in HSV-borne SAR system. First, the HSV-borne radar platforms fly quickly and with high maneuverability, which is different from typical air-borne and space-borne radars. Besides, the HSV-borne radar platforms typically have a skipping trajectory rather than the traditional horizontal flight trajectory in air-borne and space-borne radar platforms. The flight trajectory of HSV consists of four major parts: boost, periodic skipping cruise, glide, and landing. The HSV-borne SAR system can be set to work only in the descending stage of periodic skipping cruise part because the movement of the aircraft becomes very complicated when accelerated, and the acceleration time is only 1/6 of the entire skipping period [6]. Then, the study of the descending stage is significant for GMTI in HSV-borne SAR system, and in this paper we propose signal models of clutter and moving target for multichannel SAR system in the descending stage. The flight trajectory of the descending stage can be approximated as a straight line within a short processing time. In [7–12], stationary targets imaging algorithms (including beamforming, target azimuth ambiguity-free reconstruction and focusing processing, etc.), are proposed for HSV-borne SAR system, but all of the algorithms utilize the horizontal flight geometry, which is impractical. In addition, the descending stage SAR geometry is used in maneuverable SAR platforms [13,14], However, the SAR system in these papers is designed with mono channel, where spatial filtering and clutter suppression cannot be implemented.

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Since the speed of the HSV-borne radar platform is high, it will encounter stronger clutter than air-borne SAR system, which can influence the performance of moving target detection heavily. In order to improve the detection performance, clutter suppression is necessary before GMTI. Conventional multichannel clutter suppression approaches mainly include displaced phase center antenna (DPCA) [15], and space-time adaptive processing (STAP) [16,17]. However, DPCA is optimum for two-channel systems [18] but suboptimum when more than two channels are available, and DPCA condition has to be satisfied for the method. In addition, fully adaptive STAP methods [19] and some suboptimal STAP approaches, such as post-Doppler STAP [19,20], are developed for an arbitrary number of receiving channels. However, the coherent processing interval (CPI) is always chosen to ensure that a moving target stays in one range Doppler cell, and then conventional STAP methods are not suitable for GMTI in the HSV-borne radar, because the radar platform will have a strong range migration during the descending stage, which can cause a signal to clutter plus noise ratio (SCNR) loss. The imaging STAP (ISTAP) [21] and extended DPCA (EDPCA) [22] approaches are developed for improving the detection performance by utilizing a long CPI to improve the target SCNR and focusing the target with moving target parameter set. In addition, the deramp-STAP approach is proposed in [23] and used for multichannel clutter suppression [24]. In [25], a chirp Fourier transform (CFT) based approach is proposed to suppress clutter, which compensates the channel mismatch and has a performance improvement over the method in [24]. Unfortunately, all the aforementioned clutter suppression and SAR GMTI methods are designed for the traditional horizontal flight radar platforms such as air-borne and space-borne radars, but GMTI methods for the descending stage HSV radar platform have not been found yet.

In this paper, a clutter suppression and moving target imaging algorithm for HSV-borne radar is proposed and analyzed. The contributions and differences compared with the existing methods, are summarized as follows: 1) Different from the traditional horizontal flight SAR system, this paper deals with the HSV-borne radar platform, and presents a descending stage geometry for multichannel SAR system. 2) In the traditional azimuth deramp methods [24,31], only the quadratic phase item is compensated, and then it cannot focus the azimuth signal effectively. In the proposed approach, both the quadratic and cubic phase items are analyzed and compensated during azimuth compression. In this way, the azimuth signal can be compressed for HSV-borne SAR GMTI. 3) This paper analyzes the azimuth frequency spectrum for the target, and points out that there is a shift of the azimuth frequency spectrum in the descending flight geometry, which is different from the traditional horizontal flight SAR system. Based on this, the paper derives the steering vectors of the moving target and clutter for the descending flight SAR system, and proposes the clutter suppression and moving target imaging algorithm.

The rest of the paper is organized as follows. In Section 2, the geometry of a descending stage multichannel SAR system for HSV-borne radar with moving targets is described. Based on the geometry relationship, the clutter and moving target signal models for the descending stage multichannel SAR system are presented in the azimuth frequency domain. Then, a novel clutter suppression and moving target imaging approach is proposed in Section 3. In Section 4, the GMTI performance and some related issues are discussed. In Section 5, simulation examples are taken to evaluate the proposed method for moving targets. Finally, some conclusions are given in Section 6.

2. Geometry and signal model for HSV-borne GMTI

2.1. Geometry of descending stage multichannel SAR system for HSV-borne radar

The geometry of a descending stage multichannel SAR system for HSV-borne radar platform is shown in Fig. 1. X axis is in the direction of the horizontal front of the platform flight trajectory, Y axis points to the left direction of X axis, and Z axis is away from the center of the earth. With a proper pulse number during a CPI, the radar platform can be considered as moving along a downward sloping direction with a constant velocity v. v_x and v_z denote the horizontal and vertical radar velocity components, respectively, and $v = \sqrt{v_x^2 + v_z^2}$. The pulse number during a CPI is analyzed in Section 4. α is the slope angle (the angle between the direction of radar antennas and X axis), ϕ is the depression angle, H is the platform height, and W_g denotes the swath width. The parameters of the HSV-borne radar platform (v_x, v_z, α, H, etc.) are considered as known, or can be obtained from global position system (GPS) and inertial navigation system (INS). It can be noticed that the influence of inaccuracies on these parameters and the compensation algorithms for the HSV-borne SAR system are not considered in this paper, but in practice there are motion errors between the ideal and real platform trajectories. The caused inaccurate platform parameters can lead to phase mismatch and SCNR loss in clutter suppression, and also result in azimuth defocussing and Doppler centroid offset during moving target imaging. As a consequence, compensation for the motion errors of the platform is important for SAR GMTI, and in recent years some available compensation algorithms based on data processing (e.g., reflectivity displacement method, phase gradient autofocus, and so on) have been proposed [26–28]. In this paper, however, we mainly focus on the difference between the horizontal and descending geometries, and propose the corresponding clutter suppression and moving target imaging algorithm. Therefore, the influence of inaccuracies on these parameters and the compensation algorithm will be discussed in the future. In addition, the radar platform is working in side-looking mode, i.e., the squint angle is equal to zero. In squint-looking mode, the clutter suppression and imaging algorithm is complicated for the geometry of the descending stage, and then it is beyond the scope of this paper. The algorithm for squint-looking mode will be further studied in the future.

The whole antenna is divided into N channels, which is used to implement multichannel SAR GMTI. In this paper, a three channel SAR system is taken as an example, i.e., $N = 3$. A linear frequency modulated (LFM) pulse signal is transmitted by the middle channel (reference channel), whereas all of the channels receive the echoes simultaneously. The distance between each two adjacent channels is equal to the channel length $2d$. When the distance between the transmitting and receiving antenna phase centers is much shorter than the slant range [29], the received echo can be transformed into an equivalent self-transmitting and self-receiving data corresponding to the effective phase center (EPC) by compensating a constant phase with respect to reference channel. The EPC of each channel is shown in Fig. 1, and the EPC coordinate of the nth channel is $(x_n, 0, H + z_n)$, $n = 1, 2, \cdots, N$. The interval between two adjacent channels becomes d after the EPC processing. In addition, the constant phase item compensated in the descending stage for EPC is $\exp(j2\pi d_n^2 \cos^2\alpha / r\lambda)$, where $d_n = n \cdot d$, r is the distance between the radar platform and the moving target, and λ represents the signal wavelength. Note that the EPC compensation function for the descending movement, which is related to the slope angle α, is different from the one in the traditional horizontal flight situation. When $\alpha = 0$, the EPC compensation function can be simplified as that in the horizontal flight SAR system, i.e. $\exp(j2\pi d_n^2 / r\lambda)$. Moreover, the antenna position for the descending