A Miniature HRWS SAR Concept for Near-Space Vehicles

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Abstract—**Near space is the region of Earth's atmosphere that lies between 20km to 100 km above sea level, which is of interest for military surveillance purposes, as well as to commercial interests for communications. Currently there is a considerable effort to design and build synthetic aperture radar (SAR) payloads for near-space vehicles. This paper describes a high resolution wide swath (HRWS) synthetic aperture radar (SAR) system for near-space vehicles. The technical challenges for near-space microwave radar remote sensing are investigated. According to the miniature characteristic by the sensor, Frequency Modulation Continuous Wave (FMCW) radar type is chosen. The imaging characteristic of FMCW SAR is demonstrated. The system parameters are designed. At last the system performance is analyzed and the simulation result is also given.**

Keywords-frequency modulation continuous rada; synthetic aperture radar; near-space vehicles

I. INTRODUCTION

Near-space is recognized as the region between 20 km and 100 km above sea level, which is high for airplanes and too low for satellites. The region is becoming more and more important in military surveillance or commercial communication application [1-3]. Near-space vehicles offer several advantages such as persistence, robust survivability, and cost efficiency, which are particularly valuable for future remote sensing. There is now a considerable effort to design and build miniature synthetic aperture radar (SAR) for near-space vehicles.

The combination of frequency modulated continuous wave (FMCW) technology and SAR pave a way to light-weight, cost-effective, high-resolution active microwave remote sensing instrument. In the last years, several FMCW SAR systems have been constructed and have been successfully used in many applications such as ice measurement, environment monitoring and so on [4-6]. However, these systems are currently operating on small platforms such as unmanned aerial vehicles (UAVs) and applied in the short range and narrow swath case, which is the main disadvantage for FMCW SAR on near-space vehicles. Another problem is the dilemma between the wide swath and the high azimuth resolution.

In pulsed SAR systems, wide unambiguous swath coverage and high azimuth resolution is also a contradicting requirement. Several proposals, such as multiple beam SAR system operating in a squinted imaging geometry [7], displaced phase centre antenna technique [8], Quad Array system [9] and High-Resolution Wide-Swath (HRWS) SAR system [10], have been presented to resolve the aforementioned dilemma. The HRWS SAR concept relies on separate antennas, which is also the characteristic of a FMCW SAR system. So the HRWS concept may be a suitable solution for FMCW SAR operating on near-space vehicles.

One basic idea of the HRWS concept is the ambiguity resolution by digital beamforming (DBF) technology in the range and azimuth direction. The conventional multi-channel azimuth reconstruction algorithm [11] is based on "stop and go" hypothesis, which is valid for pulsed SAR. However, for FMCW SAR, the continuous antenna motion during a pulse time can not be negligible. In the paper, the approximation error introduced by the antenna continuous motion is computed and its impact to conventional DBF algorithm is estimated. From the point of noise equivalent sigma zero (NESZ), the system performance of DBF FMCW SAR is analyzed. Finally, simulation results are also given by comparing with classic FMCW SAR.

II. MISSION CHALLENGES

A. Antenna isolation

In a FMCW radar system, the transmitter and receiver work simultaneously, which causes the antenna isolation problem. The common resolution for FMCW SAR systems on UAVs is using two separate antennas placed at a very short baseline and a sharp cut-off Band Pass Filter (BPF) [4-6]. In order to meet the range specification demanded by near-space vehicles, the most immediately method is to increase the transmission power of FMCW SAR. However, the maximum transmission power is limited by the antenna isolation level. And moreover, this method will increase the system complexity.

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B. *Minimum antenna area*

Although there are separate antennas, FMCW SAR is also regarded as a monostatic system because of the short baseline. For SAR with high resolution over a wide swath, a basic limitation is the minimum antenna area constraint, which can be represented by [12]:

$$A_{\min} = \frac{4v\lambda R \tan(\theta_{in})}{c_0} \quad (1)$$

where v is the platform velocity, λ is the radar wavelength, R is the radar slant range, θ_{in} is the incidence angle, and c_0 is the light speed.

TABLE I. SYSTEM GEOMETRY

Parameter	Value
Operational Altitude	20km
Operational Velocity	100m/s
Swath width	15km
Range Resolution	0.3m
Azimuth Resolution	0.3m
Incident Angle	30-55°

C. *Motion compensation*

Strict relative position or altitude is essential for SAR systems. However, there are motion errors between the real platform trajectory and the ideal position or altitude (roll, pitch, and yaw angles) because of the atmospheric turbulence and other weather conditions. Hence, the motion compensation is in fact a critical task for SAR imaging. And this problem is more important for FMCW SAR operating on near-space vehicles than general SAR systems. One reason is that the synthetic range is very long and the other is that the platform velocity is relatively slow, which introduce the longer synthetic time than air-borne or space-borne SAR systems. For example, the synthetic range is ~1km and the synthetic time is ~10s respectively using the system geometry parameters listed in the table I.

In current SAR systems, global positioning system (GPS) and inertial navigation system (INS) are usually deployed for the motion compensation task. For FMCW SAR operating on near-space vehicles, on the one hand, a high accuracy INS is required. And on the other hand, the INS-based motion compensation should be assisted by an auto focus approach.

III. THE CHARACTERISTIC OF FMCW SAR IMAGING

According to the mission requirements, conventional single channel FMCW SAR is not suitable for near-space remote sensing. Multi-channel technology should be introduced to conventional FMCW SAR.

In principle, digital beamforming technology combined with multiple receiver channels can be considered as a method of azimuth ambiguity resolution. A multi-channel reconstruction algorithm for pulsed SAR is presented in [11] and the derivation of the reconstruction filter matrix $\mathbf{P}(\mathbf{f})$ can also be seen detailed in the literature. The reconstruction algorithm in [11] is based on "stop and go" hypothesis. However, the hypothesis is not valid for FMCW SAR.

The reconstruction filter matrix $\mathbf{P}(\mathbf{f})$ is determined by the impulse response function of every receive channel, one of which can be described as:

$$h_m(t;\Delta x_m) = a_T(t) \cdot a_{R,m}(t) \cdot \exp\left[-j\frac{2\pi}{\lambda}R_{total}(t)\right] \quad (2)$$

where $a_T(t)$ and $a_{R,m}(t)$ are the pattern of transmit antenna and receive antenna of channel m respectively, $R_{taotal}(t)$ is the total range history between the antenna and a specific point target and can be written as:

$$R_{taotal}(t) = \sqrt{R_0^2 + v^2t^2} + \sqrt{R_0^2 + (vt - \Delta x_m)^2} \quad (3)$$

where R_0 is the closest range between the antenna and a specific point target and Δx_m is the separation between phase center of the receiver m and the transmitter. For pulsed SAR, using the "stop and go" hypothesis, $R_{total}(t)$ can be approximated as:

$$R_{total,p}(t) \approx \sqrt{R_0^2 + v^2t_a^2} + \sqrt{R_0^2 + (vt_a - \Delta x_m)^2} \quad (4)$$

where t_a is the slow time or azimuth time. However, the "stop and go" hypothesis is not valid for FMCW SAR. Using the Taylor series expansion method, the total range history in (3) can be approximated as:

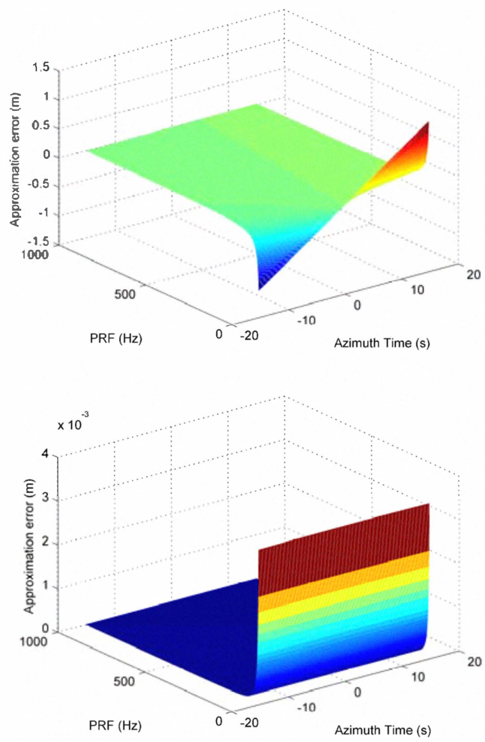

Fig. 1: Approximation error in FMCW SAR system. (Top) neglecting the continuous antenna motion and (down) taking account of the motion.

$$R_{app}(t) \approx \sqrt{R_0^2 + v^2 t_a^2} + \sqrt{R_0^2 + (vt_a - \Delta x_m)^2} + \frac{2v^2 t_a}{\sqrt{R_0^2 + v^2 t_a^2}} t_r \quad (5)$$

where t_r is the fast time.

The approximation error in FMCW SAR is shown in Fig. 1. The top figure is with neglecting the continuous antenna motion and the down figure is with considering this motion. In the simulation, we assume that the closest range R_0 is 28km and the platform velocity v is 100m/s. This error is directly proportional to the azimuth time t_a and is inversely proportional to the pulse repetition frequency (PRF). The maximum error is about 0.9m, which is about 3 times the range resolution. The approximation error should be compensated before the process of the azimuth reconstruction for DBF FMCW SAR.

In order to using the azimuth reconstruction algorithm for pulsed SAR, we should compensate the continuous antenna motion in FMCW SAR. In fact, the continuous motion can be seen as a linear term of azimuth frequency in the range Doppler domain. It is can be compensated integrated with the range cell migration correction.

IV. System Parameters Design

Regarding the geometric resolution in azimuth listed in Table I, we can first estimate the processed Doppler bandwidth B_D in the order of ~350 Hz to achieve the value of 0.3 m. As this assumes the optimum rectangular pattern, the obtained value is a lower bound for the required bandwidth which increases for increasing azimuth dimensions of transmit and receive aperture. In the near-space case, there is no rigorous limit to the PRF of the system. The inequality $M \cdot PRF \geq B_D$ must to be hold, where M is the number of the receive apertures. For example, the PRF should be more than 175Hz when the value of M is equal to 2. The PRF should be as low as possible because of the lower PRF can lead to higher range processing gain. So the PRF is chosen to 175Hz in the two-channel situation. If these parameters can not meet the performance requirements, we should increase the M value and so the value of PRF will be changed accordingly.

To ensure a slant range resolution of 0.3 m, a chirp bandwidth of 500 MHz is necessary and hence the appropriate bandwidth for the required ground range resolution of 0.3 m is given by the projection of the slant range on ground. This means that depending on the incident angle θ_i a bandwidth of $500/\sin(\theta_i)$ MHz is necessary. Using the system geometry parameters listed in Table I, the transmitted signal bandwidth should be up to 1GHz. The main system parameters of two-channel FMCW SAR are shown in Table II.

TABLE II. System parameters

Parameter	value
RF center frequency	15GHz
Number of Receive Apertures	2
Processed Bandwidth	333Hz
PRF	175Hz
Transmitted Signal Bandwidth	1GHz
Range Processing Gain	66dB
Transmitted Power	5W

V. System Performance Analysis and Simulation

A. Performance Analysis

The NESZ is a quantity directly related to SAR imaging performance, which is defined as the target RCS when the signal noise ratio (SNR) of the image is equal to one [12]. The NESZ of DBF FMCW SAR can be expressed by:

$$NESZ = \frac{(4\pi)^3 R^4 \sin\phi K T_0 F B_N L_s}{P_t G_{tr} G_{re} \lambda^2 \rho_a \rho_r G_a G_r} \quad (6)$$

where ϕ is the incident angle, K is the Boltzmann constant, T_0 is the system noise temperature, F is the receiver noise figure, B_N is the noise bandwidth, L_s is the loss factor, P_t is the transmitted signal power, G_{tr} is the transmit antenna gain, G_{re} is the receive antenna gain, ρ_a and ρ_r are the azimuth and range resolution respectively and G_a and G_r are the azimuth and range processing gain respectively.

Compared with classic FMCW SAR, the transmit and receive antenna gain of DBF FMCW SAR are not equal. Its PRF is lower without azimuth ambiguity, and then higher range processing gain is obtained. The sampling frequency is also lower.

B. Performance Simulation

The parameters of DBF FMCW SAR for near-space vehicles are listed in Table I and Table II.

With these parameters, NESZ for DBF FMCW SAR on near-space vehicles has been calculated over a range of incidence angles, which is shown in Fig. 2. The result for classic system is also shown in Fig. 2. DBF FMCW SAR achieves a NESZ below -10 dB along all the swath. 5 W of transmitted power is sufficient to image vegetation and farmland. However, the result of classic FMCW SAR in the edge of the swath is only -5dB, which is not sufficient to obtain good far-range imagery. The reason is that there are higher receive antenna gain and range processing gain for DBF FMCW SAR.

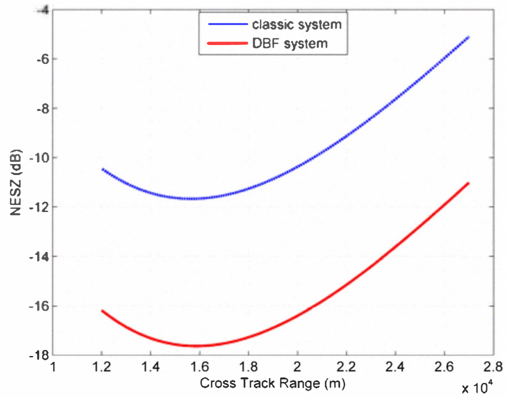

Fig. 2: NESZ versus cross track range for DBF (solid) and classic FMCW SAR (dotted)

VI. DISCUSSIONS

A multi-channel receive antenna FMCW SAR system combined with DBF is introduced, which is suitable for near-space vehicles. The continuous antenna motion in FMCW SAR can not be neglected. The error caused by the continuous motion should be compensated when using conventional azimuth reconstruction algorithm. An example system is also given and its performance is analyzed compared with classic FMCW SAR.

DBF FMCW SAR overcomes the limitation of high PRF caused by high azimuth resolution. It has higher receive antenna gain and range processing gain than classic system. It may also obtain potential benefits for moving target indication (MTI). The size and weight of receive antenna are increased at the same time, which is another challenge for the miniature characteristic of FMCW SAR. Future works include performance analysis thoroughly, MTI and the miniaturization of the system.

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